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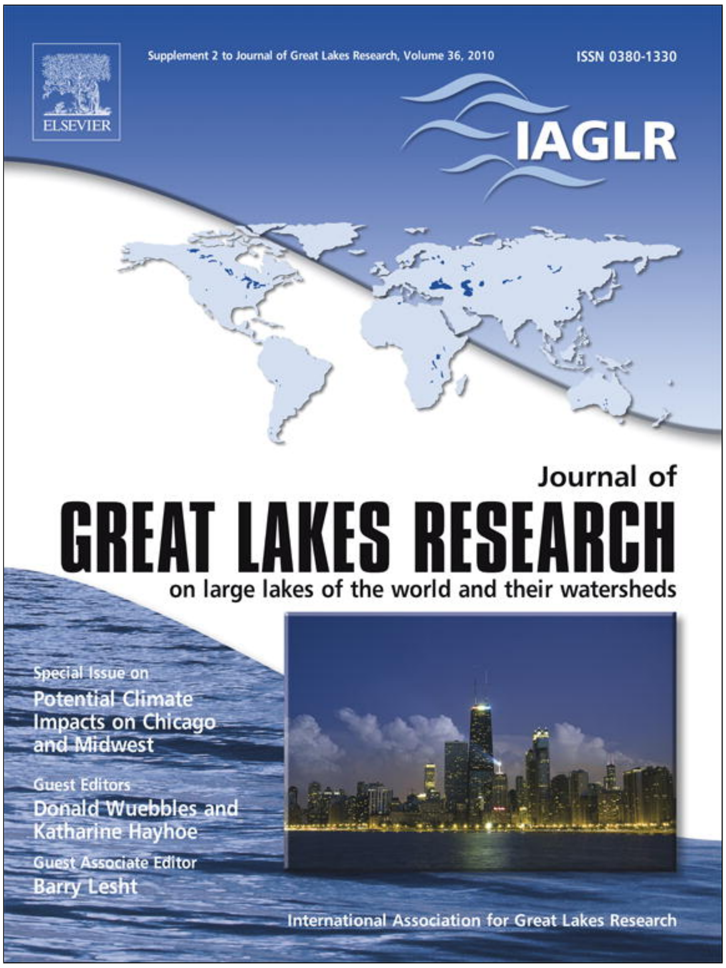
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# An integrated framework for quantifying and valuing climate change impacts on urban energy and infrastructure: A Chicago case study

Katharine Hayhoe [a,f,*], Mark Robson [b], John Rogula [c], Maximilian Auffhammer [d], Norman Miller [e], Jeff VanDorn [a], Donald Wuebbles [g]

[a] ATMOS Research & Consulting, Lubbock, TX 79490, USA
[b] Oliver Wyman, 161 Bay Street, Toronto, Ontario, Canada M5J 2B5
[c] Oliver Wyman, 10 South Wacker Drive; Suite 1700, Chicago, IL 60606, USA
[d] Department of Agricultural and Resource Economics, University of California Berkeley, 207 Giannini Hall #3310, Berkeley, CA 94720, USA
[e] Atmospheric and Ocean Sciences Group, Earth Sciences Division, Lawrence Berkeley National Laboratory, Berkeley, CA 94720, USA
[f] Department of Geosciences, Texas Tech University, Lubbock, TX 79409, USA
[g] Dept. of Atmospheric Sciences, University of Illinois, Urbana, IL 61801, USA

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ABSTRACT

We use a quantitative modeling framework capable of translating increasing stress on energy demand and costs, infrastructure maintenance, and capital investments into economic impacts to estimate future climate change effects on urban infrastructure and economy. This framework enables quantitative estimates of the economic impacts of climate change based on observed relationships between key climate thresholds and their impacts on energy and infrastructure. Although the version presented here is based on information specific to city departments, the generalized modeling framework can be applied across entire urban and metro areas. For the City of Chicago, energy and infrastructure impacts, including both costs and savings, are driven primarily by increases in mean annual temperature and secondarily by increases in the frequency of extreme-heat events and decreases in cold days. With more frequent, severe, and longer periods of extreme-heat, annual average and peak electricity demands will increase. Aggregated costs for Chicago's maintenance, labor, and capital investments could be as much as 3.5 times greater under a higher (A1FI) emissions scenario as compared to the lower (B1) scenario. These differences highlight how even partial success at reducing emissions could produce a disproportionately large reduction in economic costs for the City, the Great Lakes Region, and the nation at large. At the same time, since a single city's mitigation efforts represent only a small proportion of what is required at the global scale, adaptation to anticipated changes is also essential.


## Introduction

Urban centers such as Chicago are uniquely vulnerable to climate change, due to their high concentrations of people, infrastructure, and industry (US GCRP, 2009). Many large cities are already subject to a number of stressors affecting the quality of their air and water, the health and welfare of their population, the availability of key resources such as energy and water, and the cost of maintaining and repairing their infrastructure. For most, climate change is likely to exacerbate these existing pressures (Wilbanks et al., 2007).

Previous studies have made it clear that assessing the magnitude and economic value of potential climate change impacts on infrastructure and energy requires resolving these impacts at the local to regional scale (e.g., Kirshen et al., 2008; Wilbanks et al., 2007; Jollands et al., 2007; Ruth, 2006 and chapters therein). Chicago's vulnerability to climate change, for example, is specific to its location in the center of North America, which tends to enhance projected summer temperature increases relative to the global average (Meehl et al., 2007). At the same time, Chicago is located beside a large body of water, Lake Michigan, which can moderate summer temperatures along the lakeshore, depending on wind direction.

A city's vulnerability also depends on the nature of its existing infrastructure systems. This includes the degree to which these are able to cope with current conditions and their flexibility in adapting to future change. Finally, climate change impacts also depend on interactions between different sectors, specifically the extent to which impacts on one sector can have a “ripple effect” on others throughout the city itself, as well as the surrounding area (Ruth, 2006).

Urban infrastructure, energy, and society tend to be more vulnerable to changes in extreme weather events than to shifts in mean temperature or precipitation (Wilbanks et al., 2007). Chicago is fortunate in that it is shielded from many climate-related extremes likely to impact

* Corresponding author. Department of Geosciences, Texas Tech University, PO Box 41053, Lubbock, TX 79409, USA.
*E-mail addresses:* katharine.hayhoe@ttu.edu, hayhoe@atmosresearch.com (K. Hayhoe), mark.robson@oliverwyman.com (M. Robson), john.rogula@oliverwyman.com (J. Rogula), auffhammer@berkeley.edu (M. Auffhammer), NLMiller@Berkeley.edu (N. Miller), vandorn@atmosresearch.com (J. VanDorn), wuebbles@atmos.uiuc.edu (D. Wuebbles).

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the infrastructure of coastal and high-latitude cities: sea level rise, increases in hurricane intensity, storm surges, permafrost melting, and coastal subsidence (NRC, 2008). Chicago is still vulnerable, however, to increases in temperature, particularly extremely hot days and extended heat waves, as well as projected increases in heavy rainfall events associated with flooding.

Chicago has already experienced the effects of extreme weather events. During the 1995 Chicago heat wave, for example, daily maximum temperatures were equal to or greater than 90 °F (32.2 °C) for 7 consecutive days, setting an all-time high temperature of 106 °F (41.1 °C) for the Chicago Midway weather station on July 13, 1995. City streets buckled, electricity usage records were broken, and power failures left some residents without electricity for up to 2 days (Klinenberg, 2002). Just 1 year later, in July 1996, a record-breaking 43 cm (17 in.) of rain fell in a single 24-hour period. The resulting flash floods in Chicago and its surrounding suburbs damaged over 35,000 homes, streets, and bridges, with a total estimated cost of flood losses and recovery of $645 million (Changnon et al., 1999).

As discussed in Hayhoe et al. (2010), by the end of the century, temperature increases are projected for the City of Chicago of 1.5–2 °C under lower and 4–4.5 °C under higher emissions. The number of days where maximum temperatures exceed 32 °C or 90 °F (also, 38 °C or 100 °F) is likely to increase from present-day 15 (2) days per year to 36 (8) under the lower and 72 (31) under the higher emissions scenario. The average high temperature of the hottest day of the year, currently 100 °F (38 °C), is projected to rise to 108 °F (42 °C) under lower and 117 °F (47 °C) under higher emissions (Table 1; also Hayhoe and Wuebbles, 2008). Winter and spring precipitation is projected to increase, as are the frequency of single-day and multi-day extreme rainfall events during those seasons (Table 1; also Hayhoe et al., 2010).

Given the magnitude of the impacts experienced in the recent past, projected future changes in heat wave and heavy rainfall events are likely to have significant impacts on many aspects of life in Chicago. Here, we describe the development and application of a quantitative modeling framework capable of assessing the potential impacts and economic costs of changes in mean and extreme climate on Chicago's energy use, peak electricity demand, transportation, and its built environment including its parks and recreation systems. Other studies (Cherkauer and Sinha 2010; Hayhoe et al., 2010; Wuebbles et al., 2010) address expected climate change impacts on public health, air quality, and water resources. Our approach is unique in that it is the first effort to provide detailed linkage between high-resolution climate projections and specific city functions and infrastructure. It is also distinctive in that the model is based on specific information and insight from city experts. However, the overall construct of the model is designed to ensure portability to other cities, including integration of their specific impact information.

