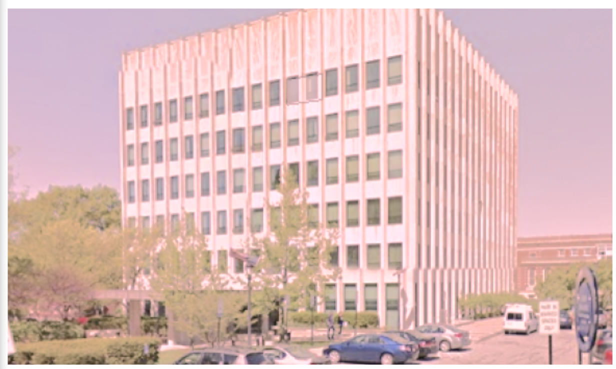
Mitigation and Adaptation Strategies for Public Health Impacts of Heatwaves for Town of Brookline, MA



Prepared by:

Sustainability and Data Sciences (SDS) Lab
Northeastern University

467 Snell Engineering Building, Northeastern University
360 Huntington Avenue, Boston, MA 02115

contacts:	Auroop Ganguly	a.ganguly@northeastern.edu
	Hanieh Hassanzadeh	h.hassanzadeh@norheastern.edu

Website: http://www.northeastern.edu/sds
Phone/Fax: (617) 373-3710 / 4419

Mitigation and Adaptation Strategies for Public Health Impacts of Heatwaves for Town of Brookline, MA

Sustainability and Data Science (SDS) Lab
Northeastern University

Babak J.Fard
Hanieh Hassanzadeh
Mary Elizabeth Warner
Udit Bhatia
Auroop Ganguly

November 2016

Table of Contents

Executive Summary

Global Climate change is no more a matter of doubt. More specifically, heatwaves are expected to increase in their frequency and intensity throughout the 21st century. Heatwaves are defined as prolonged periods of extraordinary hot temperatures that can cause health and high energy consumption problems for different regions. Moreover, the phenomenon of an Urban Heat Island (UHI) adds to the heatwave intensity in urban areas. The UHI effect is the increased temperature found in an urban area, compared to its surrounding rural areas, as a result of human activities and changes to surfaces materials.

Studies show that the mortality caused by heatwaves in developed cities is greater than the mortality from lightning strikes, rain, floods, hurricanes, and tornadoes combined. Therefore, this research has been conducted to address the impending heatwave problem in the Town of Brookline and to use a quantifiable framework that can help decision makers understand the current and probable future conditions.

For the purpose of this research the risk framework outlined by the Intergovernmental Panel on Climate Change (IPCC) is used to identify climate risks and development strategies. The intended use of the IPCC framework is to assess risks on a global scale. Therefore, it was adapted in order to accurately capture the regional effects of heatwaves on the Town of Brookline. The social factors that are correlated with the highest impact on health threats are used as vulnerability measures. Additionally, hazards are measured by the changes in Land Surface Temperature (LST), which is affected by climatic parameters and the UHI phenomenon. Exposure is quantified through the geographic location of vulnerable populations using census Block Groups (BG). Mitigation and adaptation strategies are suggested, emphasizing a modification of land and rooftop surfaces as a mitigation strategy and the accessibility of available public cooling centers as an adaptation strategy.

Census 2010 BGs are used to partition the city into different sectors. The latest data from American Community Survey (ACS) is used to evaluate various population characteristics and determine the composition of vulnerable populations in each BG. Based on a review of the literature and availability of data, the most vulnerable populations are those who live in poverty, are above the age of 65, live alone, have an education level below high school diploma, or those who identify as a race other than white.

Historic heatwave-related risk is evaluated for the BGs using census data and UHI calculations from available satellite imagery. This indicates the regions, and corresponding populations, that were at higher risks under heatwave conditions during the last three decades. To determine future conditions, a Regional Climate Model (RCM) with two emission scenarios is used. The results indicate that BGs that currently have higher levels of hazard will be reclassified as the highest hazard level by 2070.

Based on this information, adaptation and mitigation measures are considered. As a mitigation strategy, tree canopy cover is analyzed based on two scenarios: one that considers the potential for increasing tree canopy coverage throughout the entirety of Brookline, and one that accounts for the existing availability of open spaces changeable into tree canopy areas. It is determined that due to the unavailability of adequate open lands, increasing tree canopy coverage may not be sufficient. Therefore, the possibility of using green

or reflective roofs as another efficient mitigation policy is considered, specifically in parts of the town where open lands are scarce. It is suggested that this latter solution to be considered in further detailed research and decision making.

Cooling center availability is investigated as an adaptation strategy for the town. In its current state, 61.4% of all existing buildings are in a distance of less than half a mile to the nearest cooling center. It contains 24.7% closer than a quarter mile, and 36.7% between a quarter and half a mile. A risk to consider moving forward is the ability of a person over the age of 60 to access these cooling centers under severe heat conditions. In addition, the capacity of the cooling centers and their adequacy to accommodate high portions of vulnerable people is a matter to be considered for further study and planning.

The authors also suggest that the results from the current analysis should be incorporated with other available resources. Developing a Heatwave Action Plan (HAP) that is tailored to the specific situation of the town is a preliminary suggestion. The U.S. Environmental Protection Agency (EPA) and World Health Organization (WHO) have developed guidelines for implementing an HAP that can be tailored to the specific requirements of the Town of Brookline. It is suggested that the Town of Brookline incorporate the experiences from other cities that have employed these systems, and work with neighboring cities to enhance HAP effectiveness.

1. Introduction

Over the recent decades, casualties and economic losses due to extreme weather events have increased around the world. Specifically, heatwaves were responsible for a large number of lives lost. For instance, in the United States, the loss of human life as a result of hot spells in summer exceeds that caused by all other weather events combined, including lightning, floods, hurricanes, and tornadoes (Klinenberg 2015). About 6,200 Americans on average are hospitalized each summer due to excessive heat, and those at highest risk are poor, uninsured, or elderly (Agency for Healthcare Research and Quality 2008).

Different urban design parameters within the cities increase the likelihood of higher temperatures as compared to rural neighborhoods. This phenomenon is known as the Urban Heat Island (UHI) effect (Grimm et al. 2008), and its mechanisms are well-documented (Rizwan et al. 2008). This effect indicates that the downtown region of a city experiences higher vulnerability than its rural regions, which impacts exposure to temperature extremes (Reid et al. 2009). One of the approaches to quantify UHI is by using remote sensing data in the format of digital numbers or GeoTiff images (Hu and Brunsell 2015). Research based on the analyses of ensemble simulations from a global earth system model show upward warming and more severe heatwaves combined with larger regional variability and greater uncertainty in 21st century (Ganguly et al. 2009). Due to combination of future climate change and increasing urbanization (Stewart and Oke 2012; Stone 2007; Mishra et al. 2015), the impact of heatwave on the mortality rates are expected to grow. For example, mortality rate by heatwaves in NYC is predicted to increase five times by 2080, considering the acclimatization factor (Petkova et al. 2016). This factor considers the adaptation of human body to the higher temperatures in the future.

In a research on the three northeastern US cities of NYC, Boston, and Philadelphia, the change in mortality by heatwaves is estimated to continue to increase over the 2020s, 2050s, and 2080s. Table 1 shows the mortality rates for Boston, Massachusetts throughout these intervals as a result of two climate change scenarios (Petkova et al. 2013). The data from Table 1 is extracted and summarized, due to the proximity of Boston to the Town of Brookline and the high possibility for similar conditions. The climate change scenarios are explained in section 3.2.

Different heatwave related studies have been conducted for different cities in the US and around the world, containing studies on the cities of Boston and Cambridge in Massachusetts. (City of Cambridge 2015; Coutts et al. 2015). Coutts et. al 2015 published a report about mitigation strategies for UHI in the City of Boston. They considered vegetation, and pavement improvements as potential green infrastructure mitigation strategies, and described the benefits of these solutions and related considerations for each case. They also included suggestions for community engagement in implementing green infrastructure strategies. The report then concluded with city wide recommendations and conclusions. Adler et. al 2010 published a report in 2010 based on a study on Boston heatwave preparation measures and vulnerability analysis. It focused on studying the Boston heatwave plan and realized that the city suffered from the lack of a comprehensive plan.

	RCP4.5			RCP8.5		
	2020s	2050s	2080s	2020s	2050s	2080s
Median	5.9 (28.7)	8.8 (29.9)	10.5 (30.1)	6.5 (28.7)	11.7 (30.0)	19.3 (32.4)
Mean	6.03 (28.4)	8.85 (29.6)	10.51 (29.9)	6.32 (28.5)	11.78 (29.9)	20.04 (32.2)
Sd	1.07 (3.4)	2.10 (3.6)	2.94 (3.5)	0.88 (3.5)	2.81 (3.6)	5.66 (3.6)

Table 1. Mortality per 100,000 population (90th percentile of temperature from Regional Climate Models). The baseline period of 1985-2006 contains 2.9 deaths (Petkova et al. 2013)Some resources for planning purposes were suggested, and the report concluded with short-term policy recommendations, and short and long-term cooling recommendations. City of Cambridge 2015 provided a step by step method to calculate emissivity and Land Surface Temperature (LST) from satellite data, and calculated Heat Index (HI) values for different parts of the city. The cooling impact of tree canopies, as a very effective vegetation strategy for mitigating UHI, was calculated for different parts of the city

This report first focuses on analyzing the influence of temperature extremes with respect to the current state of the Town of Brookline and concentrates on the impact of these extremes to public health. A Risk Framework- with hazards, vulnerability, and exposure measures as its central components (Crichton 1999) - is used to understand the susceptibility of different regions within the Town of Brookline to heatwaves. The same model has been used in similar studies (Tomlinson et al. 2011; Buscail et al. 2012). The goal is to assess the vulnerability and hazard intensity in different parts of the town for the purpose of preliminary prioritizing and decision making. In the next sections of this report a regional climate model considering different climate change scenarios is used to quantify probable future conditions of heatwaves in the town. Then, analyses for a mitigation and an adaptation measure assessment are performed. For mitigation, increasing the tree canopy percentage is considered and investigated. To conduct an analysis of available adaptation strategies, the accessibility to the available cooling centers is assessed.

