Temperature and Mortality in New York City:

Past, Present and Future

Elisaveta P. Petkova

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I PREFACE

The complex interplay between climate change, demographics and socioeconomic conditions is transforming the global environmental health landscape. In the aftermath of recent heat waves around the world, especially the 2003 heat wave in Europe, heat is being recognized as an emerging public health issue worldwide, particularly in urban areas.

This work explores the historical and future heat-related mortality in New York City, from the beginning of the 20th until the end of the 21st century. New York City is among the largest cities in the world and has been a thriving metropolis over the entire period covered by this study. The unique makeup of the city makes it particularly suitable for studying the impacts of heat over an extended period of time. The presented work encompasses multiple domains of knowledge and illustrates the necessity for applying highly interdisciplinary approaches in addressing the emerging challenges of our time.

The background chapter provides an overview of methodological approaches and findings from previous studies with direct relevance to the specific aims of this work. Chapter I is focused on characterizing the impacts of heat on daily mortality since 1900. Here, heat effects are presented in a historical context and changes over time are analyzed and discussed. Chapter II provides a comparative assessment of recent historical and heat impacts until 2100 in New York City, Boston and Philadelphia. This analysis illustrates the differences and similarities between heat impacts in New York City and the other two major urban areas in the U.S. Northeast. Chapter III provides a more comprehensive assessment of future heat-related mortality in New York City under a number of adaptation, climate change and demographic scenarios. The concluding chapter presents a summary of findings and recommendations for future research.

II BACKGROUND

II.1 Characterizing Historical Heat-Related Mortality

II.1.1 Definitions of Heat-Related Mortality

Estimates of heat-related mortality depend on the underlying definition of heat-related deaths. Two different approaches are commonly employed to estimate excess mortality due to heat – a very conservative approach that only takes into consideration deaths that have been listed as heat-related (or due to hyperthermia) on death certificates, and a more comprehensive approach that estimates the total burden of heat-related mortality based on deaths for specific or all causes. According to the criteria established by the National Association of Medical Examiners, hyperthermia is diagnosed when core body temperature exceeds 105˚F (40.6˚C) or when there is evidence of high environmental temperature prior to death (Donoghue et al. 1997). However, since clinical and autopsy findings of hyperthermia are nonspecific (Nixdorf-Miller et al. 2006), deaths are often misclassified. Thus, the conservative estimate of deaths directly attributable to extreme heat is likely to significantly underestimate the actual effect size and is rarely utilized in studies. Therefore, this, as other previous studies (II.1.5) defines heat-related mortality as excess all-cause mortality.

II.1.2 Exposure Metrics

Previous studies have used various exposure metrics to quantify the effects of temperature on mortality. Most studies have used daily mean, minimum or maximum temperature or composite indices of temperature, humidity and/or other variables. For example, two of the most commonly used indices, the Heat Index or apparent temperature and the Humidex, combine temperature and humidity. Other exposure metrics such as the Temporal Synoptic Index and Spatial Synoptic Indexbased are based on the Synoptic Climatological Classification (Kalkstein et al.1996) and include measures of wind speed, barometric pressure, cloud cover and others. In a recent study assessing the predictive ability of various exposure metrics, including mean, minimum and maximum temperature, as well as apparent temperature and the Humidex, Barnett and colleagues (2010) concluded that all of the metrics were highly correlated and none of them had a better predictive ability. Thus, the authors concluded that choice of en exposure metric should be based on practical considerations such as data availability. In an analysis of heat-related mortality in New York City, various exposure metrics were also found to perform similarly as predictors of heat-related mortality (Metzger et al. 2010).

II.1.3 Heat-Wave vs. Heat-Related Mortality

The impacts of heat on mortality can be assessed in the context of specific heat wave episodes or by analyzing the relationship between elevated temperatures and mortality over long periods of time. Studies utilizing the first approach assess the impacts of temperature on mortality during particularly severe heat waves, and compare those data to periods of normal temperatures. This has been used for example to quantify the impact of the European heat wave of 2003 (Le Tertre et al. 2006), as well as the 1993 heat wave in Philadelphia (Mirchandani et al. 1996) and the 1995 heat wave in Chicago (Semenza et al. 1996, Whitman et al. 1997). Early studies of heat-related impacts in New York City have also focused on specific health wave episodes (Marmor 1975, Ellis and Nelson 1978). Anderson et al. (2011) examined mortality risk during heat waves in 43 U.S. cities between 1987 and 2005 and found that mortality increased 3.74% during heat wave days compared to non-heat wave days nationally. The second approach involves regression analysis of long records of daily deaths vs. temperature in a city. The goal here is to fit an exposure-response function that can be used to quantify the excess mortality that occurs above arbitrarily chosen threshold temperatures. This approach has two advantages. First, it provides a comprehensive assessment of the heat-mortality relationship at a particular location that allows characterizing possible changes over time. Second, the derived heat-mortality response functions can be used in estimating potential future impacts of heat under different climate change scenarios. This was the approach of choice in this work due to its focus on long term historical and future heat-related mortality. Details on the methods used are provided in Chapters I-III.

II.1.4 Vulnerability Factors

In western societies, including the United States, the elderly population aged 65 and over is most vulnerable to heat-related mortality (Medina-Ramón et al. 2006, Baccini et al. 2008, Basu et al. 2002, 2008, 2009). However, Basu and colleagues (2008) reported that children and infants may also be at increased risk. Increased susceptibility among children under 15 has been reported in Mexico (O'Neil et al. 2005a), Brazil (Gouveia et al. 2003) and other countries (Xu et al. 2012). Pre-existing medical conditions such as diabetes, cardiovascular, respiratory or mental conditions have also been found to increase susceptibility to heat (Schwartz 2005, Medina-Ramón et al. 2006, Baccini et al. 2008, Schifano et al. 2009, Hajat et al. 2010). Some studies have reported female gender (Bell et al. 2008, Basu et al. 2008) as well as non-white race (Swartz 2005, O’Neil et al. 2005b, Medina-Ramón et al. 2006, Basu et al. 2008) to be risk factors. In addition, people living in social isolation, deprivation and/or poverty may also be more vulnerable (Semenza et al. 1999, O’Neil et al. 2003, Vandentorren et al. 2006). Air conditioning prevalence has been found to be among the most critical risk factors for heat-induced mortality (O’Neil et al. 2005b, Medina-Ramón et al. 2007). One study found that black households were almost half less likely than white household to have central air conditioning, and at the same time heat was more strongly associated with deaths among blacks compared to whites (O’Neil et al. 2005b).

II.1.5 Study Designs

Time series and case-crossover study designs are most commonly used in the assessment of the impacts of heat on mortality. In time series analysis, the association between daily deaths counts, used as the outcome measure and daily measurements of the temperature exposure metric of choice, is assessed over long periods of time. Smooth functions of time, and sometimes weather variables, are used to control for confounding. The case-crossover design, initially introduced in the 1990s (Maclure 1991), was subsequently developed further and gained popularity in air pollution and temperature epidemiology (Schwartz 2004, Stafoggia et al. 2006, 2008, Bell et al. 2008). In case-crossover studies, exposure during a case event is compared with the exposure during selected control periods before or after the case event. Studies comparing the use of time series and case-crossover study designs in assessing temperature-related mortality concluded that both result in comparable estimates (Basu et al. 2005, Zanobetti and Schwartz 2008). In a review ambient temperature and mortality studies published since 2001, Basu (2009) concluded that temperature has an independent effect on mortality and that the confounding effects of air pollutants are relatively small.

II.1.6 Previous Studies

II.1.6.1 North America

Curriero and colleagues (2002) examined the temperature-mortality relationships in 11 cities in eastern U.S. between 1973–1994, finding a more pronounced effect of cold temperatures in the cities located more south and a more pronounced effect of warmer temperatures in the cities located more north. The paper calculated minimum mortality temperatures as well as hot and cold slopes for each city. Of the 11 cities, Baltimore, MD had the highest hot slope (6.56) followed by New York (6.28), Philadelphia (6.1) and Boston (5.83). The lowest hot slope of 1.43

was reported in Tampa, FL. Basu et al. 2008 examined summer temperature-mortality nine California counties between 1999 and 2003 and a 2.3% increase in mortality for every 10˚C increase in temperature. In a study of temperature and cardiorespiratory mortality among the elderly in the 20 largest U.S. metropolitan areas, Basu et al. 2005 found the strongest associations in the summer. The study estimated the increase in risk of cardiorespiratory mortality associated with an increase of 10°F. For the U.S. Northeast, an odds ratio of 1.08 (0.92-1.26) was reported. Anderson and Bell (2009) examined the temperature-mortality relationships in 107 U.S. communities between 1987 and 2000 and found that heat, defined as the 99th vs. the 90th percentiles of community-specific temperatures was associated with an overall increase of 3.0% in mortality risk.

A couple of studies have examined heat-mortality relationships in Canadian cities. Kolb et al. 2007 examined the associating between weather and daily mortality among individuals aged 65 or older diagnosed with congestive heart failure in Montreal between 1984 and 1993. The study found a substantial heat effect about a threshold of 25 ˚C reported an odds ratio of 1.2 for 25-30˚C maximum temperature. In Toronto, Smoyer-Tomic et al. 2001 reported increased mortality in individuals older than 65 with increasing humidex and apparent temperature between 1980 and 1996. In Montreal, a temperature increase from the 75 to the 99th percentile was associated with a by 28.4% increase in non-accidental mortality between 1984 and 2007 (Goldberg et al. 2011)

II.1.6.2 Europe

Baccini and colleagues (2008, 2011) characterized the summer heat-mortality relationships between 1900 and 2000 and quantified the mortality burden attributable to heat in 15 European cities: Athens, Barcelona, Budapest, Dublin, Helsinki, Ljubljana, London, Milan, Paris, Prague, Rome, Stockholm, Turin, Valencia and Zurich. The city-specific heat-mortality curves were found to have a V shape, with heat effect thresholds varying by city (Baccini et al. 2008). In the second study, the authors reported elevated summer mortality due to heat in all cities except Dublin. The largest impacts were estimated among individuals 75 years of age or older and in two continental (Paris and Budapest) and three Mediterranean (Barcelona, Rome and Valencia) cities (Baccini et al 2011).

Pattenden et al. (2003) evaluated the temperature-mortality relationships for London, U.K. as well as Sofia, Bulgaria over two four year periods. The study reported a mortality increase of 1.9% (1.4 to 2.4) in London and 3.5% (2.2 to 4.8) in Sofia per 1˚C rise above the 95th centile of the two day mean temperature. Hajat et al. 2002 reported an increase of 3.34% per 1˚C above the 97th percentile for London. In Dublin, Ireland, a study that examined data from 1980 to 1996 reported a 0.4% increase in total mortality for each 1˚C increase in temperature, with most immediate effects on cardiovascular mortality (Goodman et al. 2004). A study of summer heat-related mortality in 10 regions in England and Wales between 1993 and 2006 reported a 2.1% average linear increase per 1°C above the location-specific thresholds (Gasparrini et al 2012).

Michelozzi et al. 2006 evaluated geographical and temporal variations in the heat-related mortality in four Italian cities: Bologna, Milano, Roma, and Torino. Heat impacts varied by city and time period. The reported heat effect per 1˚C above the city-specific threshold was highest in Roma, followed by Milano, Torino and Bologna. Another study (Stafoggia et al. 2006) has also investigated the effects of heat on mortality in the same four cities with focus on demographic characteristics, socioeconomic and health status. The study reported an overall odds ratio of 1.34 (1.27-1.42) at 30˚C relative to 20˚C.

II.1.6.3 Other Locations

Bell and colleagues (2008) investigated heat-related mortality in Mexico City, Mexico, Sao Paulo, Brazil and Santiago, Chile between 1998 and 2002. Individuals 65 years of age or older were most susceptible and experienced a mortality risk increase of 3.22% for Mexico City, 6.51% for Sao Paulo and 2.69% for Santiago. The temperature effect was estimated for the 95th compared to the 75th temperature percentiles (Bell et al. 2008). In another international study, McMichael and colleagues examined the effects of temperature on mortality in Delhi, Monterrey, Mexico City, Chiang Mai, Bangkok, Salvador, Sao Paulo, Santiago, Cape Town, Ljubljana, Bucharest and Sofia. The study found heat effects in all populations except Chiang Mai and Cape Town with heat thresholds being higher in cities with warmer climates. A high heat threshold of 27.5˚C was observed in Beirut, Lebanon where every 1˚C rise above this threshold resulted in a 12.3% increase in mortality (El-Zein et al. 2004). Heat thresholds between 27 and 29.7˚C were also observed across 6 Korean cities. An increase of 1˚C above the city-specific thresholds in Seoul, Daegu, Incheon, and Gwangju were associated with 16.3, 7.01 and 6.73 increase in daily mortality, respectively. A heat effect was also observed in Christchurch, New Zealand (Hales et al. 2000) where each 1˚C increase above the third quartile of maximum temperature was associated with a 1% increase in all-cause mortality and a 3% increase in respiratory mortality. The population of Sydney and especially women and the elderly, was also found to be vulnerable to heat (Vaneckova et al. 2008). Heat effects were, however, less pronounced compared to some U.S. and European cities, according to the study.

II.2 Projecting Future Heat-Related Mortality

II.2.1 Approach and Challenges

Projecting future heat-related mortality is a complex task. A common approach involves characterizing location-specific heat-mortality relationships that are subsequently applied to downscaled climate projections for the future period of interest. Assumptions at each stage of this process impact future projections. For instance, the choice of emission scenarios and climate models can result in substantial variability in the future mortality estimates. Assumptions about population change and heat adaptation can also play a critical role in long term projections. This section provides an overview of the Special Report on Emissions Scenarios, Representative Concentration Pathways (RCPs) published in the Intergovernmental Panel on Climate Change Fifth Assessment Report, and temperature projections. Population change and heat adaptation, as they relate to projecting future heat-related mortality, are also discussed.

II.2.1.1 Emission Scenarios and Representative Concentration Pathways (RCPs)

Emission scenarios are utilized in climate research in order to characterize how future greenhouse gas emissions may vary depending on various socio-economic, environmental and technological parameters. Emissions scenarios do not represent future predictions and none of them is more likely than another. Rather, based on expert consensus, they represent various plausible future emissions depending on underlying societal factors. Emission scenarios are developed on a long term scale in order to capture the response of the climate system to changes in greenhouse gas concentrations and allow sufficient time for possible socio-economic, environmental and technological changes to take place (Moss et al. 2010).

The IPCC has developed several sets of scenarios since IPCC's First Assessment Report (IPCC 1990), including the six IPCC scenarios, IS92a to f, developed in 1992 (Leggett et al. 1992) and published in the 1992 Supplementary Report to the IPCC Assessment. In 2007, IPCC has published a Special Report on Emissions Scenarios (SRES) where four ‘families’ of scenarios (A1, A2, B1, and B2) were developed to characterize possible future developments in the global environment that could result in different greenhouse gas emission levels (Nakicenovic, N. et al. 2000). According the these scenarios, future levels of greenhouse gas emissions depend on a complex mix of driving forces including socio-economic development, demographic change, political conditions and the rate of adoption of new technologies (*Figure I.1*). For example, the A2 scenario assumes a highly heterogeneous world, characterized by continuous population growth, regionalization, uneven per capita economic growth, slow technological change and a focus on wealth generation. The B1 scenario, on the other hand assumes a more homogenous world with global population that starts declining after reaching a peak at mid-century. In B1, the world economy is characterized by reduced material intensity, rapid technological change and a focus on sustainability and equity. Global average temperature is projected to increase by around 3.4˚C under the A2 scenario and 1.7˚C under the B1 scenario.

The IPCC emission scenarios have proved to be valuable in climate modeling, impact assessment, adaptation and mitigation. For example, previous studies have used a high (A2) and a low (B1) emission scenario to derive an upper and lower bound for future heat-related mortality in New York City (Knowlton et al. 2007, Li et al. 2013). The improvements in the scenario’s methodology and, the introduction of multiple storylines and baseline scenarios, in particular, has enhanced the credibility of the scenarios published in the SRES Report (Girod et al. 2009).

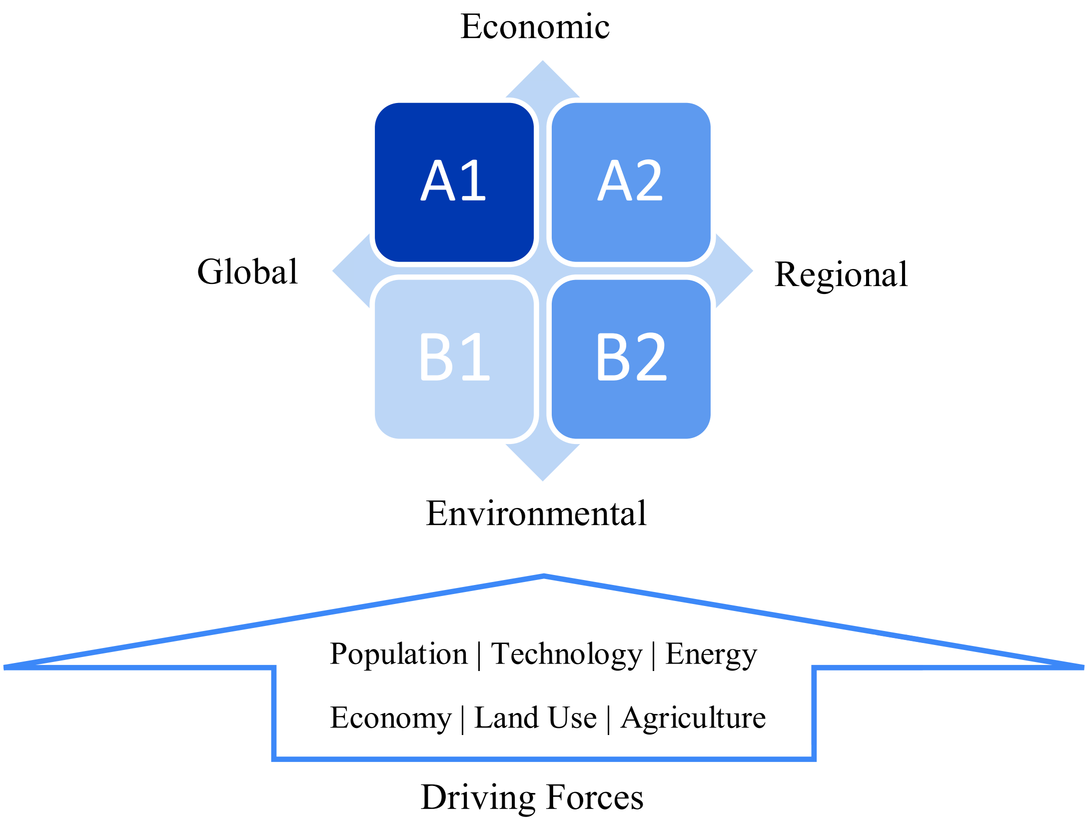

Figure I.1 SRES storylines. Adapted from Nakicenovic, N. et al. 2000

Until the Fifth Assessment Report, emissions scenarios were developed as a part of a sequence starting with consideration of socio-economic factors (Moss et al. 2010). Next, emissions scenarios were utilized in projecting future atmospheric greenhouse gas concentration and future changes in climate based on various General Circulation Models (GCMs). Finally, these scenarios were used in impact assessment studies (*Figure I.2*). Due to the multiple stages and scientific communities involved, the process was cumbersome and time consuming. A new, parallel approach was developed for Fifth Assessment Report in order to allow a more efficient collaboration across research communities and lead to faster advances in climate research (Moss et al. 2010) (*Figure I. 2*).

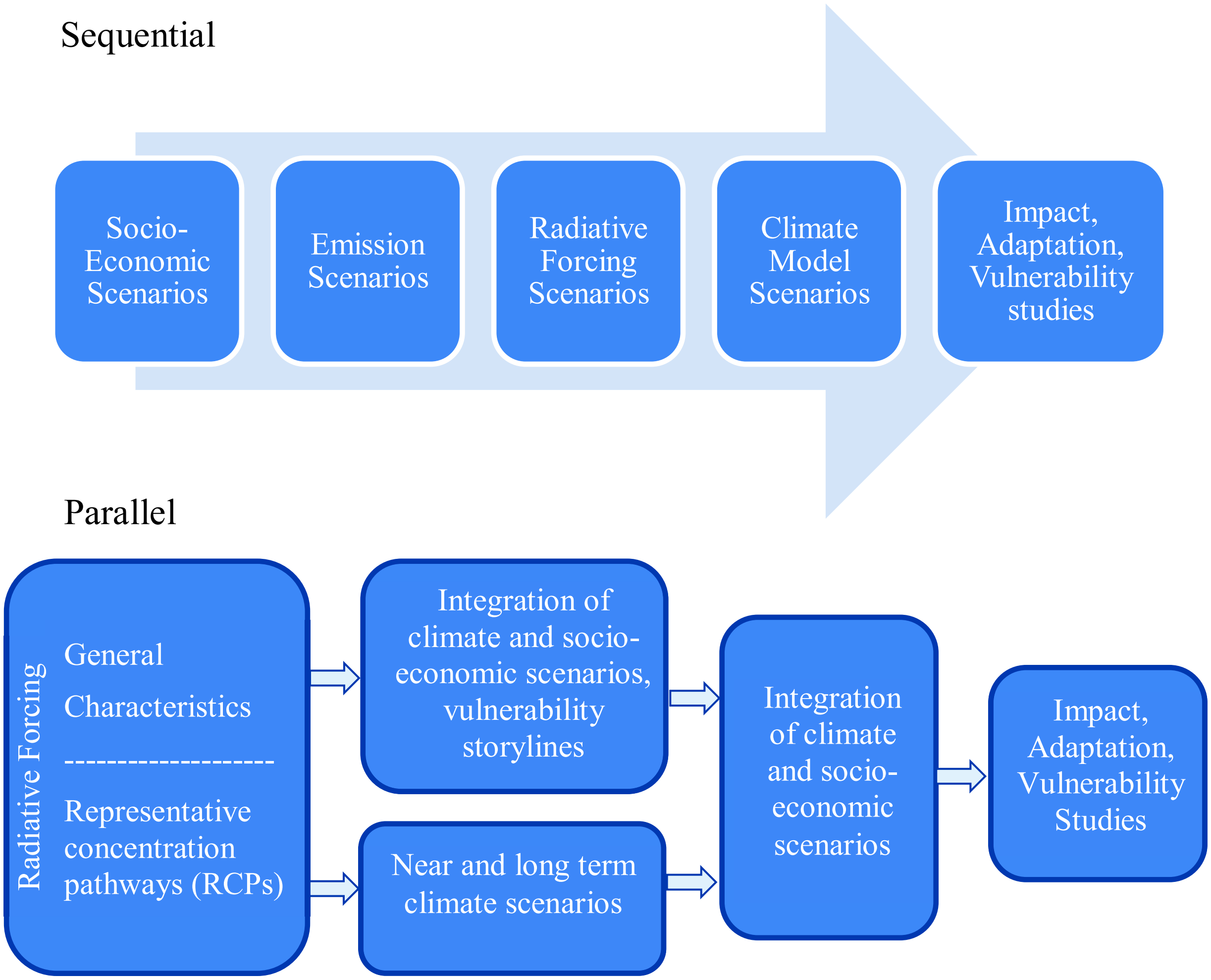

Figure I.2 Sequential vs. Parallel Approach to Scenario Development. Adapted from Moss et al. 2010

As a part of this approach, four Representative Concentration Pathways (RCPs) (van Vuuren et al. 2011) are developed at the onset. The four RCPs represent four different radiative forcing scenarios, RCP2.6, RCP4.5, RCP6, and RCP8.5, corresponding to +2.6, +4.5, +6.0, and +8.5 W/m^2, respectively (*Table I.1*).The RCPs along with the model used to derive them are presented in *Table I.1*).

	Description	**Reference**
RCP8.5	*"Rising radiative forcing pathway leading to 8.5 W/m2 in 2100"*	Riahi et al. 2007, 2010 Rao & Riahi 2006
RCP6	*"Stabilization without overshoot pathway to 6 W/m2 at stabilization after 2100"*	Fujino et al. 2006 Hijioka et al. 2008 Masio et al. 2011
RCP4.5	*"Stabilization without overshoot pathway to 4.5 W/m2 at stabilization after 2100"*	Smith and Wigley 2006 Clarke et al. 2007 Wise et al. 2009 Thomson et al. 2011
RCP2.6	*"Peak in radiative forcing at ~ 3 W/m2 before 2100 and decline"*	van Vuuren et al. 2006, 2007, 2011b

Table I.1 Representative Concentration Pathways (RCPs) published in the Intergovernmental Panel on Climate Change Fifth Assessment Report.

Using the four RCPs, socio-economic and climate scenarios are being developed in parallel by various research groups (*Figure I.2*). In contrast with the previous approach, the new underlying assumption is that RCPs can be achieved through a wide range of socio-economic, environmental and technological pathways. This flexibility allows the exploration of various combinations of factors, including the potential impacts of specific climate change mitigation and adaptation policies. Thus, in addition to improved efficiency, the new approach is aimed at fostering interdisciplinary collaborations and developing even more comprehensive emissions scenarios.

II.2.2 Global Circulation Models and Temperature Projections

Global Circulation Models (GCMs) are the most advanced tool for global climate system simulation. Nonetheless, their resolution is quite coarse, usually 150-400 km by 150-500 km. Downscaling, or generating finer spatial scale data from GCMs, can be useful for developing locally relevant temperature projections that can be used in assessing future temperature-mortality impacts. There are two general approaches to model downscaling: dynamical and statistical. Dynamical downscaling is a computation-intensive process in which a regional climate model, driven by GCM boundary conditions, is used to generate finer-scale data. In statistical downscaling, large scale climate variables are statistically related to regional climate and the established relationships are used to simulate regional climate according to GCMs outputs.

Statistically downscaled mean temperature projections for Boston, Philadelphia and New York from 33 GCMs used in the Intergovernmental Panel on Climate Change (IPCC)'s Fifth Assessment Report (AR5), in conjunction with RCP 4.5 and RCP 8.5 were used in this work. Details are provided in Chapters II and III.

II.2.3 Heat Adaptation

Populations have the capacity to gradually adapt to high temperatures as demonstrated by several studies (Davis et al. 2003, Carson et al. 2006). Adaptation measures can be classified based on the timing, goal and motive of their implementation. Broadly, adaptation can be classified as planned or autonomous depending on whether it results from reactive or anticipatory actions (IPCC 2007).

Heat adaptation is a complex process that may involve physiological, behavioral and technological components. Technological advances such as the introduction of heat warnings and the increased prevalence of air conditioning are likely to play a critical role in the process.

Increased awareness of in heat impacts on mortality and morbidity has led to the introduction of heat warning nationwide and in major urban areas. The National Weather Service (NWS) local offices issue heat advisories and excessive heat warnings since the summer of 1993. Until 2003, these alerts were based on the same heat index (HI) thresholds for the entire country. In 2003, thresholds were slightly adjusted to account for regional differences. Excessive heat warnings and advisories are currently issued using the Heat Index (HI), based on Steadman's models (Steadman 1979, Steadman 1984). The NWS offices in Boston, New York City and Philadelphia make the decisions about issuing heat warnings, watches and advisories and may specify local heat advisory and warning criteria. In the Northeast, a heat advisory is currently issued when the heat index is projected to reach 100 to 104°F for any length of time or 95 to 99°F for 2 or more consecutive days. Heat warnings are issued when the heat index is forecasted to exceed 105°F for minimum 2 consecutive hours.

A couple of studies have attempted to evaluate the effectiveness of heat warnings in preventing heat-related mortality. Ebi et al. (2004) performed a cost-benefit analysis of the utilization if the Philadelphia HHWS between 1995 and 1998. The paper explored the statistical relationship between excess mortality among people 65 years of age or older and various heat wave and weather variables and concluded heat warnings saved 2.6 lives per day on average or a total of 117 lives during the studied period. Alberini et al. (2008) assessed the effect of NWS heat warnings on excess mortality in 86 counties in the 50 major metropolitan statistical areas using data from 1985 to 2005. Heat warnings were found to be most effective in the Midwest, Northeast and the Mid-Atlantic and not effective in the South, probably due to adaptation to local climate conditions. Although an evaluation of the effectiveness of heat warnings on heat-related mortality is beyond the scope of this study, this is an important factor to consider.

Previous studies have also demonstrated that air conditioning use is among the most important modifiers of the heat-mortality relationship but estimates vary significantly. Detailed data on air conditioning use is unfortunately not available.

Several previous studies focused on assessing future heat-related mortality have incorporated models of heat adaptation in the derived projections. These studies are discussed in *II.2.5*.

II.2.4 Population Change

Many recent studies have indicated that the elderly may me most susceptible to the impacts of heat. At the same time, individuals aged 65 or older constitute the fastest growing segment of the U.S. population according to the U.S. Census Bureau. Due to the demographic shift towards the elderly, a growing segment of the population may be at risk to the impacts of heat, leading to possible increases in heat-related mortality. Since city-specific population projections are rarely available beyond several decades into the future, many studies have assumed no demographic changes while projecting future heat-related mortality. Previous studies that have incorporated population projections in their estimates of future heat-related mortality are discussed in *II.2.5*.

