Appendix B | Additional Information on Climate Inputs and Assessment Methods

1. Climate Inputs

1.1 Sources of Climate Projections and Data, Summary of Application, and Expert Peer Review

As noted in Chapter 3 of the Statewide Report, a key input to the Climate Assessment is high-quality and up-to-date climate projections, which are critical to evaluating the areal extent, severity, and frequency of relevant climate hazards, and how they may change relative to the "current climate" baseline. The Climate Assessment relies on five sources of climate projection or impact -based climate datasets:

1. ***Cornell University's Stochastic Weather Generator Dataset.*** This source provides projections of temperature and precipitation variables, for four future eras (2030, 2050, 2070, and 2090) for the 10th, 90th, and median percentile results. It relies on results from among 20 Global Climate Models (GCMs) for the Representative Concentration Pathway (RCP) 8.5 greenhouse gas emissions scenario.
2. ***Cornell University's Scaled Intensity-Duration-Frequency (IDF) Curve Dataset.*** This dataset scales "current climate" IDF curves provided in NOAA Atlas 14 by the theoretical rate of increase in atmospheric moisture holding capacity that is correlated with projected temperature increases.[1] The data is provided for a range of future potential temperature increases.
3. ***Downscaled Global Climate Models (GCMs) from the Multivariate Adaptive Constructed Analogs (MACA) repository.*** The Climate Assessment preferentially uses information from the Stochastic Weather Generator or Scaled IDF curves, which synthesize and interpret information from global climate models in readily accessible formats, such as estimates of the number of days exceeding certain temperature thresholds.
4. ***The Metropolitan Area Planning Council (MAPC) Land Surface Temperature Index.*** This source provides a spatially downscaled representation of temperature peaks for historical periods, taking explicit account of local heat island and other anomalies. Originally developed for the Greater Boston metropolitan area, this product was recently extended to all of Massachusetts.
5. ***The Massachusetts Coast Flood Risk Model (MC-FRM).*** This source incorporates climate projections, including sea level rise and coastal storm frequency and intensity projections, and processes those projections to develop risk-based climate datasets for water surface elevation (corresponding to "stillwater levels" excluding wave heights) and annual exceedance probability scenario layers, which are the primary outputs used

[1] NOAA Atlas 14 contains precipitation frequency estimates for the United States and U.S. affiliated territories with associated 90% confidence intervals and supplementary information on temporal distribution of heavy precipitation, analysis of seasonality and trends in annual maximum series data, and other information useful for design of infrastructure and hazard mitigation projects.

in the Climate Assessment. The tool can also generate other outputs, such as wave height, but those were not used in the Climate Assessment.[2]

Summary of Application

Many of the models and approaches used in the Climate Assessment are flexible in their inputs and can be readily applied using data from a wide range of sources. Some use a combination of the above listed sources to estimate impacts. Examples include the National Coastal Property Model, a model of impacts to coastal resources which can be re-estimated, with results down to block group or 150m grid cell resolution, using custom annual trajectories of relative sea level rise or storm surge exceedance data, or flood depth data and other inputs from the MC-FRM.[3] Other models, such as recent efforts to apply the Variable Infiltration Capacity (VIC) macroscale hydrologic model (see Wobus et al. 2021 for details on connecting comprehensive VIC model results for multiple future climates to flood outcomes for residential properties[4]), and the U.S. EPA's air quality modeling system used to estimate the "climate penalty" from regionally downscaled temperature and precipitation inputs, are more data intensive to run and so the results will likely need to be interpolated from existing runs using some source of temperature and precipitation data (see Fann et al. 2021 for details on the air quality health risk modeling approach[5]).

The VIC and the air quality model mentioned above, any many other impact models or approaches used in the Climate Assessment, were initially calibrated using the Localized Constructed Analogs (LOCA) dataset, which consists of statistically downscaled Global Climate Model (GCM) output from Earth system models participating in the Coupled Model Intercomparison Project Phase 5 (CMIP5). LOCA was commissioned by the U.S. Bureau of Reclamation and Army Corps of Engineers and developed by the Scripps Institution of Oceanography and collaborators.[6] This dataset is also used in the U.S. Global Change Research

[2] For the coastal climate impact assessment, the MC-FRM tool was applied using a specific set of climate data projections relevant to estimating coastal flood risk, specifically, a projection of sea level rise and coastal storm activity (both extratropical and tropical storms). The MC-FRM does not directly estimate these climate projections but processes them as inputs to assess risks of coastal flooding. Details are provided in the next section of this appendix.

[3] For details of the NCPM see: Neumann, J.E., Chinowsky, P., Helman, J., Black, M., Fant, C., Strzepek, K., and Martinich, J. (2021) Climate effects on US infrastructure: the economics of adaptation for rail, roads, and coastal development. Climatic Change 167, 44 (2021). https://doi.org/10.1007/s10584-021-03179-w

[4] Wobus, C.W., Porter, J., Lorie, M., Martinich, J., & Bash, R. (2021). Climate change, riverine flood risk and adaptation for the conterminous United States. Environmental Research Letters. doi: 10.1088/1748-9326/ac1bd7.

[5] Fann, N., C. Nolte, M. Sarofim, J. Martinich, and N. Nisokolas (2021). Associations between simulated future changes in climate, air quality, and human health. *JAMA Network Open*, doi:10.1001/jamanetworkopen.2020.32064

[6] U.S. Bureau of Reclamation, Climate Analytics Group, Climate Central, Lawrence Livermore National Laboratory, Santa Clara University, Scripps Institution of Oceanography, U.S. Army Corps of Engineers, and U.S. Geological Survey. 2016. Downscaled CMIP3 and CMIP5 Climate Projections: Release of Downscaled CMIP5 Climate Projections, Comparison with Preceding Information, and Summary of User Needs. Available online at https://gdo-dcp.ucllnl.org/downscaled_cmip_projections/techmemo/downscaled_climate.pdf. Data available at http://gdo-dcp.ucllnl.org/downscaled_cmip_projections/

Program's (USGCRP) Climate Science Special Report, which provides the physical climate science basis for the USGCRP's Fourth National Climate Assessment.[7] The LOCA dataset provides daily projections through 2100 at a 1/16th latitude-longitude degree resolution (corresponding to roughly 6.25 km, or about 3.9 miles) and daily temporal scale for three variables: daily maximum temperature (tmax), daily minimum temperature (tmin), and daily precipitation. The 2018 State Hazard Mitigation and Climate Adaptation Plan (SHMCAP) also relied on LOCA-downscaled output.

The Stochastic Weather Generator and the Scaled IDF Curve Dataset used in the Climate Assessment are outputs of the Executive Office of Energy and Environmental Affairs' (EEA's) Massachusetts Climate and Hydrologic Risk Project (Phase 1). These outputs can be used with multiple sources of climate data to generate temperature and precipitation projections for the 21st century. Both documentation reports currently reference the Multivariate Adaptive Constructed Analogs (MACA) statistically downscaled product,[8] but other climate data can be used with these tools. MACA is based on the same CMIP5 GCM ensemble as LOCA, and employs a quantile mapping and constructed analogs approach, a methodology that is similar to LOCA but which also provides a daily synoptic weather field and additional climate inputs such as wind speed and solar radiation that are not available from LOCA. In the Climate Assessment, LOCA is used in cases where it was not feasible to re-run physical effects modeling under the time and resource constraints of the Climate Assessment, and MACA cases where the Stochastic Weather Generator or the IDF curves did not provide the required climate inputs.

The analyses here utilize the Representative Concentration Pathway (RCP) 8.5 greenhouse gas emissions scenario as a high-end emissions scenario, while also acknowledging that there are small differences through 2050 in the RCP8.5 and the more moderate RCP4.5 emissions scenario, and that the most meaningful differences in global emissions pathways arise only after mid-century. The Project Team recognizes that ongoing efforts in Massachusetts to decarbonize energy use and reach a net zero-emissions goal by 2050 will meaningfully reduce emissions from Massachusetts sources,[9] which when combined with efforts at the U.S. Federal and global level to reach net-zero emissions goals could also meaningfully reduce the impacts of climate change for the 2070 and 2090 time periods of this Climate Assessment.