2. Data and Methods

2.1. Data

The acquisition of data for this project is based on the requirements of Risk Framework (Figure 1) as suggested by (Crichton 1999) and IPCC special report on *Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation* (SREX) (IPCC 2012). Appendix A introduces SREX risk framework and an urban scale adaptation from it, developed for this study. The three factors of vulnerability, exposure, and hazard are required to be calculated. To compute the vulnerability and exposure, data from Census 2010 (United States Census Bureau/American FactFinder. 2016a) and American Community Survey (ACS)[1] (United States Census Bureau/American FactFinder. 2016b) are acquired. The data considered for the vulnerability and exposure factors are as follow, the percentage of population under poverty level, the percentage of population above 65, the percentage of population above 65 and living alone, the percentage of population with education below high school diploma, the percentage of households with single occupant,

[1] http://www.census.gov/2010census/data/

and the percentage of population in races other than white (Reid et al. 2009).

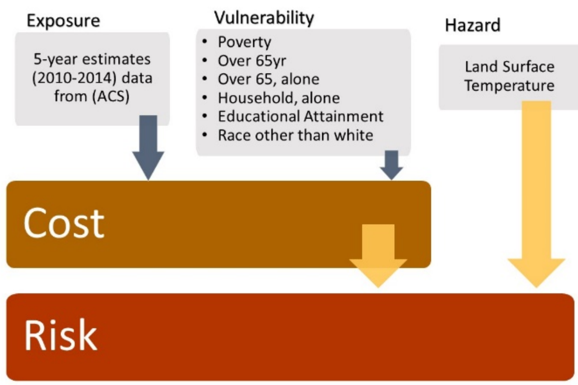


Figure 1. The Risk framework adapted for this study (Crichton 1999).

Considering the size and population of Brookline (area of about 6.83 mi^2 and total population of about 59,000), census Block Group (BG) is considered as the spatial unit of calculation for the purpose of this study. A BG usually contains a population in the range of 600 to 3,000 individuals. Brookline contains 38 BGs. The data gathered by the weather station at Logan International Airport, and processed by the *National Climate Data Center (NCDC)* is used to capture the heatwave periods, which constitutes the hazard layer. The dataset covers daily air surface temperature data for the period of 1964 to 2016. To predict the future changes, daily values of maximum surface air temperature, from *Bias Corrected and Downscaled WCRP* CMIP3[2] Climate Projections archive (Maurer et al. 2007) are used. This is based on the fact that surface air temperature and ground surface temperature, although not equal, are expected to follow similar patterns (Arnfield 2003). WCRP contains downscaled model of ⅛ degree grids for North America. For the purpose of this work, the nearest grid point to the Town of Brookline, located 5.3 km (3.29 mi) east of the town, is considered, and its temperature time series data is acquired. For temperature changes, the parameter of surface temperature is considered as the main defining factor for modeling and measuring UHI (Tomlinson et al. 2011; Cheval and Dumitrescu 2008; Buscail et al. 2012). Remote sensing images from *Landsat 7 Enhanced Thematic Mapper Plus (ETM+)* are acquired for a day in a heatwave period to estimate the LST values for different places in Brookline (Appendix B).

To calculate the vegetation effect in reducing temperature, four datasets are required. Two sets of data - LST and *The Normalized Difference Vegetation Index (NDVI)* - are acquired from the remote sensing images and the calculations are described in the methods section and in Appendix B. Land cover types, tree canopy percentage, and percentage of developed imperviousness (Xian et al. 2011) are obtained from National Land Cover Database (NLCD) 2011 (Homer et al. 2015). Tree canopy is defined as the ratio of the area covered by vertical projections of tree canopies, and is available throughout the USA as values between 0 and 100% in 30 m by 30 m grids (Coulston et al. 2012). Elevation is extracted from the Light Detection and Ranging (LiDAR) raster map covering Brookline (Reutebuch et al. 2005) and transformed into 30 m by 30 m resolution for the calculations.

To calculate the roof outline areas in each BG, two-dimensional roof outline map provided by MassGIS is utilized. It contains orthoimagery of roof outlines for all buildings larger than 150 square-feet. These areas are calculated to evaluate the efficiency of roof improvement methods as a mitigation strategy. These methods are generally categorized as green roofs and reflective roofs solutions. Green roofs use

[2] World Climate Research Programme's (WCRP's) Coupled Model Intercomparison Project phase 3 (CMIP3) multi-model dataset

vegetation on roof tops to bring down the temperature of close by areas through evapotranspiration mechanism. They may be as simple as thin layers of vegetation, or as complex as a full garden with trees (Madre et al. 2013). Reflective roofs use different methods to create lighter colored and more reflective surfaces, therefore increasing emissivity and bringing down the temperature of close by areas (Scherba et al. 2011).

2.2. Methods

The vulnerability and exposure maps are created directly from gathered data using GIS tools. Reid et al. 2009 states that one can expect differences in the level of contribution of each factor in vulnerability calculation for different regions and among local and regional models. For the current work, equal weights for the six considered factors are assigned, as done by (Tomlinson et al. 2011; Buscail et al. 2012).

There are different definitions for a heatwave (Smith et al. 2013). For the study of historical heatwaves one of the commonly used criteria is considered, which is "three or more consecutive days with maximum temperature of 90 degrees Fahrenheit, or higher". This definition is applied to the daily acquired data from NCDO (1985-2014) to distinguish the heatwave periods during this timeframe. Landsat data groups provide high spatial, low temporal resolution remote sensing data. This data is collected every 16 days for each geographical part of the world in 30 m by 30 m resolution. The heatwave periods calculated from CDO database are compared with the available remote sensing images of the study area. June 27, 2007 was selected as the most recent available period during which a heatwave occurred and remote sensing data was available through Web-Enabled Landsat Data (WELD) system (Roy et al. 2010). The remote sensing data for this day is used in UHI calculation (Appendix B). Finally, the hazard layer is calculated by averaging LST values over each BG and categorizing them in different levels of severity. The next step contains calculating the risk map, as shown in Figure 1, by multiplying the values in the two layers of vulnerability/exposure and hazard, and classifying the results.

For the study of future heatwaves, the 95th percentiles for the summer maximum surface air temperatures from WCRP model for the study periods (2035-2064 and 2055-2084) are used as the threshold values. The main reason for contemplating a percentile rather than a fixed value is to consider the effect of the acclimatization (the human adaptation to higher temperatures). Additionally, here the 95th percentile is preferred over three consecutive hot days threshold- used for observed values - to avoid the high uncertainty associated with the second method applied for predicted values.

Several researches show that the UHI pattern will not change by changes in climate, but are affected by changes in land cover/ land use (Richter 2015; Brazel et al. 1993). Therefore, calculating the changes in UHI patterns with a high accuracy is not possible, unless the detailed urban development plans for the future are available. In the absence of such detailed plans, UHI pattern is considered constant over time for the Town of Brookline. It means that the same urban configuration is considered for the future and equal increases in the calculated LSTs for different BGs are expected. These increased values are calculated from the changes in the heatwave temperature values between the historical value (June 27, 2007) and the calculated values for 2030s and 2070s.

Heatwave Action Plans (HPA) are developed for addressing different problems related to heatwaves. Those are based on some public guidance by different organizations and the experiences of the cities for which these systems are developed and used. A comprehensive HAP contains different parts such as Heat-Health Warning Systems (HHWS), educational plans, mitigation and adaptation strategies and more, which need to be customized for the unique conditions of each city (McGregor et al. 2015). To develop the customized HAP for the cities, several general and worldwide known guidelines are available, such as the "Excessive Heat Events Guidebook," by the U.S. Environmental Protection Agency (EPA). Strategies for dealing with heatwave conditions, such as warning systems, involvement of different organizations, and guidelines for establishing and facilitating access to cooling centers, are part of this guidebook. It considers four important elements for a heatwave action plan which includes risk assessment, mitigation strategies, predictor systems for heat events and response and notification systems. The World Health Organization (WHO) has developed a guideline for heatwave plans that outlines eight factors for an effective heatwave plan system and generally fall into the same categories as for a general HAP system.