II.2.5 Previous Studies

A brief summary of studies that have projected future heat-related mortality is presented in *Table I.2.* The majority of these studies concluded that climate change will result in an increase of heat-related mortality. A few studies that focused on quantifying both heat- and cold- related mortality found that the increases in heat-related mortality may be offset by decreases in cold-related mortality in some cities (Guest 1999, Martens 1998). Net decreases, however, are more likely to be the case in cities currently experiencing higher burden of cold-related mortality (Martens 1998) which is not the case in the U.S. urban Northeast. For example, the most recent study by Li and colleagues (2013) projected substantial increases of net annual temperature-related mortality in New York City across a wide range of climate models and scenarios. In addition, although quantifying net annual temperature-related mortality is without a doubt of great importance, findings cannot easily translate into policy actions because measures to reduce cold- and heat-related mortality take place separately. This work focuses on heat-related mortality because it has been recognized as an issue of critical importance in New York, Boston and Philadelphia and relevant research is necessary to support heat adaptation strategies in the region.

As discussed in II.2.3 and II.2.4, acclimatization and population change will potentially play a crucial role in shaping the future burden of heat-related mortality. Given the challenges involved with modeling both factors, only half of the studies in *Table I.2* have included adaptation scenarios and only five have considered population change.

Studies that have included adaptation scenarios have been utilized several approaches in modeling heat adaptation. One approach is to use temperature-mortality curves from ‘analogue cities’ that currently have climates similar to those projected at a location of interest (Kalkstein and Greene 1997; Knowlton et al. 2007). Similarly, the hottest ‘analogue summers’ from the same location have been used by Hayhoe and colleagues (2004) by applying their temperature-mortality curves to future periods. Another approach to modeling adaptation is to develop scenarios for acclimatization to specific increases in temperatures over time (Gosling et al.2009, Dessai et al.; Kalkstein et al 1997). A weakness of these approaches is that adaptation is not modeled using long term historical data from the same location. This issue is discussed further in Chapter III, where we propose a heat adaptation model for New York City based on historical data and illustrate its application in projecting future heat-related deaths.

Since future population data is not readily available, most previous studies have assumed no population change. Some of the studies have used population projections available until 2025 (Jackson et al.2010) or 2030 (Guest 1999) but assumed constant population beyond that. Dessai and colleagues (2003) have adopted a more comprehensive approach by applying the population growth rates from the corresponding SRES storylines (A1, A2, B1 and B2) to the 1990 population in deriving estimates of heat-related mortality in Lisbon until 2100. In this study, we collaborate with the Cornell program on Applied Demographics to develop population change scenarios for New York City until 2100 and use them in projecting heat-related deaths among the elderly (Chapter III). The novel approach to modeling adaptation and developing population scenarios for New York City demonstrated in Chapter III can be further developed and applied for other cities.

Only three of the identified studies published to date have utilized multiple GCMs (Peng et al. 2011, Ostro et al. 2012, Li et al. 2013), while most other studies have focused on up to four. Given the substantial variation in the temperature projections depending of the choice of GCMs, the use of multiple models allows a more comprehensive assessment of potential mortality impacts. Here we utilize projections from 33 different GCMs in order to derive a wider range of estimates for future heat-related mortality. In addition, we haven’t been able to locate studies quantifying heat related impacts under the new RCPs. In this work, we utilize the next-generation climate models and RCPs in order to provide a timely assessment of heat-related mortality that can be of value to the science community, policy makers and the public.

Table I.2 Studies of future heat-related mortality

Reference	Location(s)	Projection Period	SRES scenarios	Climate models	Adaptation	Population Change	Main Findings
Baccini et al. 2011	15 European cities	2030	A1B, A2, B1	n/a	n/a	n/a	• *Heat highest impact in three Mediterranean cities (Barcelona, Rome and Valencia) and in two continental cities (Paris and Budapest);* • *Largest impact on persons over 75 years but heat-attributable deaths also found among younger adults in some cities;* • *Heat-attributable deaths substantially increased under warming scenarios.*
Dessai 2003	Lisbon (Portugal)	2020s, 2050s	n/a	PROMES, HadRM2	Acclimatization to an extra 1˚C (compared to the 1990s) to be reached after three decades	Population scenarios constructed according to the IPCC SRES	• *Estimated annual heat-related death rates per 100,000 to increase from 5.4 to 6 for 1980–1998 to 5.8 to 15.1 by the 2020s and to 7.3 to 35.6 by the 2050s;* • *Lower burden of deaths if*

							acclimatization is considered.
Doyon et al. 2008	Québec (Canada)	2020s, 2050s, 2080s	A2, B2	HadCM3	n/a	n/a	• *Projected increased summer mortality that was not balanced by decreases in fall and winter mortality;* • *Summer increase and the annual mortality range from about 2% and 0.5% for the 2020 period, to 10% and 3% for the years around 2080.*
Gosling et al. 2009	Boston, Budapest, Dallas, Lisbon, London and Sydney	2080s	A2, B2	HadCM3	Acclimatization to an extra 2˚C or 4˚C relative to present (1961–1990)	n/a	• *Summer heat-related mortality rates per 100,000 lowest in Sydney and highest in Lisbon;* • *Acclimatization to an extra 2°C in mean temperatures reduced future heat-related mortality by approximately half; acclimatization to 4°C would result in further decreases.*

Guest 1999	Adelaide, Brisbane, Melbourne, Perth, Sydney (Australia)	2030	n/a	CSIRO	n/a	Population projections until 2030	• *Estimated climate-attributable summer and winter mortality resulted in net mortality decrease of 10% in 2030.*
Hayhoe et al. 2004	Los Angeles (U.S.)	2080s	A1fi, B1	PCM, HadCM3	The five hottest “analog summers” from the historical period that best duplicate the summers as expressed in the climate change scenarios.	n/a	• *Heatwaves and extreme heat in Los Angeles to quadruple in frequency and heat-related mortality to increase two to three times by the end of the century under B1.* • *Heatwaves in Los Angeles to become six to eight times more frequent and heat-related excess mortality to increase five to seven times under A1fi,*
Hayhoe et al. 2010	Chicago (U.S.)	2020s, 2050s, 2080s	A1fi, B1	GFDL CM2.1, HadCM3, and PCM	n/a	n/a	• *Projected that annual average mortality rates projected will equal those of 1995 under lower emissions and be twice 1995 levels under higher emissions;* • *Concluded that a heat event like the 2003 European heat wave may result in more than ten times the*

							annual average heat-related mortality.
Jackson et al.2010	Washington State (U.S.)	2025, 2045, 2085	A1B, B1	PCM1, HADCM	n/a	constant population beyond 2025	• *Individuals 65 and older to experience the largest number of heat-related deaths in all periods and scenarios in the greater Seattle area.* • *96 excess deaths projected in 2025, 148 excess deaths projected in 2045 and 266 excess deaths projected in 2085 among individuals 65 and older under the middle scenario*
Kalkstein et al 1997	44 U.S. cities	2020s, 2050s	n/a	GFDL,UK MO,MPI	used "analogue cities" where present climate is similar to that expected in target locations	n/a	• *Projected a sizable net increase in weather-related mortality with summer mortality to increase dramatically and winter mortality to decrease slightly, even if acclimatization takes place.*

Knowlton et al. 2007	New York City (U.S.)	2050s	A2, B2	GISS–MM5	used 2 "analogue cities" where present temperatures similar to that expected in the 2050s for New York City		• *Projected heat-related mortality to increase from 47% to 95% by the 2050s compared to the 1990s, with a mean 70% increase* • *Acclimatization reduced projected summer heat-related mortality by about 25%.* • *Urban counties experienced greater numbers of deaths and smaller percentage increases compared to less-urbanized counties.*
Li et al. 2013	Manhattan (U.S.)	2020s, 2050s, 2080s	A2, B1	multiple	n/a	n/a	• *Projected warm-season increases and cold-season decreases in temperature-related mortality, with a positive net annual temperature-related mortality in all cases.*

Martens 1998	Mauritius, Buenos Aires, Caracas, San Jose, Santiago, Beijing, Guangzhou, Singapore, Tokyo, Amsterdam, Athens, Budapest, London, Madrid, Zagreb, Los Angeles, New York, Toronto, Melbourne, Sydney	2040–2100	n/a	ECHAM1-A, UKTR, GFDL89	physiological and socioeconomic adaptation considered (change in 'comfort temperature')	n/a	• *Concluded that global climate change is likely to lead to a reduction in mortality rates due to decreasing winter mortality in most of the cities included in the study;* • *The observed effect most pronounced for cardiovascular mortality in elderly people in cities that currently have temperate or cold climates.*
Martin et al. 2012	Calgary, Edmonton, Halifax, Hamilton, London, Montreal, Ottawa, Quebec City, Regina, Saskatoon, St. John's, Toronto, Vancouver, Windsor, Winnipeg (Canada)	2040s, 2060s, 2080s	A2	CRCM4	n/a	n/a	• *Predicted an increased burden of annual temperature-related mortality due higher temperatures in Hamilton, London, Montreal and Regina and decreases in the rest of the cities*

Ostro et al. 2012	Barcelona, Tarragona, Lleida, Girona (Spain)	2025, 2050	A1B	multiple	projections for Catalonia until the year 2041 linearly extrapolated to 2050.	n/a	• *Estimated that 520 additional annual deaths attributable to the change in temperature will occur in the four cities in 2025* • *For 2050, the estimated annual deaths increases to 1,610 during the warm season*
Peng et al. 2011	Chicago (U.S.)	2081–2100	A1B, A2, B1	multiple	n/a	used B1, A1 and A2 age-stratified population estimates	• *Chicago could experience between 166 and 2,217 excess , eat wave attributable deaths annually, in the absence of adaptation;* • *Considerable variability in the projections of annual heat wave mortality with choice of climate model being the largest source of variation.*

Sheridan et al. 2012	nine metropolitan areas in California (U.S.)	2030s, 2060s, 2090s	A1fi, A2, B1	CCSM3, CGCM3	Acclimatization accounted for by neglecting heat-related mortality occuring in the first 3 days of a heat event	low, medium and high growth projections until 2100	• *Major urban centers may experience more than a tenfold increase in heat-related mortality in the over 65 age group by the 2090s;* • *Across all regions, acclimatization may reduce heat-related mortality by 37 to 56 % in the 2090s.*

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III RESEARCH AIMS

III.1 Analyze historic heat-related mortality in New York City since the beginning of the 20th century

III.1.1. Analyze historic heat- related mortality and in New York City, from 1900 to 1948 and from 1973 to 2006

III.1.2. Investigate if the heat-mortality response has changed over time during the two time periods

III.1.3. Provide a quantitative assessment on whether adaptation to heat has occurred in New York City since the beginning of the century

New York has experienced remarkable social and technological changes since the beginning of the 20th century, and, as a result the population's sensitivity to heat could have changed considerably over time. We hypothesize that there has been a gradual adaptation to heat, and consequently a decrease in heat-related mortality since the beginning of the century due to various factors, including but not limited to: improved housing conditions, access to ice and cold liquids as well as the introduction and increased use of air conditioning. To test this hypothesis, this study examines daily temperature and mortality data during two periods spanning more than a century in New York City: a historical period between 1900 and 1948 and a more recent period between 1973 and 2006. We investigate how the heat-mortality response has changed over time in both periods and discuss of the observed adaptation patterns and the possible implications of our findings for projecting future impacts of heat on mortality in the city of New York

III.2 Provide an assessment of historical and future heat-mortality in New York City compared to Boston and Philadelphia, 2020s-2100s

III.2.1. Analyze historic heat- related mortality and in New York City, Boston and Philadelphia from 1985 to 2006

III.2.2. Apply the exposure-response relationships between daily temperature and daily mortality developed in III.1. to downscaled temperature projections up to the year 2100 under selected CGMs and RCPs.

III.2.3. Provide an analysis of future heat- related mortality and in New York City, Boston and Philadelphia, 2020s-2100s

New York City, Boston and Philadelphia represent the largest population agglomeration in the country and among the largest in the world. This study aims to characterize the future heat-related mortality impacts in the region as a whole and compare the projected impacts of heat in New York City to these in Boston and Philadelphia. We hypothesize that climate change will result in increased heat-related mortality across the three cities but that they would be most pronounced in Boston where summers are the coolest followed by New York City and finally Philadelphia, where summers are the hottest overall. We test our hypothesis by first characterizing the summer heat-mortality relationships in each city and then applying an ensemble of daily temperature projections based on two RCPs and 33 GSMs to calculating future heat-related mortality. Due to data limitations, this study does not take into consideration population change and adaptations in the projections.

III.3 Quantify future heat-related mortality impacts for New York City

III.3.1. Based on the findings in I., define a baseline period most appropriate for modeling future heat-related mortality and characterize the heat-mortality relationship for New York City during the selected period.

III.3.2. Develop adaptation, population and climate change scenarios to utilize in developing estimates of future heat-related mortality impacts

III.3.3. Apply the heat-mortality relationship between daily temperature and daily mortality developed in III.3.1.to downscaled temperature projections during the 2020s, 2050s and 2080s under the adaptation, population and climate change scenarios identified in III.3.2

This study builds upon findings in I. to develop projections of heat-related mortality in New York City until the 2100. We hypothesize that the future heat-related mortality impacts in New York City will be influenced by three key factors: the demographic characteristics of the population, its sensitivity to heat impacts and the greenhouse gas concentrations in the atmosphere. To characterize the possible impacts of these factors, we develop numerous adaptation, population and climate change scenarios in collaboration with experts in demographic and climate change modeling. The next-generation climate models and Representative Concentration Pathways (RCPs) developed for the Intergovernmental Panel on Climate Change (IPCC)'s Fifth Assessment Report (AR5) are utilized the analyses. The adaptation, population and climate change scenarios together with the heat-mortality relationship model for New York City are used to calculate a range of possible heat-related mortality estimates.

IV CHAPTER I Heat and Mortality in New York City since the Beginning of the 20th Century*

Elisaveta Petkova[1], Antonio Gasparrini[2] and Patrick Kinney[1]

[1]Department of Environmental Health Sciences, Mailman School of Public Health, Columbia University, 722 West 168th St., New York, NY 10032, USA, Email: plk3@columbia.edu (Kinney), Email:epp2109@columia.edu (Petkova)

[2]Department of Medical Statistics, London School of Hygiene and Tropical Medicine, Keppel Street WC1E 7HT London, UK, Email: antonio.gasparrini@lshtm.ac.uk

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IV.1 Abstract

Heat is recognized as one of the deadliest weather-related phenomena. Although the impact of high temperatures on mortality has been a subject of extensive study, few previous studies have assessed the impact of population adaptation to heat. This study examines adaptation patterns by examining daily temperature and mortality data spanning more than a century in New York City. To our knowledge, this is the first study to examine daily temperature effects over such a long period in the United States using modern statistical methods. Using a distributed lag non-linear model, the study analyzes the heat/mortality relationship in adults age 15 or older in New York City during two periods: 1900 to 1948 and 1973 to 2006, in order to quantify population adaptation to high temperatures over time. During the first half of the century, decade-specific relative risk at 29 ˚C vs. 22 ˚C ranged from 1.30 (1.25 to 1.36) in the 1910s to 1.43 (1.37 to 1.49) in the 1900s. Since the 1970s, however, there was a gradual and substantial decline in the relative risk, from 1.26 (1.22 to 1.29) in the 1970s to 1.09 (1.05 to 1.12) in the 2000s. Age-specific analyses indicate a greater risk

for the elderly in the first part of the century, while a more homogeneous and consistently decreasing risk is suggested in the second period. Our analyses reveal that, although rapid adaptation to heat has occurred between 1973 and 2006, no such adaptation is evident in the historical period between 1900 and 1948. These findings may have important implications for projecting future mortality impacts of climate change.

IV.2 Introduction

Heat-related mortality has become a research topic of increasing importance as a result of rising concerns about potential increases in average temperature - as well as temperature extremes - due to climate change. Since the early 2000s, and particularly after the 2003 European heatwave (Bouchama et al. 2004, Fouillet et al. 2006, La Tertre et al. 2006), multiple studies have been carried out in various locations to characterize temperature effects (Anderson et al. 2009, Basu et al. 2005, Braga et al. 2002, Curriero et al. 2002, Davis et al. 2003, Medina-Ramon et al. 2006). These studies identified J- or U-shaped temperature-mortality relationships, depending on the location. Some studies have limited the analysis to the summer months in order to characterize heat effects.

In a literature review of recent epidemiologic studies, Basu (2009) concluded that temperature has an independent effect on mortality and that the confounding effects of particulate matter and ozone are relatively small. Heat extremes have also been associated with increases in hospitalizations and emergency room visits (Jones et al. 1982, Semenza et al. 1999, Knowlton et al. 2009, Green et al. 2010). Very young or old age, pre-existing medical conditions, social isolation and poverty are the leading risk factors for heat-induced morbidity and mortality (Kovats et al. 2008, Rey et al. 2009, Vandentorren et al. 2006). In western societies, including the United States, the elderly population aged 65 and over is most vulnerable to heat-related mortality (Basu et al. 2005, Kovats et al. 2006, Whitman et al. 1997).

Since daily mortality data are rarely available before the 1960s, most of the studies to date have analyzed temperature effects over relatively short periods of time. A better understanding of historical impact of temperature on mortality may provide valuable insights about future population adaptation to high temperatures and improve the accuracy in projecting heat-related deaths. Carson and colleagues (2006) have previously reported declining temperature impacts on cold- and heat-related mortality in London, United Kingdom in the course of the 20th century. The study, however, utilized weekly mortality data, making comparisons to study findings from more recent time periods challenging. Ekamper and colleagues (2009) analyzed 150 years of daily temperature-related mortality in the Netherlands in 25 year increments and reported a reduction in the heat effect since the 1930-1954 period. A recent study by Åström and colleagues (2013) of 110 years of daily mortality and temperature data in Stockholm County, Sweden found a declining trend in heat-related mortality over time. Interestingly, the observed declining trend has plateaued in recent decades.

In the United States, population adaptation to heat over long periods of time has not been thoroughly investigated. In this study, we address this issue by characterizing the summer relationship between daily temperature and mortality since 1900 in New York City. New York City is particularly susceptible to the effects of high temperatures due to the substantial heat island effect, as well as its large population, including many vulnerable individuals (Kinney et al. 2008). Heat has been recognized as a public health hazard in New York City for over a century. In 1896, after a prolonged heat wave, over 1500 people were reported to have died in the city (Kohn 2010). Dating back to this time are some of the earliest city efforts to prevent the impacts of heat, particularly among vulnerable populations. During the 1896 heat wave, Theodore Roosevelt, a mayoral candidate at the time, championed the idea of distributing free ice to the poorest communities of

New York City (Kohn 2010). Today, the city has implemented numerous comprehensive city level measures during heat wave episodes, such as heat warning systems and cooling centers.

Although numerous studies have focused on temperature-related mortality in the city to date, long term trends in heat adaptation are yet to be well understood. The study of weather-related phenomena on daily mortality in New York City was pioneered by Ellworth Huntington in the beginning of last century. In “Civilization and Climate”, Huntington hypothesized that there are physiologically optimal climatic conditions, such as temperature and humidity and that maintaining these conditions may have influence on morbidity and mortality (Huntington 1915). In a subsequent analysis of daily mortality data for New York City data between 1882 and 1888, Ellworth Huntington and Margaret Justin found that mortality increased rapidly with increasing temperature above 63˚F (Justin 1923, Huntington 1930).

Mortality impacts of high temperatures in New York City did not become a subject of rigorous study until the 1970s. At this time, several studies investigated the possible impact of air conditioning on reducing heat wave mortality across the United States. Marmor (1975) investigated ratios of predicted to observed heat-wave mortality during 12 summers between 1949 and 1970 in New York City. This period was selected for the study because air conditioning ownership in the city had increased from virtually non-existent in 1949 to 13.5% in 1960 and 37.5% in 1970. The study reported decreasing excess mortality during early summer heat waves but no similar change in excess mortality during heat waves occurring later in the summer (Marmor 1975).

Davis and colleagues (2003) examined decadal changes in summer weather- mortality relationships for 28 U.S. cities between 1964 and 1998 and found an overall decline in mortality on hot and humid days. For New York City, the mortality increase above an apparent temperature threshold of 30˚C, was greater in the 1960s and 1970s compared to the 1990s (Davis et al. 2003). However, in a study of year round weather- related mortality in eastern U.S. cities, including New York City by Curriero and colleagues (2002), the relationship between weather and mortality from 1973 to 1994 was found to be quantitatively similar to that for four shorter periods within the same time frame. Comparison of findings across studies is challenging due to the utilization of different modeling approaches.

To our knowledge, this is the first study that provides an analysis of the impact of daily heat and heat waves in any large U.S. city over a period spanning a century. We first present a historical analysis of the heat- mortality relationship in New York City between 1900 and 1948 and compare it to that of a more recent period, between 1973 and 2006. Next, we investigate how the heat-mortality response has changed over time in both periods, reflecting possible population adaptation. We conclude with a discussion of probable underlying mechanisms of adaptation to heat and New York City during the studied period and implications for modeling future impacts of high temperatures on mortality.

IV.3 Materials and Methods

IV.3.1 Mortality Data, 1900-1948

Death records prior to 1949 are stored at the New York City Department of Records and Information Services. Death records for later years are stored at the New York City Department of Health and Mental Hygiene and were not directly accessible. Death indexes including each documented death in all New York City boroughs (Bronx, Brooklyn, Manhattan, Queens, Kings and Richmond) from 1900 to 1948, were scanned by the Genealogy Federation of Long Island. Permission to scan these records was obtained from Commissioner Brian Anderson. All scanned records were entered into an electronic spreadsheet and subsequently proof read and edited to ensure accuracy. Each individual record contains day, month, year, borough and age at death. All records were merged and converted into a database where each of the fields is stored in a consistent format. Where possible, age information recorded in various formats in the original death certificate (e.g. 50 ½ years, ¾ months, stillborn) was converted into integers rounded to the lower value. Records containing ambiguous information such as unrealistic numeric values for date or age, and spelling errors such as extra symbols or spaces, were eliminated. Records containing missing values were also eliminated. Altogether, eliminated records constituted less than 0.5% of the total.

Annual numbers of deaths were compared to the numbers published in the New York City Department of Health's annual Summary of Vital Statistics reports. Annual data after 1936 was available from the New York City Department of Health's website . Annual data prior to 1936 was obtained directly from the Bureau of Vital Statistics (*Supplemental Material, Table IV.S1*). Annual calculated number of deaths was between 0.02% and 4.94 % (median 0.95%) higher than those reported. The number of deaths that have occurred during well documented events such as the PS General Slocum fire of June 15, 1904, the Triangle Fire of March 25, 1911 and the 1918 Flu epidemics are consistent with reported data.

IV.3.2 Mortality Data, 1973-2006

Daily multiple-cause-of-death mortality data for 1973-2006 were obtained in collaboration with Dr. Joel Schwartz and colleagues at Harvard University School of Public Health from the U.S. National Center for Health Statistics. The dataset contains daily death counts for all New York City counties: New York County, Kings County, Queens County and Richmond County for New York.

IV.3.3 Temperature Data

Daily temperature data between 1973 onwards for the New York Central Park were obtained from the National Climatic Data Center (NCDC) station. Daily temperature data before 1949, also for New York Central Park, was obtained from the United States Historical Climatology Network. There were five missing records in the data prior to 1949 that were substituted with the averages of the previous and following day temperatures.

IV.3.4 Analysis of temperature-mortality relationships

We characterized the temperature-mortality relationships for each period using the distributed lag non-linear model (DLNM) module in R (Gasparrini 2011). Distributed lag non-linear models allow a simultaneous characterization of the non-linear and lagged effects of temperature on mortality (Armstrong 2006, Gasparrini et al. 2010). The temperature mortality analysis was restricted to the summer months (June to September) because the cause of death was not available in our data, and we were unable to account for influenza deaths during the winter months. We limited the analysis to adults (15 years or older) and derived models using the total number of deaths as well as for three age groups: 15-44, 45-64 and over 65. Note that life expectancy was relatively short at the beginning of the century and the number of deaths in the over 75 and over 85 age groups was very small. The data were analyzed by decade: 1900-1909 (1900s), 1910-1919 (1910s), 1920-1929 (1920s), 1930-1939 (1930s), 1940-1948 (1940s), 1973-1979 (1970s), 1980-1989 (1980s), 1990-1999 (1990s) and 2000-2006 (2000s).

We developed the decadal models using mean daily temperature and 22 ˚C (corresponding to approximately the 80th percentile of annual temperature) as a reference temperature for calculating relative risk. The models were fitted using a quadratic spline with 4 degrees of freedom (two equally spaced knots) for temperature, a natural spline with 4 degrees of freedom for the lag, and controlling for seasonal and day of week effects. Quadratic splines have the advantage of not being constrained at the boundaries and thus are flexible enough to capture mortality effects at the highest temperatures (Gasparrini et al. 2011). Lag durations between 3 and 10 days were tested in order to explore possible changes in the lag structure over time and a lag of 5 days was selected for the main model. We also tested models with both quadratic and natural cubic splines and found that the Akaike's Information Criterion for quasi-Poisson (Q-AIC) was consistently lower for models with quadratic splines. In sensitivity analyses, we fitted models with quadratic splines ranging from 4 to 6 degrees of freedom for the temperature and from 3 to 5 degrees of freedom for the lag. This amount of smoothing is considered enough to capture the underlying non-linear relationship. We controlled for seasonal cycles using a natural spline with 2 degrees of freedom per year, and for within summer seasonal variation using a natural spline with 4 degrees of freedom for day in year (Hajat et al. 2006, Gasparrini et al. 2011). The decadal cumulative relative risk estimates at 29˚C, corresponding to approximately the 99th percentile of mean daily temperature, were chosen as a marker of the heat effect. To test for the difference in the effect of heat on mortality over time, we carried out univariate random-effects meta regression estimated by restricted maximum likelihood (REML) (Van Houwelingen 2002).

IV.4 Results

Summary temperature and statistics and population data (Gibson 1998, U.S. Census 2000) for New York City during the time periods included in this study are presented in *Table IV.1* and *Figure IV.1,* respectively.

Previous studies have reported that the seasonality of mortality has changed substantially over time. In Japan, for example, the mortality peak has flipped in the course of a century from the summer to the winter months (Sakamoto-Momiyama 1977). We did not observe a similar transition in New York City. We found that the seasonality of mortality in New York City was similar for each decade since the 1900s (*Supplementary Figure IV.S2*) but that the mortality peak occurred between January and April in the beginning of the century and between December and March in recent years (*Supplementary Figure IV.S3*). The gradual change in the seasonal effect is controlled for in our analysis by the use of different models in each decade, each of which can flexibly control for seasonal effects on mortality.

Table IV.1 Temperature and population statistics for New York City by decade, 1900s-2000s

	Annual mean temperature (Tmean)	**90th percentile of Tmean**	**95th percentile of Tmean**	**99th percentile of Tmean**	**Population**
1900s	11.9	25	26.4	29.2	3,437,202
1910s	11.7	24.2	25.8	28.7	4,766,883
1920s	11.8	23.9	25.6	28.3	5,620,048
1930s	12.5	25	26.4	28.9	6,930,446
1940s[i]	12.3	25	26.4	29.2	7,454,995
1970s[ii]	12.6	25	26.7	29	7,894,862
1980s	12.9	25.3	27.2	29.7	7,071,639
1990s	13.2	25.3	26.7	29.4	7,322,564
2000s[iii]	13	25	26.7	29.6	8,008,278

i.The 1940s include data from 1940 to 1948; ii. The 1970s include data from 1973-1979; iii. The 2000s include data from 2000 to 2006.

The non-linear distributed lag models showed a similar relationship between temperature and mortality for all of the periods. Decadal temperature-mortality curves of overall cumulative risk are presented on *Figure IV.2*. The heat effect, however, was much more pronounced in the first five decades. For the last four decades, the temperature effect was substantially higher in the 1970s and diminished during the next three decades. The lag structure (*Figure IV.3.*) also changed over time. During the first half of the century, we observed a partial mortality displacement effect immediately after the substantial increase in mortality in the first two days following heat exposure. The effect was particularly pronounced during the 1910s. Nonetheless, the heat effect was only partially compensated for by the mortality displacement. Decade-specific temperature-mortality curves and lag structure charts are presented in *Supplementary Figures IV.S4* and *IV.S4,* respectively.

