Smart Growth & Regional Collaboration

Climate Vulnerability in Greater Boston
Technical Documentation

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I. Introduction

To construct the climate vulnerability indices, several aspects had to be considered, including the temporal nature of the vulnerability under study, the relative influence (i.e. weights) of each indicator on vulnerability, and the geographic scale of data. For this analysis, we chose to focus on current vulnerability to extreme heat and both current and future vulnerability to flood hazards. We decided to equally weigh all indicators and use census tracts as our spatial unit of data collection.[1]

II. Exposure Indicators

Heat Island Exposure

Justification

As our climate warms, all of metropolitan Boston can expect higher temperatures and more very hot days. Areas covered by dark and impervious surfaces heat up more than areas covered in reflective surfaces and vegetation, resulting in even more extreme "heat islands" on days that are already very hot. While hot days affect the entire region, people who live in areas prone to heat island effects are exposed to even greater temperatures.

Data

Massachusetts Land Parcel Database, July 2019 Update (MAPC, 2015)

Census 2010 Geometry

LANDSAT image courtesy of United States Geological Survey

MAPC Land Surface Temperature Analysis Raster Dataset, imagery from July 13, 2016

Metric

Using land cover data, assessors' records, and satellite imagery of the region for a hot day with clear skies, MAPC estimated the severity of the heat island effect on housing units in each census tract. We attached

[1] The chronic disease and job exposure indicators were not obtainable at the census tract-level, so municipal-level data were used instead for these indicators. In order to incorporate these data into our analysis, we assigned the value of the indicator at the municipal level to each census tract within a given municipality, assuming a similar distribution of an indicator for all census tracts. For example, if a municipality had a diabetes prevalence of 5%, then each census tract within the municipality was given a 5% prevalence rate.

the maximum value of the land surface temperature raster within each parcel to that parcel, then calculated a "heat island temperature increase" at each parcel as the difference between land surface temperature and regional air temperature on that day as recorded at Logan International Airport. Parcels for which land surface temperature was the same or lower than regional air temperature were assigned temperature increase values of zero. This metric reflects an estimate of the degree to which surface properties cause local temperature increase.

We then multiplied the number of housing units on the parcel by the temperature increase at that parcel, summed the results over all parcels, and divided the sum by the total number of housing units in that census tract. The result is the average heat island temperature increase for housing units in that census tract.

Flood Exposure

One flood exposure dataset is calculated by tabulating the percentage units each census tract (Massachusetts Land Parcel Database) that overlap with SFHAs. This best reflects the exposure to flooding near large rivers and coastlines.

Justification

Extreme precipitation and storm surge can cause damaging flooding along rivers, streams, coasts, wetlands, and areas with high proportions of impervious surfaces. As a warmer atmosphere is able to hold more moisture and atmospheric circulation patterns change, the Metropolitan Boston region can expect more extreme storms, resulting in more frequent and severe flooding (Commonwealth of Massachusetts Executive Office of Energy and Environmental Affairs and Adaptation Advisory Committee, 2011).

Data

Massachusetts Land Parcel Database, July 2019 Update (MAPC, 2015)

Census 2010 Geometry, U.S. Decennial Census, 2010

National Flood Hazard Layer, FEMA, 2017

Metric

The Federal Emergency Management Agency (FEMA) produces maps of Special Flood Hazard Areas (SFHAs) that indicate where riverine flooding and storm surge have a more than 1% chance of occurring each year (this is often referred to as the 100-year floodplain.) The exposure metric is the fraction of housing units in each census tract that lie within a 1% chance SFHA.

Future Storm Surge Exposure

Justification

Coastal storms may be more extreme in the future, approaching our region with stronger winds and driving higher surge. Sea level rise will exacerbate these changes. By 2050, climate model simulations suggest sea level at Boston Harbor may increase by between nine inches and two feet depending on greenhouse gas emissions and ice sheet dynamics (Kopp et al., 2017). Sea level rise and more severe coastal storms would multiply the area exposed to surge along coastlines, estuaries, and coastal rivers.

MAPC analysts used summaries of an ensemble of Boston Harbor Flood Risk Model (BHFRM) (MassDOT, 2013) simulations to assess the residential exposure to storm surge flooding under 8” sea level rise scenario and a 40” (3.39’) sea level rise scenario.[2] The eight inch sea level rise scenario reflects the chance of flooding from storm surge given eight inches of sea level rise relative to 2013 sea levels and an ensemble of historically inspired coastal storms. The 3.39 ft. scenario reflects the risk of flooding from storm surge given 3.39 feet of sea level rise relative to 2013 sea levels and an enhanced ensemble of coastal storms intended to indicate stronger, more severe future storms.