This study conducts tree canopy analysis and cooling centers distance analysis for Brookline as mitigation and adaptation strategies respectively. In heatwave studies ambient temperature is used to estimate the effect of heatwaves on human health, and reducing it is a goal of heatwave mitigation plans. In the absence of recorded time series of ambient temperature, which is the case for this study, predictive methods are used to approximate it from other parameters for which enough data is available. This research uses a proposed method by (Kloog et al. 2014), which was also used for a mitigation study for the City of Cambridge, MA (City of Cambridge 2015). The details of this calculation is provided in Appendix C. In the next step, a relationship between the ambient temperature and tree canopy percentage is calculated by conducting regression analysis on these two variables in different parts of the town. This research then considers a scenario for using tree canopies to decrease the BG hazard level from the mean of highest LST group level to one level down. For this purpose, the worst case of LST increase in 2070s is considered, and calculations are performed - using the acquired relationship between tree canopy percentage and decrease in ambient temperature - to determine the required tree canopy percentage. In the next step, the calculated relationship between air temperature and tree canopy percentage is used to find the effect of increasing tree canopies in reducing ambient temperature. The potential areas for increasing tree canopy percentage are located using categorizations in NLCD Land Cover Database (Homer et al. 2015). These areas contain barren land, forest lands with different types of tree patterns and percentages, and grasslands. For these areas, the decrease in ambient temperature by increasing the tree canopy percentage to 100% is calculated.

As an adaptation metric, a cooling center distance analysis is done for two distances of a quarter and half a mile from the centers. These distances take 5 and 10 minutes, respectively, on average for an adult over 60 years to walk at a comfortable speed (Bohannon 1997). The ratio of the buildings that are within these distances are then calculated.

3. Results

3.1. Current Risk Levels

Figure 2 shows the six vulnerability factors for which data is extracted from Census in BG scale. For each factor the values are categorized into five different levels. Figure 2.a is the classification of poverty ratio for each BG.

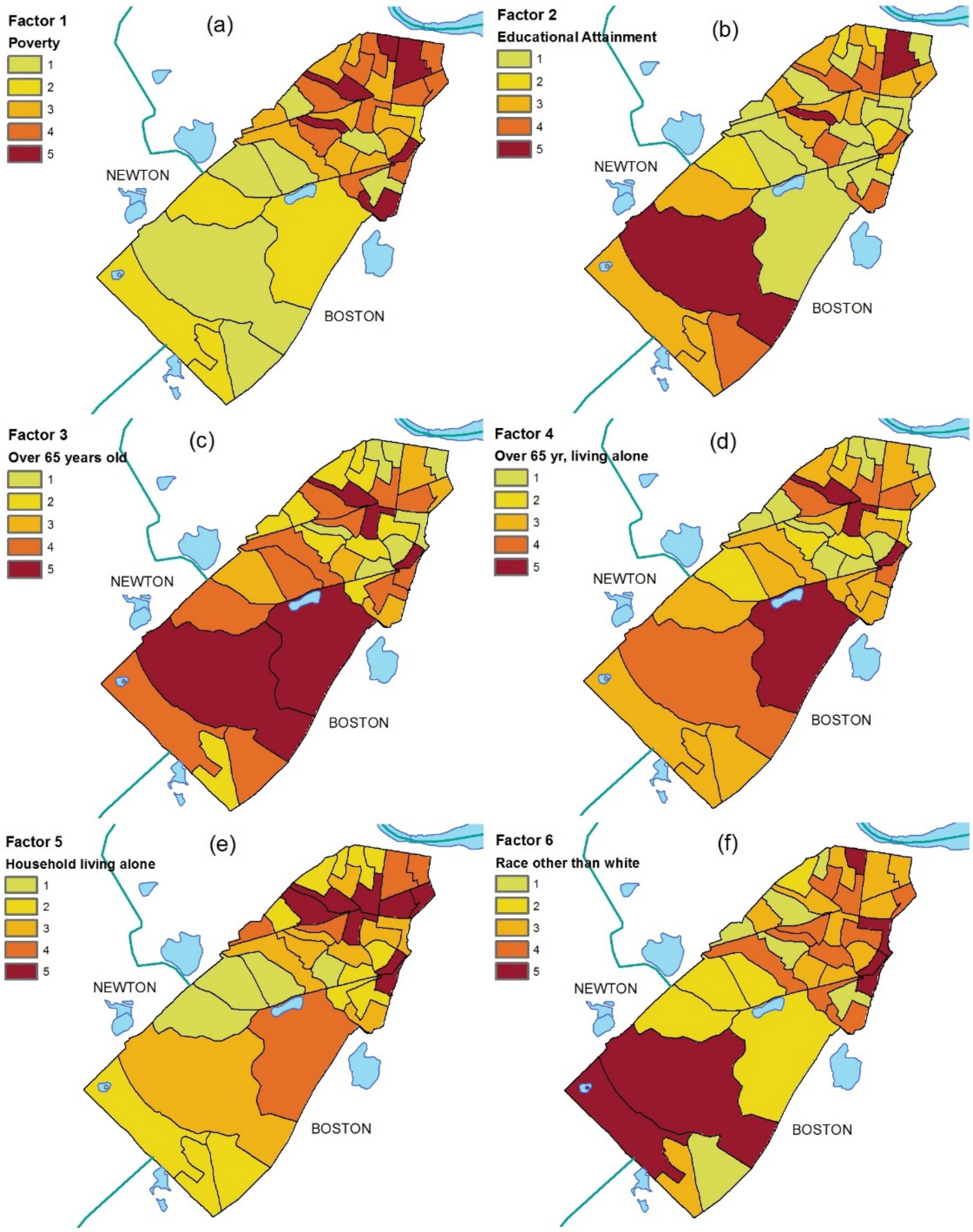


Figure 2. Vulnerability and exposure Layers. (a) poverty levels, (b) prevalence of people with below high school diploma, (c) percentage of people above 65 years old, (d) percentage of people over 65 years old, living alone, (e) percentage of households living alone, (f) race other than white. The data are leveled in 5 groups, 1 representing the lowest and 5 the highest vulnerability. Data are gathered from 2010-2014 ACS Estimates.

The line of poverty is defined by the Census Bureau (Short 2011). For the Town of Brookline the poverty level varies from 0% to 37% for the last 12 months of 2010-2014 ACS. Figure 2.b shows the population above 25 years old who have an education below high school diploma. The range varies from 0% in about one-third of BGs to maximum of 6% - 9% in the remaining BGs. Figure 2.c depicts the percentage of population over 65. This varies from 4% at the lowest to the highest value of 33.5% of the population in the BGs. Living alone makes this already vulnerable population even more vulnerable. This fact is considered by adding a layer for the percentage of population over 65 years old who live alone, and shown in Figure 2.d. Class 1 of this layer represents 2% to 4.5% of the population, and Class 5 corresponds to the range of 16% to 30% of population. The percentage of households who live alone is captured in Figure 2.e, with the lowest value of 12% to 17% of all households, and the highest of 41% to 59% of households. Finally, the population of races other than white is considered as another vulnerability layer for this work. It varies from 6% at lowest to 53% in the highest classification for the BGs of Brookline. A composition of all vulnerability factors is used to create an overall vulnerability index, which is shown in Figure 3.

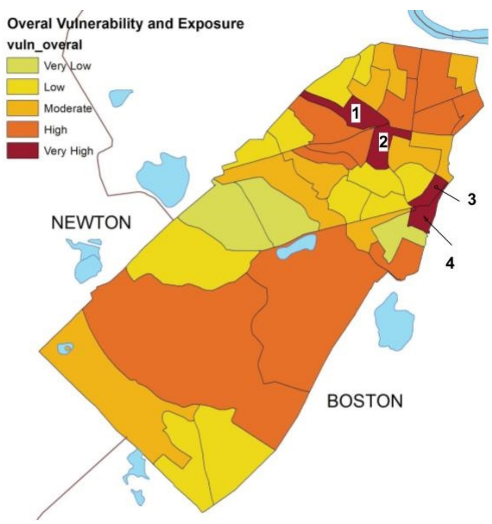


Figure 3. Overall Vulnerability and Exposure layer. This is the result of the 6 vulnerability/ exposure factors in Figure 2, considering equal weights for all of them.

Comparing Figures 1 and 2, we notice that the highest vulnerable regions (BGs 1 to 4 in Figure 3) correlate with the highest vulnerability in several individual vulnerability factors (Figure 2). BG number 3 has the highest rank in five of the six vulnerability factors (Figure 2), which makes it the most vulnerable area. BG 1 is the next most vulnerable area with four out of six factors in the highest vulnerability group. BG 2 has three factors out of six vulnerability factors at the highest rank, and BG 4 has two out of six factors in the highest vulnerability group. Figure 4 shows the calculated LST for Brookline on June 27, 2007.

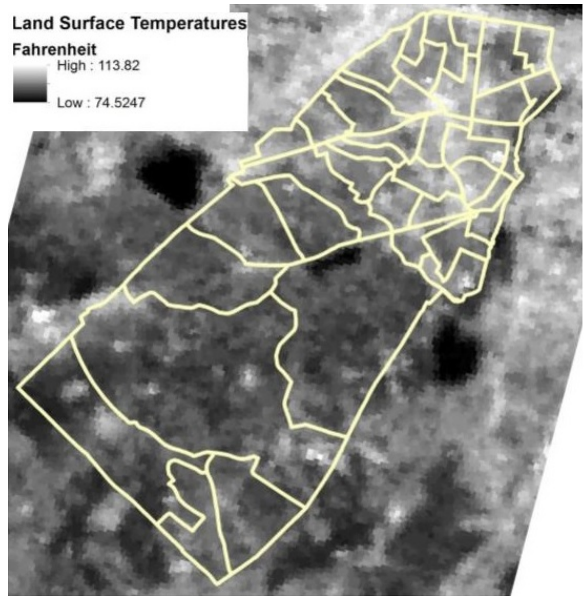


Figure 4. Digital map of the calculated LST for the day of June 27, 2007 for the town of Brookline and its vicinity. Values are in degrees of Fahrenheit. The resolution is 30x30 m^2.