In terms of climate-related impacts on the energy sector, observed correlations between daily mean near-surface air temperature and peak electricity demand during summer suggest the potential for significant increases in future electricity demand for air conditioning as temperatures rise (Belzer et al., 1996; Amato et al., 2005; Mendelsohn and Neumann, 1999; Rosenthal et al., 1995; Henley and Peirson, 1998; Cartalis et al., 2001; Sailor, 2001; Valor et al., 2001). The impact of increasing temperatures on air conditioning demand is expected to have a disproportionately large effect in already heavily air-conditioned regions such as the Southwest (Miller et al., 2008). However, significant increases in electricity demand for air conditioning have also been projected for northern cities such as Chicago. For example, Colombo et al. (1999) found that a 3 °C increase in the daily maximum temperature would lead to a 7% increase in the standard deviation of current peak energy demand during the summer for nine Canadian cities. Similar studies for Boston (Amato et al., 2005) and Maryland (Ruth and Lin, 2006) also find the potential for significant increases in residential and commercial electricity demand under scenarios of future climate change.

Projected increases in peak electricity demand in particular raise concerns regarding electricity shortages. The continent's energy infrastructure, its refinery capacity, and electricity line transmission system have not adequately kept up with peak demand. In the summer of 2003, for example, a system failure resulted in the largest blackout in US and

**Table 1**
Climate indicators driving projected energy, infrastructure and economic impacts of climate change on the City of Chicago. Projections are based on the average of the Chicago Midway, O'Hare, and University of Chicago weather stations and 3 AOGCMs as simulated for the SRES A1fi (higher) and B1 (lower) emissions scenarios. Changes in annual, seasonal, and monthly temperature and precipitation projections and lake levels used in this analysis are already summarized in Hayhoe et al. (2010).

| Climate Indicator | Units | Present Day (1997–2006) | Near Future (2010–2039) | B1 Lower (2070–2099) | A1FI Higher (2070–2099) |
|---|---|---|---|---|---|
| *Temperature related* | | | | | |
| Tx>60/80 °F (16/27 °C) | Days per year | 189/76 | 191/86 | 203/101 | 221/131 |
| Tx>90/100 °F (32/38 °C) | Days per year | 18/2 | 25/5 | 36/8 | 72/31 |
| 3/5/7 Consecutive days with Tx>80 °F (27 °C) | Events per year | 20/10/6 | 23/11/7 | 28/14/8 | 38/21/13 |
| 3/5/7 Consecutive days with Tx>90 °F (32 °C) | Events per year | 3/1/0.5 | 5.5/2/1 | 8/3.5/1.8 | 19/9/5.5 |
| 3/5/7 Consecutive days with Tx>100 °F (38 °C) | Events per year | 0.5/0/0 | 1/0/0 | 1.5/0.6/0.3 | 7/3/2 |
| Tn<40/30/20 °F (4/-1/-7 °C) | Days per year | 167/99/47 | 163/93/43 | 154/83/33 | 134/62/21 |
| Extreme heat events [a] | Events per year | 0.3/0/0 | 1/0.5/0.5 | 1.6/1.4/1.5 | 7/7/9 |
| Tn<33 °F (0.6 °C) | Days per year | 122 | 118 | 107 | 86 |
| 3/5/7 Consecutive days with Tx between 80 and 90 °F (27–32 °C) | Events per year | 16.5/8.5/5 | 17/9/6 | 20/10/6.5 | 19/11.5/8 |
| 3/5/7 Consecutive days with Tx between 90 and 100 °F (32–38 °C) | Events per year | 3/1/0.5 | 5/2/1 | 6.5/3/1.6 | 12/6/4 |
| 3-h periods of extreme heat defined by the 99th (99.9th) percentile [b] | Periods per year (weekdays only) | 20.8 (2.0) | 51.1 (10.6) | | 74.6 (15.7) |
| *Precipitation-related indicators by season: MAM/JJA/SON/DJF* | | | | | |
| Seasonal average $P$>0.5 in. (13 mm) | Days per season | 8.5/9.9/7.4/4.0 | 7.9/9.0/6.8/4.3 | 10.1/9.8/6.7/4.5 | 10.4/8.9/7.7/4.6 |
| Seasonal average $P$>1 in. (25 mm) | Days per season | 2.5/3.9/2.8/0.8 | 2.1/3.4/2.4/1.1 | 3.0/4.0/2.5/1.3 | 3.4/3.5/3.0/1.4 |
| Seasonal average $P$>2 in. (51 mm) | Days per season | 0.13/0.53/0.38/0.05 | 0.14/0.48/0.33/0.06 | 0.30/0.44/0.36/0.11 | 0.47/0.44/0.62/0.20 |
| Seasonal average $P$>4 in. (102 mm) | Days per season | 0/0.05/0/0 | 0.01/0.02/0.01/0 | 0/0.03/0.01/0 | 0/0/0.01/0 |
| Seasonal average $P$ between 0.5 and 1 in. (13–25 mm) | Days per season | 6.0/6.0/4.6/3.2 | 5.8/5.6/4.4/3.2 | 7.1/5.8/4.2/3.2 | 6.9/5.4/4.7/3.2 |
| Seasonal average P between 1 and 2 in. (25–51 mm) | Days per season | 2.4/3.4/2.5/0.7 | 2.0/2.9/2.1/1.1 | 2.7/3.5/2.1/1.2 | 3.0/3.1/2.4/1.2 |
| Seasonal average $P$ between 2 and 4 in. (51–102 mm) | Days per season | 0.13/0.48/0.38/0.05 | 0.13/0.46/0.32/0.06 | 0.030/0.41/0.35/0.11 | 0.47/0.44/0.62/0.20 |
| Annual snowfall | in.(cm) | 45 (114) | 44 (112) | 48 (122) | 40 (102) |

[a] Chicago-specific extreme-heat events are defined as either (1) 3 consecutive days with daily maximum temperature between 100 and 105 °F (37.8 and 40.6 °C) or (2) 2 consecutive days with daily maximum temperature between 105 and 110 °F (40.6 and 43.3 °C) or (3) 1 day with daily maximum temperature greater than 110 °F (43.3 °C).

[b] Time periods for 3-h extreme-heat projections are 1990–2000 for present day, 2021–2040 for near term, and 2081–2099 for end of century. As simulated by the PCM model for the SRES higher (A1FI) scenario for grids covering ComEd's service territory. Simulations for lower emissions not available.

Canadian history. An estimated 50 million people across the Great Lakes and Northeast were left without power for several days. The cascade of impacts from this event for Great Lakes provinces and states such as Ontario, Michigan and Ohio, included disruption of water supply; flooding and water contamination when heavy rain occurred but sewage pumps could not be operated; major transportation interruptions and delays due to unavailability of fuel, traffic light signals, and public transit outages; major drop in river levels due to increased hydroelectric generation on the Niagara River; and emergency shutdowns, increased pollution release, and even explosions at refinery plants in Michigan and Ontario.

In terms of climate-related impacts on transportation, a recent report by the National Research Council concludes that climate patterns based on the last century, traditionally used by transportation planners to guide their operations and investments, may no longer provide a reliable guide to the future (NRC, 2008). In particular, climate change is projected to affect the frequency of extreme-heat and heavy rainfall events (Meehl et al., 2007), both of which are known to affect transportation infrastructure.

Other aspects of human infrastructure systems include residential, commercial, and industrial buildings, waste- and storm-water management, and flood control. Only a limited number of such assessments have been conducted for New Zealand (Jollands et al., 2007) and Boston (Kirshen et al., 2008), likely due to the necessity of working in close collaboration with the city to ensure the relevance of the future projections to observed impacts.

Finally, although a number of studies have examined climate change effects on winter tourism (Scott et al., 2003, 2008; Lise and Tol, 2002) or on visits to national parks in Canada and the United States (Richardson and Loomis, 2004; Suffling and Scott, 2002), few have yet considered the effects of climate change on urban parks and recreation, including summer tourism. Chicago is host to a vibrant outdoor culture during the summer, with numerous festivals, outdoor theaters, and special events, revenues from which totaled $433 million in 2005, excluding admission costs (The Arts and Economic Prosperity III, 2007). Projected increases in extreme heat and humidity, coupled with more intense downpours, could also have a significant negative economic impact on the City through decreasing tourism-related revenue generated by these events, and increasing maintenance cost for parks, beaches, and other lakefront recreational facilities such as harbors.