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[7] USGCRP. 2017. *Climate Science Special Report: Fourth National Climate Assessment, Volume I* [Wuebbles, D.J., D.W. Fahey, K.A. Hibbard, D.J. Dokken, B.C. Stewart, and T.K. Maycock (eds.)]. U.S. Global Change Research Program, Washington, DC, USA, 470 pp, doi: 10.7930/J0J964J6.; and USGCRP. 2018. Impacts, Risks, and Adaptation in the United States: Fourth National Climate Assessment, Volume II: [Reidmiller, D.R., C.W. Avery, D.R. Easterling, K.E. Kunkel, K.L.M. Lewis, T.K. Maycock, and B.C. Stewart (eds.)]. U.S. Global Change Research Program, Washington, DC, USA, 1515 pp. doi: 10.7930/NCA4.2018.

[8] Abatzoglou, J. T. 2013. Development of gridded surface meteorological data for ecological applications and modelling. Int. J. Climatol., 33, 121–131; and Abatzoglou, J.T., and Brown, T.J. 2012. A comparison of statistical downscaling methods suited for wildfire applications. International Journal of Climatology, 32, 772-780.

[9] See for example the Massachusetts Clean Energy and Climate Plan for 2025 and 2030, details at: https://www.mass.gov/info-details/massachusetts-clean-energy-and-climate-plan-for-2025-and-2030

A brief summary of the application of each of these tools is provided below:

1. ***Cornell University's Stochastic Weather Generator Dataset.*** The Weather Generator is designed to provide projections of relevant temperature and precipitation variables at the level of spatial and temporal detail needed for the Climate Assessment. The technique takes best advantage of what at least some climate scientists have concluded are some of the more reliable outputs from GCMs (barometric pressure), which when combined with projections of future synoptic weather patterns as affected by future climate change has great potential for improving climate projections relative to other available products, such as LOCA. The Phase 1 Weather Generator results do not yet incorporate the changes in atmospheric dynamics from climate change. In addition, the Phase 1 results do not yet incorporate changes in mean precipitation under climate change, which are in evidence in the historical record and which are plausible for climate projections. For these reasons the Phase 1 Weather Generator results are supplemented by the use of GCMs in many of the analyses performed for the Climate Assessment.
2. ***Cornell University's Scaled Intensity-Duration-Frequency (IDF) Curve Dataset.*** The IDF curves derived from the scaling approach focuses on extremes of precipitation, which is distinct from the results provided by the Weather Generator. For the precipitation extremes output the IDF curve provides a best available product for application to impact categories that require estimates of the intensity and frequency of precipitation events in the Climate Assessment, such as the assessment of health effects associated with extreme rainfall events.
3. ***Downscaled Global Climate Models (GCMs) from the Multivariate Adaptive Constructed Analogs (MACA) repository.*** The Climate Assessment preferentially uses information from the Stochastic Weather Generator or Scaled IDF curves, which synthesize and interpret information from global climate models in readily accessible formats, such as estimates of the number of days exceeding certain temperature thresholds. In some cases, however, impact model input requirements provide a rationale for the use of the detailed temporal and spatial scale results available from the downscaled Global Climate Models (GCMs) which are used as inputs to the Stochastic Weather Generator and the Scaled IDF curves.
4. ***The Metropolitan Area Planning Council (MAPC) Land Surface Temperature Index.*** The Land Surface Temperature (LST) index results are a best available source for identifying local heat island and other anomalies in historical data, and are available for all of Massachusetts. Results such as this have not yet been incorporated in the relevant extreme heat and health impact epidemiological functions in the current health science literature. As a result, it is not yet possible to adjust health risk estimates for our Magnitude of Consequence component of the Climate Assessment. The LST results, however, provide a basis for assessing the Disproportionality of Exposure metric, and are applied in the Climate Assessment to identify extreme heat event impacts that

potentially fall disproportionately on Environmental Justice block group populations in the Commonwealth.

5. ***The Massachusetts Coast Flood Risk Model (MC-FRM).*** The MC-FRM is the best available source for incorporating the currently adopted statewide SLR projections and state-of-the-science storm activity projections to estimate the relevant risk-based climate datasets for the Climate Assessment. Some aspects of storm activity, such as the potential impact of climate on extratropical storms (also known locally as "Noreasters"), remain the subject of ongoing but not yet complete research and improvement of the MC-FRM and may be considered in future assessments.

Expert Peer Review

The Climate Assessment team worked with an external peer review panel of climate scientists, with expertise in forecasts of temperature, precipitation, sea level rise, and coastal and inland storm incidence specific to Massachusetts. The panel included Mathias Collins (National Oceanic and Atmospheric Administration); Robert DeConto (University of Massachusetts Amherst); Adam Schlosser (Massachusetts Institute of Technology); Scott Steinschneider (Cornell University); and Stephen Young (Salem State University). The panel reviewed the proposed application of climate inputs for impact assessment, provided comments on the proposal, and the Project Team revised the climate input application strategy in response to the panel recommendations. As the external peer review panel acknowledged, for some impact categories data from statistically downscaled global climate models was directly accessed, to more closely align with specific temporal or spatial aspects of impact models applied in the Climate Assessment. The panel acknowledged that GCMs produce large amounts of data that should be carefully interpreted, but the detailed daily projections of both temperature and precipitation are useful for some impact estimates that rely on the daily sequence of hot/cold and wet/dry days and agreed that both MACA and LOCA represent statistically downscaled interpretations of GCMs that are well-suited for use in the Climate Assessment.

The peer review panel noted, among other comments, that the climate inputs used in the Climate Assessment are based on temperature and precipitation projections, as well as temperature arrival times that are derived from CMIP5 GCMs (that is, from the bias-corrected and downscaled MACA dataset), but the next generation of GCMs from the CMIP6 simulations is now available. The Project Team considered the possibility that CMIP6 results might be used in this study and concluded that the current lack of a well-accepted and publicly available CMIP6 downscaled product severely limits the feasibility of adopting CMIP6 results for the MA Climate Assessment. The panel agreed with this conclusion.

The Project Team also reviewed information about differences between CMIP5 and CMIP6 outcomes for Massachusetts from two sources. The first source is Agel and Barlow (2020), which is focused on comparison of observed and CMIP6-model-simulated historical extreme precipitation outcomes for the Northeast US region.[10] The paper concludes that most of the

[10] Agel, L. and Barlow, M. 2020. How Well Do CMIP6 Historical Runs Match Observed Northeast U.S. Precipitation and Extreme Precipitation–Related Circulation? Journal of Climate, 33: 9835-9848.

CMIP6 models capture the seasonality of precipitation intensity well but produce more frequent precipitation than observed. They also find divergence in the simulation of precipitation and circulation results, which is consistent with the conceptual logic supporting the use of the Stochastic Weather Generator, and note that with respect to extreme precipitation metrics, the CMIP6 results “do not appear to reflect a substantial improvement over a similar analysis of selected CMIP5 models.” The second source is work in progress by Preston, Strzepek, and Schlosser (in preparation) which focuses on outcomes for the Cambridge, MA area.[11] These authors find that the CMIP6 simulations yield somewhat fewer days per year with maximum temperatures above 85, 90, 95, and 100°F than CMIP5 simulations, perhaps owing to improved simulation of cloudiness in the CMIP6 models. This finding, however, runs counter to other information which suggests that CMIP6 simulations show more temperature sensitivity to GHG emissions than CMIP5 as measured by global mean surface temperature – suggesting that projection results may be highly localized and cannot yet be readily compared. The absence of a thorough comparison of CMIP5 and CMIP6 projections for Massachusetts at the present time suggests that adoption of CMIP6 scenarios as “best available” is premature until a well-accepted bias-corrected and downscaled product is available for evaluation.

1.2. Additional Details on Climate Projections and Data Inputs

Below are additional methodological details on each of the five sources of climate projections and data inputs used in the Climate Assessment.