Sea level is expected to increase by 8” by 2030 at the earliest and 2040 at the latest. Sea level could exceed 40” relative to 2000 sea level by 2060 at the earliest, or after 2100.[3] Because a 40” sea level rise is assumed to occur later in the future and reflect a more advanced state of climate change, the 40” scenario was modeled with a more extreme set of coastal storms than the 8” scenario.

Data

Massachusetts Land Parcel Database, July 2019 Update (MAPC, 2015)

Census 2010 Geometry

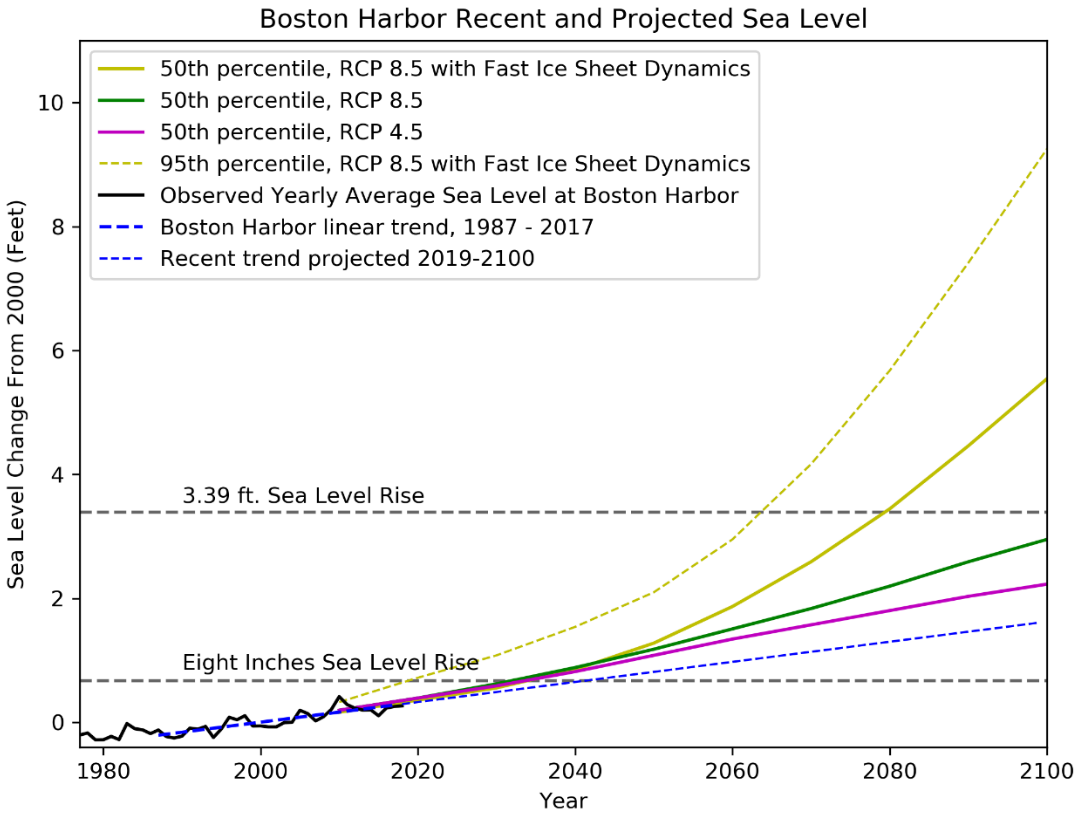
Boston Harbor Flood Risk Model storm surge simulation summaries (MassDOT, 2013; Commonwealth of Massachusetts Executive Office of Energy and Environmental Affairs and Adaptation Advisory Committee (2011))

Metric

The storm surge simulation ensembles were summarized as rasters whose pixels represent the chance of that pixel flooding in a given year under the sea level rise scenarios. To estimate exposure to storm surge flooding under both scenarios, we attached an annual probability of flooding from the raster model output summary to each parcel within the simulation extent based on the maximum value of the raster pixels within that parcel. We then calculated the number of housing units at parcels that had a 1% chance or greater of flooding each year. The resulting exposure metric is the percentage of housing units in each census tract expected to experience a 1% chance storm surge under each sea level rise scenario.

[2] Sea level rise is relative to mean sea level in 2000.