Our objective in this study was to draw on observations of the impacts of shifts in climate and the frequency and severity of extreme weather events specific to the City of Chicago in order to assess the potential impacts of climate change on Chicago's energy, transportation, infrastructure, and economy. In Data and methods section, we describe the unique approach, data sources, methods, and development of the prototypical economic modeling framework used in this analysis. The next section describes projected changes in energy-related indices specific to Chicago's climate, and their effect on peak electricity demand; analyses of specific thresholds and climate indicators related to Chicago infrastructure; and the economic impacts and the estimated economic costs of these impacts. Finally, in the Conclusions and further discussion section, we draw specific conclusions regarding the likely magnitude and cost of climate change on Chicago's energy and infrastructure, quantifying the motivation and potential for preventative action to reduce the city's vulnerability to likely change.

## Data and methods

### *Projections of future change in impact-relevant climate thresholds*

Daily weather observations for the Chicago Midway Airport, O'Hare, and University of Chicago weather stations were used to derive the historical characteristics of extreme heat and precipitation in Chicago. Simulations by three global coupled atmosphere–ocean general circulation models (AOGCMs) were used to generate future projections: GFDL CM2.1, HadCM3 and PCM (Delworth et al., 2006; Pope et al., 2000; Washington et al., 2000). Further descriptions of the data and models are provided in Hayhoe et al. (2010).

Historical AOGCM simulations are based on the standard 20C3M scenario, which represents the best available estimates of twentieth-century total (anthropogenic+natural) forcing. The 20C3M scenario includes observed historical emissions of carbon dioxide, methane, and other greenhouse gases; sulfate aerosols, soot, and other particulates; and other radiatively active species produced by human activities such as nitrogen oxides and carbon monoxide. The historical scenario also includes observed changes in solar output and emissions from natural sources.

Future AOGCM simulations (2000–2099) are based on the IPCC Special Report on Emission Scenarios (SRES, Nakićenović et al., 2000) higher (A1FI) and lower (B1) emissions scenarios. These scenarios use projected future changes in population, demographics, technology, international trade, and other socioeconomic factors to estimate corresponding emissions of greenhouse gases and other radiatively active species. Although the SRES scenarios do not include any explicit policies aimed at reducing greenhouse gas emissions to mitigate climate change, the B1 scenario can be seen as proxy for stabilizing atmospheric $CO_2$ concentrations at or above 550 ppm, as levels reach this value by 2100. Atmospheric $CO_2$ concentrations for the higher A1FI scenario reach 970 ppm by 2100. Input from these scenarios used to drive the future AOGCM simulations includes regional changes in emissions of greenhouse gases, particulates, and reactive species.

Daily temperature and precipitation were statistically downscaled to the Chicago O'Hare, Midway, and University of Chicago weather stations using a statistical asynchronous regression technique described by Hayhoe et al. (2010). This method downscales by individual quantile, ensuring that AOGCM-simulated extreme events during the historical period 1961–1990 match observed statistical frequency and intensity in order to reproduce the characteristics of Chicago's location and topography that can influence both extreme-heat and precipitation events at the scale of an individual weather station. Projected changes in more than one hundred relevant climate indicators, such as the number of days over or under a given temperature threshold, the total amount of precipitation falling during a given time interval, and other aspects of climate relevant to human systems within the City of Chicago, were then derived from these daily downscaled temperature and precipitation series. Those indicators that were determined to be directly relevant to observed impacts on city departments were retained for the economic analysis described below, as summarized in Table 2.

### *Estimating temperature impacts on energy demand and peak electricity*

To estimate the relationship between temperature and electricity demand, we examined the correlation between hourly reported electricity load and average hourly temperature for Commonwealth Edison (ComEd), the primary provider of electricity for the City of Chicago and surrounding area. ComEd is a unit of Exelon Corporation, one of the nation's largest electric utilities with a customer base of 5.2 million. ComEd maintains more than 78,000 miles of power lines that make up the electric transmission and distribution system in Northern Illinois. It also provides customer operations for more than 3.7 million customers across the region, or 70% of the state's population. Commonwealth Edison's service territory borders Iroquois County to the south, the Wisconsin border to the north, the Iowa border to the west, and the Indiana border to the east.

Hourly electricity load data as reported on the Federal Energy Regulatory Commission Form 714 from 1993 until 2004 were combined with temperature measurements taken at 3-h intervals from monitors within the ComEd service territory. The impact of temperature on load was extracted by statistically separating out the impacts of factors, which also affects loads and vary across the hours of the day, days of the week, and seasons. As shown in Fig. 1, the estimated relationship between

**Table 2**
Climate risk drivers and associated impacts identified for Chicago City departments.

| Department | Climate Risk Driver | Projected Impacts |
|---|---|---|
| Revenue | Average temperature increase | Utility tax revenues |
| Transportation | Average temperature increase | Planting and plant maintenance along boulevards |
| | | Road repair and replacement |
| | Changes in heavy rainfall | Managing flooding in parking lots |
| | Changes in snowfall | Snow removal |
| Chicago Transit Authority | Average temperature increase | Bus cooling and heating: additional stress on bus engines with increased demand for cooling |
| | | Bus maintenance: additional stress on tires with extreme heat |
| | | Train cooling and heating |
| | Frequency of extreme-heat days | Retrofitting maintenance facilities with cooling capability |
| | | Cooling retrofitted facilities |
| | | Demand for cooling buses on hot days during blackouts |
| | | Overtime costs |
| Chicago Park District | Average temperature increase | Heating and cooling facilities |
| | | Tree replacement due to road salting |
| | | Algae treatment at beaches and in ponds |
| | | Beach revenues from extended season |
| | | Landscape contractor costs from extended season |
| | Frequency of extreme-heat days | Retrofitting facilities with cooling capability |
| | | Cooling retrofitted facilities |
| | Lower lake levels | Harbor dredging |
| Streets and Sanitation | Average temperature increase | Tree replacement |
| | Changes in snowfall | Snow removal |
| Metropolitan Water Reclamation District | Average temperature increase | Operations costs affected by heat |
| | Average precipitation change | Operations costs affected by rain |
| | | Premature flood and pollution costs |
| Aviation | Average temperature increase | Fuel tax revenue |
| | | Heating and cooling facilities |
| | | Landscape contractor maintenance costs |
| | | Landscape contractor capital costs (irrigation) |
| | Changes in snowfall | Snow removal |
| Chicago Public Schools | Average temperature increase | Heating and cooling facilities |
| Cultural Affairs | Average temperature increase | Revenue from cultural events |
| Chicago Fire | Frequency of extreme-heat days | Accelerated vehicle replacement and lengthier usage of equipment |
| | | Increased volume of fire responses and safety checks |
| | | Increased worker stress |
| | | Firehouse maintenance |
| | | Medical system labor cost |
| General Services | Average temperature increase | Heating and cooling of facilities |
| | | Roof repair and replacement |
| Human Services | Frequency of extreme-heat days | Overtime cost |
| Chicago Police | Frequency of extreme-heat days | Overtime cost and more frequent safety checks |

hourly temperature and hourly electricity load for ComEd displays the classic U-shaped temperature electricity load relationship.

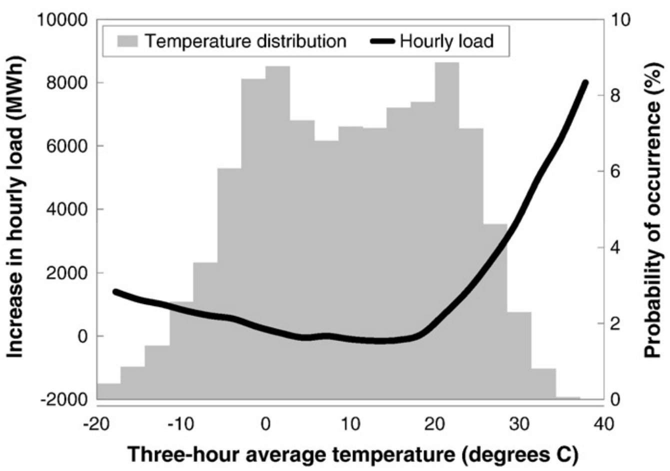


**Fig. 1.** Estimated electricity load–temperature relationship using a 20-knot spline function, to allow for maximum flexibility of the load temperature relationship. The red line depicts the observed increase in Commonwealth Edison hourly load due to one period spent at each ambient temperature, with a balance point of 59 °F (15 °C). The grey histogram displays the observed distribution of 3-hourly average temperature over the sample period, excluding weekends.

The balance point, where the slope of the relationship between temperature and electricity changes sign, defines the threshold beyond which increasing temperature implies increases in electricity demand. Although a value of 65 °F (18 °C) is typically used in most energy analyses, in this analysis, we empirically derive a Chicago-specific balance point, as this value has been found to be location and sector-specific, depending on characteristics such as infrastructure, cultural preferences, and aspects of climate other than temperature. For the state of Maryland, for example, Ruth and Lin (2006) identify electricity balance point temperatures of 60 °F (15.5 °C) and 53 °F (11.7 °C), respectively, for the residential and commercial sectors. For Massachusetts, similar balance point temperatures of 60 °F (15.5 °C) for residential and 55 °F (12.8 °C) for commercial sectors have been identified by Amato et al. (2005). Here, we do not separate out commercial from residential demand but instead find a combined balance point of 59 °F (15 °C) using a 20-knot spline fit to the data (Fig. 1), beyond which point electrical load displays a positive correlation with temperature.