Massachusetts Coast Flood Risk Model (MC-FRM)

While understanding changing coastal climate conditions are the foundational elements of evolving coastal flood risk, these climate factors also need to be translated into potential “on-the-ground” flooding information, and subsequently, damages levels and recovery costs. This section of the Appendix covers two specific elements associated with changing risk along Massachusetts’ coastlines, and how they are incorporated in the MC-FRM:

1. ***Coastal climate change data*** – These are the actual coastal variables that are projected to potentially undergo significant changes due to changing climate conditions. For the purposes of this section, this topic addresses sea level rise projections and potential influence on coastal storm events, (tropical and extra-tropical) cyclones that have their genesis in the ocean and ultimately impact coastlines in Massachusetts. These data on their own are critical, but do not result in information that is directly actionable.
2. ***Application of the climate data to “on-the-ground” flood risk*** – This is not explicitly climate data, rather the application of the climate data projections to determine the evolution of flooding risk in coastal areas of Massachusetts. There are several methods

[11] Preston, M., K. Strzepek, and A. Schlosser. (in preparation). Assessment of precipitation changes over Cambridge, MA: A comparison of CMIP5 versus CMIP6. MIT Office of Sustainability Working Paper. The analysis for this work is complete but the working paper is currently in preparation. The Project Team is grateful to the authors for sharing these results in advance of the release of their working paper.

and approaches that have been used to identify these flood risks, the MC-FRM is one of these methods.

Sea Level Rise

Scientific understanding of global mean sea level rise processes, particularly related to how warming atmospheric and ocean temperatures will affect ice sheet mass loss and redistribution, has advanced greatly in the recent years. The relative sea level rise projections developed for the Commonwealth of Massachusetts, and used as input into the MC-FRM, use a probabilistic approach, closely following the methodology developed by Kopp et al. (2014), with the ice mass model outputs presented by DeConto and Pollard (2016).[12] This methodology produced a continuum of location-specific probability distributions (in this case, based on tide gages at Boston, Woods Hole and Nantucket), informed by state-of-the-art process modeling, expert assessment, and expert elicitation. A multi-year reference time period for relative sea level was used to minimize biases caused by tidal, seasonal, and inter-annual climate variability, following the accepted practice of using a 19-year tidal datum epoch.

Following the approach in the 2017 National Climate Assessment and the Global and Regional Sea Level Rise Scenarios, conditional probability distributions for sea level rise projections can be integrated into different scenarios to support planning and decision-making, given uncertainty and future risks. This approach allows for the many different probabilistic projections (i.e., two models each using two greenhouse gas concentration pathways for multiple time series and several probabilities groups) to be filtered into representative scenario groups. The Commonwealth of Massachusetts has selected the High scenario as the preferred scenario for assessment of vulnerability and flood risk. This scenario is consistent with the following probabilities from Kopp et al. (2017):

- Unlikely to exceed (83%) under RCP8.5 when accounting for possible ice sheet instabilities
- Extremely unlikely to exceed (95%) under RCP4.5 when accounting for possible ice sheet instabilities

These sea level rise projections provide the background sea level estimates used for detailed, site-specific hydrodynamic modeling (the MC-FRM) and mapping storm surge impacts and influences of localized processes along the coast. These sea level rise projections were developed specifically for the Commonwealth of Massachusetts and the conditions expected to occur in the Northeast United States, as well as follow guidance on emissions scenarios generated by the IPCC. Therefore, it is reasonable to conclude that these projections are both adequate and best available for the current vulnerability assessment, while acknowledging that this area of science and research is an ongoing and evolving subject matter. Sea level rise science is evolving rapidly and updates to the flood projections might be required in the near future as the science evolves.

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[12] Kopp, R.E., Horton, R.M., Little, C.M., Mitrovica, J.X., Oppenheimer, M., Rasmussen, D.J., Strauss, B.H., and Tebaldi, C. 2014. Probabilistic 21st and 22nd century sea-level projections at a global network of tide-gauge sites. Earth's Future, 2, 383–406, doi:10.1002/2014EF000239;DeConto, R. M., and Pollard, D. 2016. Contribution of Antarctica to past and future sea-level rise. Nature, 531(7596), 591–597.

All sea level rise projections are relative to a 2000 start year (or baseline) and are also consistent with the projections presented on the Massachusetts Climate Change Clearinghouse (resilientma.mass.gov) and being used in the Climate Resilience Design Standards Tool.[13] The MC-FRM uses an updated mean water level datum centered on the most recent tidal epoch - at the time of model development that was 2008 - which incorporates the actual sea level observations from 1999-2017. In this way, MC-FRM includes the actual observed sea level rise conditions that have occurred at each of three NOAA tide-gauge stations between 2000 and 2008, and also uses the relative sea level rise projections (which are referenced to mean-sea level, NAVD88).

Because the present-day MC-FRM results are centered around a 2008 based tidal epoch, and the sea level rise projections are based on a 2000 start point, it is important to recognize and account for this discrepancy when describing sea level rise scenarios, as is done internally in MC-FRM. The datum used for sea level rise projections in state documents is the mean sea level elevation relative to NAVD88 datum, although sea level rise can be expressed relative to other reference points, as in done in Chapter 3 of the Climate Assessment (relative to an estimate of 2020 levels) and in Appendix A (relative to the MC-FRM present day centered on 2008). Table B-1 below resolves these three ways of expressing the same sea level rise projections, in three panels. Panel A shows the inputs to MC-FRM relative to the NAVD88 datum. Panel B shows the same sea level rise projection, but relative to sea level in 2008. Note that the "present day" value is calculated based on the 2008 centered tidal epoch and data from the Boston tide station.

Panel C shows the same sea level rise projection, but relative to an estimate of the 2020 sea level as a reference point, where the 2020 sea level was derived by linear interpolation between the 2008 and 2030 values in Panel A.

[13] See sea level rise projections summary, https://eea-nescaum-dataservices-assets-prd.s3.us-east-1.amazonaws.com/resources/production/MA%20Statewide%20and%20MajorBasins%20Climate%20Projections_Guidebook%20Supplement_March2018.pdf starting on page 15; and the MC-FRM FAQ on page 5: https://eea-nescaum-dataservices-assets-prd.s3.amazonaws.com/cms/GUIDELINES/MC-FRM_FAQ_04-06-22.pdf. Please note the temperature and precipitation projections provided in the March 2018 report are superseded by EEA's Massachusetts Climate and Hydrologic Risk Project (Phase 1) outputs developed by Cornell University.

Table B-1. Sea level rise projections used in the Climate Assessment

Panel A: Inputs to MC-FRM, relative to NAVD88

	Present Day Epoch (2008)	2030	2050	2070
Mean Sea Level - North	-0.09 ft (-1 in)	1.2 ft (14.4 in)	2.4 ft (28.8 in)	4.2 ft (50.4 in)
Mean Sea Level - South	-0.17 (-2 in)	1.2 ft (14.4 in)	2.5 ft (30 in)	4.3 ft (51.6 in)

Panel B: Sea level rise projection relative to the 2008 Present Day tidal epoch

	Present Day Epoch (2008)	2030	2050	2070
Sea Level Rise – North	0 ft (0 in)	1.29 ft (15.5 in)	2.49 ft (29.9 in)	4.29 ft (51.5 in)
Sea Level Rise – South	0 ft (0 in)	1.37 ft (16.4 in)	2.67 ft (32.0 in)	4.47 ft (53.6 in)

Panel C: Sea level rise projection relative to estimated 2020 sea level

	2020 (estimated)	2030	2050	2070
Sea Level Rise - North	0 ft (0 in)	0.59 ft (7.0 in)	1.79 ft (21.4 in)	3.59 ft (43.0 in)
Sea Level Rise - South	0 ft (0 in)	0.62 ft (7.5 in)	1.92 ft (23.1 in)	3.72 ft (44.7 in)

The Panel A and Panel B approaches are consistent with how other MC-FRM documentation describes these sea-level rise scenarios; Panel B estimates are used in the Appendix A assessment of the impact category Damage to Coastal Buildings and Ports. Panel C estimates are used in Chapter 3 for ease of communication of the sea level rise scenarios used in the study. All three approaches differ only by their base sea level reference point.