[3] The “latest” sea level scenario is derived from linear extrapolation of Boston Harbor mean sea level between 1987 and 2017. The “earliest” sea level scenario is derived from 95% simulation frequency ocean-ice sheet modelling assuming RCP 8.5 and fast ice sheet collapse (Kopp et al., 2017).



Boston Harbor Recent and Projected Sea Level
50th percentile, RCP 8.5 with Fast Ice Sheet Dynamics
50th percentile, RCP 8.5
50th percentile, RCP 4.5
95th percentile, RCP 8.5 with Fast Ice Sheet Dynamics
Observed Yearly Average Sea Level at Boston Harbor
Boston Harbor linear trend, 1987 - 2017
Recent trend projected 2019-2100
3.39 ft. Sea Level Rise
Eight Inches Sea Level Rise
Sea Level Change From 2000 (Feet)
0
2
4
6
8
10
1980
2000
2020
2040
2060
2080
2100
Year

III. Sensitivity and Adaptive Capacity Indicators

Dozens of research studies, white papers, and government reports have attempted to produce indicator-based vulnerability analyses at a variety of geographic scales and across numerous types of climate hazards (Tonmoy, El-Zein, & Hinkel, 2014). Upon a review of the literature, we selected the following sensitivity and adaptive capacity indicators (Table 1), with a focus on applicability to extreme heat or flood hazards. While we sought to describe as many aspects of vulnerability as possible, our choices of variables were restrained to what has been measured regionally and reliably.

Sensitivity

Indicator	**Hazard**	**Relationship to vulnerability (+ = increases, – = decreases)**
Proportion of occupied housing units with overcrowding (more than one occupant per room)	Heat Flood	Heat (+): High density of people in enclosed spaces impacts thermal conditions of a space (Holt, 2015); groups in overcrowded accommodations are also at higher risk of adverse health effects from indoor air pollution (Vardoulakis, et al., 2015) Flood (+): Increased exposure to waterborne and vector-borne diseases in crowded housing and shelters after floods (Alderman, Turner, & Tong, 2012)
Proportion of population living in group quarters	Heat Flood	Heat (+): Group quarters include correctional facilities, nursing homes, and other institutions that house vulnerable populations or produce vulnerabilities due to the conditions within a given building. (USGCRP, 2016) For example, people who are incarcerated are at increased risk of heat stroke and other heat-related illnesses due to the high population density/overcrowding of jails and prisons, poor building infrastructure, and a disproportionate level of poor mental and/or physical health (Holt, 2015) Flood (+): See above
Proportion of population age 5 or below	Heat Flood	Heat (+): Young children, especially those with pre-existing health conditions (e.g., asthma, diabetes), are at increased risk for hyperthermia and other heat-related illnesses. Heat-regulating mechanisms are also reduced in young children. (McGeehin & Mirabelli, 2001) Flood (+): Reliance on others to move out of harm's way; increased risk of waterborne and vector-borne diseases due to relatively-naïve immune systems (Cutter, Boruff, & Shirley, 2003) (Lane, et al., 2013)
Proportion of population age 65 and up	Heat Flood	Heat (+): Increases in hospital visits and death during heat events (Basu & Samet, 2002) (Lin, et al., 2009) Flood (+): May need assistance with evacuation and access to medical services, but may also desire to stay in place, all of which increases risk of harm and mortality (Alderman, Turner, & Tong, 2012)
Proportion of housing units built before 1960	Heat	Heat (+): Proxy for housing units without central air conditioning, a key factor in the reduction of heat-related morbidity and mortality (Weber, Sadoff, Erica, & de Sherbinin, 2015)
Proportion of housing units built in 1980 or later	Flood	Flood (–): Housing units in the 1% chance flood zone are required to have their lowest floor above the base flood level (e.g. elevation at least some level above the ground – fewer basements). As such, this measure serves as a proxy for housing that is less susceptible to flooding (FEMA, 1998) (Anne Herbst, MAPC, internal correspondence)
Percentage of population with a disability	Heat Flood	Heat (+): Those with mobility or cognitive impairments may have greater difficulty responding to, evacuating from, and recovering from climate events, particularly when the functional needs of people with disabilities are not accounted for in risk communication and emergency response plans (USGCRP, 2016) Flood (+): See above
Proportion of population with cardiovascular disease	Heat Flood	Heat (+): Increases risk of cardiovascular disease-related hospital visits and deaths during heat waves (McGeehin & Mirabelli, 2001) (Lin, et al., 2009)