This balance point can then be used as input to an initial measure of the potential impacts of climate change on electricity demand in Chicago, namely degree-days. Annual cooling degree-days (CDDs) are defined by the National Climatic Data Center (Owenby et al., 2005) as CDD = (Ta - Tac)*days, where "Ta" is the daily mean near-surface air temperature and "days" is the number of days with temperatures exceeding Tac. Here, the empirically derived, Chicago-specific balance point temperature threshold of Tac = 59 °F (15 °C) is used.

The CDD approach has the advantage of being able to be applied to any set of daily temperature projections, including the six projections used as the basis of this analysis. A more sophisticated method of estimating projected future climate change impacts on electricity load for Chicago was also used, however. This second method was based on simulations from the only AOGCM to provide 3-h surface temperature projections, PCM, as these match the hourly grid load data more closely. Fig. 1 shows an empirically estimated temperature load relationship between hourly average temperature and hourly load in the main population centers served by ComEd. The statistical model applied removes confounding factors that vary by the day of week, week of year, and hour of day.

*Development of economic modeling framework and impacts assessments*

The purpose of the economic analysis was to identify the point at which long-term climate trends would impact the City's infrastructure and operations and to estimate the associated costs of these impacts. To this end, representatives from the global management consulting firm Oliver Wyman (OW) worked closely with the City of Chicago departments and the authors of this work to ensure the sensitivity of Chicago's infrastructure and economy were reflected in the analysis through selection of appropriate climate drivers and quantification of associated impacts (Oliver Wyman, 2007). The goal of the analysis was to improve insight into adaptation and mitigation planning on departmental and city-wide levels. To that end, the economic analysis focused on the following questions:

- What are the primary climate-related drivers of infrastructure and/or economic impacts?
- What is the nature of the impact (e.g., deterioration of building facades)?
- What is the likely magnitude of potential impacts?
- What are the areas likely to be most affected from a financial perspective?
- What type of financial impact would result—changes in capital investment, operational costs, or other?

To estimate the economic impacts of climate change on the City of Chicago, an in-depth integration of multiple data sources including climate indicators, anticipated impacts, and economic costs was the input to an economic model. The output of the model provides a wide range of economic insights into the potential impacts of climate change on a city, as well as quantifying the relative costs of adaptation vs. mitigation.

The economic model was constructed relative to a “business as usual” scenario that assumed current operational levels and authorized investments to provide a solid baseline for evaluation of incremental costs stemming from anticipated climate changes. Once the relationships have been codified, the model can be updated with new cost estimates and technology efficiency gains. This gives the ability to generate updated impact estimates in a more automated fashion as knowledge improves and more empirical data become available. In this application, we did not account for possible future technological advances, due to uncertainty of timing and effectiveness, although those aspects could be integrated into a revised version of the model.

The dataset itself presents a new perspective for the City of Chicago into the insights provided by the model framework. To build the dataset, OW gathered information directly from Chicago departmental experts most familiar with potential impacts on the infrastructure and service elements. This allowed the model to provide a level of granularity unique to this study. The data also provided a clear view of causal and impact linkages across departments, enabling a solid framework from which to quantify impacts.

Development of the model included two fundamental steps. Step 1 consisted of identifying climate change-driven impacts and defining the variance of impact given different climate thresholds. Each potential physical or operational impact, or set of impacts, was considered from the perspective of its larger economic affect on the city. This bottom–up analysis resulted in the development of Climate Impact Pathways (CIPs) such as the causal analysis illustrated in Fig. 2. Using a framework generalizable across departments, sectors, and even other urban areas, these CIPs form the basis of multiple impact scenarios specific to each department that capture specific economic dollar impacts by department and by climate thresholds. For example, emergency response

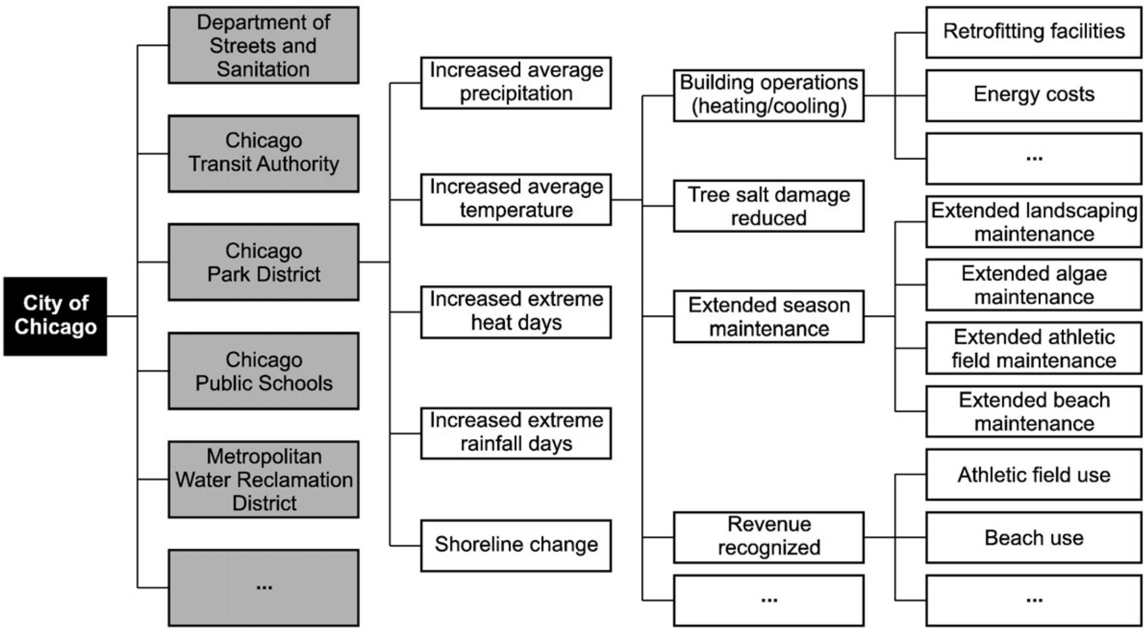


**Fig. 2.** Sample climate impact pathway for causal analysis representing the results of information gathering and analysis from eighteen City of Chicago departments, developed in step 1 of the economic model development. Example shown here is for the Chicago Park District. Projected impacts, which include both increased costs and revenues, are driven primarily by a lengthening of the outdoor recreation and growing seasons. Secondary effects arise from projected increases in extreme-heat days and, under higher emissions by end of century, the potential need for harbor dredging due to lower lake levels. Diagrams of climate impact pathways for all the city departments used in this analysis are available online at http://temagami.tosm.ttu.edu/chicago.

systems for a city could experience an increase in costs driven by an increase in frequency and duration of heat events. Heat events with duration of 2–3 days could have a cost of $57,000 per day associated, while heat events of 4–5 days could have a cost of $80,000 per day associated. These scenarios and step functions were defined through critical information gathering, compilation, and level setting.

Given that this type of analysis was new for the city and the questions asked had not previously been investigated, much of the data developed in the impact pathways were parameterized using the judgment of experienced city officials. The research team identified and interviewed 18 content experts from 18 city departments to determine the extent to which their respective department's operations, assets, personnel, and services would be physically and operationally affected by projected climate changes. Changes considered here focused on heat increases (magnitude and duration) and precipitation (frequency and volume). Fourteen of the eighteen city departments interviewed identified potential economic impacts due to climate-related impacts (listed in Table 2), while specific projections for the climate thresholds and indicators identified in step 1 have already been summarized in Table 1. Four departments – Public Health, Housing, Environment, and Planning and Development – did not identify any infrastructure or operating costs that they expected to change in relation to climate, although the potential impacts of climate change on public health itself are explored elsewhere in this volume (Hayhoe et al., 2010).

After the CIPs were defined, the team continued with defining the magnitude of the impacts. In step 2, impact, probability, and rate distributions for drivers within the CIPs were developed. Cost/revenue-related data (e.g., equipment replacement, asset repair) that would be anticipated relative to each future climate scenario were determined specific to each city department. The data included factors such as triggers for timing of expenditure; type of expenditure, such as capital investments or increased operating costs; magnitude of expenditure; nature of expenditure, specifically new versus incremental costs; etc.