As a representative of UHI, the average LST value for each BG is calculated and classified in five severity groups in Figure 5.

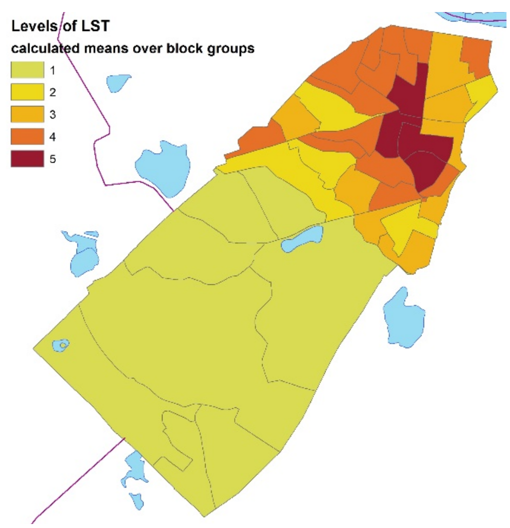


Figure 5. Hazard layer. The BGs are classified into five levels based on the average LST values. The values are calculated for each 30m by 30m rectangle, then averaged over each BG, and classified.

This is then used as the hazard layer. Figure 5 shows a clear distinction between the least hazardous areas in the southern part of the town, where more open green spaces are available, and the hazardous BGs in the north, with denser buildings and less vegetated areas. Figure 6 shows the calculated risk levels for the BGs. The BG with the very high level of risk is the one which also has the highest rate of vulnerability. The high risk BGs are all concentrated in the northern part of the town. This result could be expected from the vulnerability and hazard layers, which both have higher values in the north. Other BGs, however, do not seem to follow any specific pattern.

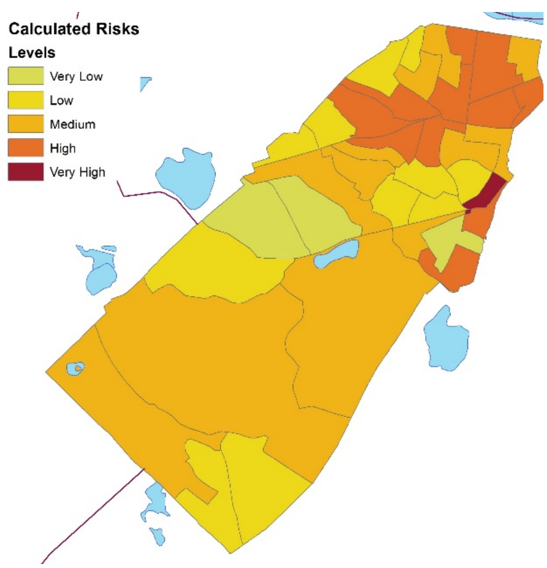


Figure 6. The final Risk map calculated for different census BGs. This is the result of the multiplication of the overall vulnerability/exposure and LST categorized values (Figures 3 and 5) for BGs.

3.2. Future Changes in Heatwave Temperature and Hazard Levels

Figure 7 shows the calculated heatwave values for two future timeframes, three climate change scenarios known as *Representative Concentration Pathways (RCP)* (Van Vuuren et al. 2011), and the historical heatwave threshold value for the grid point of study. RCPs are adopted by IPCC Fifth Assessment Report to model different possible climate change scenarios until 2100, using different greenhouse gas concentration scenarios. Three scenarios of RCP2.6, RCP4.5, and RCP8.5 available in WCRP dataset are used in this study. The numbers represent the radiative forcing values in year 2100 in comparison to pre-industrial values, in watts per square meter. For simplicity, and having a sense about these scenarios, they are named *Optimistic, Realistic, and Pessimistic* in this study (Figure 7).

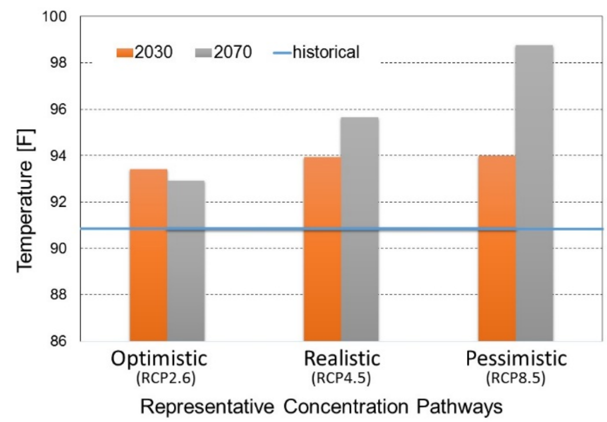


Figure 7. Change in the 95th quantiles of summer daily maximum temperature for different scenarios for the nearest grid point to Brookline. The historical value (1985-2015) is 90.86 Fahrenheit. Data from Bias Corrected and Downscaled WCRP CMIP3 Climate Projections archive (Maurer et al. 2007).

Figure 8 shows different levels of hazard for the optimistic and pessimistic scenarios. The differences between scenarios results and the historical value in Figure 7 are added to the LST values in Figure 5 to calculate the hazard levels in 2030 and 2070 based on the thresholds for current hazard levels. Prediction for 2070s shows 29 of total 38 BGs in highest level of hazard condition for the pessimistic scenario (Figure 5). This number is 14 BGs for the optimistic scenario.

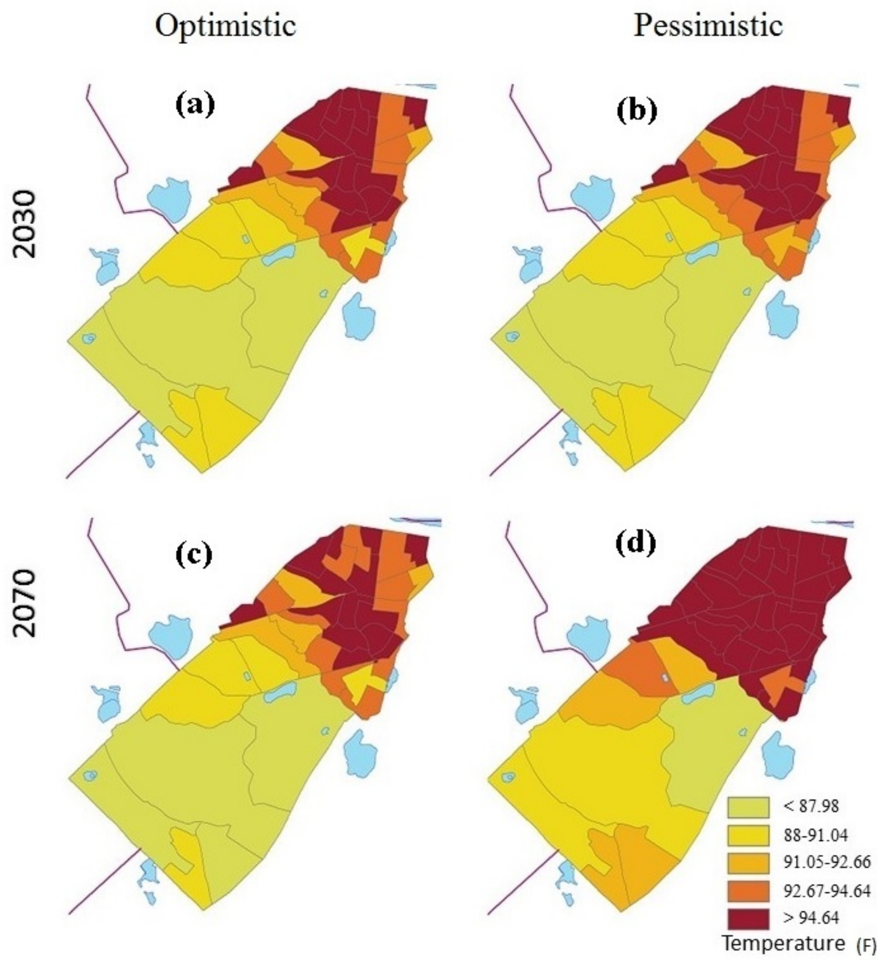


Figure 8. Changes in LST levels for the optimistic (Left side) and pessimistic (Right side) climate change scenarios for 2030s and 2070s.

3.3. Tree Canopy Analysis as a Mitigation Strategy

Figure 9 shows different independent variables used in calculating ambient temperatures, for which the details are provided in Appendix C. The left column of Figure 10 shows the calculated ambient temperature from the four mentioned parameters, and the right column shows the tree canopy percentage map. Figure 11 demonstrates the result of the regression analysis as described earlier. The pessimistic scenario of heatwave changes is considered (Figure 8.d) and calculations are performed to determine the required tree canopy coverage percentage in each BG to bring down the mean LST from above 94.64 Fahrenheit for the highest hazard areas to 93.74 Fahrenheit, which is the mean value of the second highest level (Figure 8). The computed tree canopy percentage - ambient temperature relationship is used for this purpose and the results are shown in Figure 12.

In the next step, the calculated equation is used to find the effect of increasing tree canopies, wherever possible. Figure 13.a shows the pixels for which increasing tree canopy to 100% is possible. The corresponding decrease in ambient temperature is then calculated for each pixel and the results are shown in Figure 13.b.