Changing Storm Frequency and Intensity

The MC-FRM includes simulations of both extra-tropical storms (i.e., nor-easters) and tropical cyclones (i.e., hurricanes). This section describes the potential impact of climate change on storm intensity and frequency, which is integrated into the model effort such that storm intensities increase in future climate scenarios. While rising sea levels will increase water depths along the coastline, which will in turn result in the greater potential for wave and surge propagation further inland, there may also be increased intensity and frequency of large coastal storm events that are induced by the changing climate. Essentially, the heating of the ocean may also be increasing the probability and intensity of storm events. This is important to consider for both extratropical cyclones (ETC) and tropical cyclones (TC), which have varying levels of dominance throughout the Commonwealth of Massachusetts. The role of ETCs is much more important than TCs for the regions north of Cape Cod, and especially Boston Harbor (Baranes et al., 2020[14]), while the shorelines of southern Cape Cod and Buzzards Bay can be much more strongly influenced by TCs than ETCs.

Extratropical cyclones - An extratropical cyclone (ETC) is a large-scale, low-pressure system that originates in the mid- and high latitudes; there is a statistically significant increasing trend in both frequency and intensity of extratropical storm activity during the cold season in the Northern Hemisphere since 1950 (Karl et al. 2009). Vose et al. (2014) also found evidence of a northward shift in extratropical storm tracks, which is consistent with the findings of Karl et al. (2009).[15] Hawcroft et al. (2018) found that despite uncertainty in the response to warming of the atmospheric circulation, projections of frequencies of intense ETCs are large and consistent across models, with large increases predicted by 2100. [16] In a study focusing on the northeastern United States, Lin et al. (2019) found that projections based on most of the climate models examined indicate small effects of climate change on storm surges driven by ETCs, although differences between model forecasts exist, and one model shows a large increase in surge return levels, indicating a high level of uncertainty.[17]

In summary, while the fundamental mechanisms of extratropical cyclone generation are fairly well founded, the potential non-linearities and complexities that influence ETC development and intensities under changing climate conditions are far more challenging. Hence it is difficult at this point to make precise conclusions about the effect of human-forced climate change on extratropical storms in the future. Douglas et al. (2016)[18] reported that future changes in extratropical storm characteristics remain highly uncertain, and hence no robust estimates of changes in extratropical cyclone intensity, frequency, or trajectory were included in the MC-FRM.

This means that in the MC-FRM runs used for the Climate Assessment, the ETCs are assumed to remain the same in terms of wind fields and pressures under future climate conditions as they were historically within the MC-FRM framework.

Tropical cyclones - While global frequency of events has remained relatively constant, the intensity of tropical cyclones is increasing and the duration of tropical cyclones is increasing.

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[14] Baranes, H. E., Woodruff, J. D., Talke, S.A., Kopp, R. E., Ray, D., DeConto, R. M., 2020. Tidally Driven Interannual Variation in Extreme Sea Level Frequencies in the Gulf of Maine. Research Article JGR Oceans.

[15] Karl, T. R., J. M. Melillo, and T. C. Peterson, Eds. 2009. Global Climate Change Impacts in the United States. Cambridge University Press, 192 pp.; Vose, R. S., S. Applequist, M. A. Bourassa, S. C. Pryor, R. J. Barthelmie, B. Blanton, P. D. Bromirski, H. E. Brooks, A. T. DeGaetano, R. M. Dole, D. R. Easterlin, R. E. Jensen, T. R. Karl, R. W. Katz, K. Klink, M. C Kruk, K. E. Kunkel, M. C. MacCracken, T. C. Peterson, K. Shein, B. R. Thomas, J. E. Walsh, X. L. Wang, M. F. Wehner, D. J. Wuebbles and R. S. Young. 2014. Monitoring and understanding changes in extremes: extratropical storms, winds and waves. Bulletin of the American Meteorological Society. 95(3): 377-386.

[16] Hawcroft, M., E. Walsh, K. Hodges, and G. Zappa. 2018. Significantly increased extreme precipitation expected in Europe and North America from extratropical cyclones. Environ. Res. Lett. 13 124006

[17] Lin, N., Marsooli, R. & Colle, B.A. Storm surge return levels induced by mid-to-late-twenty-first-century extratropical cyclones in the Northeastern United States. Climatic Change 154, 143–158 (2019). https://doi.org/10.1007/s10584-019-02431-8

[18] Douglas, E., P. Kirshen, R. Hannigan, R. Herst and A. Palardy. 2016. Climate Change and Sea Level Rise Projections for Boston, a report prepared by the Boston Research Advisory Group for Climate Ready Boston, available on line at https://www.boston.gov/sites/default/files/document-file-12-2016/brag_report_-_final.pdf.

There also may be an increase in the frequency of tropical cyclones in the Atlantic (making up 11% of the total global hurricanes), indicating a potential shift in hurricane activity. This activity is increasing in concert with ocean temperature. In the Atlantic, therefore, the intensity and duration of events are clearly increasing in concert with tropical ocean temperature (Emanuel, 2005), and perhaps the frequency is as well, and these changes are likely to lead to a significant change in this climate hazard for the Atlantic coast (Emanuel et al. 2013; Dinan 2017; Marsooli et al. 2019).[19]

In addition to the historically occurring events, the MC-FRM includes a large, statistically robust set of synthetic TC storms generated using the statistical-deterministic approach of Emanuel et al. (2006).[20] This approach uses a combination of statistical and physics-based modeling to produce parameterized storms with behavior that mimics the natural variation commonly observed in nature, including storm genesis location, storm movement, evolution of storm size and intensity. These storms were created using different global climatological models and were generated by a storm seeding process following Emanuel et al., (2006). There is an increasing storm intensity and frequency included in these synthetic TC datasets.

Other Key Aspects of the MC-FRM Application

1. *The MC-FRM is calibrated to historical and contemporary storm events that impacted Massachusetts directly by comparing model results to observed high water data and measurements.* While the base models used in the Boston Harbor Flood Risk Model (BH-FRM; Bosma et al., 2015) pilot project (i.e., ADCIRC, SWAN) are rooted in sound science and utilize standard governing equations of water motion, the propagation of water through a unique geographic setting results in site-specific variations that may require adjustment of model parameters to more accurately represent the real-world system. For example, in an urban landscape, an area consisting of numerous buildings will influence flow differently than a marsh, which will influence flow differently than a parking area, which will influence flow differently than a sub-tidal estuary. For these types of cases, it is reasonable to adjust parameters, such as frictional factors within accepted bounds to better represent the water propagation. As such, the MC-FRM model was calibrated using both normal tidal conditions and representative storm events for the northeast. The calibrated model was then validated to multiple additional storm events to ensure accuracy. This calibration and validation process was completed for not only water surface elevation levels (tides and storm surges), but also for wave heights during storm events.
2. Coastal storm events striking an area result in different impacts depending on factors such as the timing of the storm with the tide cycle, the storm track, radius to maximum wind of

[19] Emanuel, Kerry. 2005. Increasing destructiveness of tropical cyclones over the past 30 years. Nature, 436, 686-688. Online supplement to this paper; Emanuel, K., 2013. Downscaling CMIP5 climate models shows increased tropical cyclone activity over the 21st century. Proc. Natl. Acad. Sci. 110 (30), 12219–12224; Dinan, T. 2017. Projected increases in hurricane damage in the United States: the role of climate change and coastal development. Ecol. Econ. 138: 186–198. https://doi.org/10.1016/j.ecolecon.2017.03.03; Marsooli, R., Lin, N., Emanuel, K., and Feng, K. 2019. Climate change exacerbates hurricane flood hazards along US Atlantic and Gulf Coasts in spatially varying patterns. Nature Communications, 10:3785. Doi:10.1038/s4146-019-11755-z.
[20] Emanuel, K., S. A. Ravela, E. A. Vivant and C.A. Risi. 2006. A Statistical-Deterministic Approach to Hurricane Risk Assessment. Bull. Amer. Meteor. Soc., 87, 299-314.

the tropical storm, the amount of precipitation, etc. Probabilistic modeling evaluates a statistically robust set of viable coastal storm conditions that produce spatially distributed flood probabilities. *The MC-FRM doesn't just simulate one storm or a few storms – the MC-FRM dynamically simulates hundreds to thousands of storms via a Monte Carlo methodology to produce flood exceedance probabilities at high spatial resolution.* Using this statistically robust approach, the annual coastal flood exceedance probability (ACFEP) can be defined as the annual probability of flood water inundating the land surface at a particular location. For example, a building that lies within the 2% ACFEP zone would have 2% chance every year that this location will get wet with salt water during a coastal storm event. Stakeholders can then determine if that is tolerable, or if some action may be required to improve resiliency, engineer an adaptation, consider relocation, or implement an operational plan. Critical assets, such as hospitals and evacuation routes, have different risk tolerances than parklands or parking lots.