Figure IV.1 Mean summer temperature histograms for New York City by decade, 1900s-2000s

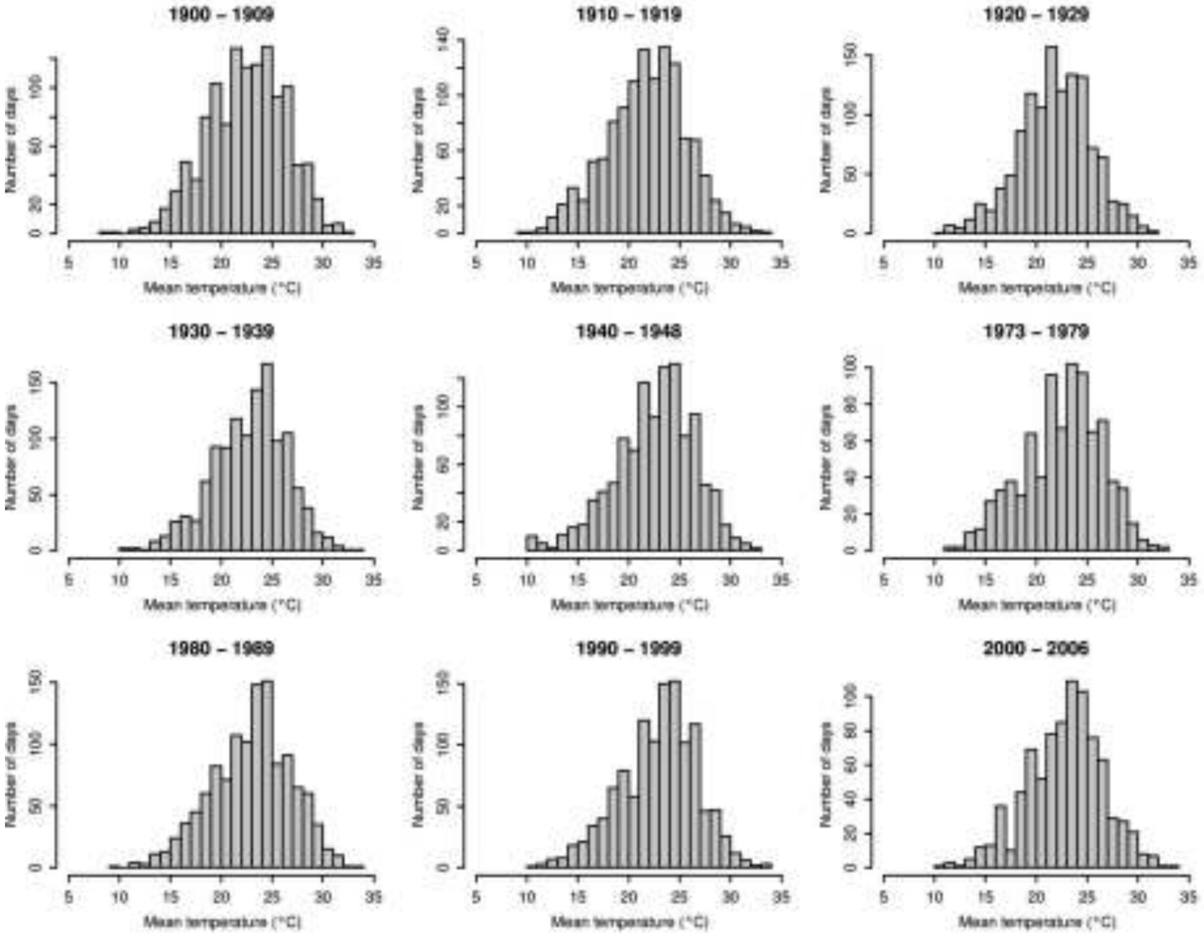


Figure IV.2 Temperature – mortality curves of overall cumulative relative risk for New York City by decade, 1900s -2000s. Calculated using a distributed lag non-linear model with a quadratic spline with 4 degrees of freedom for the temperature and a natural cubic spline with 4 degrees of freedom for the lag and 22°C as a reference temperature.

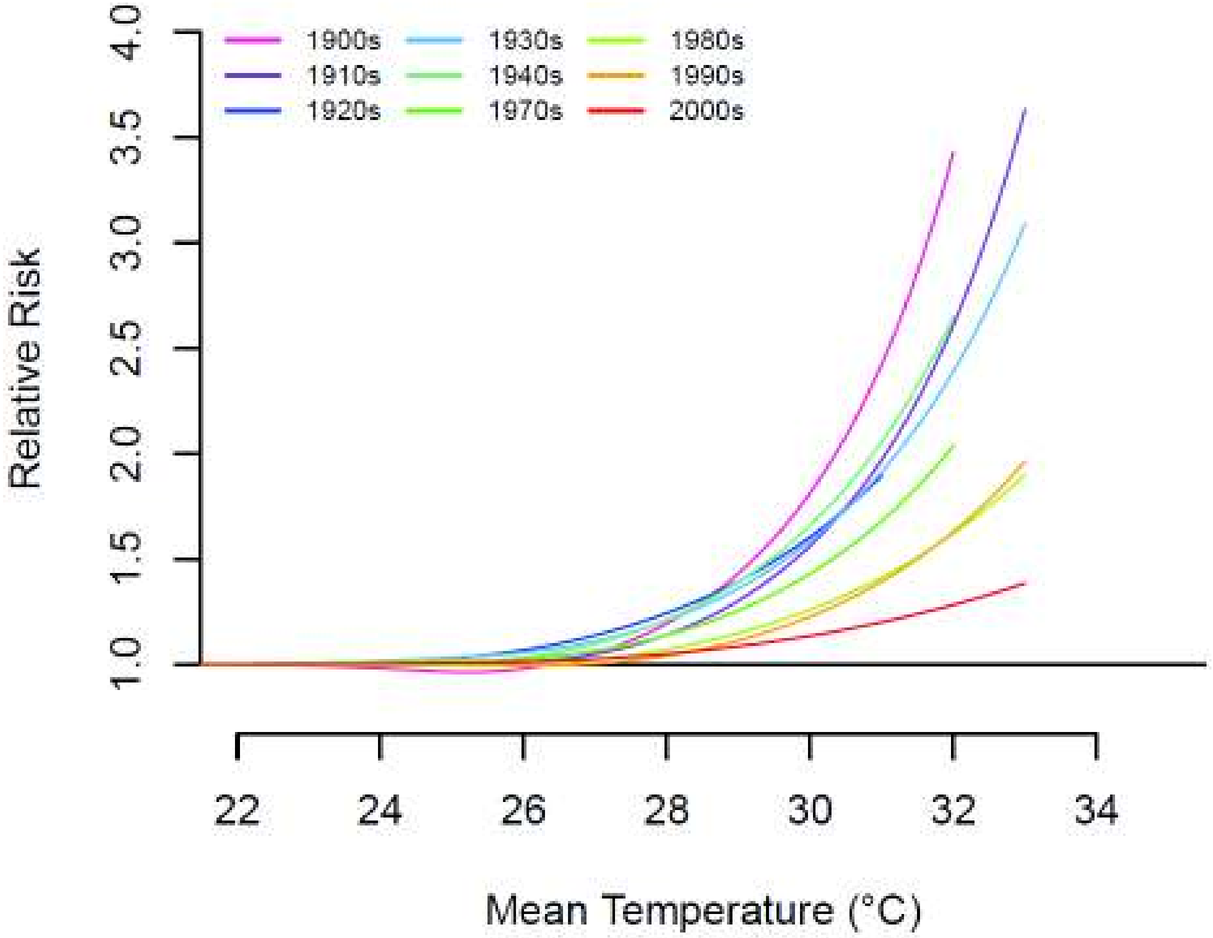
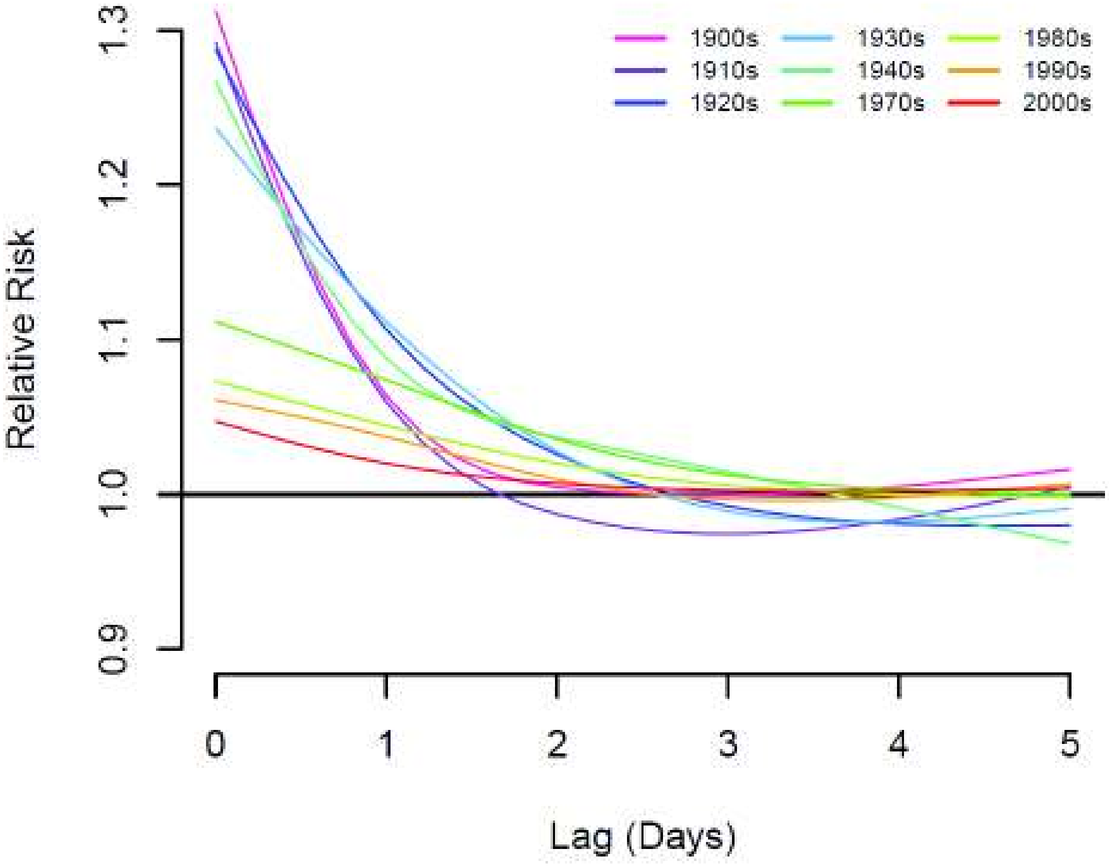
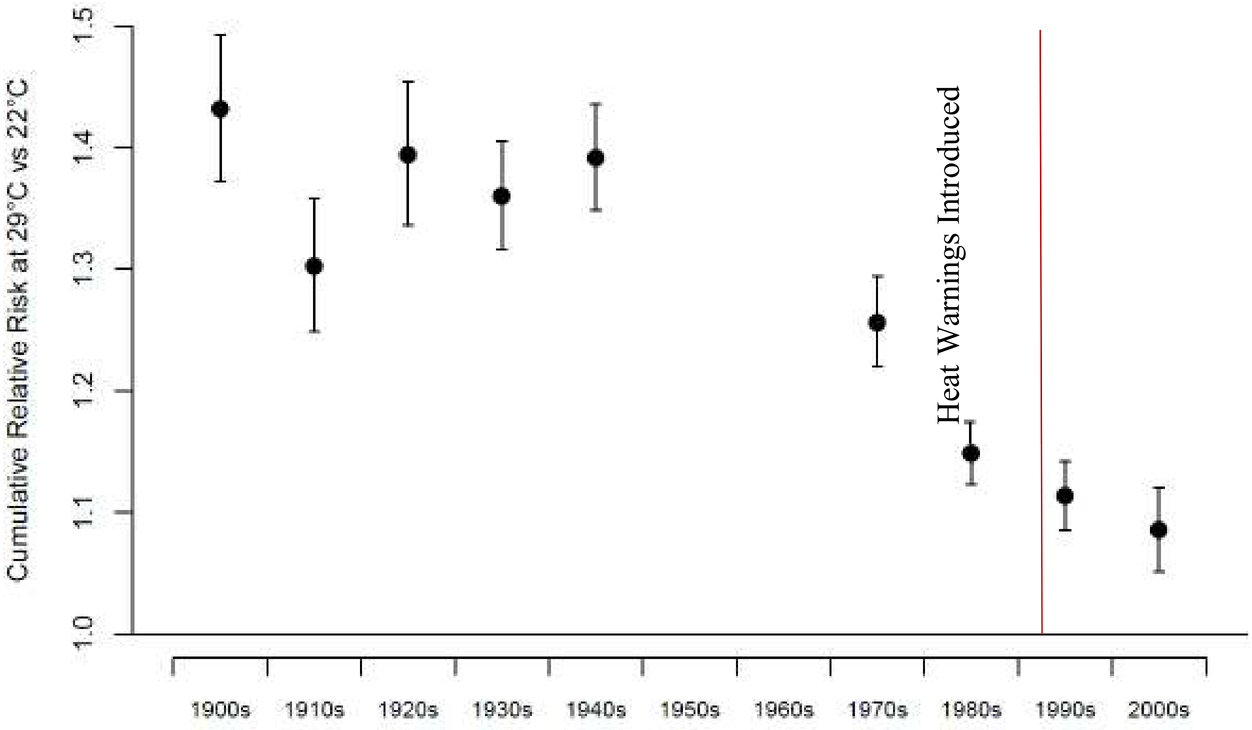


Figure IV.3 Lagged relative risks at 29°C relative to 22°C by decade, 1900s-2000s. Calculated using a distributed lag non-linear model with a quadratic spline with 4 degrees of freedom for the temperature and a natural cubic spline with 4 degrees of freedom for the lag.



To summarize the change in the temperature effect over time, we plotted cumulative relative risk estimates at 29˚C, corresponding to approximately the 99th percentile of mean daily temperature over a year (*Figure IV.4*), versus the reference temperature of 22˚C.

Figure IV.4 Overall cumulative relative risk at 29°C relative to 22°C on mortality in New York City by decade, 1900s-2000s. Calculated using a distributed lag non-linear model with a quadratic spline with 4 degrees of freedom for the temperature and a natural cubic spline with 4 degrees of freedom for the lag.



As the plot illustrates, there was no evidence of adaptation during the first half of the century. Relative risks fluctuated between 1.30 (1.25 to 1.36) in the 1910s to 1.43 (1.37 to 1.49) in the 1900s during this period. The random-effects meta-regression including a binary indicator for period as meta-predictor indicates a strong evidence for a difference between the first and the second part of the century. Predicted average relative risks were 1.38 (95%CI:1.31 to 1.44) for the period between 1900-1948 and 1.15 (95%CI:1.09 to 1.2) for 1973-2006 (p-value <0.001). Since the 1970s, there was a gradual and substantial decline in the relative risk, indicating population adaptation to heat.

The random-effects meta-regression including a linear term for decade predicts a decrease of 4.6% (95%CI: 2.4%-6.7%) per decade (p-value <0.001).

Results from the age-specific analyses are presented in *Table IV.2*. During the first part of the century, the temperature effect was most substantial for the elderly. More homogeneous and consistently decreasing risk is indicated in the second part of the century.

Table IV.2 Age-specific overall cumulative relative risk of death at 29°C relative to 22°C in adults (age 15 or older) in New York City by decade, 1900s-2000s. Calculated using a distributed lag non-linear model with a quadratic spline with 4 degrees of freedom for the temperature and a natural cubic spline with 4 degrees of freedom for the lag.

	Total (95%CI)	**15-44 (95%CI)**	**45-64 (95%CI)**	**Over 65 (95%CI)**
1900s	1.43 (1.37, 1.49)	1.33 (1.26, 1.40)	1.48 (1.39, 1.58)	1.57 (1.46, 1.68)
1910s	1.30 (1.25, 1.36)	1.25 (1.17, 1.33)	1.24 (1.17, 1.32)	1.48 (1.38, 1.58)
1920s	1.39 (1.34, 1.45)	1.24 (1.16, 1.33)	1.32 (1.24, 1.40)	1.64 (1.53, 1.77)
1930s	1.36 (1.32, 1.41)	1.26 (1.18, 1.33)	1.34 (1.28, 1.41)	1.45 (1.38, 1.52)
1940s	1.39 (1.35, 1.44)	1.23 (1.15, 1.31)	1.30 (1.24, 1.35)	1.52 (1.46, 1.59)
1970s	1.26 (1.22, 1.29)	1.10 (0.99, 1.22)	1.17 (1.11, 1.24)	1.30 (1.26, 1.35)
1980s	1.15 (1.12, 1.17)	1.20 (1.11, 1.29)	1.07 (1.02, 1.12)	1.17 (1.14, 1.20)
1990s	1.11 (1.09, 1.14)	1.12 (1.04, 1.21)	1.10 (1.04, 1.16)	1.11 (1.08, 1.15)
2000s	1.09 (1.05, 1.12)	1.07 (0.94, 1.23)	1.07 (0.99, 1.15)	1.09 (1.05, 1.13)

Age–specific temperature-mortality curves and lag structures are displayed in the *Supplementary Figures IV.S6 – S11*. Results from the sensitivity analysis for the temperature effect along with Akaike's Information Criterion for quasi-Poisson (Q-AIC) values for each alternative model are presented in the *Supplementary Material, Tables IV.S2 and IV.S3,* respectively. Estimates were robust to alternative modeling choices, except for the 1900s. The differences across models for this decade are due to the 1901 heat wave, the deadliest heat wave that occurred in New York City since the beginning of the study period.

IV.5 Discussion

The issue of heat-related mortality has taken on increasing relevance in recent years as a result of rising concerns about potential increases in average temperature - as well as temperature extremes - due to climate change. Our analysis of daily mortality in New York between 1900 and 1948 and 1973 and 2006 provides important insights about the summer temperature-mortality response since the beginning of the 20th century.

Using non-linear distributed lag models to characterize the overall relationship between temperature and mortality during the five decades between 1900 and 1948 and the four decades between 1973 and 2006, we observed more pronounced heat effects in the first five decades, compared to the second four. Clearly, many factors may underlie the substantial heat effect in the first half of the 20th century. For example, housing conditions, particularly in the lowest income, immigrant communities were particularly poor in the beginning of the century. During this period, a substantial part of the new immigrants to the United States settled in tenement buildings, or multifamily dwellings with one or two rooms. Many of the tenements did not have windows which may have enhanced the death toll in such communities during hot days. Although the *Tenement House Act*, which required tenements to meet basic sanitary and health standards, was passed in 1867, few improvements were introduced until the 1920s. Many tenements were not replaced with modern buildings until several decades later. In addition, access to ice and cold liquids, which were among the primary means for alleviating the heat stress at the time, was likely limited in the early part of the century. For instance, commercial refrigerators were not introduced until the 1915 and didn’t become common until the

1930s. Nonetheless, despite technological and lifestyle improvements during the first part of the 20th century, the population sensitivity to heat did not decline.

It seems plausible to hypothesize that the observed adaptation to heat in the second part of the century may be largely due to increased use of air conditioning. By the 1970s, the heat effect has already started to decline gradually as air conditioning prevalence was increasing. Individual room and central air conditioning did not become mainstream until the 1950s and the 1970s, respectively. In 1970, only 39% of households surveyed in the NYC metropolitan area had air conditioning, and less than 4% of them had central air conditioning (U.S. Census Bureau 1978). By 2003, 84% of surveyed households had air conditioning and 16% of them had central air conditioning (U.S. Census Bureau 2004). Together, these findings suggest that access to comfortable indoor environments, particularly during the hottest days may be the most important factor in the declining heat-related mortality since the 1970s. The introduction in more recent years of heat warning systems and, subsequently, cooling centers may also have contributed to decreasing vulnerability. As discussed previously, adaptation can be classified as planned or autonomous depending on whether it results from reactive or anticipatory actions. Thus, it can be argued that the adaptation process was autonomous before introducing measures aimed at reducing heat-related mortality and has an autonomous component since the introduction of such measures.

As expected, the temperature effect was most substantial in the over 65 age group during most of the investigated periods. Temperature effects have declined substantially since the beginning of the century in all age groups and the decline was particularly pronounced in individuals age 65 or older. It is possible the substantial decrease in sensitivity to heat among the elderly is due to the improvement of overall health status on one hand and a greater awareness of the risks exposure to high temperatures presents, on the other.

Another interesting finding is the change we observed in the lag structure of the temperature effect over time. The mortality displacement effect that has occurred immediately after the substantial increase in mortality during the first couple of days after exposure in the early part of the century may indicate more deaths among the most susceptible individuals, which would have been likely to seek but did not have access to any form of relief from the heat.

The study has several important limitations. We were unable to adjust for any measure of air pollution due to lack of data on particulate matter, ozone or other pollutants for the entire study period. In addition, since we did not have information on the underlying causes of death, we were unable to investigate how changing disease patterns, such as the substantial decline in cardiovascular mortality, could have influenced the observed trend in heat-related mortality.

This work has several important implications for projecting future mortality impacts of climate change. First, given the downward trend in the heat-mortality relationship in recent decades it may be inappropriate to use historical relationships to project future mortality impacts of climate change. For example, since the calculated relative risk at 29˚C decreased by 4.6% (95%CI: 2.4%-6.7%) per decade during the second part of the century, using the relative estimates from the 1970s to project mortality in the 2000s, could have led to substantially overestimating present heat impacts. A recent review found that half of the studies that have projected heat-related mortality under various climate change scenarios have based projections on historical relationships without considered any heat adaptation scenarios (Huang et al. 2011). Models for future mortality should take into account assumptions about changing risks that relate to adaptation processes including increasing air conditioner prevalence[23]. Second, despite the diminished sensitivity to heat over time, the temperature-mortality curves for New York City have maintained a similar shape throughout the century. This should be taken into account when considering the use of analogous cities to project future temperature impacts. Finally, mortality data from earlier years, particularly during heat wave episodes, may be useful in projecting possible impacts of heat in the event of future power outages or natural disasters during which the population may lose access to air conditioning for extended periods.

IV.6 Conclusions

We examined the relationship between summer daily temperature and mortality since the beginning of the 20th century. Heat effects were more pronounced in the first five decades, compared to the second four. In addition, despite the substantial technological and lifestyle improvements that took place in New York City during the first part of the 20th century, there was no decline in the population sensitivity to heat. However, a substantial decrease of the heat effect, indicating possible population adaptation to heat, took place since the 1970s.

We also found evidence of a short term mortality displacement in the first part of the century. Nonetheless, the substantial heat effects during this period were only partially compensated for by the mortality displacement.

To our knowledge, this study was the first to examine daily temperature effects in any large U.S. city over a period spanning more than a century, using modern statistical methods. Our findings can potentially have important implications for projecting future mortality impacts of climate change.

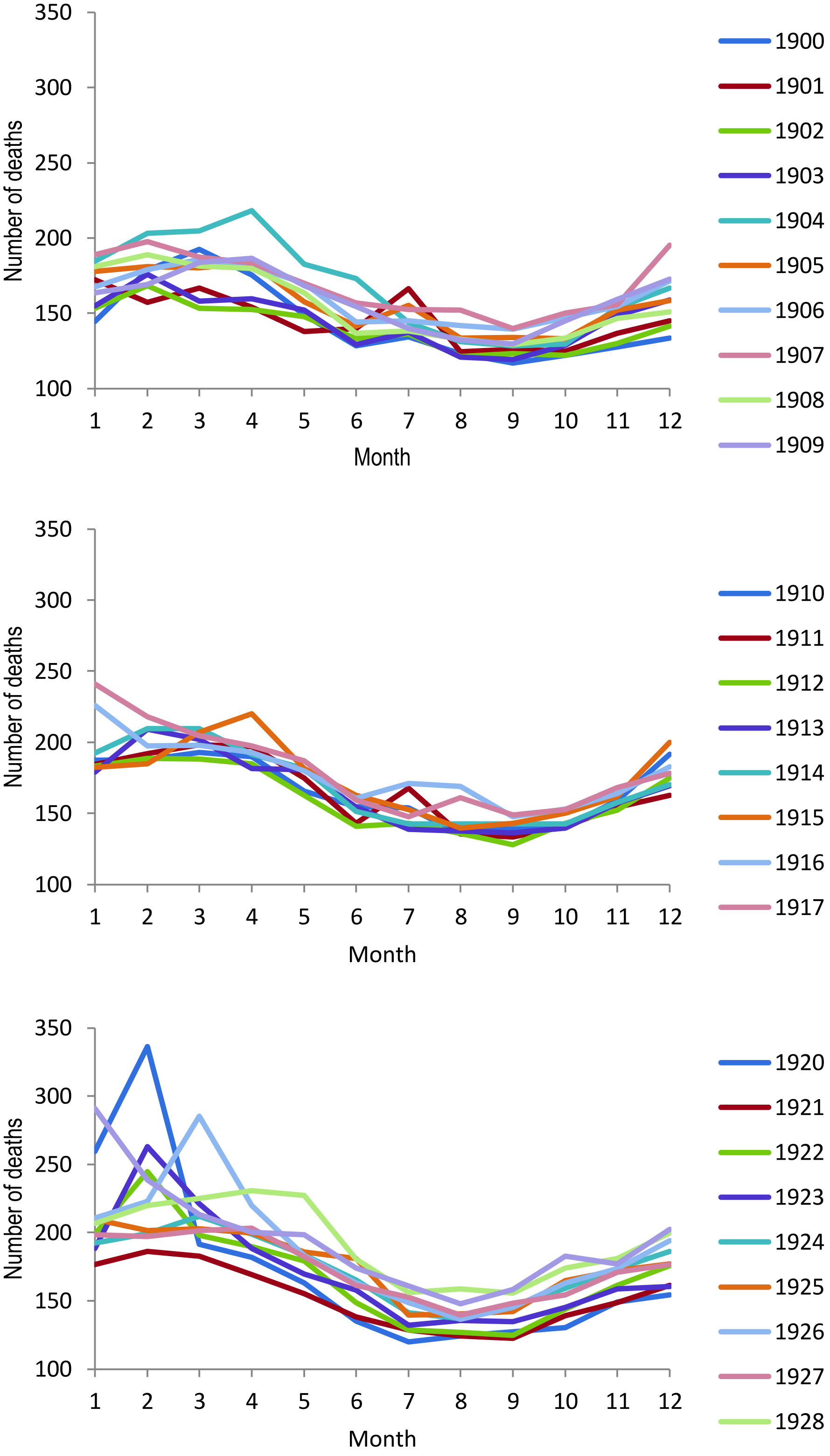
IV.7 Supplemental Material

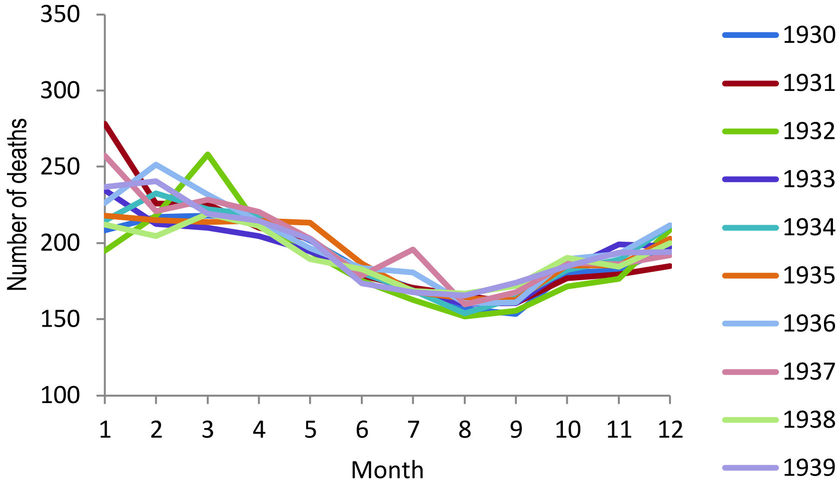
Table IV.S1 Annual deaths a) reported in the Summary of Vital Statistics for NYC and b) calculated from daily mortality data used in this study.

Year	Reported deaths [a]	Calculated deaths [b]	Difference, % of reported
1898	66294	66473	0.27
1899	65343	65623	0.43
1900	70872	71356	0.68
1901	70980	70993	0.02
1902	68132	68361	0.34
1903	67864	68252	0.57
1904	78060	78388	0.42
1905	73714	74317	0.82
1906	76203	76746	0.71
1907	79205	79651	0.56
1908	73072	73575	0.69
1909	74375	74557	0.24
1910	76742	77714	1.27
1911	75423	75934	0.68
1912	73013	73311	0.41
1913	70902	74408	4.94
1914	74803	75755	1.27
1915	76193	78210	2.65
1916	78307	78873	0.72
1917	78575	78802	0.29
1918	98119	98904	0.80
1919	74433	75534	1.48
1920	73249	74831	2.16
1921	64257	65802	2.40
1922	69690	71466	2.55

1923	69452	71514	2.97
1924	71252	73250	2.80
1925	71914	73098	1.65
1926	76082	77157	1.41
1927	70430	71073	0.91
1928	78091	79387	1.66
1929	77482	79245	2.28
1930	74888	77077	2.92
1931	77418	78619	1.55
1932	74319	75345	1.38
1933	75153	76174	1.36
1934	75857	76927	1.41
1935	75057	76064	1.34
1936	77638	77996	0.46
1937	77465	77716	0.32
1938	73775	74033	0.35
1939	75439	75762	0.43
1940	76008	76576	0.75
1941	74553	75174	0.83
1942	75675	76363	0.91
1943	83174	83971	0.96
1944	78783	79528	0.95
1945	79726	80620	1.12
1946	78481	79477	1.27
1947	80733	82680	2.41
1948	81651	82864	1.49

Figure IV.S2 Monthly Mortality (number of deaths) per year for each decade. Years 1918, 1919 and 1920 excluded due to the Spanish Flu epidemic.