For each of the impact thresholds, the participants were asked to provide a range of values for the impact drivers. These ranges were further supplemented by asking the participants to comment on the skew of the range. Allowable choices were whether they believed the range to be skewed to the low or high end, skewed to the mid-point, or no skew. For example, if the emergency response team identified an increase in cost of $5–15 million per heat event lasting 3–4 days in duration, the team was asked to describe whether the costs were skewed towards $5 million, $10 million, $15 million, or not skewed. This approach was taken to provide a realistic range of impact, as defining a point estimate would be difficult for departments. This difficulty arose from the fact that this type of analysis was new for the City, and team members were asking questions of the department officials that had not been asked of them before. The data distributions were then subjected to Monte Carlo simulations to yield a set of impact and probability distributions to support reliable cost distribution ranges (Fig. 3).

For the work described here, the model framework was limited to city departments and agencies in order to stay within the mandate of the Chicago Climate Action Task Force. However, it is recommended and entirely feasible that the model be expanded to include more aspects of the Chicago metro area including inhabitants, business concerns, and city departments not included in the initial study. The benefit of including other 'non-city owned' elements would be to support broader and more integrated solution planning and ownership of the shared metro area future. Expansion of the model in this fashion would focus business and inhabitant attention on both the discrete impacts to their

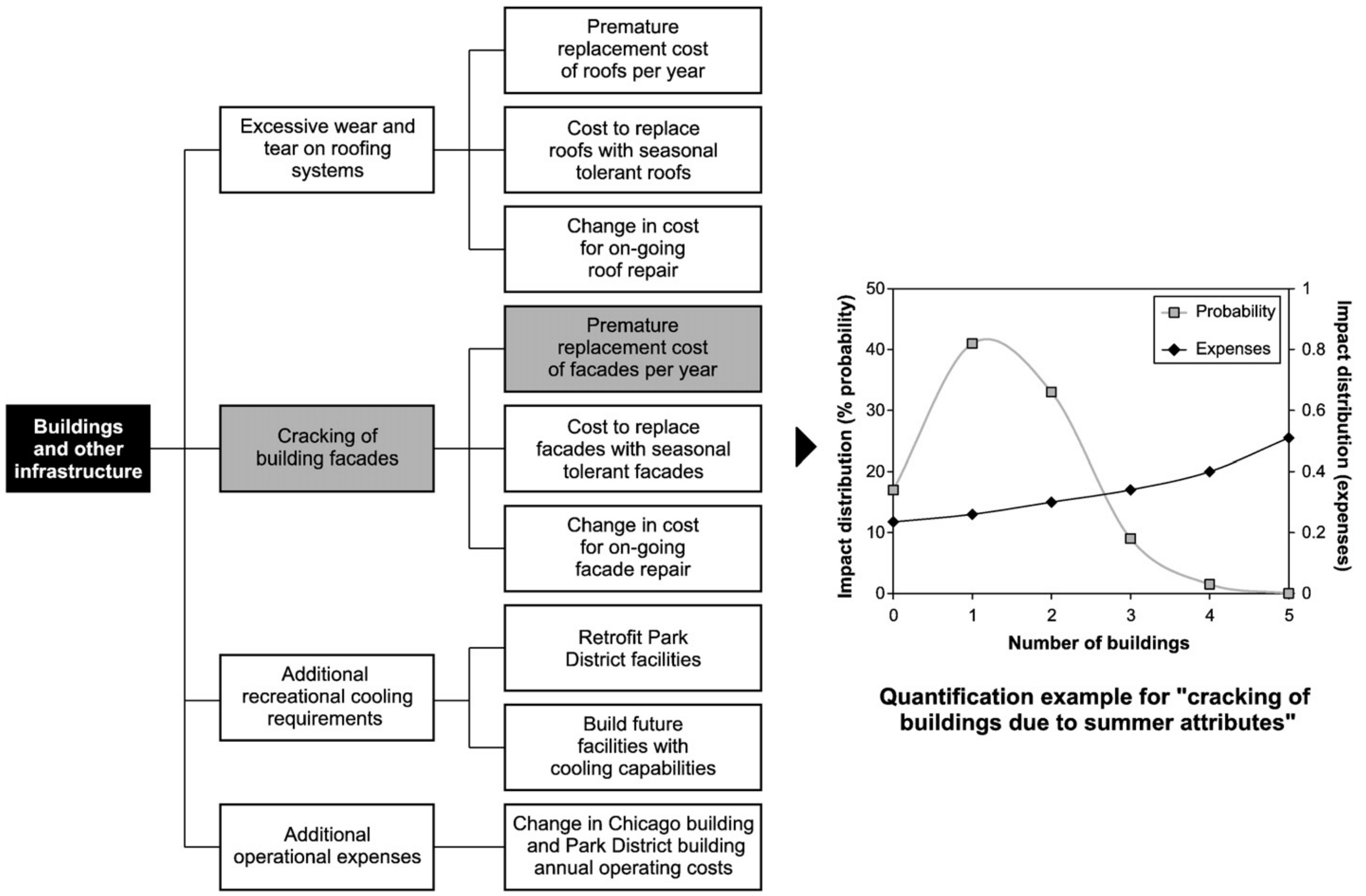


**Fig. 3.** Impact and probability distributions for future climate scenarios affecting Chicago City operations and assets, developed in step 2 of the economic model development. Example shown here is for city buildings.

environment and operations, as well as to the part that they play in the community impacts and solutions.

It is important to note that the climate-related economic impacts discussed in this report relate only to the City of Chicago government and related agencies. The results of the model are based on widely divergent levels of understanding (of climate change) among departmental respondents, and varying abilities to "look into the future" (e.g., flooding and the capacity of the TARP system). There also exists among some respondents a normal tendency to rely on either their confidence in departmental issues management, complacency on climate change considerations, or concern about budget implications. Additionally, many of the respondents only took into account the linear impact of climate change, not having the ability to quantify second or third order issues (e.g., police presence focused on assisting with heat-related evacuations could draw away from the ability to deal with concurrent crime and disorder attendant with increased heat levels). Some departments identified alternative strategies for mitigation with varying costs (e.g., selection of materials for road repair). However, to be consistent with 'business as usual,' those approaches were not incorporated unless they were already approved and built into their business cases going forward. In other cases, some departments identified potential costs (e.g., absenteeism, façade maintenance), but sufficient data were not available to model their impact. Also, some departments identified costs that could be extrapolated to other departments or the city as a whole (e.g., expand department fleet costs to the entire city fleet) but were not actually included in those other department plans so they were not included in the model. The economic impact to the larger business community in and around Chicago, as well, was not quantified. The net result of these factors leads to a potential understatement of the net impact to the City of Chicago and an overall potentially conservative picture of the economic impact.

## Climate change impacts on Chicago's infrastructure and economy

### *Projected changes in impact-relevant climate thresholds*

Climate change will increase mean annual and seasonal temperatures, as well as altering the timing, magnitude, and threshold of climatological "extreme" events that affect energy, buildings, transportation, and other urban infrastructure. This analysis focuses specifically on evaluating the impact of these climate changes on electricity demand, city infrastructure, key departments, and budgets. It is important to note that the electricity analysis is city-wide, based on electrical load data from ComEd, while the infrastructure and economic analysis is city-specific, limited to estimating the impacts and costs directly to the city itself rather than its inhabitants. As previously noted, however, the model framework could easily be expanded in future work to include additional constituencies and considerations.

Changes in mean and seasonal temperatures are summarized by Hayhoe et al. (2010). Based on direct input from city departments, a number of climate thresholds were also identified, beyond which significant impacts have already been experienced in the past, or future impacts would be expected to occur (i.e., the system would be stressed beyond its designed capacity). These climate thresholds unique to the infrastructure and economic impact analyses are summarized in Table 1, while the sectors or departments they are expected to affect are listed in Table 2.

The primary driver of many impacts is the projected increase in extreme-heat days and corresponding decrease in extreme cold conditions. Some variables (such as the annual average number of heavy rainfall events) showed little change when evaluated on an annual basis but significant increases at the seasonal scale for winter and spring, balanced by corresponding decreases in summer and fall. Other variables show changes of the opposite sign by end of century, such as the projected increase in snowfall under lower emissions as compared to the decrease in snowfall under higher emissions. This is a function of winter precipitation increases combined with a relatively smaller increase in mean temperatures under B1 as compared to A1FI, such that the number of days with temperatures below freezing when precipitation occurs actually increases under B1 as compared to the present day. The specific thresholds shown in Table 1 were then used to estimate projected impacts on Chicago's energy, infrastructure, and economy.

### *Projected increases in annual average electricity demand*

To quantify the potential impacts of climate change on average annual electricity demand, we first calculate projected changes in annual cooling degree-days using a 59 °F (15 °C) mean temperature threshold or balance point, as derived from the observed relationship between electricity demand and temperature for the ComEd (Fig. 1). Based on this threshold, annual cooling degree-days average between 1500 and 1800 °C-days per year for the historical reference period 1961–1990, depending on the weather station.