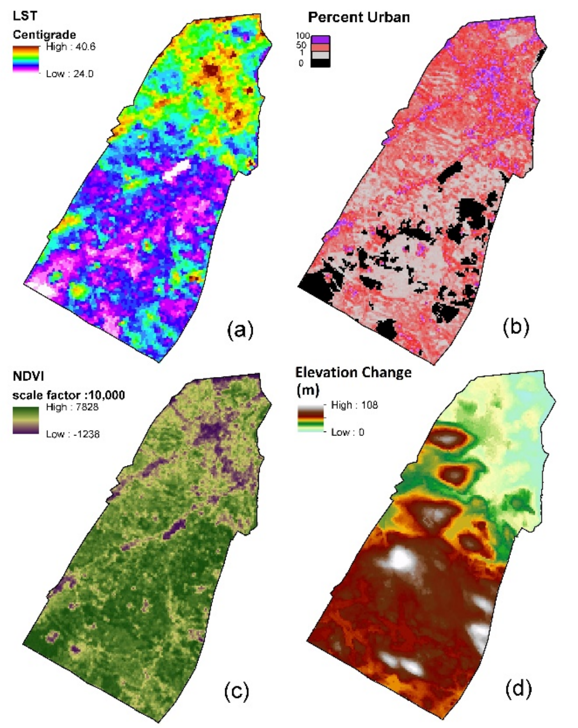


Figure 9. Maps of required parameters to calculate ambient temperatures in Brookline; (a) computed LST, as described earlier. (b) percent developed imperviousness, extracted from NLCD 2011, (c) NDVI extracted from WELD system, (d) elevation change extracted and resampled to 30x30 m^2 resolution from LiDAR system of Massachusetts.

The current average tree canopy for each BG is shown Figure 13.c. The tree canopy percentage varies from less than 1% in some higher risk and densely populated areas to 65% in less risky BGs.

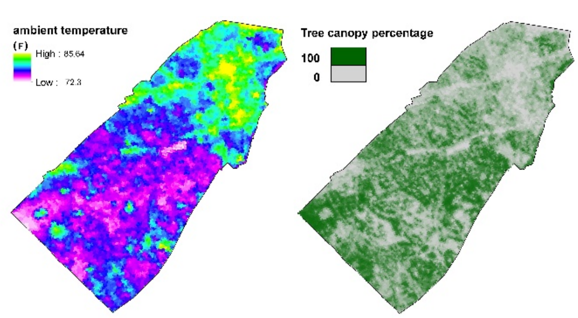


Figure 10. Left: Ambient air temperature, calculated from the four factors in figure 9. Right: tree canopy percentage. Both images are calibrated to the same resolution (30m by 30m) and the same gridding to do the regression.

Based on the development scenario in Figure 13.a, the average possible increase in tree canopy for each BG is calculated and shown in Figure 13.b.

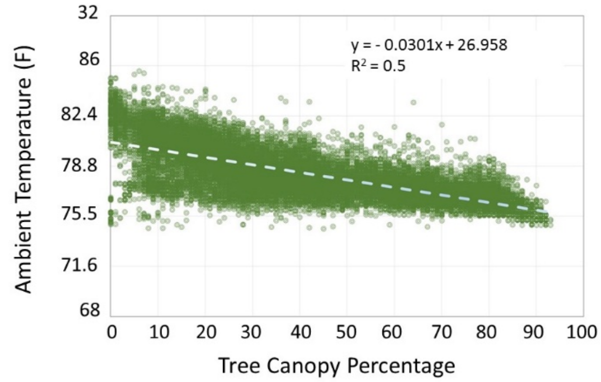


Figure 11. Regression analysis for the two series of data points in Figure 10. The spatial correlations among the neighboring points are not considered.

For many BGs the considered method and information does not allow for enough increase in canopies and the highest possible improvement in tree canopy coverage is about 5% of the area for the largest BG in the town, which already contains open spaces such as golf courses.

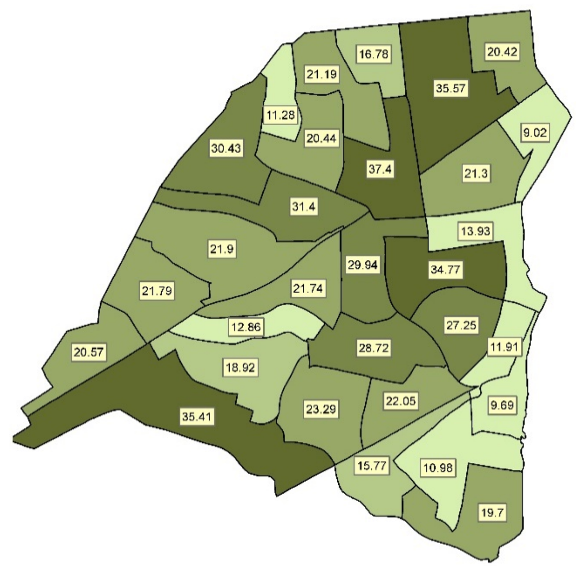


Figure 12. Required extra tree canopy area in Acres to be added in each BG in highest hazard level for 2070 (Figure 8.d). The goal is to reduce the predicted mean LST for these BGs to 93.65 Fahrenheit, the mean value of one hazard level lower than the highest in Figure 8.

Considering roof mitigation strategies as a potential solution for the parts where improving canopies is not possible, an estimation of the ratio of the roof outlines area to the total area of each BG is also provided (Figure 14).

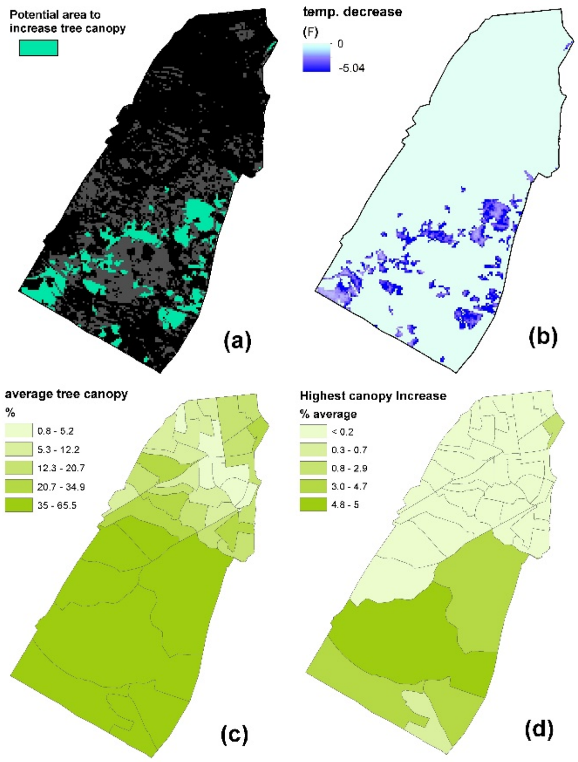


Figure 13. Effect of increasing tree canopy on ambient temperature; (a) areas which can be potentially developed to full tree canopy, (b) decrease in ambient temperature if the improvements in part "a" are done, current average of tree canopy by BG, (d) average of maximum possible canopy improvement.

3.4. Cooling Center Distance Analysis as an Adaptation Strategy

Figure 15 shows the result of buffer analysis for two distances from the public cooling centers. Calculations show that more than 61.4% of all mapped buildings are in a distance of less than half a mile to the nearest cooling center. It contains 24.7% closer than a quarter mile, and 36.7% between a quarter and half a mile. The remaining 39.6% of structures are in medium to very low hazard areas (Figure 5). In the case of the pessimistic scenario for the year 2070, the current cooling centers are in less than half a mile away from 82% of buildings contained in the highest levels of hazard (Figure 8). Figure 16 shows the MBTA bus routes and bus stops and the places of the public cooling centers. All cooling centers are close by to several bus stops which makes them accessible. However, an accurate adaptation plan should also consider whether the capacity of these centers is accountable for the future population growth.

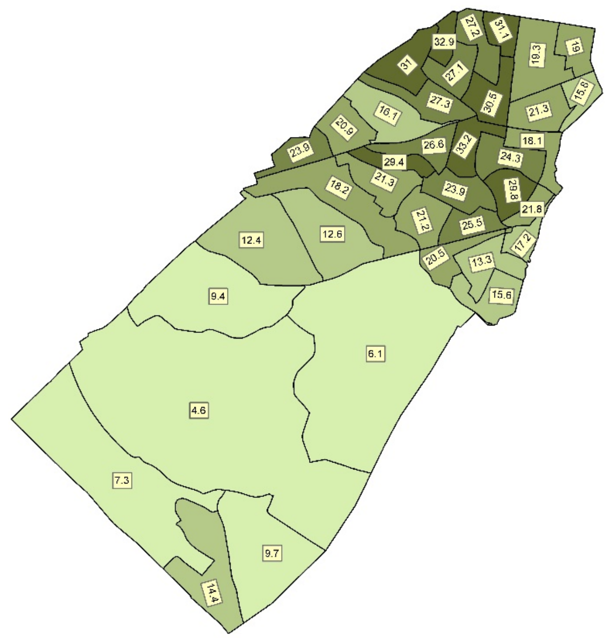


Figure 14. Roof percent analysis; Values show the percentage area in each BG occupied by rooftops. This analysis shows the best places which roof gardening or reflective roofs can have more effects in decreasing UHI. Data of roof outlines downloaded from MassGIS.