350
300
250
200
150
100
Number of deaths
1
2
3
4
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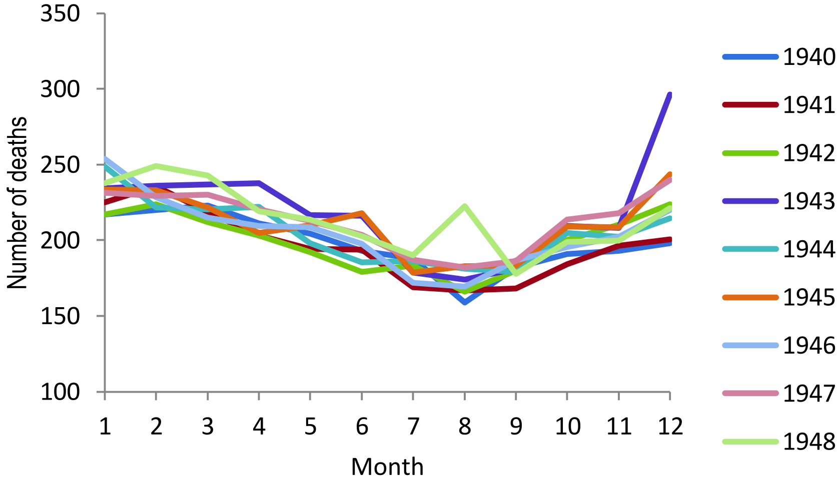
10
11
12
Month
1930
1931
1932
1933
1934
1935
1936
1937
1938
1939



350
300
250
200
150
100
Number of deaths
1
2
3
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7
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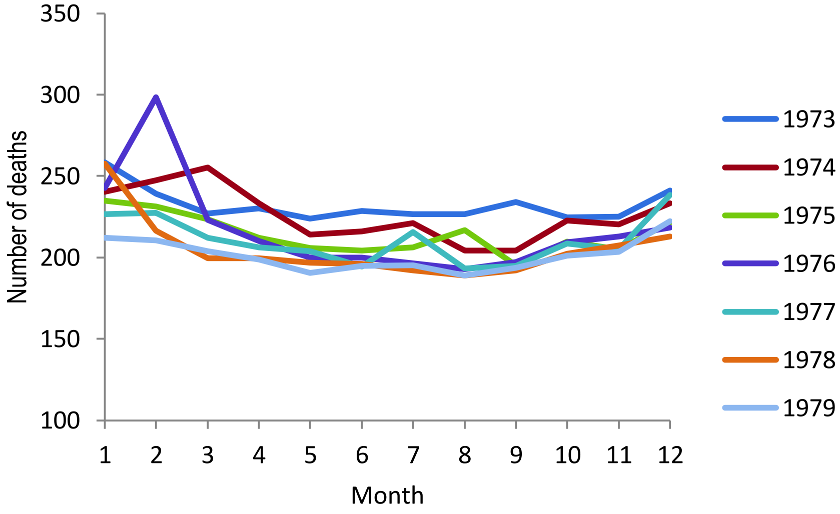
9
10
11
12
Month
1940
1941
1942
1943
1944
1945
1946
1947
1948



350
300
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150
100
Number of deaths
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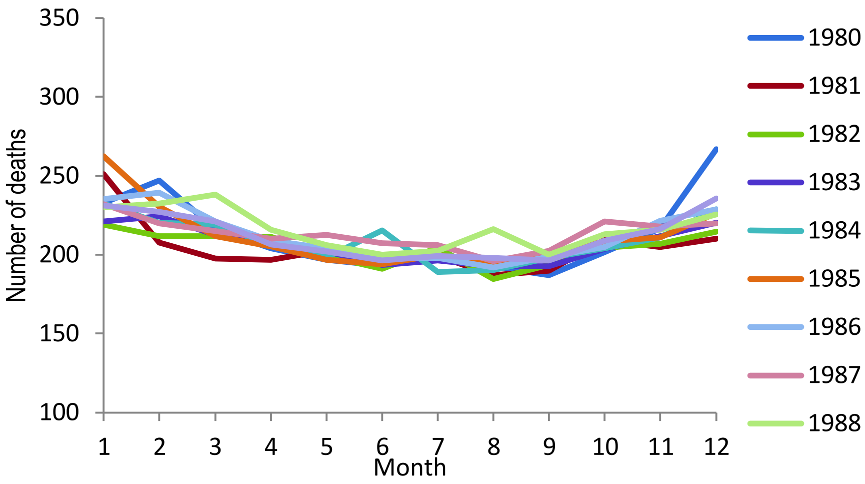
10
11
12
Month
1973
1974
1975
1976
1977
1978
1979


350
300
250
200
150
100
Number of deaths
1
2
3
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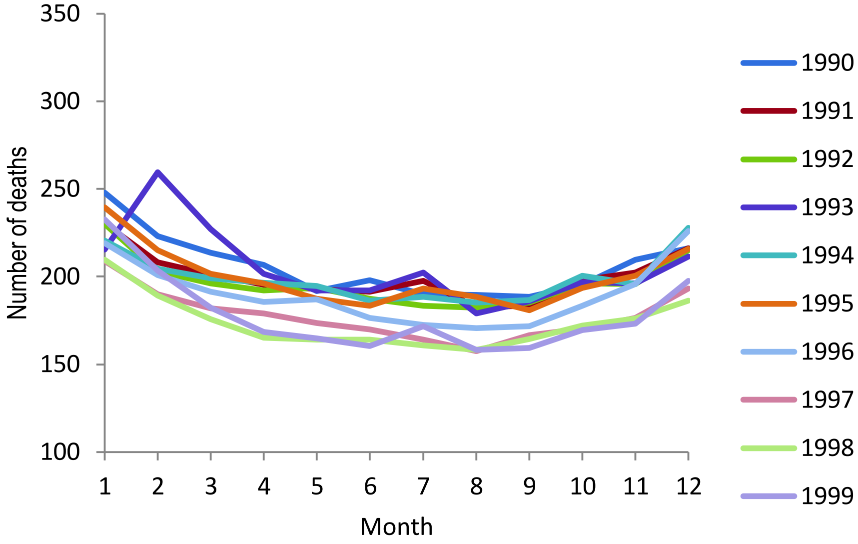
11
12
Month
1980
1981
1982
1983
1984
1985
1986
1987
1988


350
300
250
200
150
100
Number of deaths
1
2
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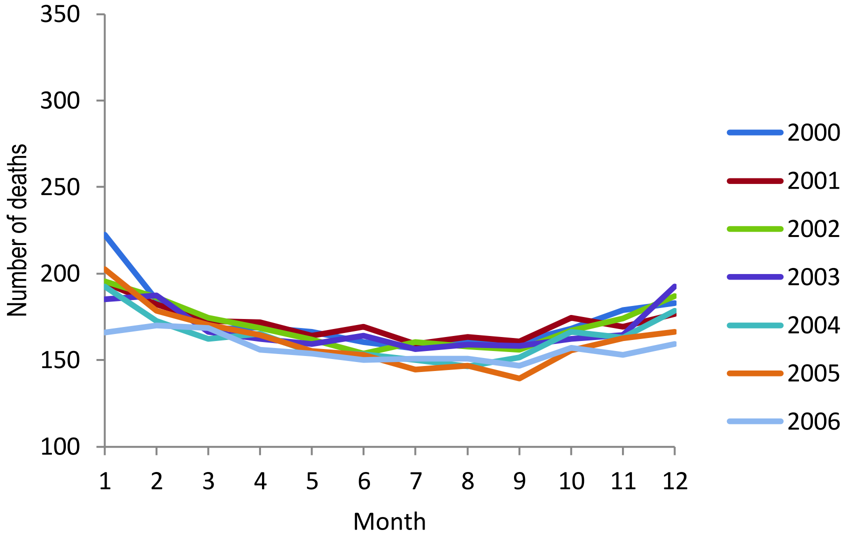
12
Month
1990
1991
1992
1993
1994
1995
1996
1997
1998
1999


350
300
250
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150
100
Number of deaths
1
2
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4
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6
7
8
9
10
11
12
Month
2000
2001
2002
2003
2004
2005
2006

Figure IV.S3 Months with minimum (blue) and maximum (red) mortality in New York City over time

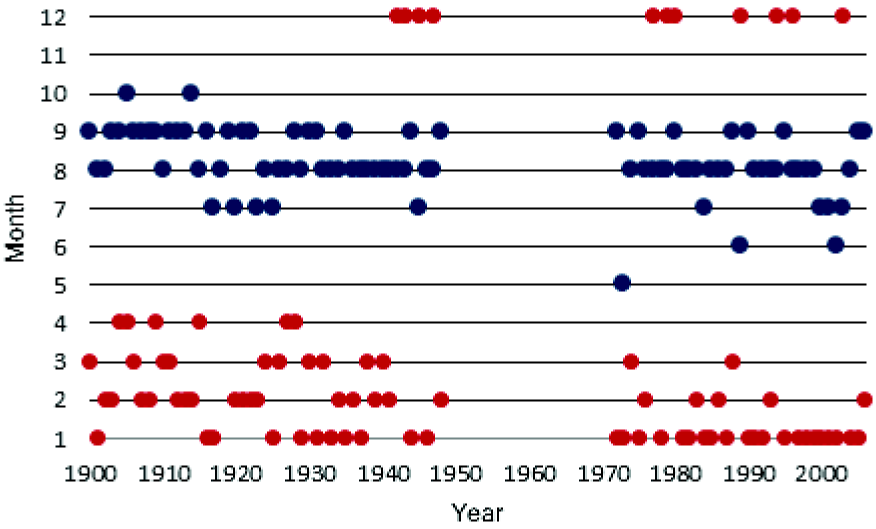

Figure IV.S4 Temperature – mortality curves of overall cumulative relative risk for New York City by decade, 1900s -2000s (separate plots). Calculated using a distributed lag non-linear model with a quadratic spline with 4 degrees of freedom for the temperature and a natural cubic spline with 4 degrees of freedom for the lag and 22°C as a reference temperature.

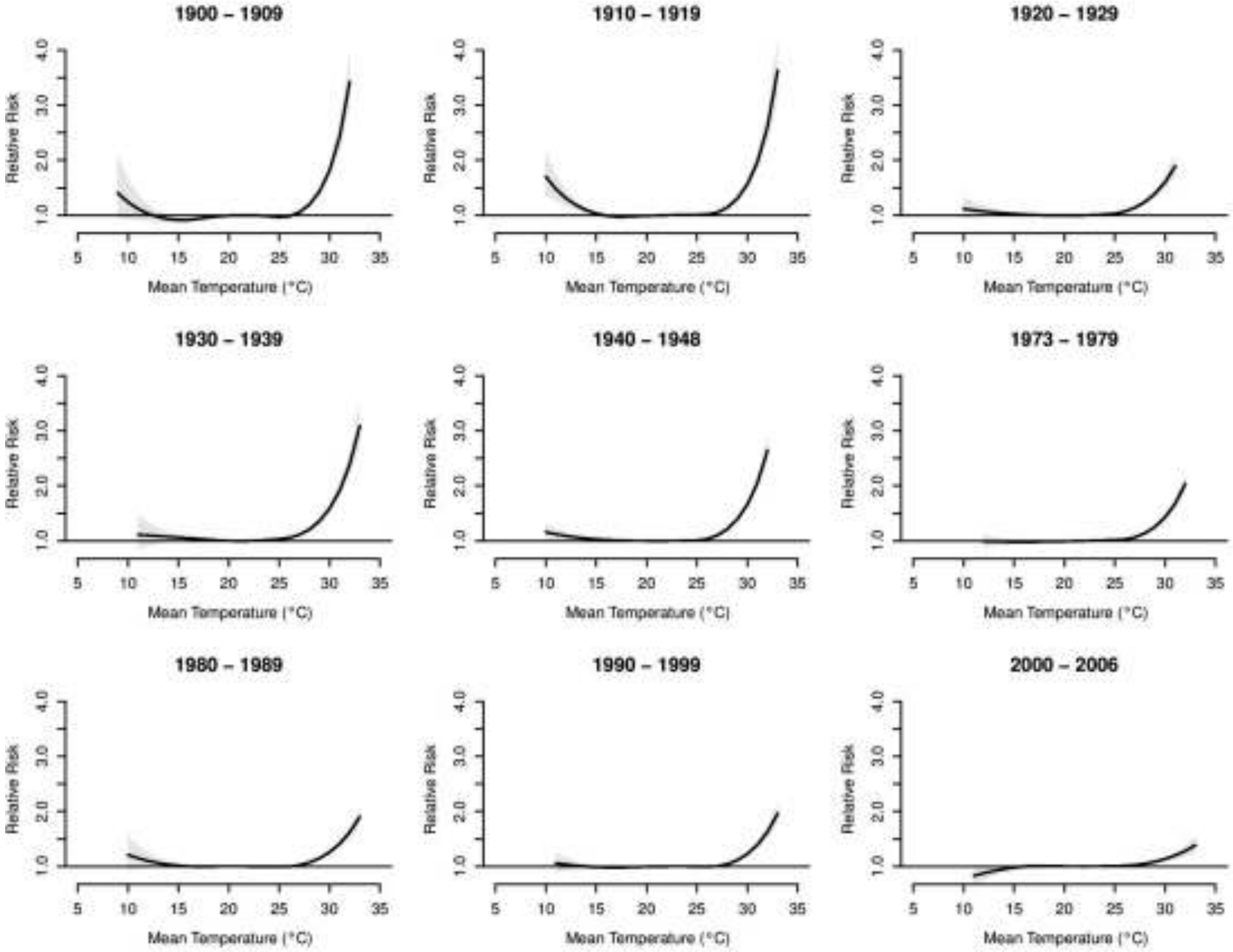

Figure S5 Lagged relative risks at 29°C relative to 22°C by decade, 1900s-2000s (separate charts). Calculated using a distributed lag non-linear model with a quadratic spline with 4 degrees of freedom for the temperature and a natural cubic spline with 4 degrees of freedom for the lag.

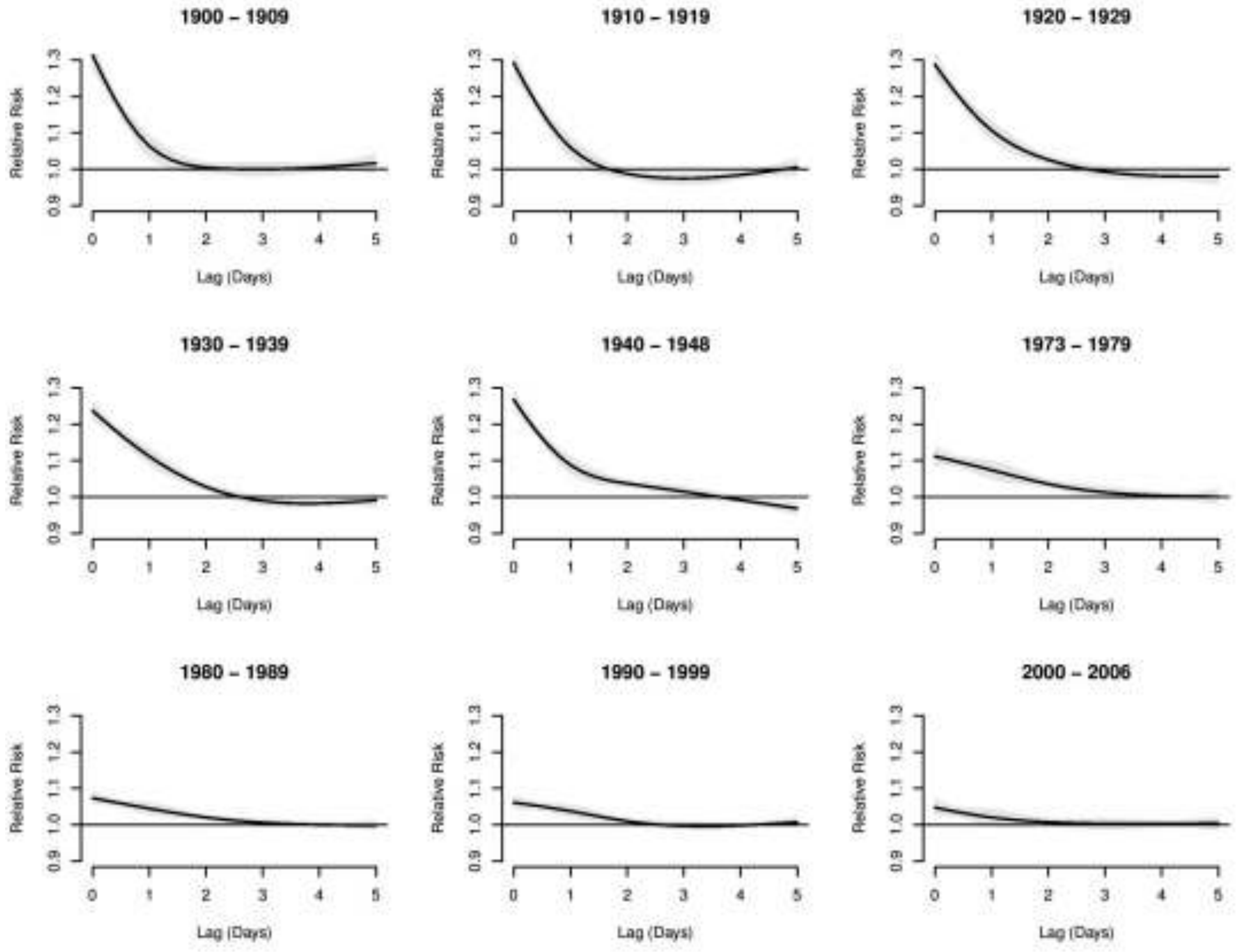

Figure IV.S6 Temperature – mortality curves of overall cumulative risk for New York City by decade, 1900s -2000s for the 15-44 age group. Calculated using a distributed lag non-linear model with a quadratic spline with 4 degrees of freedom for the temperature and a natural cubic spline with 4 degrees of freedom for the lag and 22°C (corresponding to approximately the 80th percentile of annual temperature) as a reference temperature.

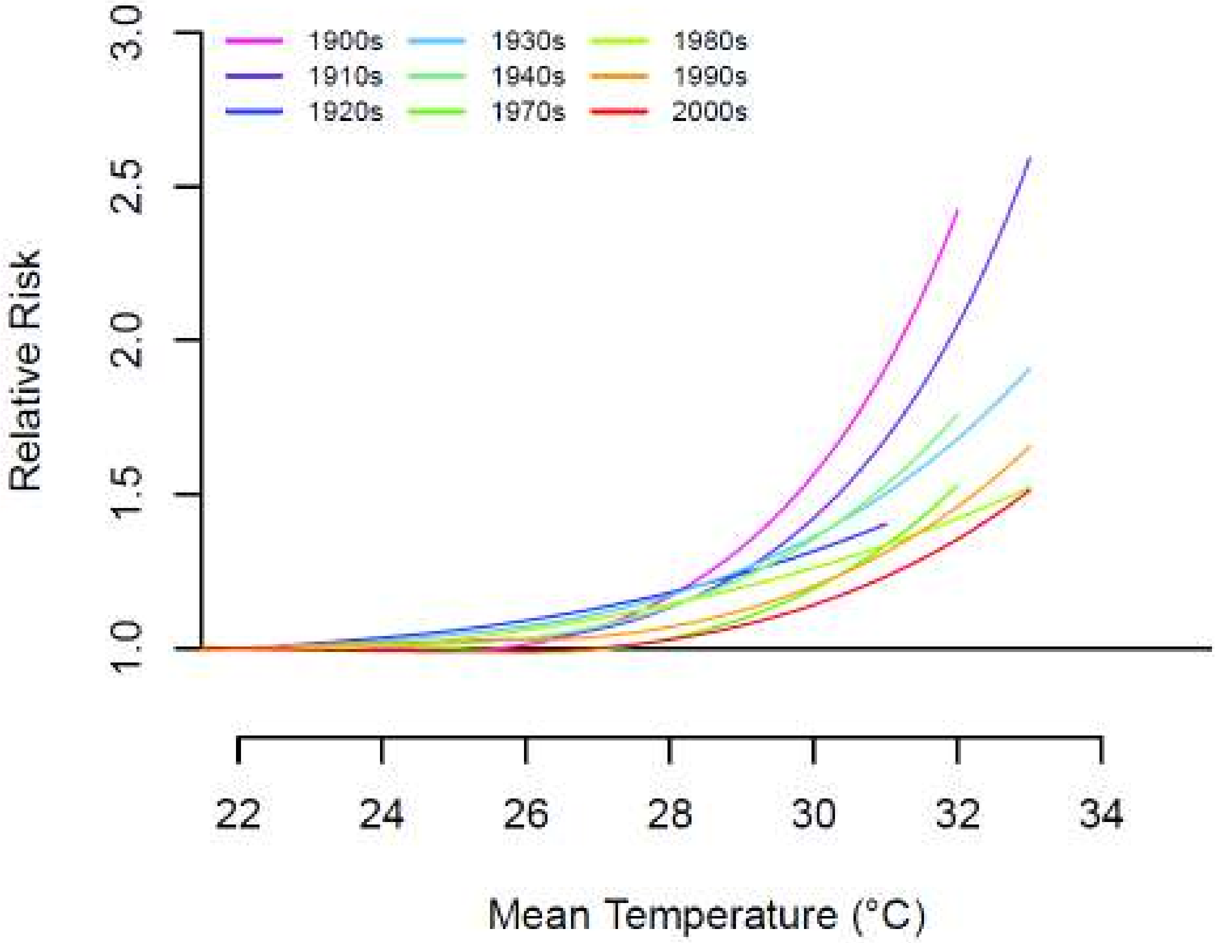

Figure IV.S7 Lag-mortality curve associated with 29°C (corresponding to approximate the 99^{th} percentile of annual temperature) relative to 22°C (corresponding to approximately the 80th percentile of annual temperature) on mortality in New York City by decade, 1900s-2000s for the 15-44 age group. Calculated using a distributed lag non-linear model with a quadratic spline with 4 degrees of freedom for the temperature and a natural cubic spline with 4 degrees of freedom for the lag.

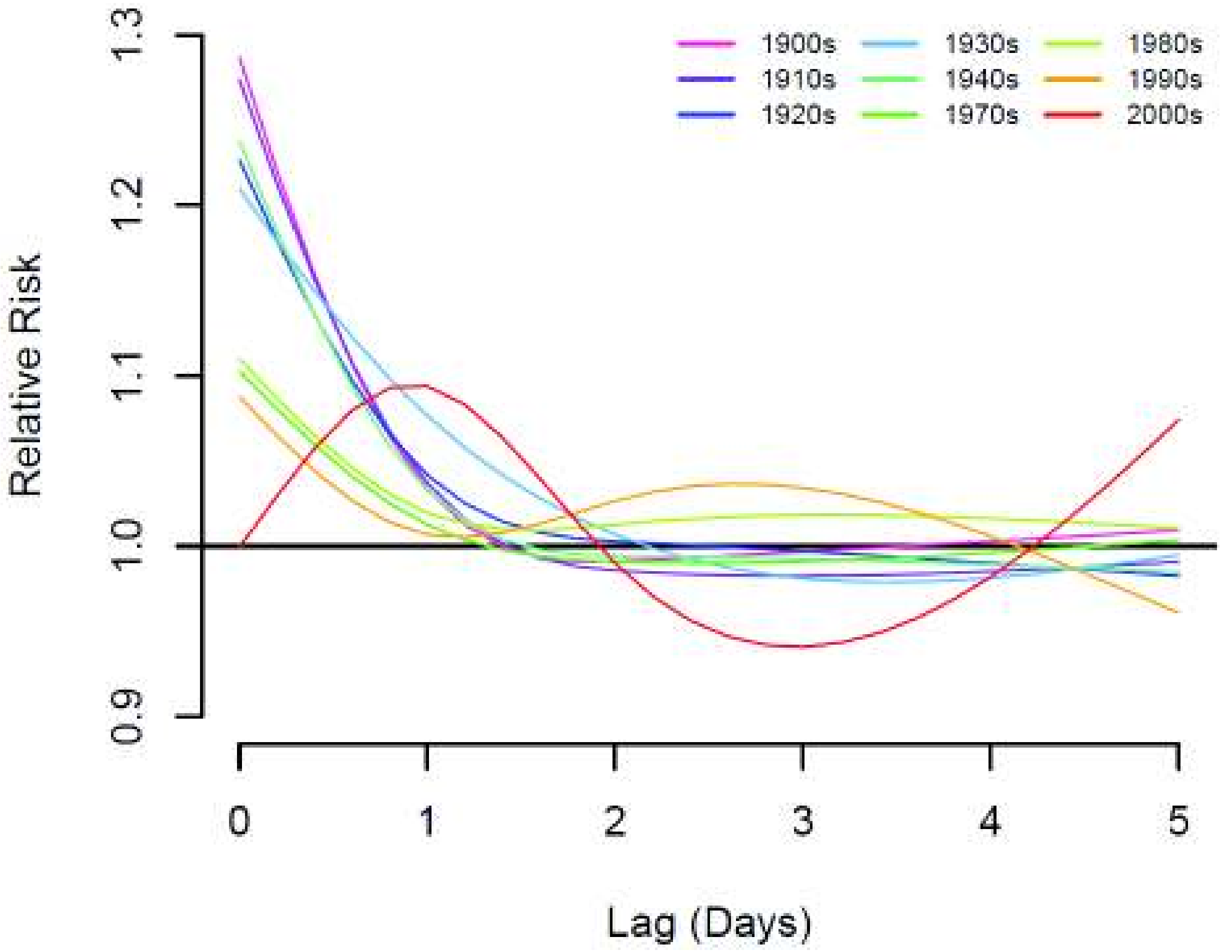

Figure IV.S8 Temperature – mortality curves of overall cumulative risk for New York City by decade, 1900s -2000s, for the 45-64 age group. Calculated using a distributed lag non-linear model with a quadratic spline with 4 degrees of freedom for the temperature and a natural cubic spline with 4 degrees of freedom for the lag and 22°C (corresponding to approximately the 80th percentile of annual temperature) as a reference temperature.

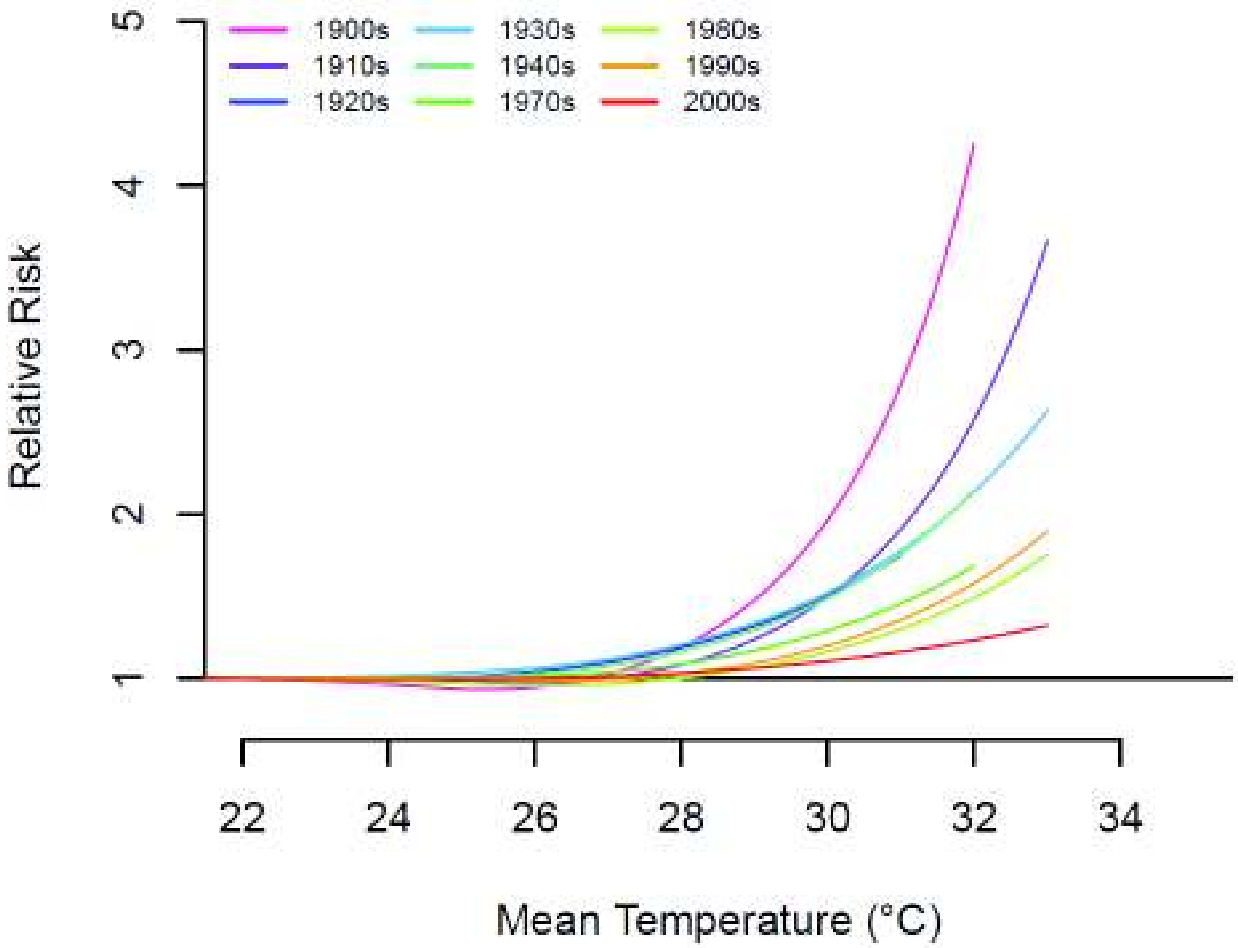

Figure IV.S9 Lag-mortality curve associated with 29°C (corresponding to approximate the 99th percentile of annual temperature) relative to 22°C (corresponding to approximately the 80th percentile of annual temperature) on mortality in New York City by decade, 1900s-2000s, for the 45-64 age group. Calculated using a distributed lag non-linear model with a quadratic spline with 4 degrees of freedom for the temperature and a natural cubic spline with 4 degrees of freedom for the lag.