3. *The MC-FRM is an extremely high-resolution model, with data results provided in overland areas on the order of 5-10 meters (16-33 feet), and as resolved as 2-3 meters (5-10 feet) in highly populated and developed areas.* This resolution allows MC-FRM to capture flood pathways in complex topographies and turn mathematical equations into high resolution maps. The MC-FRM uses a detailed modeling mesh, in which every intersecting point represents a specific set of data where the model equations are solved. Flood risk data are calculated as frequently as every second for every storm simulation. This provides more localized and accurate data for flood risk analysis and planning. It also has been shown that high resolution modeling can significantly improve predictions of inundation volumes and improve tide and surge signals (Thomas, et al., 2021).
4. *The MC-FRM integrates 4 different global climate models (GCMs) to capture the net effect of varying storm types, magnitudes, and frequencies due to projected ocean changes. The MC-FRM includes both tropical cyclones and extra-tropical cyclones* within the overall suite of events in the Monte Carlo simulations. Tropical cyclones include both historically occurring events (e.g., Hurricane Bob, Hurricane Edouard, Hurricane Carol, etc.) and storms generated using the statistical-deterministic approach of Emanuel et al. (2006). Extra-tropical cyclones are developed from those in the historic record (Blizzard of 1978, Superstorm Grayson, etc.). Overall, well over 1,000 storms are simulated.
5. The MC-FRM represents the most comprehensive and detailed "Level 3" approach21, as described by Federal Highway Administration's Highways in the Coastal Environment, Hydraulic Engineering Circular Number 25 (HEC-25), third edition (FHWA, 2020). The document presents a case study of the MC-FRM approach as "…a comprehensive Level 3 approach" and "…as an excellent example of a coastal transportation vulnerability assessment."
6. Precipitation based flooding and combined events. The primary focus of the MC-FRM is ocean-based flooding. However, this coastal based flooding also advances upstream in

[21] A Level 3 study incorporates expertise in coastal engineering, numerical modeling, hazard analysis, probability, and risk. Accordingly, such studies should be performed by accomplished engineers with demonstrated expertise in modeling extreme events as well as an understanding of the appropriate regional RSLR scenarios.

rivers, estuaries, and other connected water bodies and systems throughout the Commonwealth of Massachusetts. Therefore, all coastal rivers are included in the MC-FRM. These rivers also experience various levels of discharge, which is input into the MC-FRM as freshwater input. There are three types of freshwater boundary conditions applied in MC-FRM based on data availability. These include:

- Major rivers/estuaries that include precipitation-based storm hydrographs under present day and changing climate conditions. These rivers have changing discharge amounts based not only on the amount of precipitation/hour, but also on downscaled future precipitation intensities. The Charles and Mystic River include this type of freshwater input condition because information and data were available to add this component. Other rivers could not be treated in this manner, due to data gaps.
- Major rivers/estuaries that are represented with average discharge under current climate conditions and future conditions. These include the remaining major rivers: Taunton, Neponset, and Merrimack.
- Minor river/estuaries that do not include any freshwater discharge in the MC-FRM. These represent minor rivers and estuaries that are dominated by tidal exchange and have minimal freshwater input relative to the coastal variations.

Stochastic Weather Generator Dataset

Many of the impact analyses for the Climate Assessment require a finer geographic scale set of climate projections than are directly available from GCMs in their native form. One method to obtain such finer scaled values is the process of downscaling GCM results to smaller areas using methods such as the Delta method, or LOCA or MACA statistical downscaling (summarized above). Dynamic downscaling of GCMs is also an option – Coordinated Regional Climate Downscaling Experiment (CORDEX) from the World Climate Research Programme.[22] An alternative approach is developing a stochastic weather generator that uses statistical methods to relate local weather to the driving forces of weather and climate. Weather generators have been used to synthetically extend weather information under stationary climates and since at least 1992 to develop localized climate projections under climate change (Brown, 2013).[23]

The process of implementing a weather generator for a site starts with determining the atmospheric conditions that cause the local weather to occur. Once these conditions and their relationships to each other and the local weather are known, local weather for a site can be generated synthetically by stochastically changing the atmospheric conditions in such a manner that the relationships over time of the conditions to each other are probabilistically maintained. Because the conditions can be changed for an indefinite period of time while representing the present climate, it is possible to generate time series of the present weather that exceed the periods of record at a site. Having longer than historic periods of weather at a site is important

[22] Additional information on CORDEX, including a list of GCM/RCM availability for the North American domain, can be found at https://cordex.org/data-access/regional-climate-change-simulations-for-cordex-domains/ .

[23] Brown, C. 2013. Climate Risk Assessment of Coralville Reservoir: Demonstration of the Decision-Scaling Methodology, Report to the Institute of Water Resources, US Army Corps of Engineers, Draft: 29 November 2012, Revision: 1 February 2013, Hydrosystem Research Group, University of Massachusetts Amherst, Amherst MA.

for sites without long records so that extreme conditions of weather will be able to be determined and probabilities of their occurrence determined. To use weather generators to determine weather conditions under climate change, the atmospheric conditions that may correspond to the changed climate can be estimated and the weather generator run with the changed conditions. The most commonly applied source of these changed conditions for an area is GCMs, which are designed to simulate large scale atmospheric conditions (e.g., barometric pressure), though they are more commonly used to estimate the key parameters linked to impacts (e.g., temperature and precipitation).[24]

Weather generators are advantageous to use in local studies because unlike GCMs, which require modeling the entire global atmosphere and all its interactions with the rest of the Earth's systems, weather generators are intentionally designed to model small-scale systems. Thus, they are more computationally efficient than GCMs and, by their construction, are more explicitly calibrated to local conditions. Taken altogether, these tools allow for more rigorous analyses (e.g., computer runs) of the changing probabilities of severe and damaging weather and climate events at the local impacts scale (Ailliot et al, 2015).[25] Moreover, as previously stated, weather generators can be designed to be used with GCMs. A GCM, which models precipitation poorly, can be used to provide the changes in the atmospheric conditions that cause weather to occur (known as weather regimes), which a GCM models relatively well, which in turn can be input into a weather generator to produce local changes in precipitation and temperature.

The version of the Stochastic Weather Generator (SWG) model developed for EEA's Massachusetts Climate and Hydrologic Risk Project (Phase 1), and applied in the Climate Assessment, is designed to separately model dynamic and thermodynamic atmospheric mechanisms of climate variability and change through statistical abstractions of these processes. To capture atmospheric dynamics, the weather generator simulates sequences of weather regimes. Weather regimes are recurring large-scale atmospheric flow patterns (e.g., upper-level, quasi-stationary blocks and troughs) that appear at fixed geographic locations, persist for days-to-weeks within a season, and organize high-frequency weather systems. They represent intermediary phenomena in the stochastic continuum of atmospheric perturbations that connect local weather to hemispheric circulation and provide a parsimonious way of abstracting major patterns of atmospheric circulation into stochastic simulations of weather. To capture thermodynamic mechanisms of climate change, the weather generator post-processes simulated data to reflect patterns of warming and thermodynamic scaling of precipitation rates with that warming. These properties of the model are represented in a hierarchical structure composed of three primary modules: 1) identification and simulation of weather regimes that dictate the large-scale atmospheric flow across the eastern US; 2) simulation of local weather in

[24] Regional Climate Models might also be applied, typically using GCMs to provide boundary.