4. Conclusions

Heatwaves impose different threats on our life. In this study, we assess the spatial and temporal changes in heatwaves and their impact on the public health for the Town of Brookline in BG scale. We identify the BGs that need more attention with respect to their high vulnerabilities, and relate those vulnerable BGs to the hazard levels. Historical data is used to create a heat-health risk map for the BGs of Brookline and a Risk Framework is used to evaluate vulnerabilities, exposure, and hazard. The created vulnerability maps (Figure 2) compares the BGs in their different vulnerability measures. Among these factors, the poverty map has the most similar pattern to the UHI in Figure 5, as well as the risk map in Figure 6.

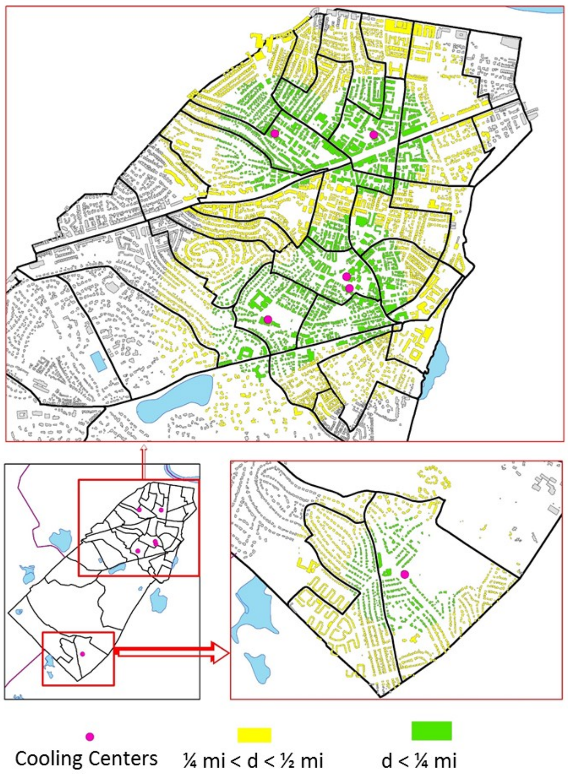


Figure 15. Cooling centers location analysis. The schematic map of the town shows the places of six public cooling centers, and the two zoomed in maps show the buffer analysis for less than a quarter mile (green structures), and less than half a mile distance to a cooling center. Studies show that for people over 60 it takes 5 and 10 min in average to walk these distances in a comfortable speed (Bohannon 1997), respectively. Five of these centers are in high risk areas of the town. The current centers provide less than half a mile distance to 80% of the buildings in high hazard areas.

A possible explanation is that, the higher the poverty, the smaller the sizes of living areas, and the denser the built environment. This results in having more surface areas with high imperviousness. The overall vulnerability and hazard maps can be used for the preliminary stages of policy and decision making and finding the priorities in the BG level. The resulted maps for future changes in LST (Figure 8) show that up to 70% of BGs can fall into highest hazard level by 2070, using the pessimistic emission scenario.

The results also show that the land surface temperature is higher over the areas with higher imperviousness due to urbanization. This expresses the link between land cover and the temperature increase.

As indicated, an accurate analysis for the current and future urban heatwaves must consider many different factors. The more complex the system, the higher levels of uncertainties are added to the calculations. For a study like this, a notable caveat in analyzing the future scenario is the unavailability of detailed urban development plans, which determined to be the most important factor in the creation and intensity of UHIs.

A comprehensive study of heatwave needs to incorporate different aspects of social, health and climate factors. In the current work the risk framework is used as a tool to deduct quantifiable assessment from the interaction of these distinct phenomena. A comprehensive solution should also consider the interdisciplinary nature of heatwave. HAP guidelines provide recommendations for implementing different adaptation and mitigation strategies. These systems and their attributes are introduced in part2.2. The tree canopy analysis outlined in this research is one of the mitigation strategies that can be applied for long term plans. The use of these guidelines and the outcomes of similarly implemented systems in other towns is a step for more research and to develop specific plans.

The roof outline percentage analysis shows considerable roof areas in higher hazard BGs with less available open spaces. Therefore as we conclude here, using roof improvement solutions – green roofs or reflective roofs – can be the subject of focused mitigation studies in the future and for different scenarios.

The lack of locally observed temperature data throughout the town increases the uncertainty both in distinguishing the heatwave periods, and in mitigation analyses (here the tree canopy analysis). Therefore, recording these data in different parts of the town is suggested for more accurate results for future studies. Additionally, conducting local surveys to update social vulnerability data in a required spatial scale is also helpful. The time intervals for such surveys depend on the time, budget, and resources provided by the town.

New and developing approaches towards sustainable urban design, different UHI analysis models, and potential changes in future Air Conditioning (AC) systems which will reduce the outdoor temperature increase effect of current ACs are samples of new approaches in addressing heatwave problems that need to be considered in any comprehensive and detailed study in the future.

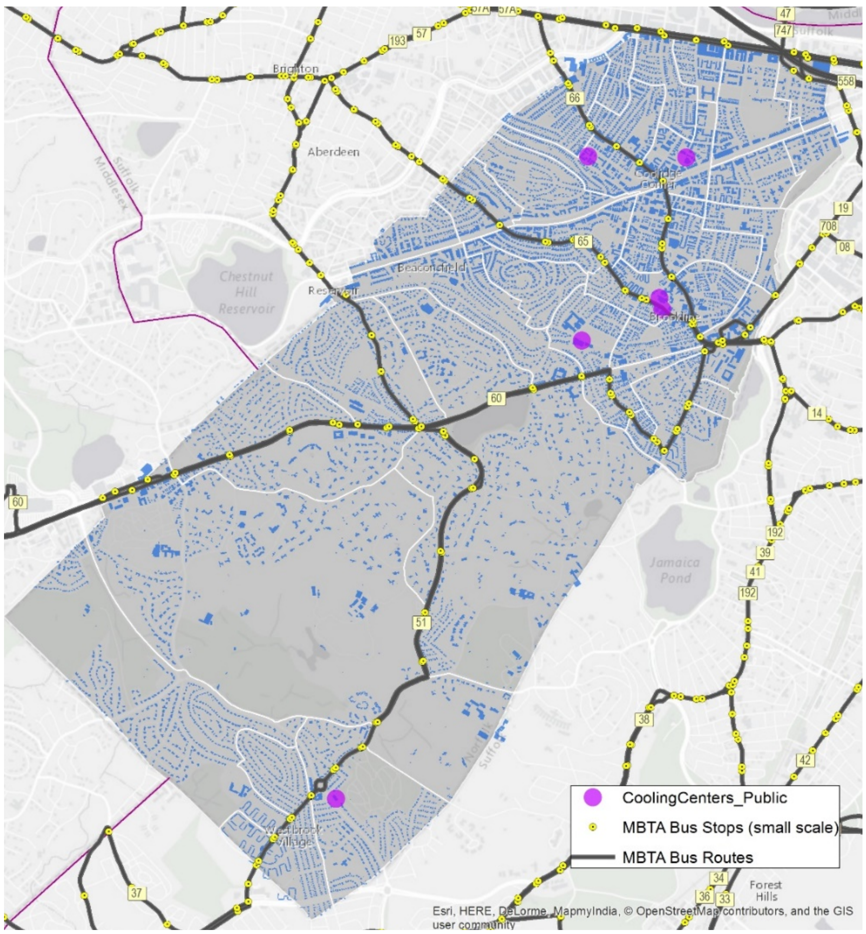


Figure 16. MBTA bus routes and bus stops throughout the Town of Brookline.

Acknowledgments

This project and community engagement was performed as part of broader impacts of multiple grants by the US National Science Foundation (NSF): NSF BIGDATA award # 1447587, Expeditions in Computing Award #1029711, and Cyber SEES award #1442728. The authors thank Bharat Sharma and Shashank Konduri, SDS lab members, for their comments and participation in various meetings of the project with officials of the town of Brookline. We acknowledge risQ Corporation (Northeastern startup) and its CEO, Evan Kodra, who was one of the original leads of the project. We gained lots of insight for this project from the Climate Ready Boston report commissioned by the Boston City Mayor's Office, and especially the work done by Auroop Ganguly and Evan Kodra on extreme temperatures. We also acknowledge the participation of the students of "Dialogue of Civilization to India 2016" program in a discussion on the initial problem definition. Our special thanks go to Francisco Franco Bulhões Mendes, for his work on heatwaves, which shared with us. Pictures of cover page are extracted from patch.com, www.chicagotribune.com, and www.businessinsider.com.

References

Adler, M., Harris, S., Krey, M., Plocinski, L., Rebecchi, J. 2010. "Preparing for heat waves in Boston – A cool way to attack global warming*." City of Boston Environmental Department & Tufts University Department of Urban and Environmental Policy and Planning*.

Agency for Healthcare Research and Quality (AHRQ). 2008. "Most People Struck Down by Summer Heat Are Poor." *Http://newswise.com/*. October 7. http://newswise.com/articles/most-people-struck-down-by-summer-heat-are-poor.

Arnfield, A. John. 2003. "Two Decades of Urban Climate Research: A Review of Turbulence, Exchanges of Energy and Water, and the Urban Heat Island." *International Journal of Climatology* 23 (1). John Wiley & Sons, Ltd.: 1–26.

Bohannon, R. W. 1997. "Comfortable and Maximum Walking Speed of Adults Aged 20-79 Years: Reference Values and Determinants." *Age and Ageing* 26 (1): 15–19.