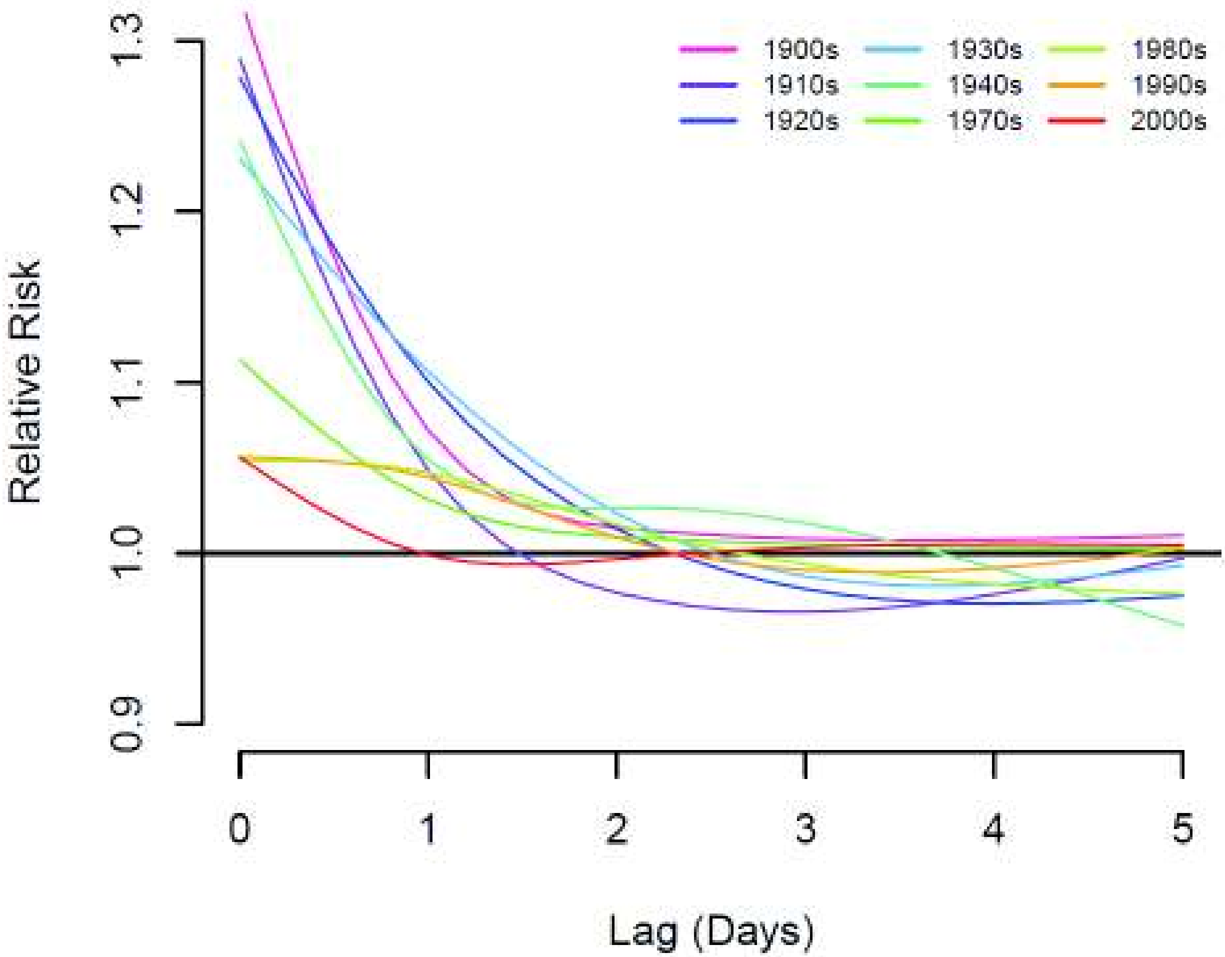

Figure IV.S10 Temperature – mortality curves of overall cumulative risk for New York City by decade, 1900s -2000s, for the over 65 age group. Calculated using a distributed lag non-linear model with a quadratic spline with 4 degrees of freedom for the temperature and a natural cubic spline with 4 degrees of freedom for the lag and 22°C (corresponding to approximately the 80th percentile of annual temperature) as a reference temperature.

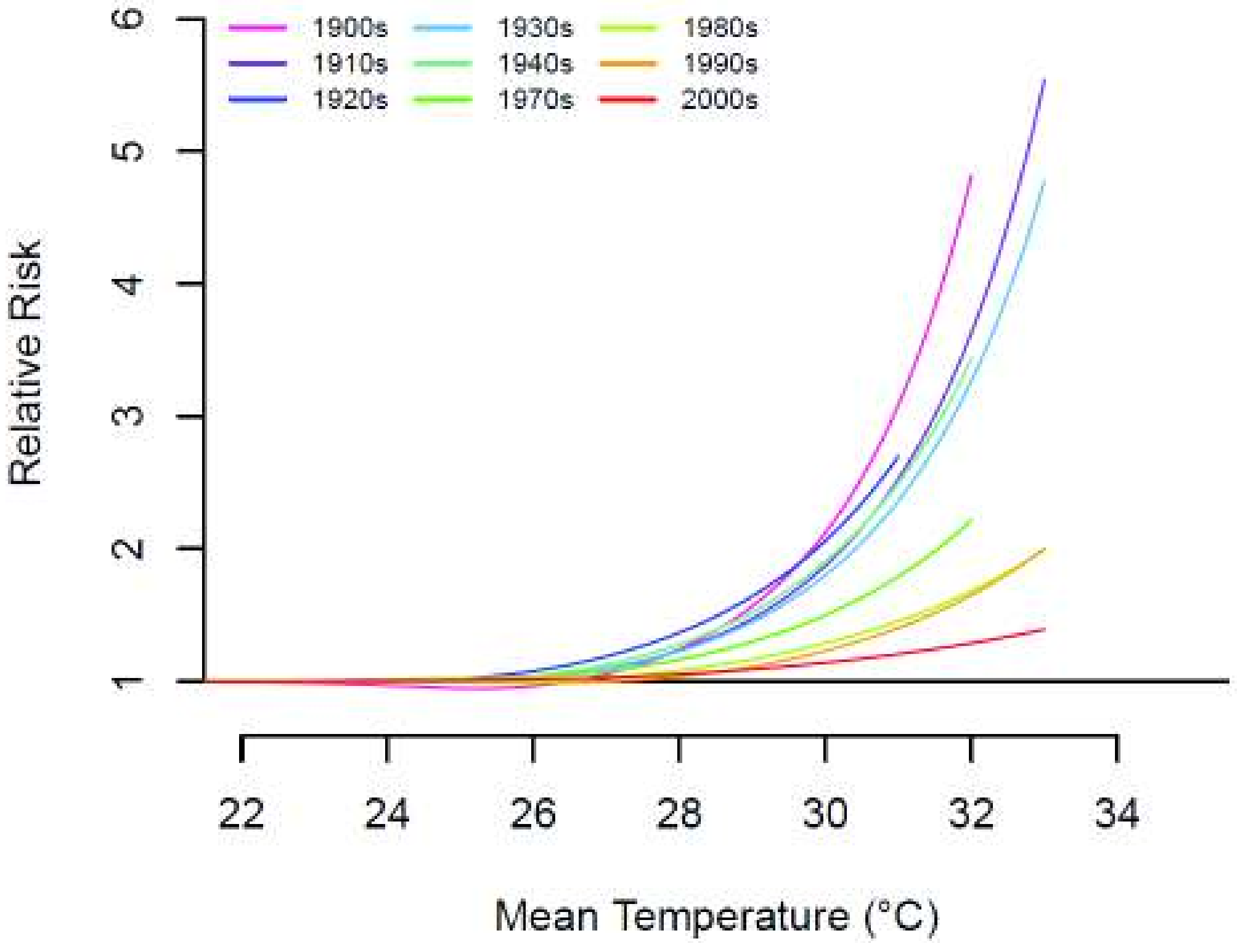

Figure IV.S11 Lag-mortality curve associated with 29°C (corresponding to approximate the 99th percentile of annual temperature) relative to 22°C (corresponding to approximately the 80th percentile of annual temperature) on mortality in New York City by decade, 1900s-2000s, for the over 65 age group. Calculated using a distributed lag non-linear model with a quadratic spline with 4 degrees of freedom for the temperature and a natural cubic spline with 4 degrees of freedom for the lag.

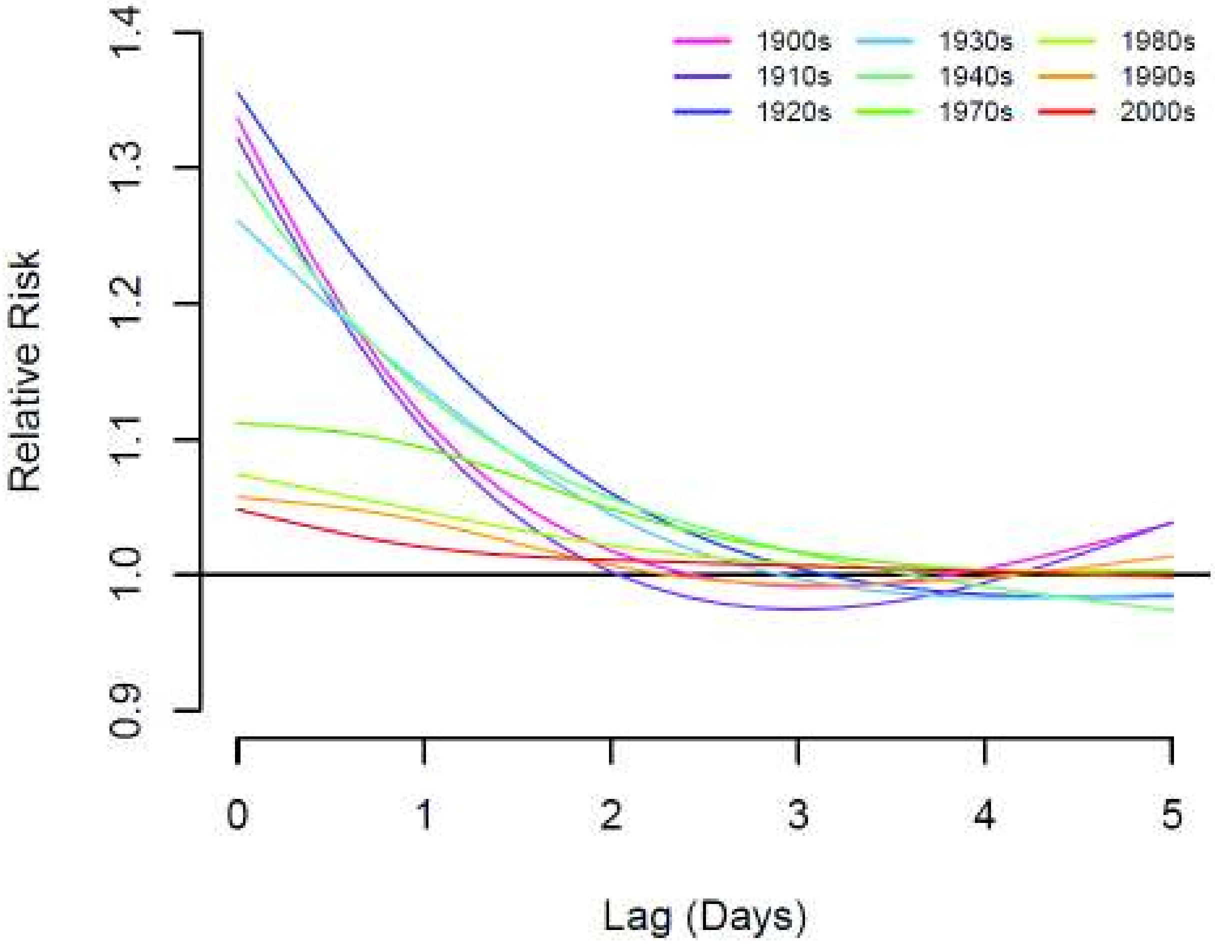

Table IV.S 2 Sensitivity analysis on lag duration and number of degrees of freedom for the temperature and lag. Overall cumulative relative risk at 29˚C (corresponding to approximately the 99th percentile of annual temperature) relative to 22°C (corresponding to approximately the 80th percentile of annual temperature) on mortality in adults (age 15 or older) in New York City by decade, 1900s-2000s.

Model	lag	lag df	temp df	1900 - 1909	1910 - 1919	1920 - 1929	1930 - 1939	1940 - 1948	1973 - 1979	1980 - 1989	1990 - 1999	2000 - 2006
main	5	4	4	1.43 (1.37,1.49)	1.30 (1.25,1.36)	1.39 (1.34,1.45)	1.36 (1.32,1.41)	1.39 (1.35,1.44)	1.26 (1.22,1.29)	1.15 (1.12,1.17)	1.11 (1.09,1.14)	1.09 (1.05,1.12)
2	5	3	4	1.43 (1.37,1.49)	1.30 (1.24,1.35)	1.39 (1.33,1.45)	1.36 (1.31,1.40)	1.39 (1.35,1,43)	1.26 (1.22,1.29)	1.15 (1.12,1.17)	1.11 (1.09,1.14)	1.08 (1.05,1.12)
3	5	3	5	1.25 (1.19,1.31)	1.24 (1.17,1.32)	1.35 (1.29,1.42)	1.29 (1.24,1.34)	1.33 (1.29,1.38)	1.24 (1.20,1.29)	1.14 (1.11,1.17)	1.07 (1.04,1.11)	1.09 (1.04,1.13)
4	5	3	6	1.16 (1.10,1.22)	1.29 (1.21,1.37)	1.32 (1.25,1.38)	1.24 (1.18, 1.30)	1.29 (1.24, 1.34)	1.25 (1.20, 1.31)	1.13 (1.10, 1.16)	1.09 (1.05, 1.12)	1.09 (1.04,1.13)
5	5	4	5	1.26 (1.20,1.32)	1.25 (1.18,1.32)	1.36 (1.30, 1.42)	1.30 (1.25, 1.35)	1.34 (1.29, 1.39)	1.24 (1.20, 1.29)	1.14 (1.11, 1.17)	1.08 (1.04, 1.11)	1.09 (1.04, 1.13)
6	5	4	6	1.16 (1.11, 1.22)	1.30 (1.23, 1.38)	1.32 (1.26, 1.39)	1.25 (1.19, 1.31)	1.30 (1.24, 1.35)	1.26 (1.21, 1.31)	1.13 (1.10, 1.17)	1.09 (1.06, 1.12)	1.09 (1.04, 1.13)
7	5	5	4	1.42 (1.36, 1.48)	1.30 (1.25, 1.36)	1.39 (1.33, 1.45)	1.36 (1.32, 1.41)	1.39 (1.34, 1.43)	1.25 (1.22, 1.29)	1.15 (1.12, 1.17)	1.11 (1.08, 1.14)	1.08 (1.05, 1.12)
8	5	5	5	1.25 (1.20, 1.31)	1.25 (1.18, 1.33)	1.36 (1.30, 1.42)	1.29 (1.24, 1.34)	1.34 (1.29, 1.38)	1.24 (1.20, 1.28)	1.14 (1.11, 1.17)	1.07 (1.04, 1.11)	1.08 (1.04, 1.13)
9	5	5	6	1.16 (1.11, 1.22)	1.30 (1.23, 1.38)	1.32 (1.25, 1.38)	1.25 (1.19, 1.31)	1.29 (1.24, 1.34)	1.25 (1.20, 1.30)	1.13 (1.10, 1.17)	1.09 (1.05, 1.12)	1.09 (1.04, 1.13)
10	10	3	4	1.35 (1.28, 1.43)	1.28 (1.20, 1.36)	1.20 (1.12, 1.28)	1.28 (1.22, 1.35)	1.29 (1.24, 1.35)	1.25 (1.20, 1.31)	1.15 (1.11, 1.18)	1.12 (1.08, 1.16)	1.11 (1.06, 1.15)
11	10	3	5	1.16 (1.09, 1.24)	1.24 (1.14, 1.36)	1.19 (1.12, 1.28)	1.22 (1.16, 1.29)	1.23 (1.17, 1.29)	1.23 (1.17, 1.29)	1.13 (1.09, 1.17)	1.08 (1.04, 1.12)	1.10 (1.04, 1.16)
12	10	3	6	1.10 (1.02, 1.18)	1.33 (1.22, 1.46)	1.19 (1.11, 1.28)	1.17 (1.10, 1.25)	1.19 (1.13, 1.26)	1.23 (1.17, 1.30)	1.12 (1.08, 1.17)	1.10 (1.06, 1.14)	1.10 (1.05, 1.16)
13	10	4	4	1.36 (1.29, 1.44)	1.29 (1.22, 1.36)	1.22 (1.15, 1.30)	1.30 (1.24, 1.36)	1.30 (1.25, 1.36)	1.26 (1.21, 1.31)	1.15 (1.12, 1.18)	1.13 (1.09, 1.16)	1.11 (1.07, 1.16)
14	10	4	5	1.17 (1.10, 1.25)	1.26 (1.16, 1.37)	1.22 (1.14, 1.30)	1.24 (1.18, 1.30)	1.25 (1.19, 1.31)	1.23 (1.17, 1.29)	1.13 (1.09, 1.17)	1.09 (1.05, 1.13)	1.11 (1.05, 1.16)
15	10	4	6	1.10 (1.03, 1.18)	1.36 (1.25, 1.48)	1.22 (1.14, 1.31)	1.19 (1.12, 1.26)	1.21 (1.15, 1.28)	1.24 (1.17, 1.31)	1.13 (1.08, 1.17)	1.10 (1.06, 1.14)	1.11 (1.05, 1.16)
16	10	5	4	1.36 (1.29, 1.44)	1.28 (1.21, 1.35)	1.22 (1.15, 1.30)	1.29 (1.23, 1.35)	1.31 (1.25, 1.36)	1.25 (1.21, 1.31)	1.15 (1.11, 1.18)	1.12 (1.09, 1.16)	1.11 (1.07, 1.16)
17	10	5	5	1.17 (1.10, 1.24)	1.27 (1.17, 1.37)	1.21 (1.14, 1.29)	1.23 (1.17, 1.29)	1.25 (1.19, 1.31)	1.23 (1.17, 1.29)	1.13 (1.09, 1.17)	1.09 (1.05, 1.13)	1.11 (1.05, 1.16)
18	10	5	6	1.11 (1.03, 1.18)	1.36 (1.25, 1.48)	1.22 (1.14, 1.30)	1.18 (1.11, 1.25)	1.22 (1.16, 1.28)	1.24 (1.17, 1.31)	1.13 (1.09, 1.17)	1.10 (1.06, 1.14)	1.11 (1.05, 1.16)

Table IV.S 3 Akaike's Information Criterion for quasi-Poisson (Q-AIC) for models presented in *Table S 2*

Model	lag	lag df	temp df	1900 - 1909	1910 - 1919	1920 - 1929	1930 - 1939	1940 - 1948	1973 - 1979	1980 - 1989	1990 - 1999	2000 - 2006
main	5	4	4	9962	9764	9523	9749	9221	7054	9705	9551	6505
2	5	3	4	9993	9832	9555	9784	9244	7053	9704	9554	6512
3	5	3	5	9716	9833	9534	9746	9201	7066	9706	9539	6510
4	5	3	6	9563	9852	9528	9735	9174	7065	9717	9550	6508
5	5	4	5	9690	9766	9500	9708	9187	7072	9708	9538	6506
6	5	4	6	9539	9786	9492	9689	9155	7074	9716	9551	6509
7	5	5	4	9931	9774	9533	9751	9213	7060	9713	9555	6503
8	5	5	5	9668	9779	9507	9703	9178	7080	9718	9545	6506
9	5	5	6	9529	9799	9502	9674	9150	7083	9727	9560	6511
10	10	3	4	9784	9639	9111	9471	8902	6771	9300	9180	6217
11	10	3	5	9489	9633	9105	9458	8859	6781	9303	9161	6219
12	10	3	6	9338	9652	9106	9451	8846	6784	9315	9163	6219
13	10	4	4	9566	9353	8925	9305	8727	6740	9280	9147	6209
14	10	4	5	9280	9341	8926	9272	8688	6754	9287	9129	6213
15	10	4	6	9140	9350	8925	9264	8672	6754	9301	9133	6212
16	10	5	4	9552	9320	8918	9273	8735	6745	9282	9147	6207
17	10	5	5	9269	9312	8921	9241	8699	6762	9289	9129	6214
18	10	5	6	9126	9325	8922	9235	8681	6765	9299	9136	6218

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V CHAPTER II Heat and Mortality in the U.S. Urban Northeast *

Elisaveta P. Petkova [1], Radley M. Horton [2], Daniel A. Bader [2] and Patrick L. Kinney [1]

[1] Department of Environmental Health Sciences, Mailman School of Public Health, Columbia University, 722 West 168th St., New York, NY 10032, USA; E-Mail: epp2109@columbia.edu (Petkova); plk3@columbia.edu (Kinney)

[2] Columbia University Center for Climate Systems Research, 2880 Broadway, New York, NY 10025, USA; E-Mail: rh142@columbia.edu (Horton); dab2145@columbia.edu (Bader)

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V.1 Abstract

Increased heat-related mortality is projected to be among the major impacts of climate change on human health, and the United States urban Northeast region is likely to be particularly vulnerable. In support of regional adaptation planning, quantitative information is needed on potential future health responses at the urban and regional scales. Here, we present future projections of heat-related mortality in Boston, New York and Philadelphia utilizing downscaled next-generation climate models and Representative Concentration Pathways (RCPs) developed in support of the Intergovernmental Panel on Climate Change (IPCC)'s Fifth Assessment Report (AR5). Our analyses reveal that heat-related mortality rates per 100,000 of population during the baseline period between 1985 and 2006 were highest in Philadelphia followed by New York City and Boston. However, projected heat-related mortality rates in the 2020s, 2050s and 2080s were highest in New York City followed by Philadelphia and Boston. This study may be of value in developing strategies for reducing the future impacts of heat and building climate change resilience in the urban Northeast region.

V.2 Introduction

Heat-related mortality is among the largest and most quantifiable of the expected impacts of climate change on human health (Confalonieri et al. 2007). Urban areas are particularly susceptible to the effects of heat due to the heat island effect, as well as large populations of vulnerable individuals (Kinney et al. 2008). The Northeastern U.S. urban corridor of New York City, Philadelphia and Boston is the largest population agglomeration in the country and among the largest in the World. Since the beginning of the 20th century, New York, Boston and Philadelphia have been experiencing a warming of 0.18, 0.15, and 0.13 degrees Celsius (°C) per decade, respectively. Prior studies have projected that average temperatures will increase by 3 to 5 Celsius (°C), by the last decades of the current century (Hayhoe et al. 2007, Horton et al. 2010), together with an approximate doubling or tripling of the number of hot days each summer (Hayhoe et al. 2008, Horton et al. 2011).

The Consortium for Climate Risk in the Urban Northeast (CCRUN) was created in 2010 under NOAA's Regional Integrated Sciences and Assessments (RISA) Program with the mission to assist stakeholders from various sectors including health, in assessing and managing climate change impacts (Rosenzweig et al. 2011). The impacts of climate change, and heat in particular, on health in the urban Northeast have become an issue of growing public concern in recent years (NYSERDA 2010, Frumhoff et al. 2007). With its current focus on Boston, New York and Philadelphia, one of CCRUN's primary health-related objectives is to derive a comparative assessment of projected heat-related mortality across the three cities, in order to support decision maker efforts to reduce heat-related vulnerability.

Various studies to date have provided assessments of the potential future impacts of heat, projecting substantial increases in heat-related mortality due to climate change (Peng et al. 2011, Dessai et al. 2003, Gosling et al. 2009, Knowlton et al. 2007, Hayhoe et al. 2004, , Hayhoe et al. 2010, Jackson et al. 2010, Kalkstein et al. 1997, Li et al. 2013, Ostro et al. 2012, Baccini et al. 2011, Sheridan et al. 2012). While some previous studies have investigated future heat-related mortality in Boston, Philadelphia and New York City (Gosling et al. 2009, Knowlton et al. 2007, Kalkstein et al. 1997, Li et al. 2013), the utilization of different metrics and methodologies makes comparing assessments across cities challenging. In addition, the impacts of climate change on heat-related mortality under the next-generation Intergovernmental Panel on Climate Change (IPCC)'s Fifth Assessment Report (AR5) models (Taylor et al. 2011) and Representative Concentration Pathways (RCPs) (Moss et al. 2010) are yet to be investigated in any of the cities of interest.

In this paper, we present the first estimates of heat-related mortality in Boston, New York City and Philadelphia based on downscaling of the new coupled global climate models and two of the Representative Concentration Pathways (RCPs), RCP4.5 and RCP8.5. We start by characterizing the heat-mortality relationships in each city based on 22 years of historical daily temperature and mortality data. Next, we present mortality projections based on the downscaled temperature projections. Heat-related mortality rates are used as the outcome measure. Finally, we calculate future heat-related deaths and mortality rates based on the ensemble of temperature projections.

V.3 Materials and Methods

We started by characterizing the summer heat-mortality relationships between observed daily mortality and mean temperature data in each city. The summer season was defined as the months of May, June, July, August and September. Daily all-cause mortality data for Boston, New York and Philadelphia from 1985 to 2006 were obtained in collaboration with Dr. Joel Schwartz and colleagues at Harvard University School of Public from the U.S. National Center for Health Statistics (CDC 2013). The following counties were included in the city-specific mortality data: Suffolk County, MA for Boston, New York County, NY, Kings County, NY, Queens County, NY, Bronx, NY and Richmond County, NY for New York City and Pennsylvania County, PA for Philadelphia.

Daily mean temperature data for the same period for each city were obtained from the U.S. National Climatic Data Center (NOAA 2013). Temperature monitoring stations are located in New York Central Park for New York City, Boston Logan International Airport for Boston, and Philadelphia International Airport for Philadelphia. While New York Central Park is located in midtown Manhattan, the Boston Logan International Airport and Philadelphia International Airport are located about 3 and 10 miles from the respective city centers, respectively.

The distributed lag non-linear module in R (Gasparrini et al. 2011a) was used to model the summer heat-mortality relationships. Models for each city were developed using natural cubic splines with four degrees of freedom for the temperature and the lag. We also fitted models with splines ranging from three to five degrees of freedom for the temperature and from three to five degrees of freedom for the lag and found that findings were robust to modeling parameters. We tested models with lags between one and seven days and found that lag duration of four days was sufficient to capture fully the heat effect in each location. Based on previous studies published in the literature (Gasparrini et al. 2011b, Hajat et al. 2006), we used two splines to control for seasonality: a natural spline with two degrees of freedom per year to control for long term seasonal cycles, and a natural spline with four degrees of freedom for day in year to control for within summer seasonal variation. Data on ozone and particulate matter with aerodynamic diameter of 10 µm or less (PM10) were not included in the model since they were found to not substantially impact results in a previous study (Li et al. 2013). All models were developed using mean daily temperature and 20 °C as a reference temperature for calculating relative risk (RR) above 25 °C. Consistent reference temperatures and temperature thresholds as opposed to city-specify percentiles were used in estimating temperature effects. This approach allows quantifying and comparing the impact of an identical temperature exposure on mortality across the three cities.

Our spatial and temporal downscaling approach begins with monthly bias-corrected and spatially disaggregated (BCSD) climate projections at 1/8° resolution derived from the WCRP CMIP5 multi-model data set. BCSD projections were obtained online (Maurer et al. 2007) for 33 global-scale general circulation models (GCMs) used in the Intergovernmental Panel on Climate Change (IPCC)'s Fifth Assessment Report (AR5), and two representative concentration pathways (RCPs) (Moss et al. 2010). Detailed information about the 33 climate models is provided in *Table V.S1.* The new RCPs were developed for the climate modeling community as a basis for long-term and near-term climate modeling experiments in support of the IPCC AR5. RCPs, which replace the emissions scenarios (Nakicenovic et al. 2000) used in prior IPCC assessments, make various underlying assumptions about radiative forcing through time, which is dependent upon future global greenhouse gas and aerosol concentrations, as well as land use changes.

For this analysis, we selected the two RCPs most used by the climate modeling community, RCP4.5 and RCP8.5, which represent relatively low and high greenhouse gas projections/radiative forcing, respectively. RCP4.5 is a scenario where greenhouse gas concentrations are stabilized after 2100, due to emissions reduction prior to 2100. RCP8.5 is a scenario with increasing emissions over the century. Increasing emissions are associated with a highly energy intensive future, that features high population growth and slow development of green technologies such as renewable energy sources and energy efficiency (Vuuren et al. 2011).

The monthly output from the land-based 1/8° grid box corresponding to Boston (Airport), New York (Central Park), and Philadelphia (Airport) was then used to create change factors for each calendar month based on the difference between a 30-year future average (or 'timeslice') for that calendar month and the same GCM's 30-year baseline average for that same calendar month (Rosenzweig et al. 2011). We next applied the calendar-month change factors to the respective observed daily weather data for each of the three cities to create a future projection with the same statistical characteristics and sequence as the observations. Our downscaled output is a set of 66 weather station-specific synthetic future temperature projections for daily mean temperature in each city from 2010 to 2099 based on three 30-year time slices, defined as the 2020s (2010 to 2039), 2050s (2040 to 2069) the 2080s (2070 to 2099), and for a baseline period of 1971 to 2000.

The approach described here does not explore how intra-annual and inter-annual temperature variability may change. By not considering sub-monthly changes in variability, we were able to use fine-spatial-resolution projections (as the 1/8° BCSD product is monthly, not daily). By applying the delta method separately for each calendar month, we do capture one component of possible changes in intra-annual variance, changes in the annual temperature cycle. Previous studies have found changes in the annual cycle to be important (Ballester et al. 2010).

The derived temperature-specific relative risk estimates for Boston, New York City and Philadelphia were applied to the daily downscaled temperature projections until 2100 for each city. Temperature curves were linearly extrapolated for temperatures up to 42 °C, the highest projected temperature, using the last four points of each curve. City-specific estimates of annual summer heat-related mortality were computed as described below.