Near-term projections based on the three long-term urban weather stations for Chicago (O'Hare, Midway, and University of Chicago) and three AOGCM simulations indicate that by 2010–2039, annual CDD values could average between 1600 and 1900 °C-days per year, regardless of the future emissions pathway followed (Table 1). By the end of the century (2070–2099), CDD values are projected to increase to more than 1990 to 2260 °C-days under lower emissions and 2450 to 2720 °C-days per year under higher, depending on the weather station used. Projected changes represent a 30% and 60% increase over the historical baseline for the lower and higher emission scenarios, respectively (Fig. 4). In terms of the financial impact for the Chicago Department of Revenue, a net negative impact is expected regarding the collection of utility tax. Tax revenue on electricity is likely to increase, but this will be outweighed by the loss of revenue collected on natural gas for winter heating.

Some measure of the adaptive potential for reducing projected increases in CDD and the subsequent rise in residential and commercial electricity demand can be obtained through comparing projected increases in CDD values calculated based on the observed 59 °F (15 °C) threshold with CDD values calculated using the higher standard threshold of 65 °F (18 °C). In this way, it is possible to provide a broad estimate of the potential for local adaptation, which could be achieved by measures such as increased building insulation standards and more

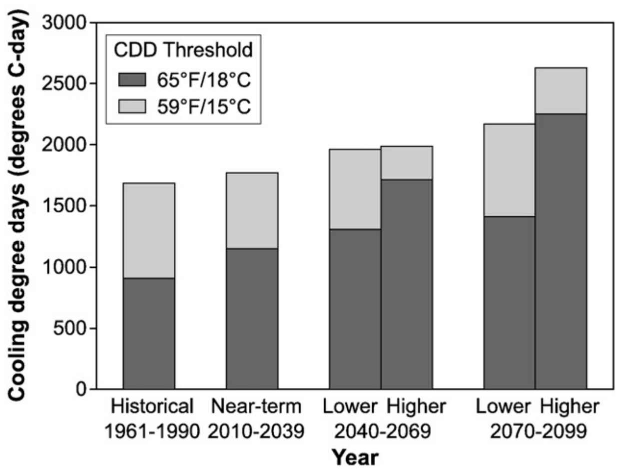


**Fig. 4.** Historical and projected future average annual cooling degree-days for Chicago using an empirically determined threshold of 59 °F (15 °C) and 65 °F (18 °C). Values are shown for historical and near-term (gray) and for mid-century and end of century under SRES A1FI higher (darker) and B1 lower (lighter) emission scenarios as simulated by the three AOGCMs used in this analysis. In this figure and all that follow, projections are based on the average of the Chicago Midway, O'Hare, and University of Chicago weather stations.

efficient cooling methods. Here, we examine the potential for a scenario where the balance point at which temperature and electricity load become positively correlated occurs at 65 °F, or in more simple terms, human behavior is modified such that most air conditioning units are not turned on by the citizens and businesses of Chicago until external temperatures reach 65 °F (18 °C) or higher.

As shown in Fig. 4, increasing the CDD threshold to 65 °F (18 °C) through adaptive measures reduces present-day and near-future CDD values by up to 40%. Albeit highly simplified, such measures appear to represent a significant adaptation option in the near-term. Over time, however, and under higher emissions, the magnitude of the adaptation potential wanes as the shape of the daily temperature distribution broadens, decreasing the total number of days with 59 °F (15 °C) < T < 65 °F (18 °C). By the end of century, the relative contribution of increasing the threshold from 59 °F (15 °C) to 65 °F (18 °C) under lower emissions is still 30%; in contrast, under higher emissions, only a 10% savings is achieved (Fig. 4).

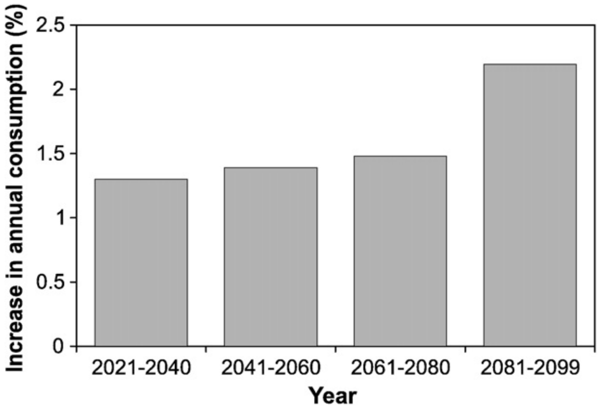


**Fig. 5.** Simulated increases in annual ComEd territory electricity consumption relative to 2000–2005, based on PCM simulations for the SRES A1FI higher emission scenario.

*Potential increases in peak electricity demand*

Climate change will affect electricity demand by shifting the mean of the temperature distribution, which increases annual consumption (as indicated by the degree-day analysis above). Perhaps more importantly, however, climate change may also affect electricity demand by simultaneous increases in both the mean and the variance of the temperature distribution (Hayhoe et al., 2010). This implies that events currently classified as “peak” will occur more frequently in the future, superimposed over simultaneous increases in peak demand.

Understanding the relationship between temperature and hourly electricity demand is essential to resolving the impact of climate change on peak load as well as on annual electricity demand. The relationship between electricity demand and temperature is highly non-linear, reflecting increasing electricity consumption at both lower and higher temperature extremes (Fig. 1). Observed correlations between hourly temperature and electricity demand for ComEd in the Chicago region already indicate the potential for drastic increases in electricity load at high temperatures. One hour at an average ambient temperature of approximately 90 °F (32 °C), for example, is likely to result in a load that is 8000 MW higher than an equivalent hour at approximately 55 °F (13 °F). This difference is roughly equivalent to the electricity consumed by 261,000 households in a day, or 6.3 million households in a single hour.

In order to simulate annual electricity consumption throughout the coming century, the estimated relationship shown in Fig. 1 was applied to 3-hourly simulations from the PCM model, the single AOGCM of these three for which continuous output has been archived at sub-daily temporal resolution. Size and composition of the population were kept constant, and income, industrial production, and technology were similarly frozen at current levels in order to isolate the effect of climate change on electricity load.

As shown in Fig. 5, annual aggregate electricity demand is projected to increase by 1.3% initially, but by up to 2.2% by the end of the century under the PCM A1FI higher scenario, relative to the 2000–2005 period. Projected increases in 99th and 99.9th percentile 3-h heat periods for each of the four periods are also summarized in Table 1. The number of extreme-heat 3-h events is projected to increase by 258% for 99th percentile periods and up to 685% for the 99.9th percentile events by the end of the century. This increase in the predicted frequency of extreme-heat events goes hand in hand with occurrences of extreme electricity demand, suggesting increased frequency of peak demand events and implying an enhanced risk of electricity shortages if capacity expansions do not keep step with demand.

This analysis is subject to three important caveats. First, uncertainty regarding future changes in socioeconomic factors (population, income, production, and technology) may dominate the uncertainty in future changes in electricity consumption. Second, however, by maintaining present-day relationships, this simulation may actually underestimate the impacts of climate change. In the future, if people alter current habits to offset some of the negative impacts of climate change, for example through increased adoption of air conditioning and increased frequency of existing air conditioner use, this may lead to additional increases in electricity consumption beyond those estimated here. Finally, this analysis is additionally conservative in that it is based on simulations from the lowest sensitivity AOGCM, PCM. The projected temperature increases even under the higher emissions scenario are therefore at the lowest end of the expected range for that scenario.

*Climate-related impacts and adaptation options for Chicago's infrastructure*

*Parks, recreation, and tourism: case study*

Chicago has an extensive park system and is also known for its outdoor recreational opportunities from late spring to early fall. This sector forms the basis for the case study presented in Fig. 2, describing the effects of climate change on Chicago's Department of Cultural Affairs and the Chicago Parks District.

Although increasing temperatures extend the period of outdoor recreation, at the same time they may also put further stress on the city's resources. Longer open periods for beaches, parks, and other facilities imply increased revenues to the city. A hotter and more humid summer season, however, could decrease the number of events held in Chicago as it would be harder to attract non-resident attendees: an estimated $4.4 million loss in revenue from special events.

Landscaping costs related to maintenance of trees, plants, and flowers increase with temperatures. This is due both to a longer growing season and more required maintenance and replacement (estimated at $2 million under the higher emissions scenario). Existing trees will have a shorter lifespan because of increased stress due to higher temperatures. Outdoor landscaping costs for the Chicago Park District are projected to be two times higher (conservatively $2 million) under the higher emissions scenario as compared to the lower.

*Roads and public transit*

Climate impacts on transportation were estimated for the Chicago Transit Authority (CTA) and the Chicago Departments of Transportation, Aviation, and Streets and Sanitation. A broad range of impacts were found to depend primarily on changes in average temperature and precipitation, extreme-heat events, and increased frequency of heavy rainfall events (Table 2). Most notably, road repairs and maintenance costs are projected to increase by end of century under the higher emissions scenario (Table 1). This is due to changes in planting and maintenance costs, road replacement, and repair related to increased heat and more severe heavy rainfall events in winter and spring.

*Building capital and maintenance*

Climate impacts on buildings owned and operated by the city fall on the Department of General Services, charged with maintaining the city's buildings; the Metropolitan Water Reclamation District, charged with conserving the city's fresh water and managing storm water; and the Chicago Public School Board.