		Flood (+): Increases in blood pressure following acute psychological stressors such as flooding can contribute to increases in cardiovascular-associated morbidity and mortality (Alderman, Turner, & Tong, 2012) (Miller & Arquilla, 2008)
Asthma hospitalization rate (cases per 100 residents)	Heat	Heat (+): Increases risk of respiratory disease-related hospital visits during heat waves (McGeehin & Mirabelli, 2001) (Lin, et al., 2009)
Proportion of population with diabetes	Heat Flood	Heat (+): Increases risk of diabetes-related hospital visits and deaths during heat waves (McGeehin & Mirabelli, 2001) Flood (+): Destabilization of medication and diet can increase diabetes-related morbidity and mortality after natural disasters (Miller & Arquilla, 2008)
Population working outside (firefighters, construction workers, farmers, fishers, and forestry workers)	Heat Flood	Heat (+): Increased exposure leads to more heat-related deaths (Schulte & Chun, 2009) Flood (+): Increased exposure to molds and allergens, new onset respiratory symptoms among aid workers and emergency responders, and economic disruptions (Schulte & Chun, 2009)

Adaptive Capacity

Indicator	**Hazard**	**Relationship to vulnerability (+ = increases, – = decreases)**
Proportion of housing units that are renter-occupied	Heat Flood	Heat (+): Renters may be (but are not exclusively) more transient than homeowners and are likely to have lower incomes than homeowners, limiting their access to certain resources or routes toward recovery (Cutter, Boruff, & Shirley, 2003) Flood (+): See above
Proportion of occupied housing units that are mobile housing	Flood	Flood (+): Mobile homes are less resilient to hazards (Cutter, Boruff, & Shirley, 2003)
Proportion of occupied housing units with no vehicle	Flood	Flood (+): Lack of transportation may reduce ability to evacuate coastal storms and floods (Lane, et al., 2013)
Percentage of households without internet access	Heat Flood	Heat (+): People without internet access may miss climate hazard warnings and information on available resources (e.g., cooling centers) if notifications are primarily provided on the Internet (New York State Energy Research and Development Authority, 2017) Flood (+): Evacuation decision making may be supported by internet access at home and social media usage (Kaufman, Qing, Levenson, & Hanson, 2012)
Percentage of people with a HS diploma or higher	Heat Flood	Heat (–): Lower education levels may reduce economic opportunities that would enable more adaptive and recovery capabilities (Cutter, Boruff, & Shirley, 2003) Flood (–): See above
Unemployment rate	Heat Flood	Heat (+): Unemployment (or the loss of employment after a climate event) increases stress (which increases risk of certain health impacts) and slows the recovery from a disaster (Lane, et al., 2013) (Cutter, Boruff, & Shirley, 2003) Flood (+): See above
Median household income	Heat Flood	Heat (–): Higher income increases ability to adapt and recover from climate impacts (Chow WTL, 2012) Flood (–): See above
Poverty rate	Heat Flood	Heat (+): People living in poverty may have less access to air conditioning, quality housing, health care, and other protective factors (McGeehin & Mirabelli, 2001) Flood (+): Difficulty recovering from floods due to heightened wage insecurity, lower likelihood of receiving low-interest loans, greater difficulty navigating bureaucratic disaster recovery assistance protocols (Fothergill & Peek, 2004)
Proportion population identifying as Hispanic Proportion of population identifying as Black or African American	Heat Flood	Heat (+) Racialization of society and racism leads to differentially distributed opportunities and risks, which can negatively impact the adaptive capacity of communities of color. (USGCRP, 2016) Flood (+): See above