[25] Ailliot, P., Allard, D., Monbet, V., and Naveau, P. 2015. Stochastic weather generators: an overview of weather type models (Générateurs stochastiques de condition météorologiques : une revue des modèles à type de temps), Journal de la Société Française de Statistique, Vol. 156 No. 1 101-113.

HUC8 watersheds conditioned on the weather regimes; and 3) perturbations to the simulation schemes in (1) and (2) reflective of thermodynamic climate change.[26]

The SWG was applied to HUC-8 watersheds in Massachusetts, and sets of long time series of daily precipitation and average temperature or daily maximum and minimum temperature were generated for the present climate. The SWG was set up to include both dynamic and thermodynamic atmospheric conditions. Steinschneider et al. (2019) state these are key to realistically generating plausible future weather conditions.[27] The dynamic regime was the 500-hPa geopotential height (the 12 weather regimes in Figure 7 of Steinschneider and Najibi, 2022) that describe the present climate; the thermodynamic parameter was the air temperature. Instead of both the dynamic and thermodynamic conditions being perturbed to reflect changed climate conditions, the SWG outputs were altered by the temperature (thermodynamic) changes possible for each watershed under climate change. Thermodynamic changes are more reliably modeled than dynamic changes; therefore, only these changes were included for this Phase 1 product. This application is different from the peer-reviewed use of the SWG for the cold season in California (Steinschneider et al., 2019) where both changes in atmospheric dynamics and thermodynamics were considered.

The temperature values of the SWG output were scaled by the possible temperature changes and were used to scale the precipitation output using the Clausius-Clapeyron rate (i.e., the theoretical rate of change between atmospheric moisture holding capacity and temperature). The temperature projections for the HUC-8 watersheds were from 20 CMIP5 GCMs for RCP 4.5 and RCP 8.5 GHG emission scenarios and MACA downscaling of GCMs. It is important to note that for the Phase 1 SWG analysis (used in the Climate Assessment) the GCMs were used only to estimate the possible temperature changes in the HUCs over time and were not part of the weather generation process in this application. The Phase 2 SWG project contemplates a more complete use of GCM outputs as inputs to the SWG.

The process was applied to each of the 20 HUC-8 watersheds in Massachusetts, reproduced in Figure B-1 below. The parameters derived from the approach are reproduced in Table B-2 below. A particular aspect of the work is that: “Without an in-depth analysis of these mechanisms for the Northeast US, which was beyond the scope of this work, a choice was made to only allow extreme precipitation to scale with temperature and to maintain mean precipitation at historical levels in all future scenarios developed in this work” (Steinschneider and Najibi, 2022, page 11). This procedure means that any increases in positive extremes in precipitation were offset by decreases in negative extreme changes. The process was extensively and rigorously calibrated and verified under conditions of the present climate. The result, however, means that while the low and high tails of the precipitation distribution change over time in the currently available Phase I SWG projections, annual and seasonal means do not change over time and remain fixed at current climate levels.

[26] Steinschneider, S., and Najibi, N. 2022. A weather-regime based stochastic weather generator for climate scenario development across Massachusetts, Technical Documentation, Biological and Environmental Engineering, Cornell University, Ithaca, NY, April 2022

[27] Steinschneider, S., Ray, P., Rahat, S.H., and Kucharski, J. 2019. A weather-regime based stochastic weather generator for climate vulnerability assessments of water systems in the Western United States, Water Resources Research, 55. https://doi.org/10.1029/2018WR024446.

Figure B-1. MA HUC-8 Watersheds

(Reproduced from Steinschneider and Najibi, 2022)

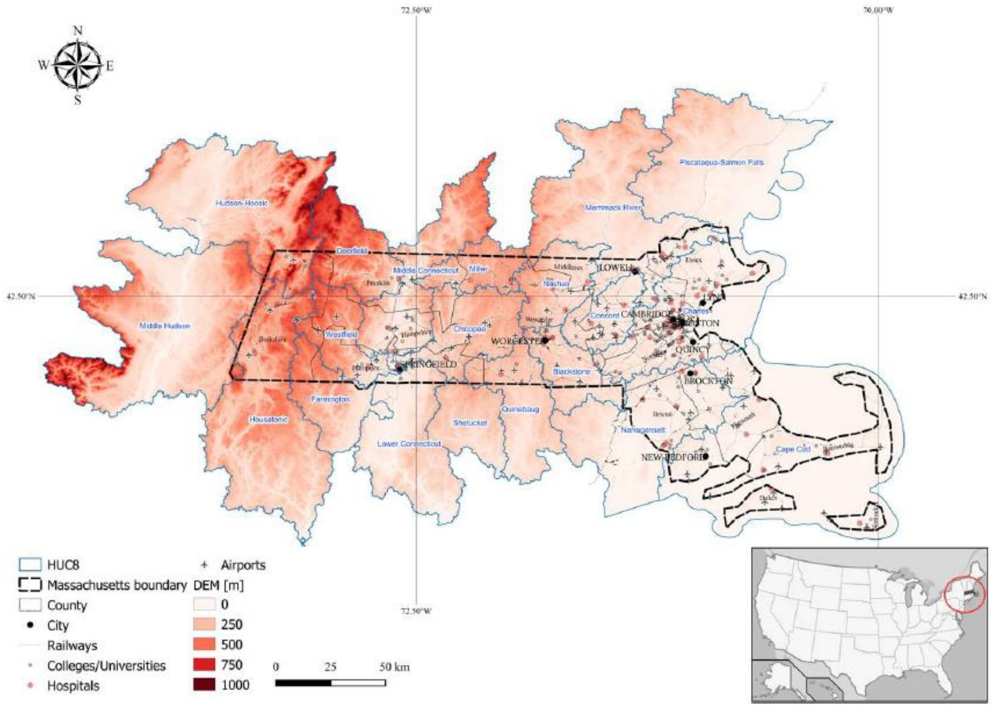


Figure 1. HUC8 watersheds across the state of Massachusetts that are modeled with the stochastic weather generator.

Table B-2. Climate Parameters for each HUC Watershed in Massachusetts

(Reproduced from Steinschneider and Najibi, 2022)

No.	Precipitation	Units of Change	No.	Temperature	Units of Change
1	Consecutive dry days	# days	1	Average temperatures	°F
2	Consecutive wet days	# days	2	Maximum temperatures	°F
3	Extreme precipitation > 1 in	# days	3	Minimum temperatures	°F
4	Extreme precipitation > 2 in	# days	4	Cooling degree days	degree-day
5	Extreme precipitation > 4 in	# days	5	Growing degree days	degree-day
6	Total precipitation*	% change	6	Heating degree days	degree-day
7	Maximum precipitation	% change	7	Days < 0 F	# days
8	90th percentile of precipitation	% change	8	Days < 32 F	# days
9	99th percentile of precipitation	% change	9	Days > 100 F	# days
10			10	Days > 90 F	# days
11			11	Days > 95 F	# days
12			12	Number of heatwaves	# events
13			13	Average duration of heatwaves	# days
14			14	Maximum duration of heatwaves	# days
15			15	Number of coldwaves	# events
16			16	Average duration of coldwaves	# days
17			17	Maximum duration of coldwaves	# days
18			18	Number of heatstress events	# events
19			19	Number of coldstress events	# events

Results are available both annually and seasonally. To use the results, the MACA downscaled temperature increase for a basin by 0.5 °C increments is selected and then the SWG results for that value retrieved. Time periods are assigned to the changes based upon the downscaling of RCP4.5 and RCP 8.5 emission scenarios. Importantly, 20 GCMs were used to determine potential future temperature changes. Therefore, the output from the SWG provides the temperature and precipitation statistics for the 10th, 90th and median percentile values from among the 20 GCMs.

The watersheds used in the SWG analysis (Figure B-1) do not match the spatial scales used in the Climate Assessment, but the values were assigned in an impact-by-impact basis as needed using area weighted GIS techniques.