Brazel, A., M. Hubble, and R. Lougeay. 1993. "Monitoring the Climatic Effects of Urbanization at Various Spatial Scales." *Conference on Applied Climatology.*

Buscail, Camille, Erika Upegui, and Jean-François Viel. 2012. "Mapping Heatwave Health Risk at the Community Level for Public Health Action." *International Journal of Health Geographics* 11 (September): 38.

Cheval, S., and A. Dumitrescu. 2008. "The July Urban Heat Island of Bucharest as Derived from Modis Images." *Theoretical and Applied Climatology* 96 (1-2). Springer Vienna: 145–53.

City of Cambridge, Kleinfelder, ed. 2015. "Appendix D." In *Climate Change Vulnerabililty Assdssment City of Cambridge, Massachussetts*. City of Cambridge.

Coulston, John W., Gretchen G. Moisen, Barry T. Wilson, Mark V. Finco, Warren B. Cohen, and C. Kenneth Brewer. 2012. "Modeling Percent Tree Canopy Cover: A Pilot Study." http://www.srs.fs.fed.us/pubs/ja/2012/ja_2012_coulston_001.pdf.

Coutts, E., Ito, K., Nardi, C., and Vuong, T. 2015. "Planning Urban Heat Island Mitigation in Boston." The Trust for Public Land.

Crichton, David. 1999. "The Risk Triangle." *Natural Disaster Management*. Tudor Rose, London, 102–3.

Ganguly, Auroop R., Karsten Steinhaeuser, David J. Erickson 3rd, Marcia Branstetter, Esther S. Parish, Nagendra Singh, John B. Drake, and Lawrence Buja. 2009. "Higher Trends but Larger Uncertainty and Geographic Variability in 21st Century Temperature and Heat Waves." *Proceedings of the National Academy of Sciences of the United States of America* 106 (37): 15555–59.

Grimm, Nancy B., Stanley H. Faeth, Nancy E. Golubiewski, Charles L. Redman, Jianguo Wu, Xuemei Bai, and John M. Briggs. 2008. "Global Change and the Ecology of Cities." *Science* 319 (5864): 756–60.

Homer, C. G., J. A. Dewitz, L. Yang, and S. Jin. 2015. "Completion of the 2011 National Land Cover Database for the Conterminous United States-Representing a Decade of Land Cover Change Information." *Photogrammetric Engineering and Remote Sensing*. researchgate.net. https://www.researchgate.net/profile/Limin_Yang5/publication/282254893_Completion_of_the_2011_National_Land_Cover_Database_for_the_Conterminous_United_States_-_Representing_a_Decade_of_Land_Cover_Change_Information/links/5693bbc808aeab58a9a2a661.pdf.

Hu, Leiqiu, and Nathaniel A. Brunsell. 2015. "A New Perspective to Assess the Urban Heat Island through Remotely Sensed Atmospheric Profiles." *Remote Sensing of Environment* 158 (March): 393–406.

IPCC. 2012. *"Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation".* A Special Report of Working Groups I and II of the Intergovernmental Panel on Climate Change [Field, C.B., V. Barros, T.F. Stocker, D. Qin, D.J. Dokken, K.L. Ebi, M.D. Mastrandrea, K.J. Mach, G.-K. Plattner, S.K. Allen, M. Tignor, and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, UK, and New York, NY, USA, 582 pp.

Klinenberg, E. 2015. *Heat Wave: A Social Autopsy of Disaster in Chicago*. University of Chicago Press.

Kloog, Itai, Francesco Nordio, Brent A. Coull, and Joel Schwartz. 2014. "Predicting Spatiotemporal Mean Air Temperature Using MODIS Satellite Surface Temperature Measurements across the Northeastern USA." *Remote Sensing of Environment* 150. Elsevier: 132–39.

Madre, Frédéric, Alan Vergnes, Nathalie Machon, and Philippe Clergeau. 2013. "A Comparison of 3 Types of Green Roof as Habitats for Arthropods." *Ecological Engineering* 57. Elsevier: 109–17.

Maurer, E. P., L. Brekke, and T. Pruitt. 2007. "Fine-resolution Climate Projections Enhance Regional Climate Change Impact Studies." *Eos, Transactions, American Geophysical Union* . Wiley Online Library. http://onlinelibrary.wiley.com/doi/10.1029/2007EO470006/full.

Mishra, Vimal, Auroop R. Ganguly, Bart Nijssen, and Dennis P. Lettenmaier. 2015. "Changes in Observed Climate

Extremes in Global Urban Areas." *Environmental Research Letters: ERL [Web Site]* 10 (2). IOP Publishing: 024005.

McGregor, G.R., Bessemoulin, P., Ebi, K., Menne, B. 2015. "Heatwaves and Health: Guidance on Warning-System Development*" World Meteorological Organization (WMO), WMO-No. 1142*

Petkova, Elisaveta P., Radley M. Horton, Daniel A. Bader, and Patrick L. Kinney. 2013. "Projected Heat-Related Mortality in the US Urban Northeast." *International Journal of Environmental Research and Public Health* 10 (12). Multidisciplinary Digital Publishing Institute: 6734–47.

Petkova, Elisaveta P., Jan K. Vink, Radley M. Horton, Antonio Gasparrini, Daniel A. Bader, Joe D. Francis, and Patrick L. Kinney. 2016. "Towards More Comprehensive Projections of Urban Heat-Related Mortality: Estimates for New York City under Multiple Population, Adaptation, and Climate Scenarios." *Environmental Health Perspectives*, June. doi:10.1289/EHP166.

Reid, Colleen E., Marie S. O'Neill, Carina J. Gronlund, Shannon J. Brines, Daniel G. Brown, Ana V. Diez-Roux, and Joel Schwartz. 2009. "Mapping Community Determinants of Heat Vulnerability." *Environmental Health Perspectives* 117 (11): 1730–36.

Reutebuch, Stephen E., Hans-Erik Andersen, and Robert J. McGaughey. 2005. "Light Detection and Ranging (LIDAR): An Emerging Tool for Multiple Resource Inventory." *Journal of Forestry* 103 (6). ingentaconnect.com: 286–92.

Richter, Michael. 2015. "Urban Climate Change-Related Effects on Extreme Heat Events in Rostock, Germany." *Urban Ecosystems* 19 (2). Springer US: 849–66.

Rizwan, Ahmed Memon, Leung Y. C. Dennis, and Chunho Liu. 2008. "A Review on the Generation, Determination and Mitigation of Urban Heat Island." *Journal of Environmental Sciences* 20 (1): 120–28.

Roy, David P., Junchang Ju, Kristi Kline, Pasquale L. Scaramuzza, Valeriy Kovalskyy, Matthew Hansen, Thomas R. Loveland, Eric Vermote, and Chunsun Zhang. 2010. "Web-Enabled Landsat Data (WELD): Landsat ETM+ Composited Mosaics of the Conterminous United States." *Remote Sensing of Environment* 114 (1): 35–49.

Scherba, Adam, David J. Sailor, Todd N. Rosenstiel, and Carl C. Wamser. 2011. "Modeling Impacts of Roof Reflectivity, Integrated Photovoltaic Panels and Green Roof Systems on Sensible Heat Flux into the Urban Environment." *Building and Environment* 46 (12). Elsevier: 2542–51.

Short, Kathleen. 2011. "The Research Supplemental Poverty Measure: 2010." *Current Population Reports*, no. P60-241. nber.org. http://www.nber.org/cps/pov/Short_ResearchSPM2011.pdf.

Smith, Tiffany T., Benjamin F. Zaitchik, and Julia M. Gohlke. 2013. "Heat Waves in the United States: Definitions, Patterns and Trends." *Climatic Change* 118 (3-4): 811–25.

Sobrino, J. A., N. Raissouni, and Zhao-Liang Li. 2001. "A Comparative Study of Land Surface Emissivity Retrieval from NOAA Data." *Remote Sensing of Environment* 75 (2): 256–66.

Stewart, I. D., and T. R. Oke. 2012. "Local Climate Zones for Urban Temperature Studies." *Bulletin of the American Meteorological Society* 93 (12). journals.ametsoc.org: 1879–1900.

Stone, Brian. 2007. "Urban and Rural Temperature Trends in Proximity to Large US Cities: 1951–2000." *International Journal of Climatology* 27 (13). John Wiley & Sons, Ltd.: 1801–7.

Tomlinson, Charlie J., Lee Chapman, John E. Thornes, and Christopher J. Baker. 2011. "Including the Urban Heat Island in Spatial Heat Health Risk Assessment Strategies: A Case Study for Birmingham, UK." *International Journal of Health Geographics* 10 (June): 42.

United States Census Bureau / American FactFinder. 2016a "P12 : Sex by Age." *2010 Census*.U.S. Census Bureau, 2010.Web. 1 January 2013 <http://factfinder2.census.gov>.

United States Census Bureau / American FactFinder. 2016b "B11001 : Household Type (Including Living Alone)." *2007 – 2011 American Community Survey*. U.S. Census Bureau's American Community Survey Office, 2011. Web. 1 January 2013 <http://factfinder2.census.gov>.

Urban, Tufts University Department of, Environmental Policy, and Planning. 2010. *Preparing for Heat Waves in Boston: A Cool Way to Attack Global Warming*. Tufts University Department of Urban and Environmental Policy and Planning.