Our approach to calculating heat-related mortality was similar to that presented in a previous study (Anenberg et al. 2010). First, using the temperature-specific relative risks derived from the models for each city, we calculated historical heat-related attributable risk and projected heat-related attributable risk for temperatures 25 °C and above. Daily observed temperatures were used in calculating the historical and daily downscaled temperature projections were used for calculating future heat-related attributable risks:

$$HAR = \frac{RR - 1}{RR}, \text{ where:} \tag{V.1}$$

- HAR is the daily heat-related attributable risk
- RR is the calculated relative risk at each temperature from the city-specific model

Next, we calculated annual May–September heat-related mortality rates as follows:

$$HMR = \frac{1}{N}\sum_{i=1}^{N}\sum_{d=1}^{D_i} Y_0 \times HAR_d \text{ , where:} \tag{V.2}$$

- HMR is the mean annual heat-related mortality rate for each time period
- N is the number of years in each time period (22 for the baseline and 30 for the future periods)
- i is an index for year in each time period
- D_i is the number of days in the i-th year

- *d* is an index of day in the i-th year
- Y_0 is daily mortality rate (per 100,000 population) calculated using the year 2000 population and city-specific mortality rates for Boston, New York and Philadelphia from the CDC Wonder database (CDC 2013)

We also calculated annual heat-related daily deaths:

$$HRD = \frac{HMR \times Pop}{100{,}000}, \text{ where:} \qquad (V.3)$$

- *HRD* is the number of annual heat-related deaths in each period
- *Pop* is the population of each city using the year 2000 population data from the CDC Wonder database (CDC 2013)

V.4 Results

Temperature, population and mortality summary statistics for Boston, New York City and Philadelphia are presented in *Table V.1*. New York City is located about 190 miles from Boston and 80 miles from Philadelphia. The region spans the transition between the humid subtropical and humid continental climates.

Table V.1. Population, mortality and temperature statistics for Boston, New York City and Philadelphia.

City	**Population (2000)** [1]	**Annual/Daily Mortality Rate per 100,000 (2000)** [1]	**Mean Summer** [2] **Temperature (°C)** [3]	**Mean Annual Temperature (°C)** [3]
Boston	689,807	795/2.18	19.6	10.9
New York City	8,008,278	754/2.07	21.7	13

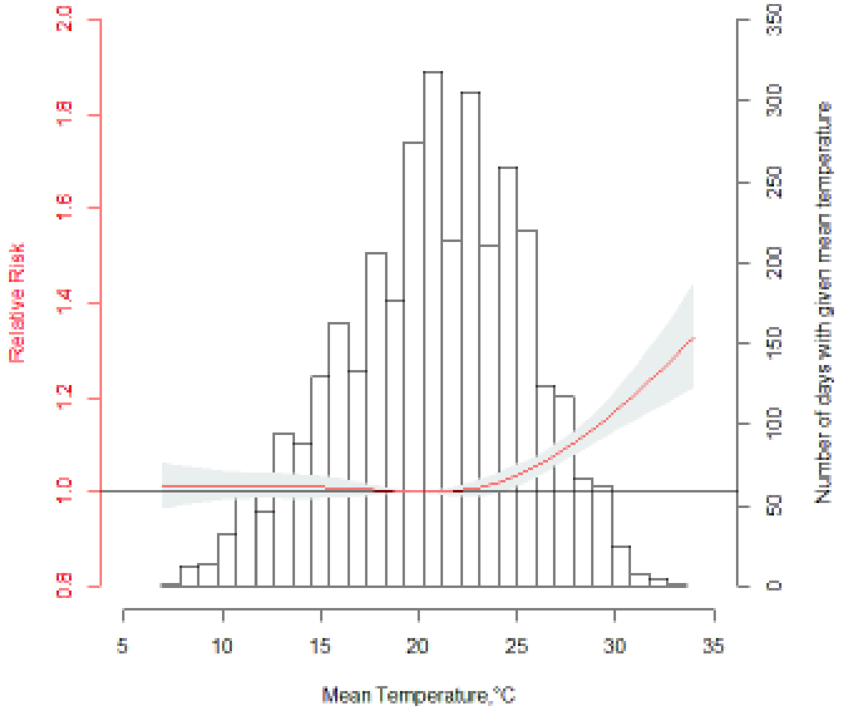
Philadelphia	1,517,550	1167/3.2	22.4	13.4

[1] Population and mortality rates obtained from the CDC Wonder Database [35]; [2] Includes data for May, June, July, August and September; [3] Temperature data obtained from the U.S. National Climatic Data Center [24].

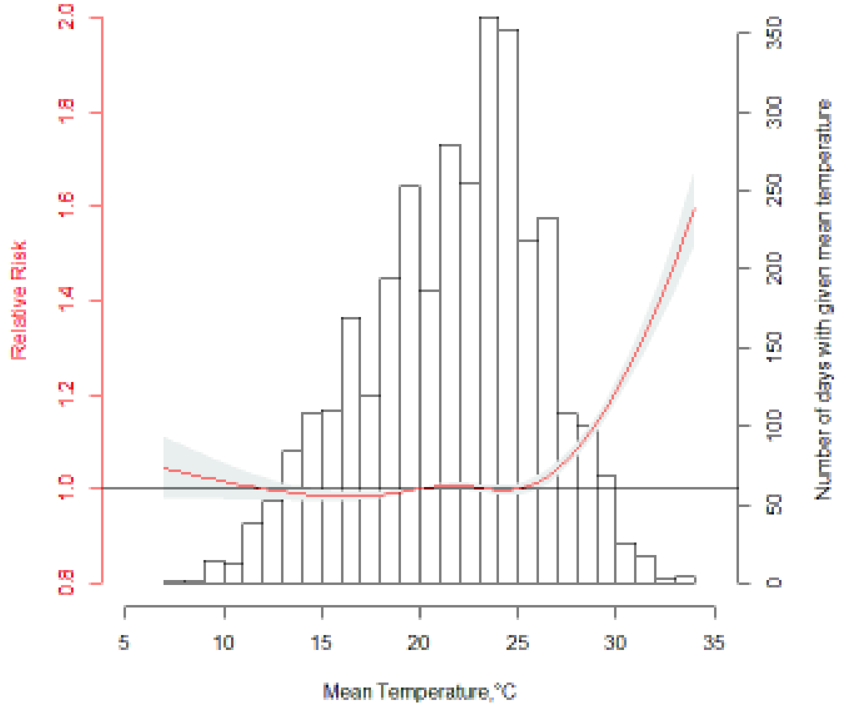
The summer temperature-mortality relationships derived using the non-linear distributed lag models along with summer temperature histograms are presented in *Figure V.1a–c*. The overall structure of the temperature-mortality relationships was similar for the three cities. Also, for all cities, cumulative relative risks were slightly elevated at the lowest temperatures. There was no difference in the lag structure across the three cities (not displayed). Nonetheless, some differences were also evident. First, a heat effect was observed above around 26 °C in New York City and Philadelphia and above 24 °C in Boston. Also, mortality risk at very high temperatures was substantially more pronounced in New York City compared to Boston and Philadelphia.

Annual baseline and projected heat-related mortality rates for Boston, New York City and Philadelphia are presented in *Figure V.2a–c* and the *Table V.S2*. Baseline heat-related mortality rates were highest in Philadelphia (4.5 per 100,000) followed by New York City (3.7 per 100,000) and Boston (2.9 per 100,000). Projected heat-related mortality rates based on the downscaled temperature projections were highest in New York City followed by Philadelphia and Boston. We first computed heat-related mortality rates for each GCM (*Table V.S2*) and then reported median values by decade and RCP. During the 2020s, median heat-related mortality rates calculated across all models and the RCP4.5 and RCP8.5, were 9.1 and 10 per 100,000, respectively, for New York City, 8 and 8.8 per 100,000 for Philadelphia and 5.9 and 6.5 per 100,000 for Boston. In the 2050s, New York City was projected to experience median mortality rates of 14.3 and 18.9 per 100,000, Philadelphia of 12.2 and 16 per 100,000 for and Boston of 8.8 and 11.7 per 100,000, for RCP4.5 and RCP8.5, respectively. By the 2080s, projected median heat-related mortality rates across all models and the RCP4.5 and RCP8.5 were 17.1 and 34.3 per 100,000 for New York City, 15.2 and 28.7 for Philadelphia, and 10.5 and 19.3 per 100,000 for Boston.

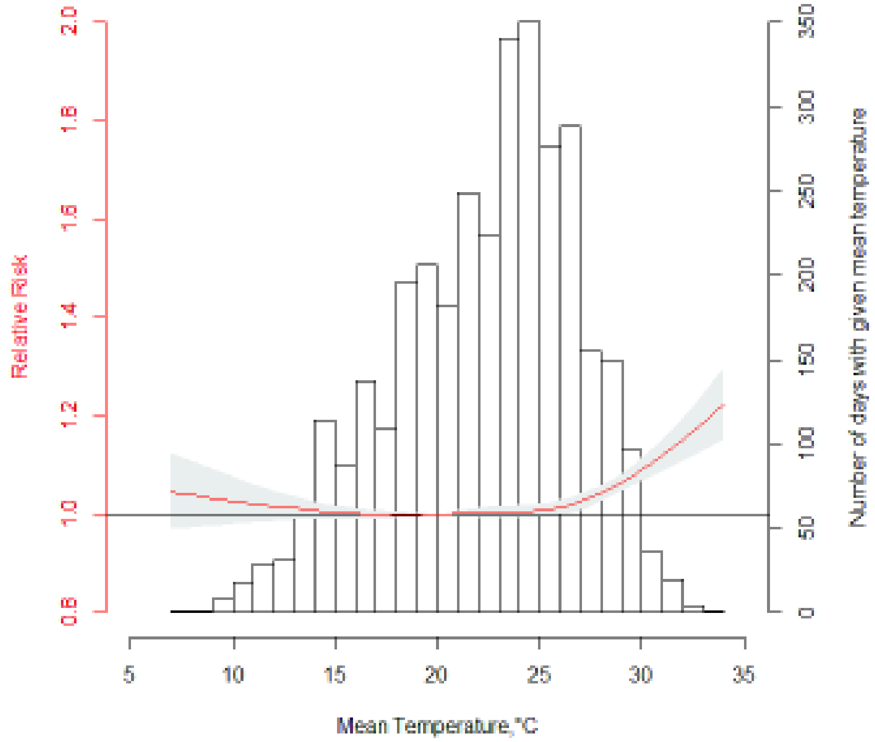
Figure V.1. Temperature–mortality curves of overall cumulative relative risk over four days of lag and mean summer temperature histograms for (**a**) Boston (**b**) New York City and (**c**) Philadelphia based on data between 1985 and 2006. Relative risks calculated using a distributed lag non-linear model with natural cubic splines with four degrees of freedom for the temperature and the lag and 20 °C as a reference temperature.



1(a)

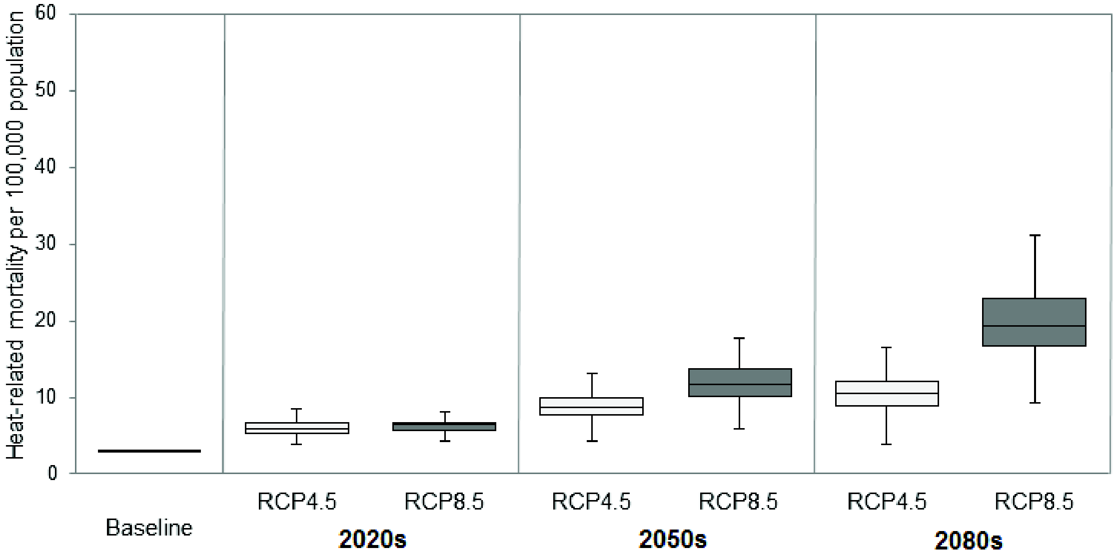

Relative Risk
0.8
1.0
1.2
1.4
1.6
1.8
2.0
Number of days with given mean temperature
0
50
100
150
200
250
300
350
5
10
15
20
25
30
35
Mean Temperature,°C

1(b)

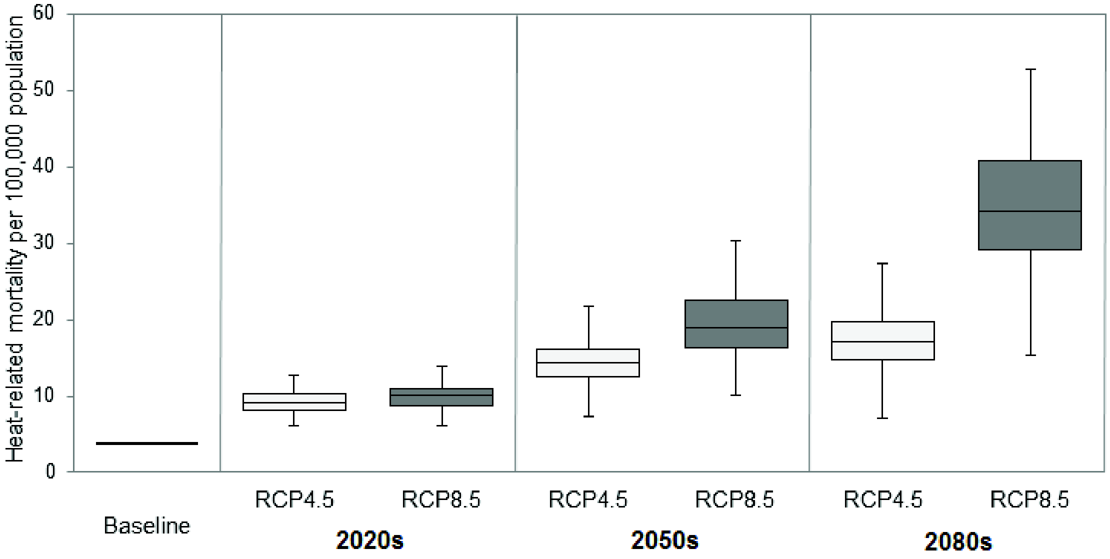

Relative Risk
0.8
1.0
1.2
1.4
1.6
1.8
2.0
Number of days with given mean temperature
0
50
100
150
200
250
300
350
5
10
15
20
25
30
35
Mean Temperature,°C

1(c)

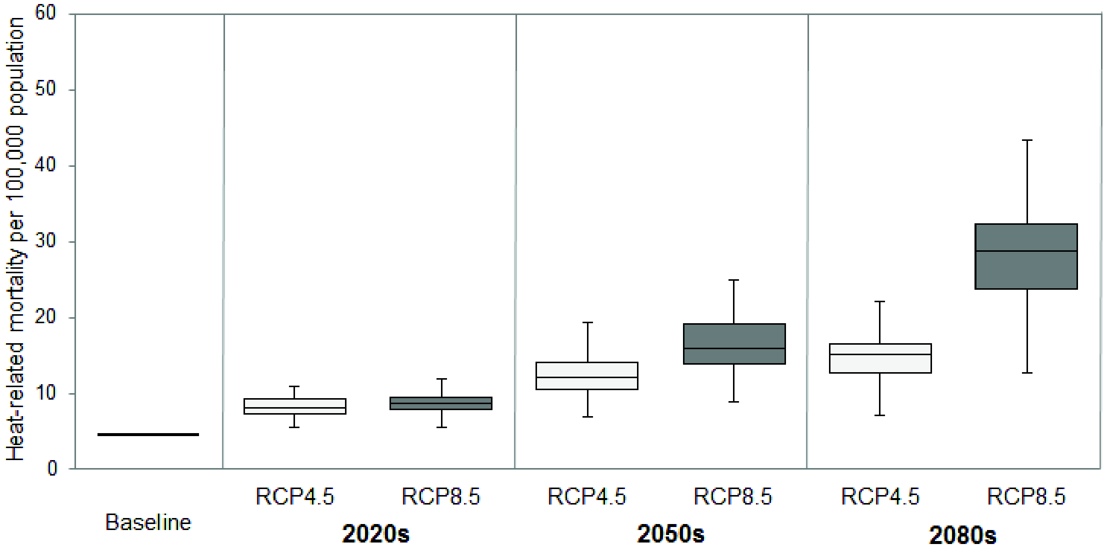
Figure V.2. Projected annual heat-related mortality rates during the 2020s, 2050s and 2080s for (**a**) Boston (**b**) New York City and (**c**) Philadelphia, during the baseline period (1985–2006) and according to the 33 global climate models (GCMs) and two Representative Concentration Pathways (RCPs), RCP4.5 and RCP8.5. Box plots illustrate the minimum, lower quartile, median, upper quartile and maximum values across the GCMs, by period and RCP. Also displayed are the annual heat-related mortality rates computed for the baseline period between 1985 and 2006, based on observed temperatures.



2(a)


Heat-related mortality per 100,000 population
60
50
40
30
20
10
0
Baseline
RCP4.5
RCP8.5
2020s
RCP4.5
RCP8.5
2050s
RCP4.5
RCP8.5
2080s

2(b)


Heat-related mortality per 100,000 population
60
50
40
30
20
10
0
Baseline
RCP4.5
RCP8.5
2020s
RCP4.5
RCP8.5
2050s
RCP4.5
RCP8.5
2080s

2(c)

The relative increase in heat-related mortality by the end of the century was greater in New York City, followed by Boston and Philadelphia. By the 2080s under RCP4.5, the calculated heat-related mortality rates represent an over three-fold increase in Philadelphia, a nearly four-fold increase in Boston and nearly five-fold increase in New York City. By the 2080s under RCP8.5, these rates represent an over six-fold increase in heat-related mortality in Philadelphia, a nearly seven-fold increase in Boston and over nine-fold increase in New York City.

New York City was projected to experience the greatest increase in the number of heat-related deaths due to its large population, followed by Philadelphia and Boston. Heat-related deaths are calculated using Equation (V.3.) and the median heat-related mortality rates from *Table V.S2*. By the 2080s, the calculated mortality rates according to the RCP8.5 or RCP4.5 correspond to 2,743 or 1,336 summer heat-related deaths annually compared to 297 during the baseline period for New York City, 436 or 231 summer heat-related deaths annually compared to 68 during the baseline period for Philadelphia, and 133 or 73 summer heat-related deaths annually compared to 20 during the baseline period for Boston.

V.5 Discussion

Characterizing the heat-mortality relationships in Boston, New York City and Philadelphia based on daily temperature and mortality data in the period between 1985 and 2006 was the first step in our assessment of future heat-related mortality in the three cities. The similarity of the heat-mortality curves across the three cities was not surprising given their close proximity and similar climates. However, the substantially higher mortality risk at very high temperatures observed in New York City during the baseline period compared to Boston and Philadelphia warrants further investigation. Based on the relative geographical location of the three cities, one might expect that the heat effect would be most pronounced in Boston where summers are the coolest followed by New York City and finally Philadelphia, where summers are the hottest overall. Several factors may be contributing to the higher historical heat-related mortality observed in New York City. First, as the biggest of the three cities, New York City may be experiencing a greater urban heat island effect, resulting in substantially higher temperatures within the city's neighborhoods compared to New York Central Park where the temperature monitoring station is located. According to the U.S. Environmental Protection Agency, temperature in cities can be up to 12 °C higher compared to surrounding areas (EPA 2013, Akbari 2005); one study in New York City found that the heat island can average 4 °C and reach up to 8 °C (Rosenzweig et al. 2009). Lack of access or underutilization of air conditioning, particularly among the New York City's most vulnerable populations may be another important factor. The elderly and those with pre-existing medical conditions have been found to be particularly susceptible to the impacts of heat (Luber et al. 2008, Hajat et al. 2007, Vandentorren et al. 2006). Although air conditioning prevalence has been increasing steadily in the Northeast region, a far greater percentage of homes did not have air conditioning in New York, compared to Massachusetts and Pennsylvania according to the Residential Energy Consumption Survey (RECS) carried out by the U.S. Energy Information Administration (EIA). According to the survey, as of 2009, 19.4% of New York homes did not have air conditioning compared to 12% in Massachusetts and 6.1% in Pennsylvania. Further, 6.9%, 8% and 6.1% in New York, Massachusetts and Pennsylvania, respectively, did not use existing air conditioning equipment in their homes. Data on air conditioning utilization during heat events was unfortunately not available. In a recent case review of 26 heat-related deaths in New York City with documented air conditioning data, 88% lacked air conditioning at home and the remaining 12% had air conditioning that wasn't used for technical or other reasons (Wheeler et al. 2013). To prevent heat-related mortality among individuals with a medical conditions exacerbated by heat, New York has started providing air conditioning to eligible individuals through the Home Energy Assistance Program (HEAP 2013).

After characterizing heat-related mortality in each city, we compared the city-specific baseline and projected heat-related mortality rates. An interesting finding of the analyses was the higher baseline heat-related mortality rate in Philadelphia compared to Boston and New York City. As described previously, heat-related mortality rates were derived by multiplying the temperature-specific heat-related attributable risks by city-specific mortality rates per 100,000. Thus, despite the more pronounced heat effect at very high temperature in New York City, the baseline heat-related mortality rate is higher in Philadelphia due to the city's high mortality rate (Table V.1). Nonetheless, projected heat-related mortality rates are greatest in New York City, followed by Philadelphia and Boston in each of the three future periods (*Figure V.2a–c*). The substantial increase in heat-related mortality projected by our models in all of the three cities provides further evidence of the vulnerability to heat in the region.

The increasing number of days with moderately and very high temperatures is a main driver of the future increases heat-related mortality. For New York City, the impacts of heat are further exacerbated by the magnitude of the mortality response at very high temperatures. Finally, the choice of RCP plays a substantial role in projecting future heat-related mortality, particularly in the second half of the century. During the 2020s, estimates derived using RCP4.5 and RCP8.5 do not vary greatly. By the 2080s, however, median heat-related mortality rates calculated across all models under RCP8.5 were near twice as high as those calculated under RCP4.5. These findings illustrate the health impacts associated with the difference between scenarios in which greenhouse gas concentrations in the atmosphere/radiative forcing continue to increase (RCP8.5) or stabilize over time (RCP4.5), respectively.

Our analysis of heat-related mortality rates across the three cities illustrates the influence and interplay of the various input parameters, such as temperature-specific relative risks, mortality rates and population in each city. Thus, assumptions about each of these inputs have important impacts on the interpretation of findings. Our study has several important limitations. First, we assumed that population in each city will remain constant at the 2000 Census level. This may lead to underestimation of future impacts because urbanization will likely continue in the region throughout the century. Similarly, we assumed constant city-specific mortality rates. Mortality rates may decrease in the coming decades if life expectancy continues to increase and improvements of the overall quality of life of the population continue to take place. We also assumed that the derived temperature-mortality curves will remain unchanged throughout the century. This may not be the case since populations are likely to acclimatize to heat over time. Therefore, this approach may represent an overestimation of future impacts of heat. Nonetheless, assuming constant temperature-specific relative risks, mortality rates and population in each city allowed the estimation of potential heat-related mortality impacts due to climate change in each city. The resulting comparative assessment of projected heat-related mortality can be of value in supporting decision maker efforts to reduce heat-related vulnerability in the region.

V.6 Conclusions

We presented an assessment of the potential impacts of climate change on heat-related mortality in the three largest cities of the Northeast U.S.—Boston, New York City and Philadelphia—using the climate models and two Representative Concentration Pathways (RCPs) from the

Intergovernmental Panel on Climate Change (IPCC)'s Fifth Assessment Report (AR5). To our knowledge this is the first such study.

We found that although heat-mortality curves across the three cities were similar, New York experienced a more pronounced heat effect at very high temperatures compared to Boston and Philadelphia. However, that heat-related mortality rates per 100,000 of population during the baseline period were highest in Philadelphia followed by New York City and Boston. Nonetheless, the projected heat-related mortality rates in the 2020s, 2050s and 2080s were highest in New York City, followed by Philadelphia and Boston. By the 2080s, these rates represent an over three-fold increase in Philadelphia, a nearly four-fold increase in Boston and nearly five-fold increase in New York City under $RCP_{4.5}$ and an over six-fold increase in Philadelphia, a nearly seven-fold increase in Boston and over nine-fold increase in New York under $RCP_{8.5}$. The presented estimates allow a comparative assessment of the potential impacts of climate change on heat-related mortality in the three cities that can be of value to various stakeholders interested in developing strategies to reduce these impacts and building climate change resilience in the urban Northeast region.

V.7 Supplemental Material

Table V.S1. IPCC AR5 GCMs used in this study. The models were developed by 22 modeling centers (left column). Some centers support multiple GCMs, and/or versions of their GCM.

Modeling Center	**Institute ID**	**Model Name**	**Atmospheric Resolution (lat × lon)**
Commonwealth Scientific and Industrial Research Organization (CSIRO) and Bureau of Meteorology (BOM), Australia	CSIRO-BOM	ACCESS1.0 ACCESS1.3	1.25 × 1.875 1.25 × 1.875
Beijing Climate Center, China Meteorological Administration	BCC	BCC-CSM1.1 BCC-CSM1.1(m)	2.8 × 2.8 1.1 × 1.1
College of Global Change and Earth System Science, Beijing Normal University	GCESS	BNU-ESM	2.8 × 2.8
Canadian Centre for Climate Modelling and Analysis	CCCMA	CanESM2	2.8 × 2.8
National Center for Atmospheric Research	NCAR	CCSM4	0.9 × 1.25
Community Earth System Model Contributors	NSF-DOE-NCAR	CESM1(BGC) CESM1(CAM5)	0.9 × 1.25 0.9 × 1.25
Centro Euro-Mediterraneo per l Cambiamenti Climatici	CMCC	CMCC-CM	0.75 × 0.75

Modeling Center	**Institute ID**	**Model Name**	**Atmospheric Resolution (lat × lon)**
Commonwealth Scientific and Industrial Research Organization in collaboration with Queensland Climate Change Centre of Excellence	CSIRO-QCCE	CSIRO-Mk3.6.0	1.9 × 1.9
LASG, Institute of Atmospheric Physic, Chinese Academy of Sciences and CESS, Tsinghua University	LASG-CESS	FGOALS-g2	2.8 × 2.8
The First Institute of Oceanography, SOA, China	FIO	FIO-ESM	2.8 × 2.8
NOAA Geophysical Fluid Dynamics Laboratory	NOAA GFDL	GFDL-CM3 GFDL-ESM2G GFDL-ESM2M	2.0 × 2.5 2.0 × 2.5 2.0 × 2.5
NASA Goddard Institute for Space Studies	NASA GISS	GISS-E2-R	2.0 × 2.5
National Institute of Meteorological Research/Korea Meteorological Administration	NIMR/KMA	HadGEM2-AO	1.25 × 1.875
Met Office Hadley Centre (additional HadGEM2-ES realizations contributed by Instituto Nacional de Pesquisas Espaciais)	MOHC (additional realizations by INPE)	HadGEM2-CC HadGEM2-ES	1.25 × 1.875 1.25 × 1.875
Institute for Numerical Mathematics	INM	INM-CM4	1.5 × 2.0
Institut Pierre-Simon Laplace	IPSL	IPSL-CM5A-LR IPSL-CM5A-MR IPSL-CM5B-LR	1.9 × 3.75 1.3 × 2.5 1.9 × 3.75

Modeling Center	**Institute ID**	**Model Name**	**Atmospheric Resolution (lat × lon)**
Japan Agency for Marine-Earth Science and Technology, Atmosphere and Ocean Research Institute (The University of Tokyo), and National Institute for Environmental Studies)	MIROC	MIROC-ESM	2.8 × 2.8
		MIROC-ESM-CHEM	2.8 × 2.8
Atmosphere and Ocean Research Institute (The University of Tokyo), National Institute for Environmental Studies, and Japan Agency for Marine-Earth Science and Technology	MIROC	MIROC5	1.4 × 1.4
Max Planck Institute for Meteorology	MPI-M	MPI-ESM-MR	1.9 × 1.9
		MPI-ESM-LR	1.9 × 1.9
Meteorological Research Institute	MRI	MRI-CGCM3	1.1 × 1.1
Norwegian Climate Centre	NCC	NorESM1-M	1.9 × 2.5
		NorESM1-ME	1.9 × 2.5

Table V.S2. Heat-related mortality rates per 100,000 population during the baseline period between 1985 and 2006 for Boston, New York City and Philadelphia (**a**) and projected annual heat-related mortality rates per 100,000 population during the 2020s, 2050s and 2080s for Boston, New York City and Philadelphia according to the each of the 33 global climate models (GCMs) and the two Representative Concentration Pathways (RCPs) used in this study: (**b**) $RCP_{4.5}$ and (**c**) $RCP_{8.5}$.