Scaled Intensity-Duration-Frequency (IDF) Curve Dataset

The Scaled IDF Curve dataset applied in the Climate Assessment is documented in the Journal of Hydrometeorology (Steinschneider and Najibi, 2022) and Geophysical Research Letters (Najibi et al. 2022).[28] IDF (Intensity-Duration-Frequency) curves are used to establish design standards across a range of civil infrastructure. These curves are developed from historical data which is collected over a shorter time period then is desired to provide statistically significant estimations of less frequent events. Figure B-2 is a sample intensity frequency curve for a 24-hour storm in the Nashua basin taken directly from the NOAA Atlas 14 Point Precipitation Frequency estimate. One can observe from this curve that the uncertainty grows with the recurrence interval reflecting lack of sufficient observations to accurately estimate these rare events.

Figure B-2: Nashua Basin 24-Hour IDF with Uncertainty Bounds

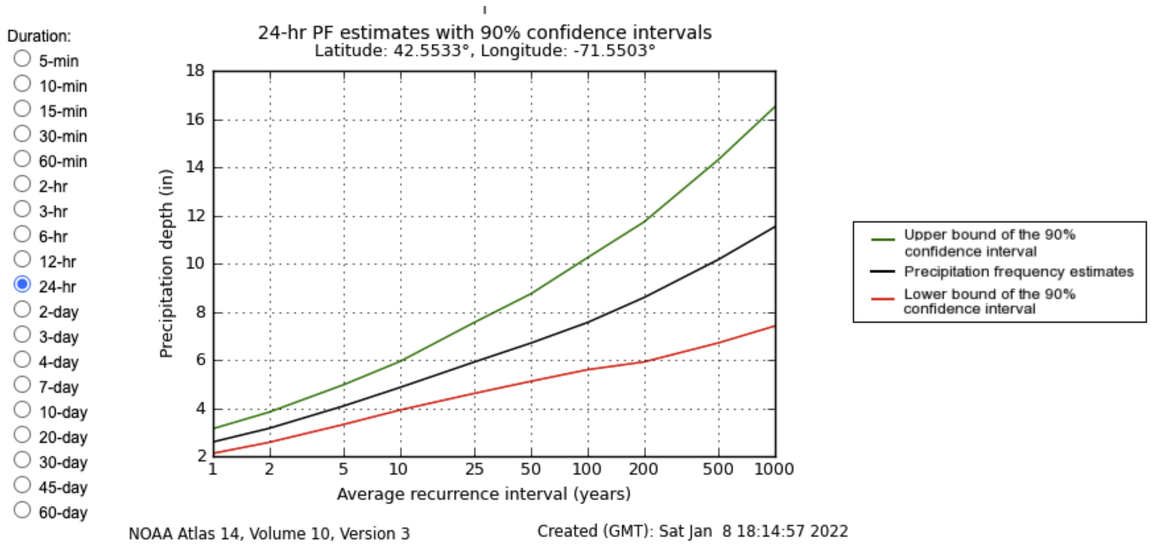
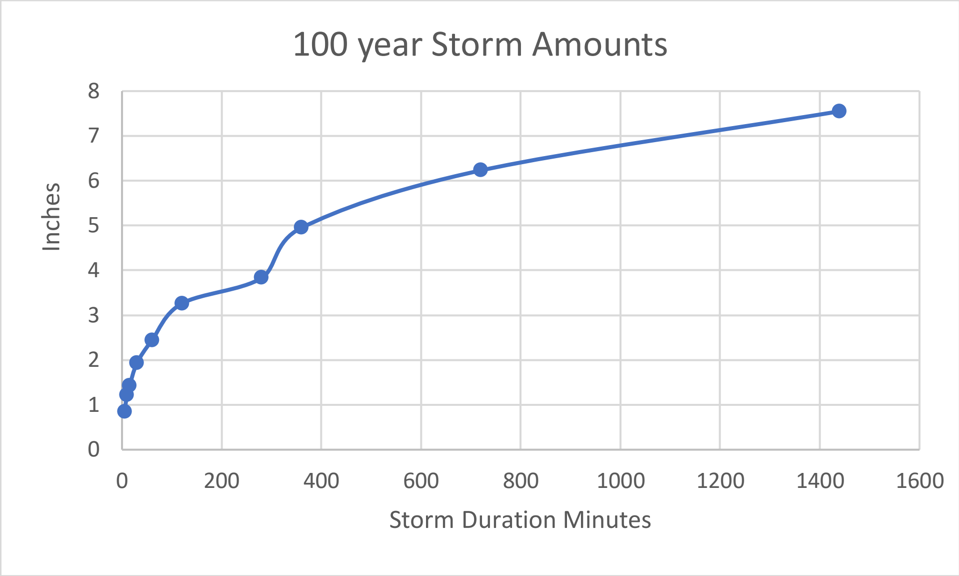


Figure B-3 provides a different look at the IDF curve for Nashua basin and examines the intensity of rainfall over different storm durations. Figure B-3 illustrates that the marginal increase of precipitation amount per time period of storm duration declines rapidly after three hours and appears linear over the range of 6 to 24 hours. This suggests that the physics/meteorology of intense rainfall is driven by different phenomenon between short and long duration storms.

[28] Steinschneider, S., and Najibi, N. 2022. Observed and Projected Scaling of Daily Extreme Precipitation with Dew Point Temperature at Annual and Seasonal Scales across the Northeastern United States, Journal of Hydrometeorology, 23 (3): 403-419, DOI: https://doi.org/10.1175/JHM-D-21-0183.1; N. Najibi, S. Mukhopadhyay, S. Steinschneider. 2022. Precipitation Scaling With Temperature in the Northeast US: Variations by Weather Regime, Season, and Precipitation Intensity. Geophysical Research Letters, 49(8). https://doi.org/10.1029/2021GL097100

Figure B-3: Intensity of 100- year Storms for Nashua Basin Massachusetts



Source: Project Team analysis of NOAA 14 data

Steinschneider and Najibi (2022) provides an application to estimating changes in IDF curves for future climate, using a theoretical scaling approach which can be cross-walked with a weather generator, GCM, or downscaled GCM analysis of arrival times for future temperature. The majority of the document is the background research that leads the authors to make the following statement:

> *"The primary conclusions of this report are that empirical scaling rates of extreme precipitation with warming range between 0% and 11% per °C, with average scaling rates across seasons and methods ranging between 3% and 5% per °C."*

Based on this finding, the authors have proposed a simple scaling mechanism where all elements of the NOAA Atlas 14 IDF table calculated at a 30 arc-second grid over Massachusetts are scaled by the theoretical rate of 7% per °C, using an estimate of the change in annual mean temperature obtained at the same 30 arc-second grid from the MACA downscaled product.

Based on comments from expert peer panel, the Project Team explored the option of adopting an approach from discussions of a Commonwealth Stormwater Advisory Team which suggested consideration of the upper limit of the 90 percent confidence interval from the current climate NOAA 14 IDF curve rainfall tables.[29] The Project Team concluded that, for the Climate Assessment, it is most appropriate to use the scaled IDF curves alone, which are consistent with best available information on future changes to the NOAA 14 IDF curves associated with changes in future climate.

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[29] The publicly available presentations from the meeting are available here: https://www.mass.gov/doc/stormwater-advisory-committee-meeting-3-presentation/download. The technique is referred to in the meeting is called "NOAA Plus."