Building infrastructure is likely to be primarily affected by changes in mean and extreme temperatures that impact heating and cooling demand, and roof and facade repairs (Table 2), and so it is projected to rise under both the lower and higher emissions scenarios. The majority of costs are a result of non-cooled facilities requiring retrofits so they can continue to be used in extreme heat and higher repair costs for roofs due to accelerated breakdown of the petroleum-based roofing materials. Facades may also need more maintenance and repairs. By the end of the century, building-related expenses under the higher emissions scenario are likely to be ten times greater (conservatively $20MM) than under the lower emissions scenario.[1]

Building losses due to damages from extreme events could represent a much larger expense than changes due to mean temperature. For example, the City of Chicago and the Park District spent $6.6 million on overtime and material to clean up after a storm on August 23–24, 2007. The storm damaged trees, homes, and buildings; flooded basements, streets, and viaducts; and left thousands of Chicagoans without power (Spielman, 2007). In 2 days, State Farm Insurance Co. received more than 7144 home claims and more than 1027 vehicle claims from Chicago area policy holders whose property was damaged in the storm (Spielman, 2007). For the specific city departments examined here, projected changes in extreme rainfall days were determined to have zero net impact. Given the magnitude of past impacts, however, it is likely that expanding the model framework to encompass additional aspect of the metro region would alter this result.

*Public safety and emergency response*

The primary climate driver of impacts on City personnel, health, safety, and welfare is the projected increase in the frequency and intensity of extreme-heat events. A doubling in the number of days with maximum temperature exceeding 32 °C/90 °F by mid-century under higher emissions, and end of century under lower (Fig. 6), is estimated to result in 5–10% more fires in the Chicago area, with economic impacts ranging from vehicle replacement costs to firehouse maintenance, as summarized in Table 1.

In addition to their direct effects on human health and the Chicago public and private health system (Hayhoe et al., 2010), shifts in the frequency and/or intensity of extreme-heat events affect departments whose employees work outdoors, such as the Department of Parks and Recreation, or that provide services that are expected to become more in demand, such as buses to cooling centers operated by the CTA; emergency services provided by the Fire Department due to more frequent power outages, well-being checks, and transportation to cooling facilities; or the frequency of wellness checks conducted by the Department of Human Services. Associated departments are projected to experience increased absenteeism due to heat stress, which also exacerbates workers' vulnerability to pre-existing health conditions such as heart or respiratory diseases. More pressure will be exerted on the medical response system, through the need for more ambulances and engines to be dispatched to provide necessary support. As hospitals become overwhelmed during heat waves, they may reject ambulances and send them to non-local hospitals, which also will raise costs and impact the effectiveness of the emergency response system.

An increase of extreme-heat days can also lead to increases in certain types of problems that require police department response, including electrical outages, loss of air conditioning in high-rise buildings, and subsequent evacuations. However, given that there are no extra resources to use during these events, police personnel who are already working are diverted to respond to these scenarios. This leads to overtime costs and a loss of efficiency in doing the everyday tasks that now become undermanned, as well as a real possibility of increased crime. This police response to extreme heat generally begins at the heat trigger of 98 or 99 °F.

Overall, it is estimated that the total economic impact of the higher emission scenario is likely to be two times more costly (conservatively $5 MM) than the lower emissions scenario, in terms of impacts on personnel and safety. These costs are primarily due to projected increases in the frequency of extreme-heat events.

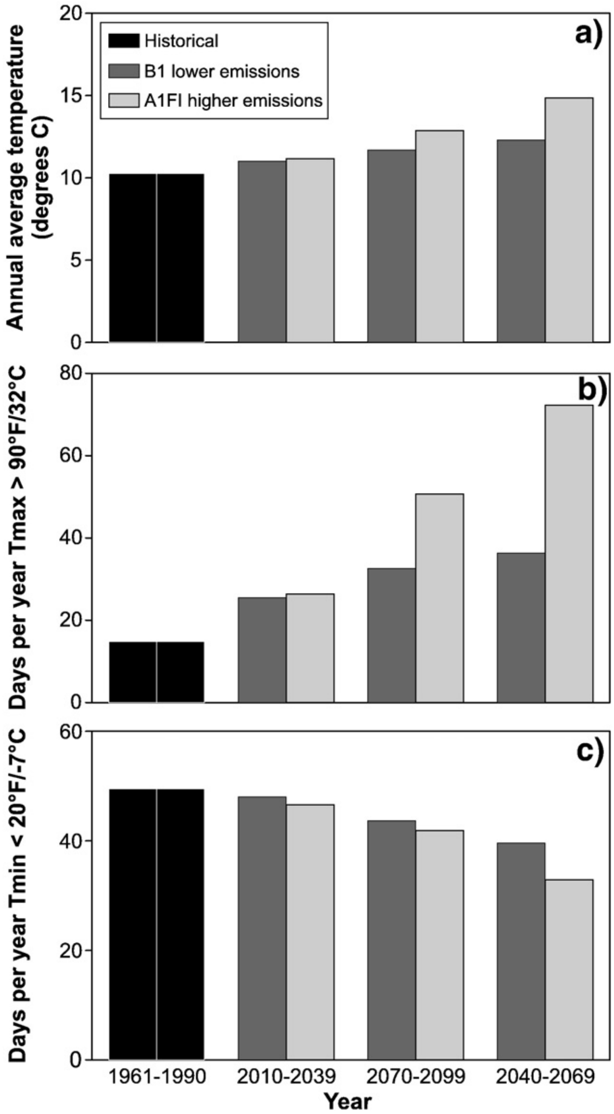


**Fig. 6.** Projected changes in the three primary climate drivers of the infrastructure and economic impacts of climate change on Chicago: (a) average annual temperature, (b) number of days per year with maximum temperatures greater than 90 °F/32 °C, and (c) number of days per year with minimum temperature below 20 °F/−7 °C. Values are shown for SRES A1FI higher and B1 lower emission scenarios as simulated by the three AOGCMs used in this analysis.

*Summary of climate change impacts on the city's economy*

The economic analysis identified some areas of potential revenue increases under climate change, such an increase in park and beach revenues due to an extended summer season. Certain departments, such as the Department of Streets and Sanitation and the Metropolitan

[1] It is important to note the impacts identified are for Chicago public buildings only; it is estimated Chicago public buildings make up less than 10% of the total commercial buildings in Chicago.

Water Reclamation District (MWRD), are projected to experience both significant costs and savings under climate change that virtually cancel each other out. For Streets and Sanitation, a relatively small net economic cost under higher emissions scenario represents the sum of two larger gross economic impacts that offset each other, namely the costs from increased tree replacement and the savings from reduced snow removal. For the MWRD, a decrease in precipitation lowers the cost of pumping as well as general operations, because sewers contain less rainwater during drier seasons. MWRD is projected to save money until the end of century (2070–2099) when precipitation is projected to increase above today's levels.

The overwhelming majority of the impacts, however, imply increased costs for the city. Furthermore, the majority of these costs are estimated to be due to increases in average temperatures, a projection with relatively high scientific certainty. Under both higher and lower future emissions scenarios, the Departments of Revenue (DOR) and Transportation (CDOT) and the CTA in particular are all projected to experience significant economic costs. A majority of these costs are attributable to increases in average temperature: DOR costs are driven by a large decrease in utility tax revenue; CDOT and CTA impacts are driven by increased maintenance costs. The Park District is projected to incur the most significant economic costs of any department under the higher emissions scenario but greatly reduced costs under the lower emissions scenario. This is due to the necessity of retrofitting buildings to accommodate the increased number of heat days occurring under the higher emissions scenario.

To determine the primary reason for projected costs to the 14 city departments that indicated the potential for climate-related costs, we broadly categorize the costs as being due to maintenance, energy demand, and labor, capital investments and local government revenue (Fig. 7). Maintenance costs are driven by two primary causes: average temperature and average precipitation. Average temperature increases over time and drives maintenance costs higher. Conversely, average precipitation falls and reduces cost until end of century when it rises. A key cause of maintenance savings in the near century is reduced pumping costs for the MWRD due to lower precipitation. Energy demand costs and savings include heating and cooling buildings, utility tax revenue, and fuel tax revenues for aviation.

Energy demand is unique in that it does not follow a specific trend and is not affiliated with mostly costs or savings. In some situations, departments use more energy as it gets hotter (i.e. cooling retrofitted buildings). In other instances, a department's taxation of energy usage is the driver (fuel taxes rise with temperature but overall utility tax falls).

In contrast, labor costs are primarily driven by the projected increase in extreme-heat days (defined as days >32 °C/90 °F in most cases). Examples of increased labor costs include absenteeism, overtime due to more fire runs, and responses to emergency situation by police. Capital investments are driven by increases in extreme-heat days for the most part. A smaller contributor to these expenditures is average temperature increase. Capital investments are made when a pre-defined climate threshold is reached (i.e. cooling needs to be installed when the current number of extreme-heat days triples). Examples of capital investments include building a new irrigation system, retrofitting facilities with cooling capability, and replacing vehicles more often.