Proportion population identifying as Asian		
Proportion of population identifying as American Indian, Alaskan Native, Native Hawaiian, Pacific Islander, some other race, or two or more races		
Proportion of population age 65 and up living alone	Heat Flood	Heat (+): Living alone may be the highest risk factor for heat-related deaths, perhaps signaling social isolation and fewer contacts with family and friends that can assist with access to cool areas or protective behaviors (e.g., adequate fluid intake) (Naughton, et al., 2002) (Semenza, et al., 1996) Flood (+): Living alone may be a consequence of social isolation and few contacts with family and friends, both of which may result in limited connections to evacuation capabilities, health care access (e.g., interruption in chronic disease management), and resource sharing (Lane, et al., 2013)
Single-parent families	Heat Flood	Heat (+): May have limited financial capacity, which alters ability to prepare for, respond to, and recover from climate events (Cutter, Boruff, & Shirley, 2003) Flood (+): See above
Linguistic isolation (no one over 14 speaking English very well)	Heat Flood	Heat (+): Limited ability to adequately prepare for and respond to climate events, especially if climate hazard warnings and information on available resources are only made available in English (USGCRP, 2016) Flood (+): See above
Population living in different residences from 5 years prior	Heat Flood	Heat (+): Social instability that may be associated with reduced social networks in a resident's neighborhood (Chow WTL, 2012) Flood (+): See above
Proportion of population without health insurance	Heat Flood	Heat (+): Lack of health insurance can reduce use of hospital services for fear of costs associated with care, leading to deferred care and greater morbidity and mortality for those with both acute and chronic health conditions (Davis, Wilson, Brock-Martin, Glover, & Svendsen, 2010) Flood (+): See above

IV. Construction of vulnerability indices

Arithmetic Mean

Arithmetic mean aggregation is a common technique for constructing vulnerability indices from a selection of indicators. Interpreting the results of an arithmetic mean aggregation is relatively easy, as the technique allows data consumers to assess the three concepts of vulnerability in isolation (i.e. via mapping of exposure, sensitivity, or adaptive capacity indices separately) or together as a composite vulnerability index. While arithmetic mean is relatively simple to implement and interpret, a key assumption is that each indicator is independent of one another, which in practice may result in double-counting of effects if some indicators are dependent on others.

For our analysis, variables were categorized as exposure, sensitivity, or adaptive capacity indicators and further subcategorized by hazard, such that extreme heat and flood (both current and future surge) hazard-specific vulnerability indices could be constructed using relevant indicators (see Table 1). All variables were then rescaled using min-max scaling across all MAPC census tracts, such that the highest value for a given variable will be rescaled to 1, the lowest value rescaled to 0, and all other values rescaled within that range. For indicators that have a inverse association with vulnerability (e.g., higher household income makes a household less sensitive to climate events), the values were inverted in order to keep the interpretation of vulnerability scores consistent.

After min-max rescaling of the individual variables, the arithmetic mean of a given index (e.g. sensitivity) was calculated for each census tract by summing the rescaled values for all indicators in the index and dividing by the total number of variables for that index. Once the exposure, sensitivity, and adaptive capacity indices were calculated for each census tract, these indices were once again rescaled using min-max scaling, resulting in relative measures of either exposure, sensitivity, or adaptive capacity. To create the final extreme heat and current flood vulnerability index values for each census tract, the arithmetic mean of the three indices (heat exposure/current flood risk exposure, and their respective sensitivity and adaptive capacity indices) was calculated by summing the exposure, sensitivity, and adaptive capacity index values for a given census tract and dividing by 3, followed by a final round of min-max scaling. This composite vulnerability index thus represents a census tract's relative vulnerability compared to other census tracts throughout the MAPC region for a given climate hazard.

For the future flood scenarios, the geographic extent of analysis was limited to census tracts that are completely encompassed by the future storm surge simulation dataset. This area includes census tracts in the following municipalities: Arlington, Belmont, Boston, Braintree, Brookline, Cambridge, Chelsea, Everett, Malden, Medford, Quincy, Revere, Somerville, Watertown, and Winthrop. In order to compare current (FEMA) flood risk data and the 8" and 40" sea level rise scenarios, the exposure values for each future climate scenario was compared to the exposure value for the current flood risk, with the max value between current and future flood risk assigned to the census tract for a given future climate scenario. For example, if the current flood exposure value was greater for a census tract than its 8" sea level rise exposure value, the tract was assigned the current (higher) flood exposure value for the 8" sea level rise scenario. Next, the resultant "maximum exposure" values for census tracts in each future climate were min-max scaled together, such that the highest level of exposure across both climate scenarios was rescaled to 1, the lowest value rescaled to 0, and all other values rescaled within that range. The rescaled values were then reassigned to their corresponding climate scenario and census tract, resulting in the final relative exposure index for a given future flood climate scenario.

The values of the final relative sensitivity and adaptive capacity indices were carried over from the full current flood regional analysis without change. The composite vulnerability indices for the 8” sea level rise or 40” sea level rise scenarios were then calculated by taking the arithmetic mean of the exposure, sensitivity, and adaptive capacity index values for a given census tract, followed by a min-max rescaling of the current flood risk and two future climate scenarios together to create the final vulnerability values that can be more directly compared to one another.

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