Van Vuuren, D. P., J. Edmonds, M. Kainuma, and K. Riahi. 2011. "The Representative Concentration Pathways: An Overview." *Climatic Change*. Springer. http://link.springer.com/article/10.1007/s10584-011-0148-z%20/fulltext.html.

Weng, Qihao, Dengsheng Lu, and Jacquelyn Schubring. 2004. "Estimation of Land Surface Temperature–vegetation Abundance Relationship for Urban Heat Island Studies." *Remote Sensing of Environment* 89 (4): 467–83.

Xian, George, Collin Homer, Jon Dewitz, Joyce Fry, Nazmul Hossain, and James Wickham. 2011. "Change of Impervious Surface Area between 2001 and 2006 in the Conterminous United States." *Photogrammetric Engineering and Remote Sensing* 77 (8). pubs.er.usgs.gov: 758–62.

Appendix

A- Climate Risk Framework from Global to Urban Scales

It is “virtually certain” that the length, frequency, and/or intensity of warm spells or heatwaves will increase in the 21st century over most land areas. The characteristics of impacts from heat waves depend not only on extremes themselves but also on exposure and vulnerability. Interaction of extreme events (heatwaves in present context) with vulnerable social conditions, and exposed population and infrastructure systems could lead to widespread adverse human and economic effects that require immediate emergency and medical response. However, to increase resilience to risks that cannot be eliminated, adaptation to these events requires the adjustment to expected extreme events and its effects, to moderate harm and/or exploit beneficial opportunities. Adaptation measures to reduce vulnerability and exposure to urban heatwaves include installation of early warning systems, health monitoring systems, early warning systems, and improved access to emergency facilities. In addition to emergency response and adaptation measures, urban mitigation measures (e.g. city planning, vegetative open space, green-roofing and pollution control), and reduction of greenhouse gases in urban areas can potentially contribute in mitigating anthropogenic climate change and reducing heat island effects (Figure A.1)

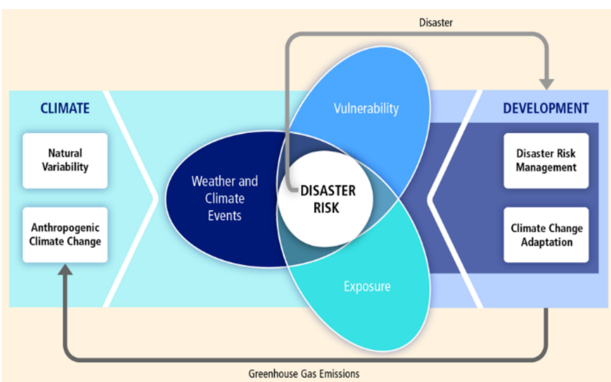
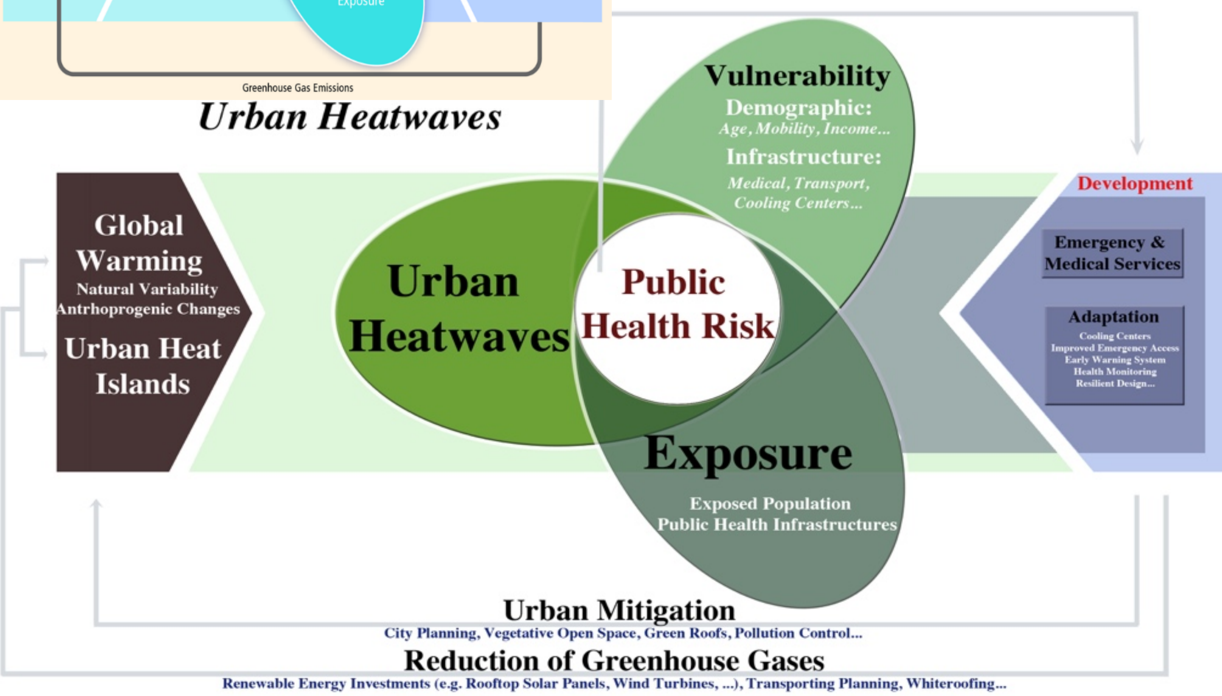


Figure A.1: **(Top)** *IPCC’s (Intergovernmental Panel for Climate Change) Risk framework to assess how exposure and vulnerability to weather and climate extremes determine impacts and the likelihood of disaster risks. (Bottom) Framework used in this report for evaluation of public health risk to urban heat waves, and assessment of adaptation and mitigation scenarios to reduce exposure and vulnerability to heatwave events and thus reduce health risks.*



B- Calculating LST from GeoTiff images of WELD system

Web-Enabled Landsat Data (WELD) is a project by NASA that generates 30 m mosaics over the United States utilizing the *Landsat Enhanced Thematic Mapper Plus (ETM+)* from 2003-2012 (Roy et al. 2010). The benefit of WELD data products is that they reduce the computational complexity of data and provides contextually meaningful information.

The following equations are used to calculate LST from Band 6-1 Top of Atmosphere (TOA) brightness temperature values, and Band3 and Band4 TOA Reflectance values. Band 3 is applied to measure differentiation in chlorophyll absorption for plant species, and Band 4 can be used to delineate water body.

To this end, first the Land Surface Emissivity (LSE) is calculated. LSE measures the intrinsic ability of a surface in converting heat energy into above surface radiation. It depends on the observation conditions and physical properties of the surface (Sobrino, Raissouni, and Li 2001). For the mixture of bare soil and vegetation land coverage, it is calculated by:

$$\epsilon_{TM6} = 0.004\, P_v + 0.986 \qquad (1)$$

in which $\epsilon$is emissivity and $P_v$is the proportion of vegetation calculated as:

$$P_v = \left[\frac{NDVI - NDVI_{min}}{NDV_{max} - NDVI_{min}}\right]^2$$

(2)

$$NDVI_{max} = 0.5, NDVI_{min} = 0.2$$

where Normalized Difference Vegetation Index (NDVI) is calculated as the difference of the near-infrared (band3) and red color bands (band4) divided by their sum, and is an indicator of availability of live green vegetation. The final step is to correct for the spectral emissivity according to the type of the surface (Weng, Lu, and Schubring 2004), and to convert the temperature unit from Kelvin to the desired unit.

$$S_t = \frac{T_B}{1 + (\lambda \times T_B/\rho) ln\epsilon} \qquad (3)$$

$$T_B: Blackbody\ temperature$$
$$\lambda: Wavelength\ of\ emitted\ radiance\ (11.5\ \mu m)$$
$$\rho = h\ x\ c/\sigma = 1.438\ x\ 10^{-2} mK\ (\sigma = Boltzman\ constant = 1.38\ x\ 10^{-23}\ J/K, h = Planck's\ constant = 6.626\ x\ 10^{-34} Js, c = velocity\ of\ light = 2.998\ x\ 10^{8} m/s)$$
$$ln\epsilon:\ Land\ surface\ emissivity\ calculated\ from\ equation\ (1)$$

C- Calculating Ambient Temperature

Following formula is used to calculate ambient temperature in each 30x30m pixel within the boundaries of Brookline (Kloog et al. 2014).

$$T_a = \alpha_0 + \alpha_1 T_{L,i} + \alpha_2 U_i + \alpha_3 El_i + \alpha_4 N_i$$

T_a : ambient temperature
$T_{L,i}$: LST in pixel i
U_i : urban percentage in pixel i
El_i : elevation in pixel i
N_i : NDVI in pixel i

Due to unavailability of enough recorded data of ambient temperature, calculating the specific coefficients for the town of Brookline is not possible. Therefore, we assumed similar condition to Cambridge, MA and used the coefficients calculated and used in a similar study for Cambridge (City of Cambridge 2015).

$$\alpha_1 = 0.38, \quad \alpha_2 = -0.00124972102607794, \alpha_3 = -0.000961258057526494,$$

$$\alpha_0 = 14.8171859697681, \alpha_4 = -1.333087855$$

Urban percentage is calculated from the mean value of NLCD Percent Urban Categorizations. Elevation is calculated from LiDAR of Massachusetts. NDVI is the NDVI from Landsat imagery, and LST is from the part B of this appendix.