(**a**)

Baseline (1985–2006)		
Boston	**NYC**	**Philadelphia**
2.9	3.7	4.5

(**b**)

	RCP 4.5								
GCM	**Boston**			**NYC**			**Philadelphia**		
	2020s	**2050s**	**2080s**	**2020s**	**2050s**	**2080s**	**2020s**	**2050s**	**2080s**
access1-0	7.7	9.9	11.7	11.7	15.9	18.8	9.3	13.8	16.3
access1-3	6.2	8.5	10.7	8.8	12.5	15.4	7.9	11.4	13.7
bcc-csm1-1	5.2	7.8	9.3	8.0	14.8	14.7	7.4	13.4	13.7
bcc-csm1-1-m	5.8	7.7	8.9	9.2	14.1	15.4	9.6	13.6	15.9
bnu-esm	7.8	11.0	14.2	12.5	17.7	22.8	10.0	14.7	18.3
canesm2	6.8	10.9	13.0	10.5	16.3	20.0	10.5	14.7	17.5
ccsm4	5.5	8.1	8.2	8.3	13.1	14.6	7.6	10.7	11.6
cesm1-bgc	5.4	8.2	8.3	9.1	15.1	15.1	7.5	11.7	11.7
cesm1-cam5	6.6	9.5	12.2	10.3	16.1	20.0	8.9	12.3	16.5

cmcc-cm	6.6	8.8	11.3	8.8	14.4	19.1	8.0	12.6	15.8
cnrm-cm5	4.9	7.4	9.7	7.3	11.1	15.4	6.8	9.0	12.7
csiro-mk3-6-0	5.4	8.9	10.5	8.3	14.1	17.1	7.7	11.9	15.3
fgoals-g2	6.6	9.9	10.8	10.4	18.0	19.4	9.3	14.1	15.2
fio-esm	4.0	4.4	3.8	6.1	7.3	7.0	5.6	6.9	7.1
gfdl-cm3	7.3	12.9	16.6	11.4	24.4	29.7	10.1	19.6	24.6
gfdl-esm2g	5.0	7.0	5.8	6.4	10.5	9.0	6.3	9.4	8.8
gfdl-esm2m	4.7	5.9	6.8	7.8	9.7	10.8	6.8	8.0	8.9
giss-e2-r	5.2	6.4	6.5	8.1	10.1	11.4	7.3	9.5	10.3
hadgem2-ao	9.2	14.1	15.1	12.7	20.0	24.4	10.9	16.7	20.9
hadgem2-cc	6.8	10.9	14.6	9.6	16.9	24.3	9.1	14.3	20.0
hadgem2-es	6.5	11.0	15.4	10.8	18.6	24.8	9.9	15.5	20.4
inmcm4	4.2	4.8	6.1	6.1	8.0	10.1	5.7	6.9	8.8
ipsl-cm5a-lr	6.4	9.0	11.6	9.1	15.3	18.8	7.9	12.8	15.7
ipsl-cm5a-mr	6.4	8.9	10.3	9.3	15.9	17.5	8.5	13.2	15.6
ipsl-cm5b-lr	5.5	8.3	10.1	8.1	13.4	15.9	7.2	11.1	12.9
mirco-esm	6.6	11.7	13.4	10.3	18.6	22.2	8.9	15.3	17.5
miroc-esm-chem	7.0	11.3	12.6	10.3	16.2	19.8	9.6	14.5	16.6

GCM	RCP 4.5								
	Boston			NYC			Philadelphia		
	2020s	**2050s**	**2080s**	**2020s**	**2050s**	**2080s**	**2020s**	**2050s**	**2080s**
miroc5	5.9	9.0	9.8	9.3	14.3	16.2	8.3	12.2	13.8
mpi-esm-lr	5.9	8.0	10.2	9.0	12.5	14.0	7.8	10.5	12.7
mpi-esm-mr	5.7	7.3	9.6	8.1	11.6	15.7	8.1	10.6	13.8
mri-cgcm3	4.7	7.0	6.9	6.9	10.7	10.8	6.3	9.0	10.0
noresm1-m	6.0	8.9	11.1	9.3	13.1	17.8	8.3	11.9	15.2
noresm1-me	5.6	8.7	11.8	8.6	14.2	19.3	7.9	12.0	15.1
median	**5.9**	**8.8**	**10.5**	**9.1**	**14.3**	**17.1**	**8.0**	**12.2**	**15.2**

(c)

GCM	RCP 8.5								
	Boston			NYC			Philadelphia		
	2020s	**2050s**	**2080s**	**2020s**	**2050s**	**2080s**	**2020s**	**2050s**	**2080s**
access1-0	6.5	12.5	20.9	10.3	19.2	37.7	9.5	17.3	32.0
access1-3	5.9	9.7	16.7	8.3	15.4	27.0	8.1	13.9	23.8
bcc-csm1-1	6.6	10.8	18.2	9.9	17.3	33.2	9.5	15.6	28.7
bcc-csm1-1-m	6.6	12.3	17.0	11.5	22.0	32.6	10.6	19.2	30.7
bnu-esm	7.3	14.2	24.5	11.5	22.8	42.6	10.1	19.4	32.3
canesm2	7.4	15.8	26.8	11.6	23.3	41.4	11.2	21.4	36.7
ccsm4	5.5	10.1	16.0	9.3	15.9	30.7	8.1	14.0	23.8
cesm1-bgc	6.3	10.1	15.9	10.0	16.4	29.1	8.2	14.4	23.4
cesm1-cam5	6.8	12.2	19.9	10.5	20.0	37.7	9.1	16.6	29.2

GCM	RCP 8.5								
	Boston			NYC			Philadelphia		
	2020s	2050s	2080s	2020s	2050s	2080s	2020s	2050s	2080s
cmcc-cm	6.5	10.1	18.2	10.0	17.3	35.3	8.8	15.4	30.7
cnrm-cm5	5.8	10.0	16.9	8.8	16.9	27.4	7.7	14.0	22.4
csiro-mk3-6-0	5.4	11.3	18.8	8.8	19.1	33.7	7.8	16.5	26.9
fgoals-g2	7.1	13.6	21.0	11.2	24.9	40.6	10.0	20.0	30.5
fio-esm	4.3	5.9	10.8	6.8	11.1	20.6	5.9	9.9	17.8
gfdl-cm3	7.3	17.8	30.4	13.9	30.3	52.8	12.5	24.9	43.5
gfdl-esm2g	5.6	8.6	15.4	8.7	14.3	24.6	7.7	12.2	21.6
gfdl-esm2m	5.6	8.9	13.0	9.5	15.3	25.0	7.7	12.2	19.7
giss-e2-r	5.6	7.8	11.8	8.5	13.4	19.9	7.3	11.8	17.2
hadgem2-ao	6.8	15.6	28.2	9.0	22.6	42.5	9.0	17.8	35.0
hadgem2-cc	7.3	15.7	30.6	11.0	25.2	49.0	9.3	21.5	40.1
hadgem2-es	5.9	15.8	31.2	9.7	23.1	51.4	9.6	21.1	40.5
inmcm4	4.2	6.3	9.2	6.1	10.1	15.2	5.5	8.9	12.7
ipsl-cm5a-lr	6.4	12.3	22.9	9.9	20.1	40.8	8.8	17.4	32.3
ipsl-cm5a-mr	6.5	12.2	22.0	10.2	19.9	40.8	8.8	17.7	34.6
ipsl-cm5b-lr	6.9	11.5	19.9	10.3	18.2	34.7	8.9	15.1	27.2
mirco-esm	8.2	14.2	25.8	13.0	23.5	43.7	10.7	19.9	33.3
miroc-esm-chem	7.6	15.8	27.7	10.9	23.5	45.8	9.5	19.5	35.4
miroc5	6.2	12.8	19.3	10.3	18.9	32.5	8.3	15.5	25.9
mpi-esm-lr	6.8	12.7	22.0	11.4	21.1	38.2	9.2	17.1	29.8
mpi-esm-mr	5.9	11.3	19.9	8.3	18.4	34.3	8.0	16.0	28.6

GCM	**RCP 8.5**								
	Boston			**NYC**			**Philadelphia**		
	2020s	**2050s**	**2080s**	**2020s**	**2050s**	**2080s**	**2020s**	**2050s**	**2080s**
mri-cgcm3	4.9	8.5	12.6	7.9	13.3	20.3	6.4	10.9	17.3
noresm1-m	6.0	10.8	19.0	9.3	17.7	32.5	7.9	15.0	25.5
noresm1-me	6.7	11.7	18.7	10.4	18.2	32.7	8.5	14.7	26.1
median	**6.5**	**11.7**	**19.3**	**10.0**	**18.9**	**34.3**	**8.8**	**16.0**	**28.7**

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VI CHAPTER III Projecting Future Heat-Related Mortality in New York City *

Elisaveta P. Petkova [1], Jan K. Vink[2], Joe D. Francis[2], Radley M. Horton [3], Daniel A. Bader[3] and Patrick L. Kinney [1]

[1] Department of Environmental Health Sciences, Mailman School of Public Health, Columbia University, 722 West 168th St., New York, NY 10032, USA; E-Mail: epp2109@columbia.edu (Petkova); plk3@columbia.edu (Kinney)

[2] Cornell Program on Applied Demographics, Ithaca, New York; Email: jkv3@cornell.edu (Vink); joe.francis@cornell.edu (Francis)

[3] Columbia University Center for Climate Systems Research, 2880 Broadway, New York, NY 10025, USA; E-Mail: rh142@columbia.edu (Horton); dab2145@columbia.edu (Bader)

**In preparation*

VI.1 Abstract

High temperatures have long been recognized to have substantial impacts on mortality and, with growing concerns about climate change, numerous studies to date have developed projections of future heat-related deaths around the world. Projections of temperature-related mortality are often limited by insufficient information necessary to formulate hypotheses about future demographics as well as population sensitivity to high temperatures. In this paper, we explore the potential future impacts of high temperatures on mortality in New York City while incorporating novel projections of heat adaptation and demographic change. We start by developing heat adaptation models that project the population response to heat until 2100 based on daily temperature and mortality data from 1900 to present. We continue with developing demographic scenarios that characterize the possible changes in the NYC population during the study period. Finally, we calculate future heat-related deaths in the city by combining the developed

temperature-mortality relationships and population scenarios with the downscaled temperature projections from the 33 global climate models and two Representative Concentration Pathways (RCPs) developed in support of the Intergovernmental Panel on Climate Change (IPCC)'s Fifth Assessment Report (AR5). Projected mortality varied substantially by RCP, demographics and adaptation scenario, highlighting the importance of these assumptions in future projections of health impacts. The study findings can be of value to future work aimed at developing comprehensive projections of future temperature-related mortality.

VI.2 Introduction

High temperatures have long been recognized to have substantial impacts on mortality. With temperature extremes expected to increase in frequency, magnitude and duration throughout the 21st century, especially in already susceptible regions (Meehl and Tebaldi 2004), the study of temperature impacts has intensified in recent years. Numerous studies have projected future heat-related mortality due to climate change (Baccini et al. 2011; Dessai 2003; Gosling et al. 2009; Hayhoe et al. 2004; Hayhoe et al. 2010; Jackson et al.2010; Knowlton et al. 2007; Ostro et al. 2012; Peng et al. 2011; Sheridan et al. 2012). Most of these studies have predicted substantial increases in heat-related mortality. Other studies have characterized the relationships between temperature and mortality over the full temperature spectrum at a given location in order to estimate current and future 'net impact' of temperature on mortality (Doyon et al. 2008; Huang et al. 2012; Guest 1999; Martin et al. 2012; Martens 1998, Li et al. 2013). Since increases in heat-related mortality in New York are likely to be more substantial and unlikely to be offset by decreases in cold-related mortality (Li et al. 2013), we focused on heat-related mortality in this study.

A common approach for estimating future heat impacts on mortality involves combining historical temperature-mortality relationship at a given location with temperature projections from global-scale climate models. However, projecting heat-related mortality ideally requires consideration of population change and acclimatization in addition to future changes in climate (Huang et a. 2011). Population change and acclimatization may have an opposite influence on heat-related mortality. On one hand, a growing segment of the population will become at increased risk to the impacts of heat due to the demographic shift towards the elderly, leading to possible increases in heat-related mortality. Adaptation over time, on the other hand, could potentially decrease the number of future heat-related deaths.

Although incorporating both population change and acclimatization is without a doubt important for improving the accuracy of long term projections, these factors are rarely considered due to insufficient understanding of the population acclimatization to heat as well limited availability of population data. Studies that have considered population change have often assumed constant population beyond 2025 or 2030 (Jackson et al.2010, Guest 1999). Dessai and colleagues (2003) apply the population growth rates from the corresponding SRES storylines (A1, A2, B1 and B2) to the 1990 population in deriving estimates of heat-related mortality in Lisbon until 2100. Several approaches have been implemented in studies that consider acclimatization to heat. Some studies have used temperature-mortality curves from ‘analogue cities’ that currently experience temperatures similar to those projected to occur in the future at a location of interest (Kalkstein and Greene 1997; Knowlton et al. 2007) or temperature-mortality curves from hotter ‘analogue summers’ that have previously occurred in the same location (Hayhoe et al. 2004). Other studies have modeled acclimatization by developing scenarios for acclimatization to specific increase in temperatures over time (Gosling et al., Dessai et al.; Kalkstein et al 1997).

For example, Gosling and colleagues (2009) estimated that heat-related mortality could be reduced by up to 80% in Lisbon if acclimatization to 4°C takes place.

Chapter II presented evidence that although no heat adaptation has taken place in in early part of the 20th century in New York City, substantial adaptation has occurred since the 1970s. Here, we start by developing scenarios of the potential future heat-related relationships based on the findings presented in Chapter II. Next, we develop scenarios for population change until the end of the 21st century. We conclude with calculating future heat-related deaths in the city by combining the developed temperature-mortality relationship and population scenarios with the downscaled temperature projections from the 33 global climate models and two Representative Concentration Pathways (RCPs) presented in Chapter III.

VI.3 Materials and Methods

VI.3.1 Temperature and Mortality Data

Daily all-cause mortality data for all New York City counties: New York County, Kings County, Queens County and Richmond County for New York for the periods between 1900 and 1948 and 1973 and 2006 were used in the study. The process of the data acquisition and preparation was described in detail in *IV.3.1* (for the period 1900-1948) and *IV.3.2* (for the period 1973-2006). Sources of temperature data were noted in *IV.3.3*.

VI.3.2 Historical heat-mortality relationships

The modeling approach utilized here was discussed in detail in *IV.3.4*. However, while a lag of 5 days was selected for the previous analysis of the historical temperature-mortality relationships in order to better capture the more pronounced mortality displacement during in the days following exposure during the first half of the century, a lag of 3 days was selected for this study in order to focus on the immediate impact of heat on mortality. This choice is consistent rexposure in the recent decades. All models were developed using mean daily temperature and 22 ˚C, corresponding to approximately the 80th percentile of annual temperature, was selected as a reference temperature for calculating relative risk. All models were fitted using a quadratic spline with 4 degrees of freedom for temperature, a natural spline with 2 degrees of freedom for the lag, and controlling for seasonal and day of week effects.

VI.3.3 Temperature Projections

We obtained statistically downscaled future mean temperature projections from New York City for 33 global-scale general circulation models (GCMs) used in the Intergovernmental Panel on Climate Change (IPCC)'s Fifth Assessment Report (AR5), and two representative concentration pathways (RCPs), RCP 4.5 and 8.5. The RCP4.5 and RCP8.5 represent relatively low and high greenhouse gas projections, respectively. The 66 synthetic future temperature projections for daily mean temperature from 2010 to 2099 are based on three 30-year time slices, defined as the 2020s (2010 to 2039), 2050s (2040 to 2069) the 2080s (2070 to 2099). Methods were described in detail in *V.3*. GCMs, along with their originating institution and the model's atmospheric resolution are presented in *Table V.S1.*

VI.3.4 Population Projections

A comprehensive set of population projections for New York State until 2040 along with a detailed methodology has been previously published by the Cornell Center for Applied Demographics (Vink 2009). Four new population scenarios were developed for this study to characterize possible population change pathways until the end of the 21st century. The four scenarios were used in addition to a no population change in deriving assessments of future heat-related mortality.

Projections were developed by establishing a set of reasonable assumptions regarding the components of the basic demographic equation based on the Cohort-Component method (Smith et al. 2001):

$POP_{t+1} = POP_t + B_{t,t+1} - D_{t,t+1} + NM_{t,t+1}$, where: (VI.1)

POP is the city population,

B is the number of births

D is the number of deaths

NM is the net migration and equals in-migration minus out-migration

The first *Baseline* scenario assumed that all parameters of the model will be kept constant. The second *Decreased Mortality* scenario assumed a decrease in mortality rates to 2/3 of the Census 2010 values. The third *Increased In-Migration* scenario assumed that the growth of the domestic in-migration will be half of the growth of the US population and that the growth of the international in-migration is half of the growth of the projected international in-migration nationwide (from the Census 2010 projections). Finally an *Increased Out-Migration* scenario assumed that the rate of out-migration would increase by 25% over the projection period.

VI.3.5 Projected heat-mortality relationships

As discussed previously in *IV.4*, little adaptation to heat was observed in the first part of the century but rapid adaptation has occurred since the 1970s, most likely due to the increased access to air conditioning in recent years. Since we do not have data from the 1950s and 1960s, we can't verify the precise onset of the adaptation process. However, if access to air conditioning is the major driving force behind heat adaptation, it is plausible to define three stages in the population response to heat: prior to the introduction of domestic air conditioning, during air conditioning penetration and after air conditioning penetration levels reach saturation. Since 84% of surveyed households in New York City in 2003 already had air conditioning in their homes, compared to only 39% in 1979, it is reasonable to assume that saturation levels will be reached in the near future (IV.5, U.S. Census Bureau 1978,2004) . However, air conditioning is unlikely the only factor influencing decreased sensitivity to heat and other factors, such as city level initiatives to reduce the public health impacts of heat play without a doubt an important role in the adaptation process. Nonetheless, the analysis of historical data suggested that a three-stage model of adaptation in New York City is plausible.

Future heat-related mortality relative risks at each degree ˚C were derived using the temperature-specific relative risk estimates from the historical decades. Decade-specific temperature curves were linearly extrapolated for temperatures up to 41˚C, the highest projected temperature, using the last four points of each curve. We chose a sigmoid function to model the decadal change in the heat-mortality response since it permits an accurate approximation of the three stages in the adaptation process:

$$RR_{ADAPT} = RR_{MAX} - \frac{RR_{RANGE}}{1+e^{-\propto *(y-y_0)}} \qquad \text{(VI.2)}$$

The initial level of temperature-specific relative risk (*RRmax*) was determined by selecting the mean relative risk form the first part of the 20th century, corresponding to the pre-adaptation part of the sigmoid curve. The *RRrange* was derived as the difference between the *RRmax* and *RRmin*, where *RRmin* is the minimal relative risk for a given temperature or the value to which the sigmoidal curve converges. We developed two future adaptation scenarios: a scenario of high adaptation where *RRmin* was set to reach a value 80% lower compared to RR calculated at each degree C observed during the 2000s and a scenario of moderate adaptation where *RRmin* was set to be 20% lower compared to the RR calculated at each degree C observed during the 2000s. *Y* represents the first year of the study period and the steepness of the transition between the periods of no adaptation and complete adaptation is determined by the coefficient α. This coefficient as well as the half decay point of the curve defined by *Yo*, were subjected to nonlinear optimization using the data points for the last four decades. We are not proposing a scenario assuming 100% adaptation because sub-populations of vulnerable individuals without access to air conditioning or other means of heat relief are likely to continue to exist in the future and thus heat-related mortality may not be completely avoidable.

VI.3.6 Projected heat-related deaths

The approach to calculating heat-related mortality was similar to that presented in V.3. The derived temperature-specific relative risks were applied to the daily downscaled temperature projections until 2100. Future summer heat-related deaths for temperatures 25 °C and above were calculated for each future time period using daily downscaled temperature projections. However, baseline heat-related mortality was not characterized since the focus here was on modeling future impacts. Also, in addition to the constant temperature-specific relative risks at each temperature from the '*No Adaptation*' scenario, we also used the relative risk estimates from the two adaptation models or the '*High Adaptation*' and '*Low Adaptation*' scenarios. Finally, the five population scenarios described in VI.3.4, *Constant Population*, *Baseline*, *Decreased Mortality*, *Increased In-Migration* and

Increased Out-Migration, as well as the scenario-specific mortality rates were also used in calculating heat-related deaths using Equation V.3.

VI.4 Results

The five population scenarios developed for this study are illustrated in *Figure VI.1* and the annual population projections along with the corresponding mortality rates are provided in the *Supplemental Table VI.S.1*.

The temperature-specific mortality curves for NYC calculated according to the low and high adaptation scenarios are illustrated in *Figures VI.2* and *VI.3*, respectively.

Future deaths estimates varied greatly depending on the choice of demographics and adaptation scenario. To illustrate the influence of each both population change and heat adaptation, we used the median projected annual heat related-deaths across the 33 global climate models and the two RCPs in Figures *VI.4* (for RCP4.5) and *VI.5* (for RCP8.5).

Projected heat-related mortality was lowest for the *Constant Population* scenario and highest for the *Increased In-Migration* scenario. Increasing levels of adaptation reduced the number of projected deaths substantially. Also, projections varied greatly by RCP.

For instance, during the 2020s and under the RCP 4.5, the median number of heat-related deaths across the 33 GCMs was 370 for the *Constant Population* scenario and *No Adaptation* and 149 for the same scenario with *High Adaptation.* For the same period and RCP 4.5, the number of projected deaths under the *Increased In-Migration* scenario was 497 with *No Adaptation* and 193 for the same scenario with *High Adaptation.* By the 2080s and RCP 4.5*,* there were 733 projected deaths for the *Constant* scenario without adaptation and 167 with *High Adaptation.* For the same period and RCP there were 1552 heat-related deaths without adaptation and 354 deaths with High Adaptation projected under the *Increased In-Migration* scenario. The estimated median number of heat-related deaths across the 33 GCMs was substantially higher under RCP 8.5.During the 2020s under the *Constant* population scenario, the number of deaths was 413 without adaptation and 167 with High Adaptation. By the 2080s the number of deaths for this scenario were 1573 and 354 with *No Adaptation* and *High Adaptation*, respectively. During the 2020s there were 546 projected deaths with *No Adaptation* and 214 with *High Adaptation* under the *Increased In-Migration* population scenario. By the 2080s, the number of projected deaths under the same scenario rose to 3331 with *No Adaptation* and 354 with *High Adaptation*.

The median number of projected heat-related deaths across the 33 GCMs used during the 2020s, 2050s and 2080s are summarized by RCP, adaptation scenario and population scenario in *Supplemental Table VI.S.2.*

Figure VI.1. New York City population by 2100 calculated according the four population scenarios developed by this study.

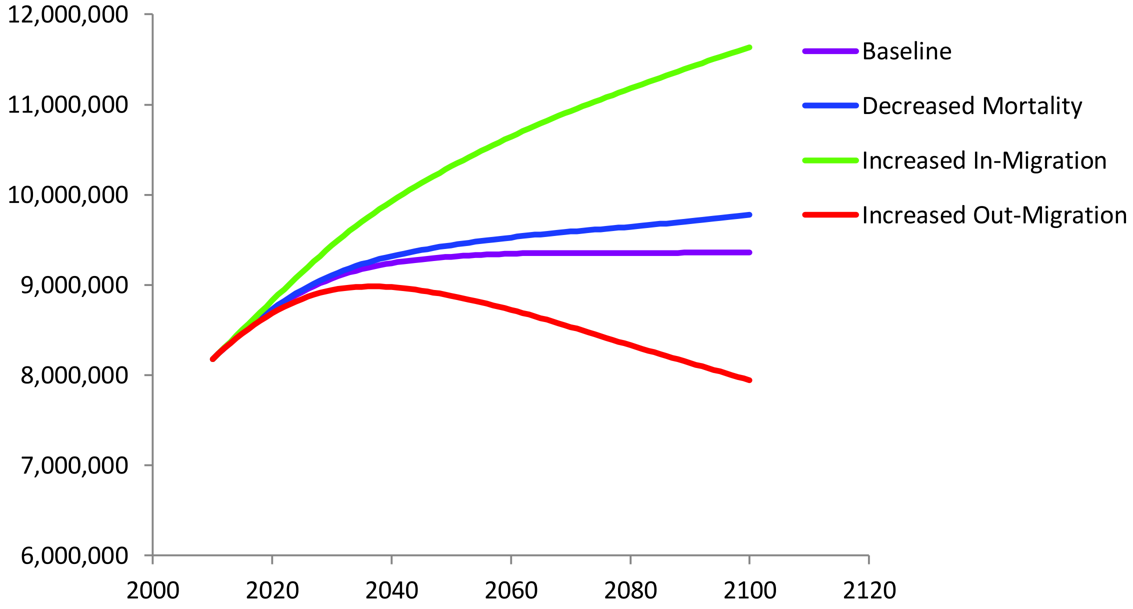


Figure VI.2. Temperature-specific mortality curves for NYC, 1900-2100. Adaptation model assumes that temperature-specific relative risks will decrease by an additional 20% between 2010 and 2100 compared to the 2000s

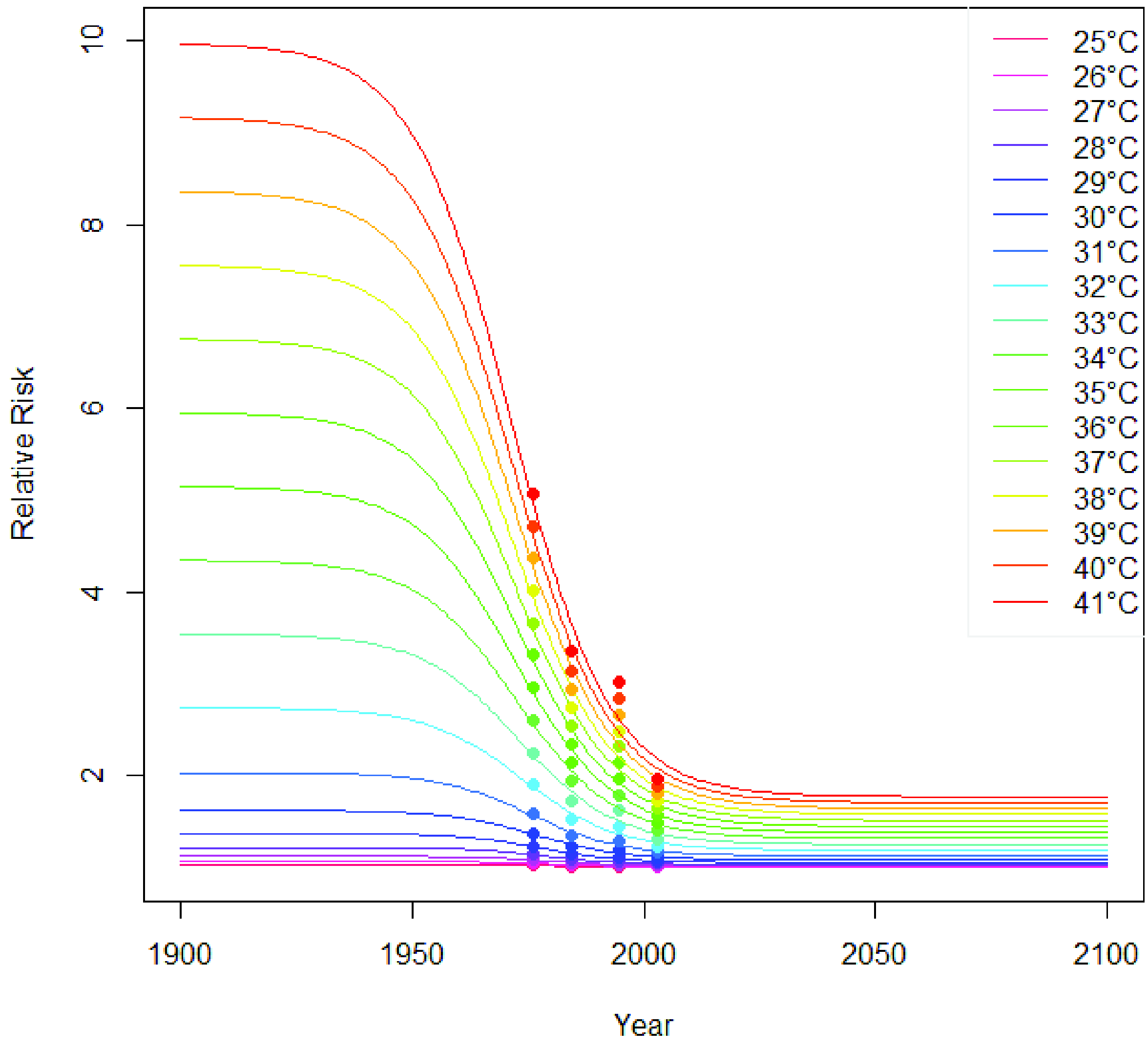


Figure VI.3 Temperature-specific mortality curves for NYC, 1900-2100. Adaptation model assumes that temperature-specific relative risks will decrease by an additional 80% between 2010 and 2100 compared to the 2000s

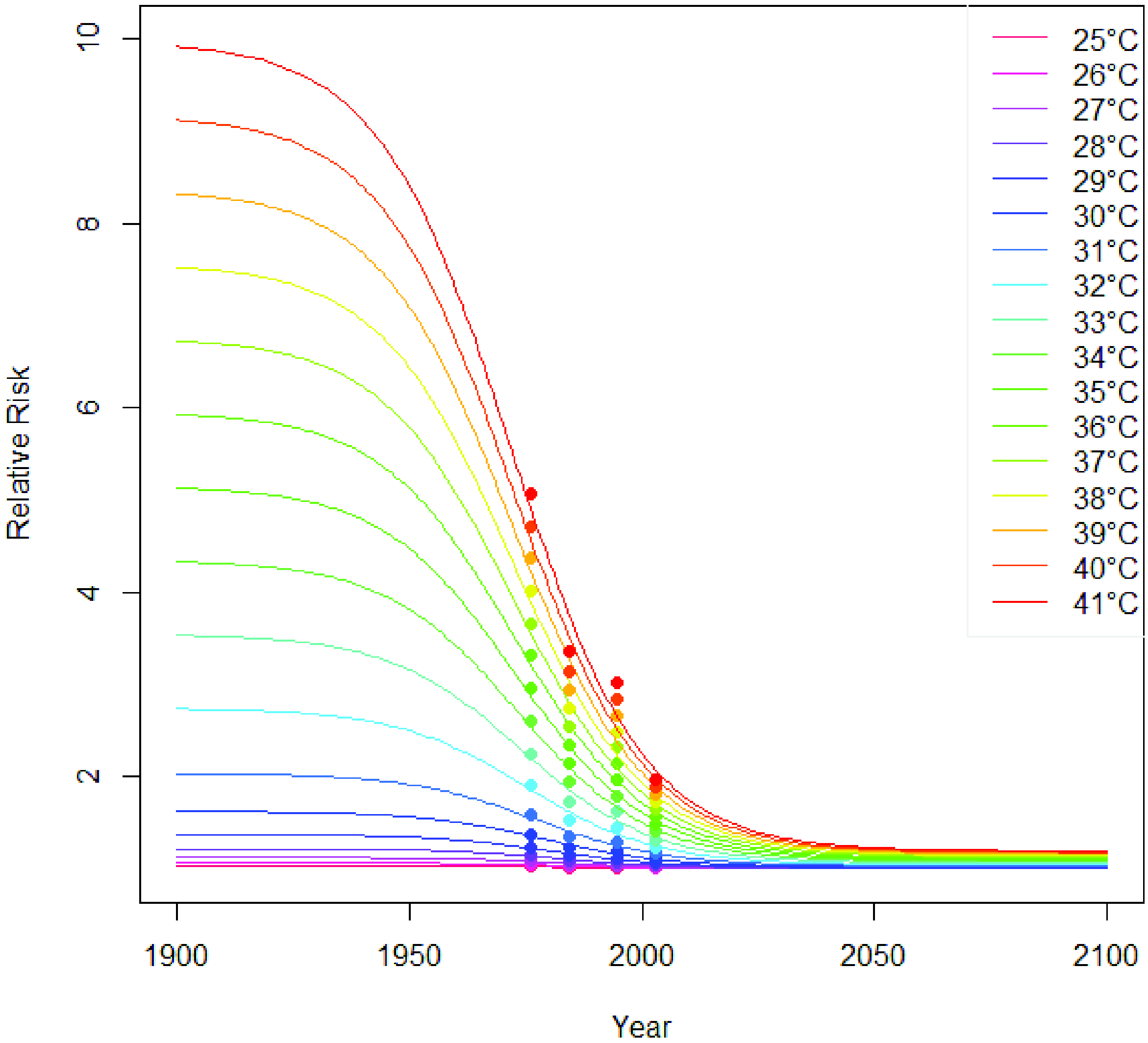


Figure VI.4. Median annual projected heat-related deaths in New York City during the 2020s, 2050s and 2080s across 33 global climate models (GCMs) and the RCP4.5 and according to the (a) no adaptation (b) moderate adaptation and (c) high adaptation scenario and the five demographics scenarios developed for this study. There were 638 deaths per year during the baseline period (2000-2006).