## Conclusions and Further Discussion

The economic modeling framework developed here provides a comprehensive evaluation of potential economic impacts on Chicago City departments. As described above, the economic analysis was limited to the city's internal operations, budgets and capital investment needs, while the electricity load analysis was applicable to all residential, commercial and industrial electricity consumers in the metropolitan area.

Future increases in average temperature and extreme heat demand drive rises in both average annual electricity demand, inferred from cooling degree-days, and peak electricity demand, calculated from three-hour temperature projections. Both indicators suggest significant increases in summer electricity demand that are greater under higher emissions as compared to lower, and by end of century as compared to the near future. These projections also suggest the potential for summer electricity shortages by the end of this century, as increasingly frequent extreme-heat events are superimposed over a growing base-level demand. Estimates of projected increases in base-level summer electricity demand are likely on the conservative side, as they do not take into account potential increases in market saturation of air conditioning, currently at relatively low levels for older Chicago residences and retail buildings which make up the greatest proportion of city structures (Table 3). In the opposite direction, results from the economic analysis also indicate that warmer winters will lower heating requirements, reducing demand for other energy sources such as natural gas or heating oil.

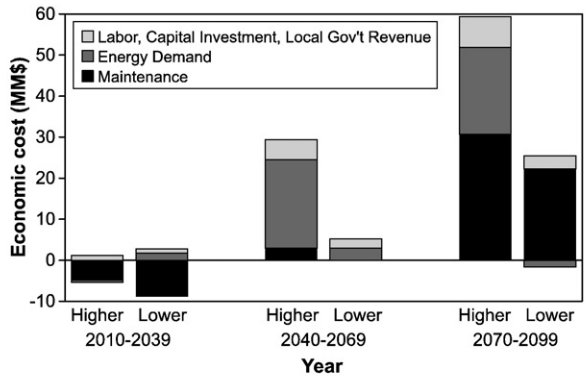


**Fig. 7.** Distribution of economic impacts of climate change on the city of Chicago by category: increased maintenance costs, capital investment required, or increased labor costs. Projected costs are shown for the average of three AOGCMs for the A1FI higher and B1 lower emissions scenarios for three future time periods: near-term (2010–2039), mid-century (2040–2069), and end of century (2070–2099).

Although economic impacts are driven by a variety of climate indicators, as summarized in Table 2, the greatest proportion of economic costs relate to capital investments and labor (Fig. 7). In order of descending importance, we find the majority of the economic costs of climate change for the city to be driven by the following three climate indicators:

1. *Increases in average temperature.* City departments most affected by average temperature increases, particularly under higher emissions, include the Department of Revenue, which currently experiences an inverse relationship between temperature and utility tax revenue, and Department of Transportation, which incurs much greater maintenance costs at higher temperatures.
2. *Increases in* extreme-heat *days (including days over 32 °C/90 °F).* The Chicago Park District was found to be most sensitive to projected increases in extreme-heat days, particularly under higher emissions. This was due to capital expenditures required to retrofit facilities with cooling after a certain frequency of temperature extremes become commonplace. The second highest cost was estimated for the Fire Department, which will have to respond to more fires induced by extreme-heat days.
3. *Decreases in extreme cold days (including days below -7 °C/20 °F).* This results in considerable savings in energy heating costs for the CTA, Chicago Public Schools and other city departments with large heating costs.

In general, however, as temperatures and the frequency of extreme precipitation rise, so do the economic costs. These costs will be offset only in a small part by savings due to warmer winters. The cost and savings estimates summarized here highlight the compelling economic

**Table 3**
Estimated market penetration of air conditioning in Chicago's residential and commercial buildings (from Konopacki and Akbari, 2002).

| Structure type (Roof Area in Cubic Meters) | Proportion of Total Roof Area | Proportion of Structures with Central Air Conditioning |
|---|---|---|
| *Residences ($1.56 \times 10^8$)* | | |
| Pre-1980 | 85% | 39% |
| Post-1980 | 15% | 84% |
| *Office buildings ($1.16 \times 10^7$)* | | |
| Pre-1980 | 75% | 95% |
| Post-1980 | 25% | 100% |
| *Retail buildings ($1.77 \times 10^7$)* | | |
| Pre-1980 | 69% | 63% |
| Post-1980 | 31% | 69% |

advantage to pursuing activities that lead to a lower rather than a higher emissions scenario.

This economic analysis represents only the costs of climate change for areas under direct City control. This analysis does not include non-City business concerns or specific resident costs. In addition, we believe the impact estimates are conservative due to the varied depth of departmental knowledge on a number of cost factors. Conservative net costs for City-controlled elements alone are almost four times higher under the higher emissions scenario ($2.54B) than under the lower emissions scenario. The significant difference in impact indicates that there is a convincing benefit to pursuing activities that reduce Chicago's average temperatures and lead to a lower emissions scenario. Even partial success in minimizing climate effects would significant reduce the large negative costs of climate change for all Chicagoans.

Conservation programs and adoption of more efficient cooling technology, as proposed by analyses of heat island reduction strategies (e.g., Akbari and Konopacki, 2005), can decrease both the economic costs and infrastructure and energy impacts projected from increases in average temperatures. Two of the five strategies proposed by the Chicago Climate Action Plan[2] (also summarized by McGraw et al., 2010) specifically address these needs. Under the Energy Efficient Buildings Strategy, the City intends to retrofit fifty percent of its residential, commercial and industrial building stock; require all building renovations to meet green standards; update Chicago's Energy Conservation Code to align with the latest international standards; and initiate a cooling program with the goal of planting 1 million additional trees and increasing rooftop gardens to a total of 6,000 buildings citywide by 2020. Under Adaptation Strategies, the City proposes to complete further research into urban heat island effect; pursue ways to cool hot spots and introduce innovative cooling ideas; implement the City's Green Urban Design plan which includes ways to reduce temperatures on extreme-heat days; and help individuals and businesses within the city take their own actions, including improving their energy efficiency and implementing green landscaping and passive cooling options.

As indicated by this analysis, adaptation can play an important role in mitigating projected future impacts, particularly under lower emissions and over the near term. For example, the Department of Transportation proposed two different options related to future road and highway repair. One assumed continued use of standard asphalt and concrete, the other assumed a switch to adaptive materials once roads needed replacement. For the overall picture, the first option was chosen since it yielded a lower cost to the department. However, the second option would be considered a forward-looking mitigation strategy and is not a component of the 'business as usual' view (though should be considered for adaptation options).

[2] http://www.chicagoclimateaction.org.

It has been noted by CDOT that this higher cost is not caused by more costly raw materials, but rather by the lower economies of scale of producing adaptive materials due to lower demand worldwide. Today, the adaptive option for road maintenance is 2.2 times more costly. However, there is a strong possibility of adaptive material prices falling in the future due to increased demand resulting in more production. To make the adaptive option financially equal to the option modeled, adaptive material prices would have to fall by 22% from current levels. Additionally, adaptive materials for roads have been identified to help with heavy precipitation given their permeable qualities. This will likely not be a significant factor in the near term given projected decreases in precipitation over the next 60 years. However, this issue is expected to become important once precipitation begins to increase in the end of century.

It is important to note, however, that there are limits to adaptation. Many common energy-savings strategies for cooling (e.g. passive strategies such as natural ventilation, night cooling, etc.) are most effective during Chicago's spring and autumn seasons, not at the peak of summer heat. More frequent extreme summer heat events will further reduce the hours that these strategies are useful. Moreover, these strategies do not significantly reduce peak demand, when traditional air conditioning is typically required. To this end, both utility-scale and building-scale cooling strategies need to be considered that avoid heat rejection to the atmosphere, as proposed by Chicago's Climate Action Plan. Alternative cooling methods such as lake-source and ground-source cooling could also be considered, as both dramatically increase the energy efficiency of cooling while avoiding even further increase of local ambient temperatures during peak cooling events. Although there are many building-scale examples of ground-source cooling, there are not any current examples of lake-source cooling, although the possibility of using this approach for the city of Toronto, situated at a similar latitude to Chicago beside a Great Lake, has been explored for some time (e.g., Boyce et al., 1993). This approach in particular is most effective as a utility-scale solution.

Ultimately, however, these estimates of the projected impacts of climate change on Chicago's energy, infrastructure, and economy beg the development of both proactive, preventative solutions through reducing or mitigating emissions, as well as anticipatory reactive responses by the City that will prepare its citizens to adapt to future change. To that end, this analysis was directed toward assisting city leadership in developing effective adaptation plans for adjusting to climate change-related effects on the city, and assessing the savings to the city of implementing mitigation plans for reducing the city's overall greenhouse gas emissions. The value of these informed plans can be quantified directly from the differences modeled in this study of the impacts and costs resulting from higher vs. lower future emissions.

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