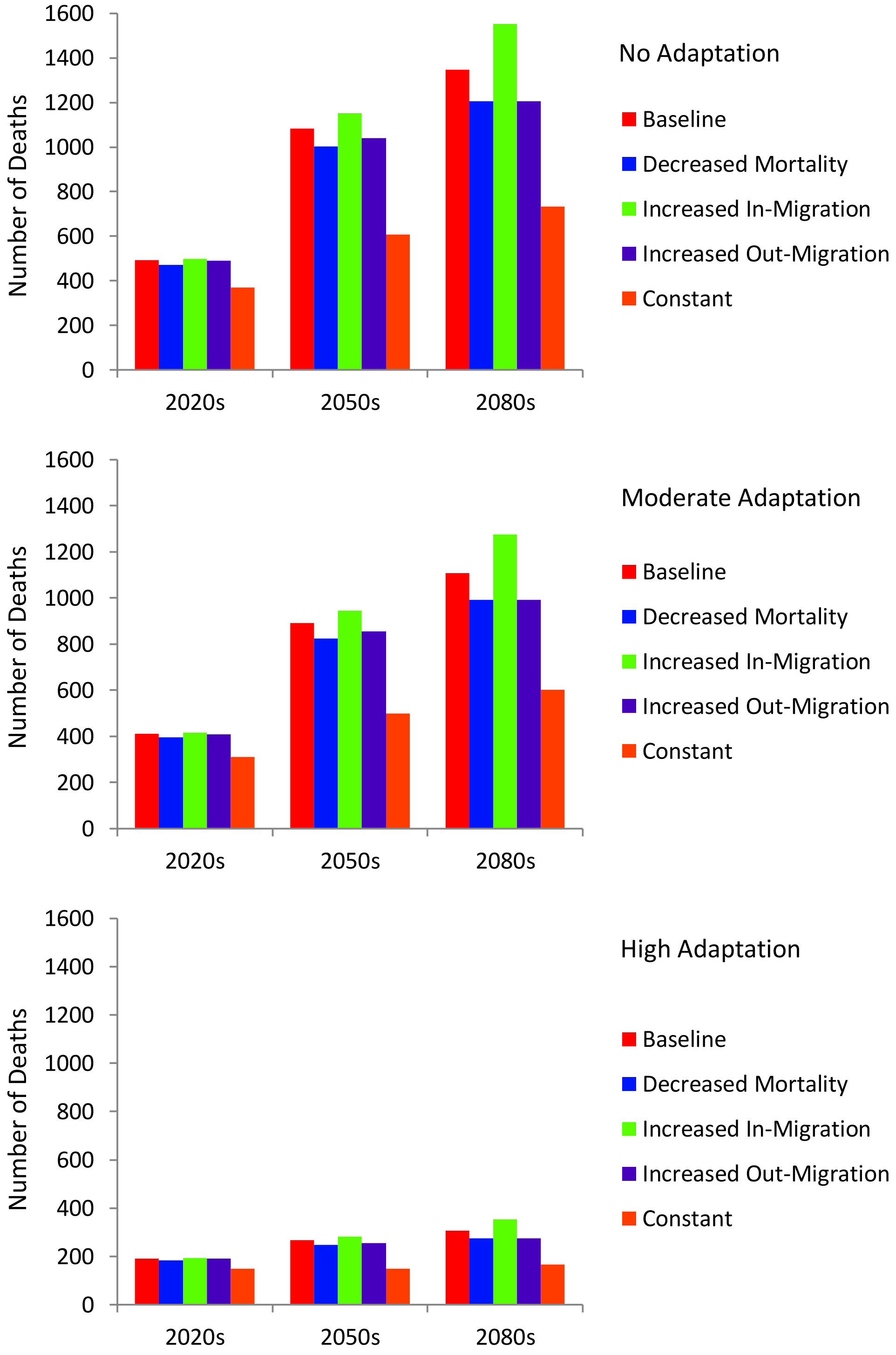
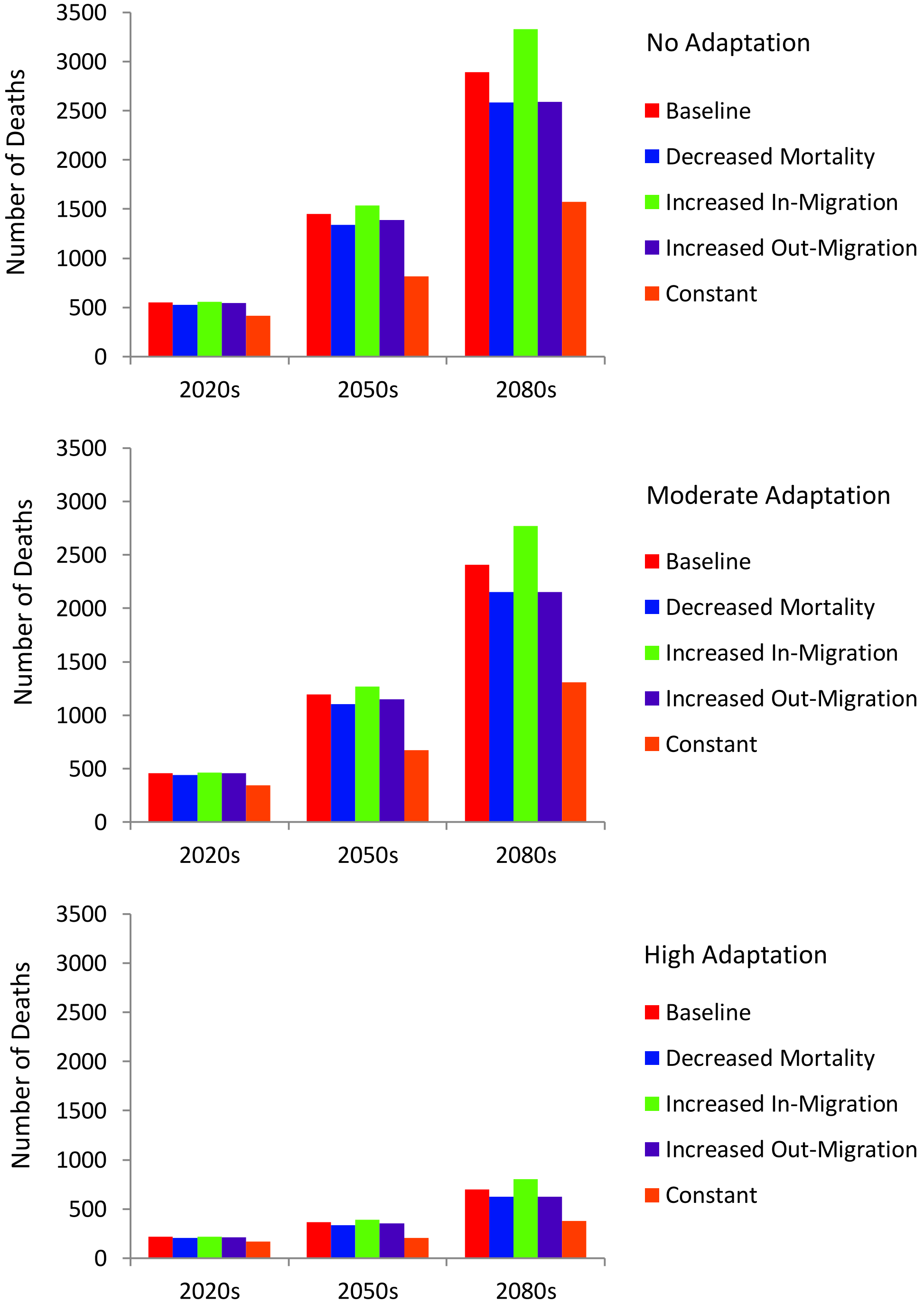


Figure VI.5. Median annual projected heat-related deaths in New York City during the 2020s, 2050s and 2080s across 33 global climate models (GCMs) and the RCP8.5 and according to the (a) no adaptation (b) moderate adaptation and (c) high adaptation scenario and the five demographics scenarios developed for this study



VI.5 Discussion

Although heat adaptation and population change are recognized as important factors in characterizing future heat-related mortality, few studies have incorporated these factors into future mortality projections. On the one hand, location-specific population projections until 2100 are generally not readily available and on the other, lack of long records of historical mortality data limit the development of comprehensive heat adaptation models. To address the first issue, we developed population scenarios that capture possible population trajectories between 2010 and 2100. To address the second issue, we developed heat adaptation scenarios for the same period based on the findings from the historical analysis of temperature and mortality presented in *IV*. We combined the developed population and heat adaptation scenarios with temperature projections from multiple GCMs and two RCPs in order to derive a comprehensive assessment for heat-related mortality until the end of the 21st century.

Not surprisingly, future deaths estimates varied greatly by RCP, as well as by population change adaptation scenario. We found that the *Constant Population* scenario produced the lowest death estimates. Therefore, keeping population constant is likely to result in underestimating future heat-related deaths. In contrast, the *Increased In-Migration* scenario produced the highest mortality estimates. This finding may be particularly relevant to estimating heat-related mortality in cities currently experiencing heat impacts and increasing urbanization and/or population growth. The choice of adaptation scenario affected the number of projected heat-related deaths substantially. Improved understanding of the historical and future adaptation to heat is necessary in order to refine projections. Nonetheless, the substantial reduction of heat-related mortality, particularly under the *High Adaptation* scenario provides evidence of the importance of public policy measures leading to continuous heat adaptation. For instance, median annual heat-related deaths calculated across all GCMs under RCP8.5 during the 2080s, were with 2527 less under the *Increased In-Migration* scenario with *High Adaptation* than under the same scenario without adaptation. Finally, the number of median annual heat-related deaths calculated across all models under RCP8.5 was in many instances over twice as high as the number of deaths projected under PCP 4.5. This difference underlines the magnitude of the potential public health benefit associated with reducing greenhouse gas concentrations in the atmosphere.

Both the heat adaptation and demographic scenarios have several limitations. First, our model of heat-related mortality over time was based on an empirical fit to historical data and extrapolation using a sigmoidal curve into the future. We didn't identify and incorporate causal factors like air conditioning use into the projection of future heat response. Future research focusing on characterizing the impact of heat over time among vulnerable populations would be particularly useful in improving the precision of the adaptation models. In addition, studies quantifying the impact of various public health interventions such as heat warning systems, cooling centers and other preventive measures on heat-related mortality would be particularly valuable for the further development of this work. Another limitation is that decade-specific mortality vs. temperature curves were linearly extrapolated to high temperatures projected to occur under changing climate for which no historical mortality data exist. Due to the non-linear response, this may underestimate mortality impacts at very high temperatures, particularly during the initial exposures of the populations to temperatures that have never occurred before. Studies of mortality responses in non-acclimatized populations could be particularly useful in better characterizing heat impacts at very high temperatures.

The demographic models developed for this work made assumptions, which although reasonable, are based on historical trends that may or may not continue. Population projections are rarely developed beyond several decades, especially on a fine geographical scale. Given the increasing importance of projecting population health impacts under a changing climate, additional work focused on developing and validating long-term population projections will be of critical importance for improving the accuracy of projecting heat-related mortality and other health impacts. Nevertheless, by including five different population projections, our study is among the first to examine sensitivity to this important assumption.

Despite these limitations, the findings of this study provide new and important insights about the role of heat adaptation and demographic factors in projecting future heat-related mortality.

VI.6 Supplemental Material

Supplemental Table VI.S.1 Population scenarios and corresponding mortality rates used in this study

Year	Total Population					Annual Mortality Rates per 100,000 Population				
	Baseline	*Decreased Mortality*	*Increased In-Migration*	*Increased Out-Migration*	*Constant*	*Baseline*	*Decreased Mortality*	*Increased In-Migration*	*Increased Out-Migration*	*Constant*
2011	8175133	8175133	8175133	8175133	8175133	652	650	652	652	652
2012	8238516	8238709	8240542	8237833	8175133	663	658	662	663	652
2013	8299751	8300330	8305808	8297714	8175133	673	667	673	674	652
2014	8358916	8360053	8370952	8354845	8175133	684	674	683	684	652
2015	8416212	8418107	8436143	8409457	8175133	694	682	692	694	652
2016	8471895	8474727	8501573	8461805	8175133	703	690	701	704	652
2017	8525758	8529698	8566979	8511698	8175133	712	697	710	713	652
2018	8577624	8582850	8632145	8558967	8175133	722	704	719	723	652
2019	8627530	8634209	8697063	8603663	8175133	732	712	727	733	652
2020	8675385	8683689	8761587	8645717	8175133	742	720	737	744	652
2021	8721390	8731487	8825880	8685346	8175133	753	729	747	755	652
2022	8765407	8777459	8889749	8722415	8175133	764	737	757	766	652
2023	8807304	8821478	8953018	8756805	8175133	776	747	767	778	652
2024	8847177	8863632	9015724	8788634	8175133	787	755	777	789	652
2025	8885095	8904000	9077902	8817986	8175133	799	765	787	801	652

2026	8921033	8942541	9139465	8844840	8175133	810	774	797	813	652
2027	8955053	8979326	9200435	8869289	8175133	822	784	808	826	652
2028	8987124	9014321	9260734	8891300	8175133	835	794	819	839	652
2029	9017255	9047537	9320328	8910900	8175133	847	804	829	851	652
2030	9045059	9078585	9378773	8927697	8175133	860	814	840	864	652
2031	9070840	9107764	9436322	8941997	8175133	872	824	851	878	652
2032	9094849	9135329	9492240	8954104	8175133	886	836	863	892	652
2033	9117093	9161272	9546449	8964009	8175133	899	847	874	906	652
2034	9137532	9185551	9598910	8971675	8175133	911	856	884	918	652
2035	9156274	9208290	9649722	8977270	8175133	923	865	893	930	652
2036	9173495	9229616	9699028	8980940	8175133	933	873	901	940	652
2037	9189405	9249750	9747035	8982920	8175133	942	880	909	950	652
2038	9204070	9268746	9793792	8983284	8175133	951	887	916	960	652
2039	9217617	9286727	9839423	8982187	8175133	960	894	923	969	652
2040	9230091	9303731	9883955	8979663	8175133	969	901	930	978	652
2041	9241489	9319745	9927365	8975731	8175133	976	906	936	986	652
2042	9251864	9334821	9969700	8970459	8175133	983	911	941	993	652
2043	9261278	9349010	10011018	8963915	8175133	989	916	946	1000	652
2044	9269889	9362449	10051431	8956269	8175133	994	919	950	1006	652
2045	9277759	9375207	10090994	8947607	8175133	1000	923	954	1012	652
2046	9284976	9387365	10129789	8938033	8175133	1004	925	957	1016	652

2047	9291622	9398996	10167893	8927644	8175133	1007	927	959	1020	652
2048	9297761	9410160	10205342	8916493	8175133	1011	929	962	1024	652
2049	9303433	9420886	10242175	8904659	8175133	1014	930	964	1027	652
2050	9308625	9431151	10278357	8892114	8175133	1016	931	966	1031	652
2051	9313369	9440993	10313920	8878911	8175133	1018	931	967	1032	652
2052	9317783	9450544	10348974	8865197	8175133	1019	931	967	1034	652
2053	9321906	9459819	10383544	8851010	8175133	1020	931	968	1036	652
2054	9325826	9468910	10417712	8836440	8175133	1022	931	969	1038	652
2055	9329481	9477757	10451402	8821437	8175133	1025	932	971	1040	652
2056	9332831	9486325	10484576	8805989	8175133	1026	932	972	1042	652
2057	9335894	9494642	10517243	8790111	8175133	1027	931	973	1043	652
2058	9338741	9502772	10549459	8773891	8175133	1028	930	974	1045	652
2059	9341456	9510800	10581307	8757412	8175133	1029	930	975	1046	652
2060	9344020	9518696	10612754	8740664	8175133	1032	930	976	1048	652
2061	9346395	9526449	10643766	8723626	8175133	1034	930	978	1050	652
2062	9348520	9533991	10674329	8706244	8175133	1036	931	980	1053	652
2063	9350392	9541313	10704452	8688518	8175133	1038	932	983	1055	652
2064	9351992	9548412	10734106	8670448	8175133	1041	932	985	1058	652
2065	9353286	9555243	10763252	8651992	8175133	1044	933	988	1061	652
2066	9354309	9561832	10791907	8633189	8175133	1047	934	991	1064	652
2067	9355007	9568146	10820021	8614023	8175133	1049	935	993	1066	652

2068	9355461	9574235	10847659	8594561	8175133	1051	935	995	1068	652
2069	9355685	9580136	10874853	8574832	8175133	1052	935	997	1069	652
2070	9355708	9585856	10901614	8554869	8175133	1054	935	999	1071	652
2071	9355566	9591414	10927984	8534707	8175133	1055	934	1000	1071	652
2072	9355290	9596846	10953987	8514390	8175133	1055	933	1001	1071	652
2073	9354935	9602203	10979675	8493968	8175133	1055	931	1001	1071	652
2074	9354541	9607530	11005096	8473499	8175133	1055	930	1002	1071	652
2075	9354144	9612840	11030284	8453014	8175133	1054	928	1002	1070	652
2076	9353765	9618152	11055246	8432517	8175133	1054	926	1002	1069	652
2077	9353405	9623494	11080008	8412056	8175133	1053	924	1002	1068	652
2078	9353110	9628889	11104603	8391647	8175133	1052	921	1002	1067	652
2079	9352922	9634378	11129069	8371325	8175133	1051	919	1002	1065	652
2080	9352842	9639977	11153430	8351130	8175133	1049	916	1002	1064	652
2081	9352876	9645697	11177693	8331045	8175133	1048	913	1001	1062	652
2082	9353015	9651530	11201852	8311075	8175133	1047	911	1001	1061	652
2083	9353268	9657484	11225923	8291215	8175133	1046	908	1001	1059	652
2084	9353616	9663551	11249877	8271464	8175133	1045	906	1001	1058	652
2085	9354054	9669718	11273722	8251808	8175133	1045	903	1001	1057	652
2086	9354555	9675981	11297444	8232243	8175133	1044	901	1001	1056	652
2087	9355110	9682332	11321033	8212757	8175133	1044	899	1002	1055	652
2088	9355709	9688761	11344496	8193341	8175133	1044	897	1002	1055	652

2089	9356337	9695256	11367821	8173985	8175133	1043	894	1002	1054	652
2090	9356981	9701808	11390996	8154679	8175133	1043	892	1003	1054	652
2091	9357622	9708412	11414014	8135407	8175133	1043	891	1004	1053	652
2092	9358255	9715049	11436862	8116171	8175133	1044	889	1004	1053	652
2093	9358866	9721707	11459546	8096959	8175133	1044	887	1005	1053	652
2094	9359453	9728390	11482065	8077773	8175133	1044	885	1005	1053	652
2095	9360006	9735084	11504414	8058587	8175133	1045	884	1006	1053	652
2096	9360502	9741785	11526581	8039417	8175133	1045	882	1007	1053	652
2097	9360944	9748471	11548566	8020245	8175133	1046	881	1008	1053	652
2098	9361320	9755136	11570353	8001060	8175133	1046	879	1009	1053	652
2099	9361633	9761789	11591959	7981876	8175133	1047	877	1009	1053	652
2100	9361885	9768438	11613408	7962707	8175133	1047	876	1010	1052	652

Supplemental Table VI.S.2 Median number of projected heat-related deaths in New York City across the 33 GCMs used in this study for the 2020s, 2050s and 2080s by RCP, adaptation scenario and population scenario.

Period	**Population Scenario**	**RCP 4.5**			**RCP 8.5**		
		No Adaptation	*Low Adaptation*	*High Adaptation*	*No Adaptation*	*Low Adaptation*	*High Adaptation*
2020s	*Baseline*	492	412	191	549	460	215
2050s	*Baseline*	1084	891	267	1449	1196	365
2080s	*Baseline*	1348	1109	308	2893	2407	698
2020s	*Decreased Mortality*	472	395	184	527	442	207
2050s	*Decreased Mortality*	1001	823	247	1339	1104	338
2080s	*Decreased Mortality*	1205	991	275	2585	2151	624
2020s	*Increased In-Migration*	497	416	193	555	465	217
2050s	*Increased In-Migration*	1151	946	283	1539	1270	387
2080s	*Increased In-Migration*	1552	1277	354	3331	2771	804
2020s	*Increased Out-Migration*	489	409	190	546	457	214
2050s	*Increased Out-Migration*	1040	855	257	1391	1147	351
2080s	*Increased Out-Migration*	1206	991	275	2587	2152	624
2020s	*Constant*	370	311	149	413	347	167
2050s	*Constant*	608	500	150	813	671	205
2080s	*Constant*	733	603	167	1573	1309	379

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VII SUMMARY AND FUTURE DIRECTIONS

This work explored the historical and future heat-related mortality in New York City, addressing three major aims: 1) to characterize the relationship between heat and mortality relationship in the city from the beginning of the 20th century to the present and quantify possible changes over time; 2) to derive a comparative assessment of present and future heat–related mortality in New York City, Boston and Philadelphia under different climate change scenarios; 3) to derive an assessment of future heat-related mortality in New York City under various heat adaptation, population and climate change scenarios until the end of the 21st century.

Chapter I examined the relationship between summer daily temperature and mortality in adults age 15 or older in New York City during two periods: 1900s to1940s and 1970s to 2000s, in order to quantify population adaptation to high temperatures over time. The presented study is the first to examine daily temperature effects in any large U.S. city over a period spanning more than a century, using modern statistical methods. Heat effects were found to be more pronounced in the first half of the century. Despite the substantial technological and lifestyle improvements that took place during this period, there was no decline in the population sensitivity to heat during this period. There was, however, strong evidence for a difference of the heat effect between the first and the second part of the century. In addition, a substantial decline in the heat effect, indicating possible population adaptation to heat, took place since the 1970s. The increasing prevalence of air conditioning may have played a major role in the observed decrease in population sensitivity to heat. The presented findings confirmed the initial hypothesis presented in III.1. Adaptation to heat, however, although gradual, did not start occurring until the second part of the century.

The findings presented in Chapter I provide a foundation for investigating several research questions. First, obtaining digital mortality records for the 1950s and 1960s and adding those missing decades to the analysis for New York City can provide an insight into the precise onset of the heat adaptation process. Next, the historical analysis of heat-related mortality since the beginning of the 20th century may be expanded to other geographical areas in the United States and internationally. Given the substantial decline of population sensitivity to heat in the last decades, a multi-city study of population adaptation to heat in the second part of the century would be of particular relevance. For instance, such a multi-city study would allow characterizing adaptation to heat in the United States over time and may be helpful in informing nation-wide heat adaptation efforts. Nonetheless, expanding the analysis of heat-related mortality in the first half of the century to several other major U.S. cities would also be interesting. Such study may be able to provide a more definite answer of the question whether heat adaptation has occurred mostly in the second part of the century, following the massive adoption of air conditioning by U.S. households. In addition, the impact of increasing air conditioning use on greenhouse gas emissions is an important question that should be addressed in future studies. Despite the beneficial role of air conditioning for heat adaptation, quantifying the additional amount of greenhouse gases emitted as a result of air conditioning usage, their potential impacts on global warming and consequently health could provide a more comprehensive picture.

An interesting area of future research may also involve utilizing the New York City historical heat wave mortality data in modeling potential impacts of heat in the event of future power outages or natural disasters in New York City during which the population may lose access to air conditioning for extended periods. For instance, New York City has not experienced a power outage occurring concurrently with a heat wave in recent history. Since air conditioning plays a critical role in preventing heat-related mortality during heat wave episodes, an eventual power outage during a heat episode may take an unprecedented toll on mortality, particularly among vulnerable individuals in the city. Therefore, a study that examines the potential impacts of such an event would be valuable in heat emergency preparedness and response planning.

Chapter II presented an assessment of the potential impacts of climate change on heat-related mortality in New York City compared to the other two major urban areas in the Northeast U.S.—Boston and Philadelphia. The study utilized fine-spatial-resolution statistically downscaled projections from thirty-three climate models and two Representative Concentration Pathways (RCPs) developed for the Intergovernmental Panel on Climate Change (IPCC)'s Fifth Assessment Report (AR5).Two RCPs, RCP4.5 and RCP8.5, were chosen to represent relatively low and high greenhouse gas projections, respectively. Heat-related mortality was more pronounced in New York City compared to Boston and Philadelphia. This finding is not entirely consistent with the initial hypothesis in III.I according to which heat effects were expected to be most pronounced in Boston where summers are the coolest, followed by New York City and finally Philadelphia, where summers are the hottest overall. Chapter II provided a discussion of the possible factors underlying the more pronounced heat effect in New York City. Additional studies exploring in greater detail how individual level vulnerability factors may influence heat-related mortality across cities would be particularly important in advancing city- and nationwide heat-related mortality prevention in the United States and around the world.

Another finding from the three cities study was that heat-related mortality rates per 100,000 of population during the baseline period were highest in Philadelphia followed by New York City and Boston but that projected heat-related mortality rates in the 2020s, 2050s and 2080s were highest in New York City, followed by Philadelphia and Boston. An important advantage of the study was the utilization of temperature projections from multiple climate models which allowed better characterizing the uncertainly associated with climate change, as well as the new RCPs that reflect the latest advances in the field. Expanding this analysis, along with the study of heat adaptation over time discussed previously, to more U.S. cities would allow a comparative assessment on a national scale that could be of important value to strengthening the nation's capacity to meet one of the great public health challenges associated with climate change.

Chapter II discussed the role of the underlying assumptions of temperature-specific relative risks, mortality rates and population on future heat-related mortality estimates. An important limitation of the study was the assumption of no heat adaptation, as well as constant population and mortality rates. In Chapter III, these limitations were addressed with the development of adaptation and population change models. Two heat adaptation scenarios, representing low and high adaptation to heat by the end of the century, respectively, were used along with a scenario assuming no further adaptation. The latter allowed the quantification of heat-related mortality due solely to climate change. In addition, four population scenarios were developed, reflecting various assumptions of mortality, migration and out-migration. The number of projected heat-related deaths varied substantially by RCP, demographic and adaptation scenario. Further research, particularly in the fields of quantification of heat adaptation and development of population change scenarios will greatly facilitate the precision of projecting future heat impacts and understanding the effectiveness of various public health interventions.

The work presented here has advanced our understanding of how heat has affected mortality in the City of New York since the beginning of the 20th century, and how, based on the historical relationship and the latest advances in climate science and demographics, the impact of heat on mortality may evolve until the end of the 21th century. While many challenges remain to be addressed, this research provides a solid ground for future investigation.