Land Surface Temperature Index

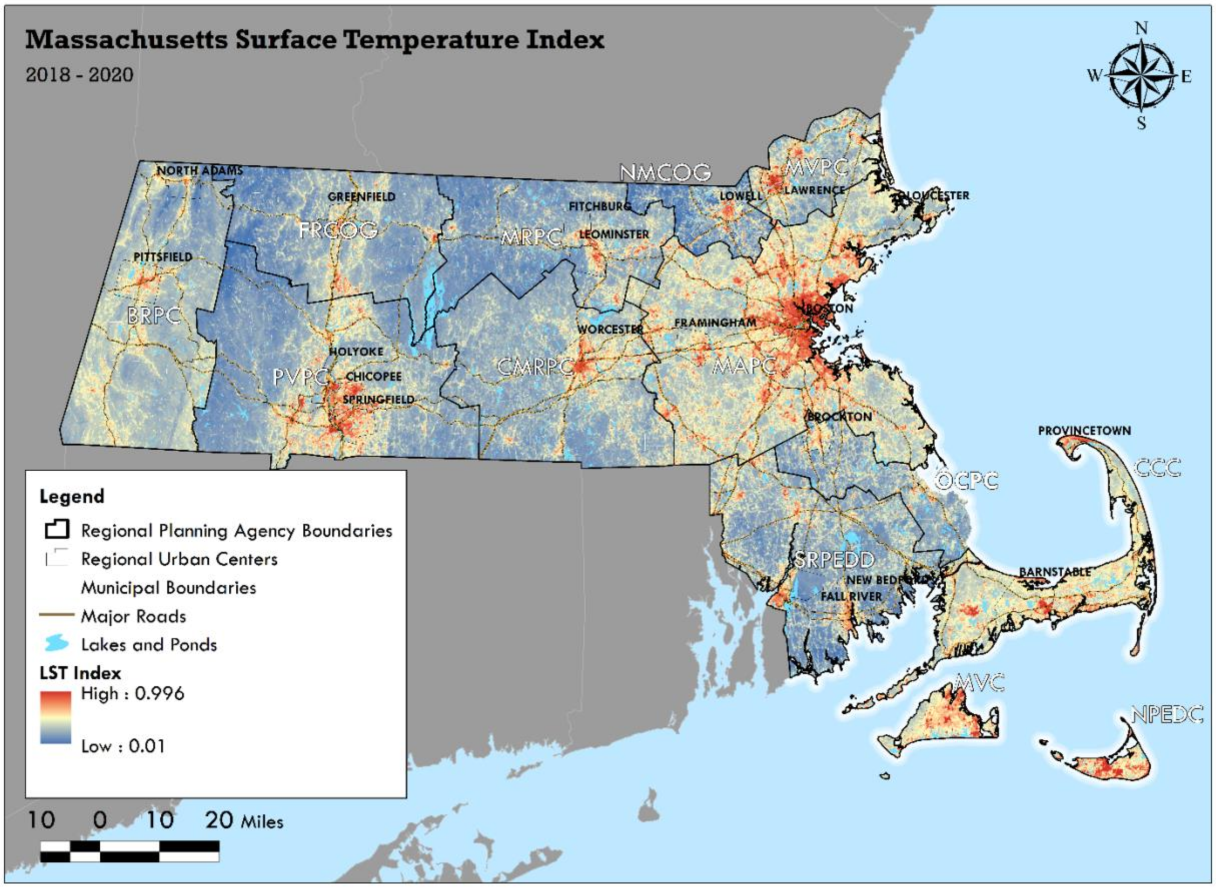
The Land Surface Temperature Index applied in the Climate Assessment is documented in the following report: Building Resilience to Climate-Driven Heat in Metro Boston; Task 2: Data Collection, Analysis, and Modeling, Sub-task 2.1: Modernizing regional land surface temperature spatial data; Extension: Statewide Land Surface Temperature Index; by Caitlin Spence PhD, Lily Perkins-High, and Timothy Reardon of the Metropolitan Area Planning Council (MAPC), November 1, 2021.

The dataset provides a new spatial land surface temperature (LST) index dataset across the entire state of Massachusetts. The new resource is based on land surface temperature estimates derived from remotely sensed imagery[30] (from 2018-2020) and is intended to help cities and towns identify areas with the most intense urban heat island effects and to prioritize adaptation interventions. In brief, the method uses LST estimates from multiple dates, and combines them into a composite index which reflects heat effects across space. The work updates the previous MAPC LST map, which estimated land surface temperatures for two days: one in August of 2010 and another in July of 2016. The updated version aggregates up to 30 images for each of the 13 Regional Planning Agency (RPA) regions. The dates for these aggregated images are selected from all available imagery based on criteria such as coverage, quality, and if the daily high temperature exceeds 70^{o}F. The criteria are evaluated across each RPA independently, rather than state-wide, which results in LST indices composed of different days for each RPA. As a result, the composite LST values are comparable within the RPA but not the across RPA boundaries.

The resulting LST index product is a gridded raster with 30m resolution showing values for the 2018-2020 period, as depicted in Figure B-4 below. Companion products include: (1) a 30m raster which depicts the variability in single-day normalized LST at each location and (2) a vector-format polygon shapefile mapping the areas which have the highest fifth percentile LST index values across each RPA region.

[30] The updated dataset is created based on Landsat 8 Collection 1 Analysis-Ready Data (ARD) available from the United States Geological Survey (USGS) Earth Explorer tool (https://earthexplorer.usgs.gov/). Historical air temperature data is from National Oceanographic and Atmospheric Administration (NOAA) Global Historical Climatology Network Daily (GHCND) meteorological stations, with a single station assigned to each of the 13 RPAs.

Figure B-4: MAPC Land Surface Temperature Index, 2018-2020



The LST is used in the Climate Assessment as a separate metric of risk for impacts such as heat mortality in the "disproportionality of exposure" metric calculation (see Statewide report for details). An overlay analysis is used to compare the spatial distribution of the LST "hot spots" corresponding with a potential for extreme heat risk, to the location of environmental justice/socially vulnerable populations, relative to the remainder of the population.

Downscaled Global Climate Models (GCMs)

The use of GCMs as climate inputs ensures that consistent atmospheric physics are reflected in the impact results, but the use of the results of climate models in raw form is potentially problematic, for two reasons: 1) A model simulation of historical conditions may be biased relative to measured historical conditions, creating a bias which can be corrected through calibration to measurements; and 2) Climate models from differing modeling groups use different grid systems, and in most cases with resolution on the order of 10,000 km^2 – spatial downscaling of results, often again using historical measured conditions as a guide, can provide a finer spatial resolution.

As noted above, the Climate Assessment makes strategic use of downscaled and bias-corrected GCM data from the MACA and LOCA datasets.

To provide more localized projections of climate changes—important for local impact assessment and adaptation planning—and to provide more consistency with historical observations, downscaling methodologies are typically employed. The approach used in this report is statistical downscaling, which develops statistical relationships between local climate variables (e.g., temperature or precipitation) and large-scale predictors (e.g., pressure fields) and applies those relationships to the GCM output. While many downscaled products using the CMIP5 archive are available, the Climate Assessment uses two of the highest-quality, publicly available, and peer-reviewed downscaled primary datasets:

- MACA: Multivariate Adaptive Constructed Analogs (MACA) is a statistical method for downscaling Global Climate Models (GCMs) from their native coarse resolution to a higher spatial resolution that captures reflects observed patterns of daily near-surface meteorology and simulated changes in GCMs experiments. This method has been shown to be slightly preferable to direct daily interpolated bias correction in regions of complex terrain due to its use of a historical library of observations and multivariate approach. The baseline "training" dataset used here is the 6-km (1/16th degree) daily product of Livneh et al. (2013) from 1950-2011. Available results include maximum temperature, minimum temperature, maximum and minimum relative humidity, precipitation accumulation, downward surface shortwave radiation, wind-velocity, and specific humidity.[31] MACA is based on the CMIP5 ensemble and employs a quantile mapping and constructed analogs approach, a methodology that is similar to LOCA but which also provides a daily synoptic weather field and additional climate inputs not available from LOCA.
- LOCA: A 2016 dataset of downscaled CMIP5 climate projections was commissioned by the U.S. Bureau of Reclamation and Army Corps of Engineers and developed by the Scripps Institution of Oceanography and collaborators. This dataset, called LOCA (which stands for Localized Constructed Analogs), has some advantages, notably, the statistical approach produces improved estimates of extremes, constructs a more realistic depiction of the spatial coherence of the downscaled field, and reduces the problem of producing too many light-precipitation days. The LOCA dataset provides daily projections through 2100 at a 1/16th degree resolution for three variables: daily maximum temperature (tmax), daily minimum temperature (tmin), and daily precipitation.

1.3. Additional Summaries of Climate Projections and Data for Massachusetts

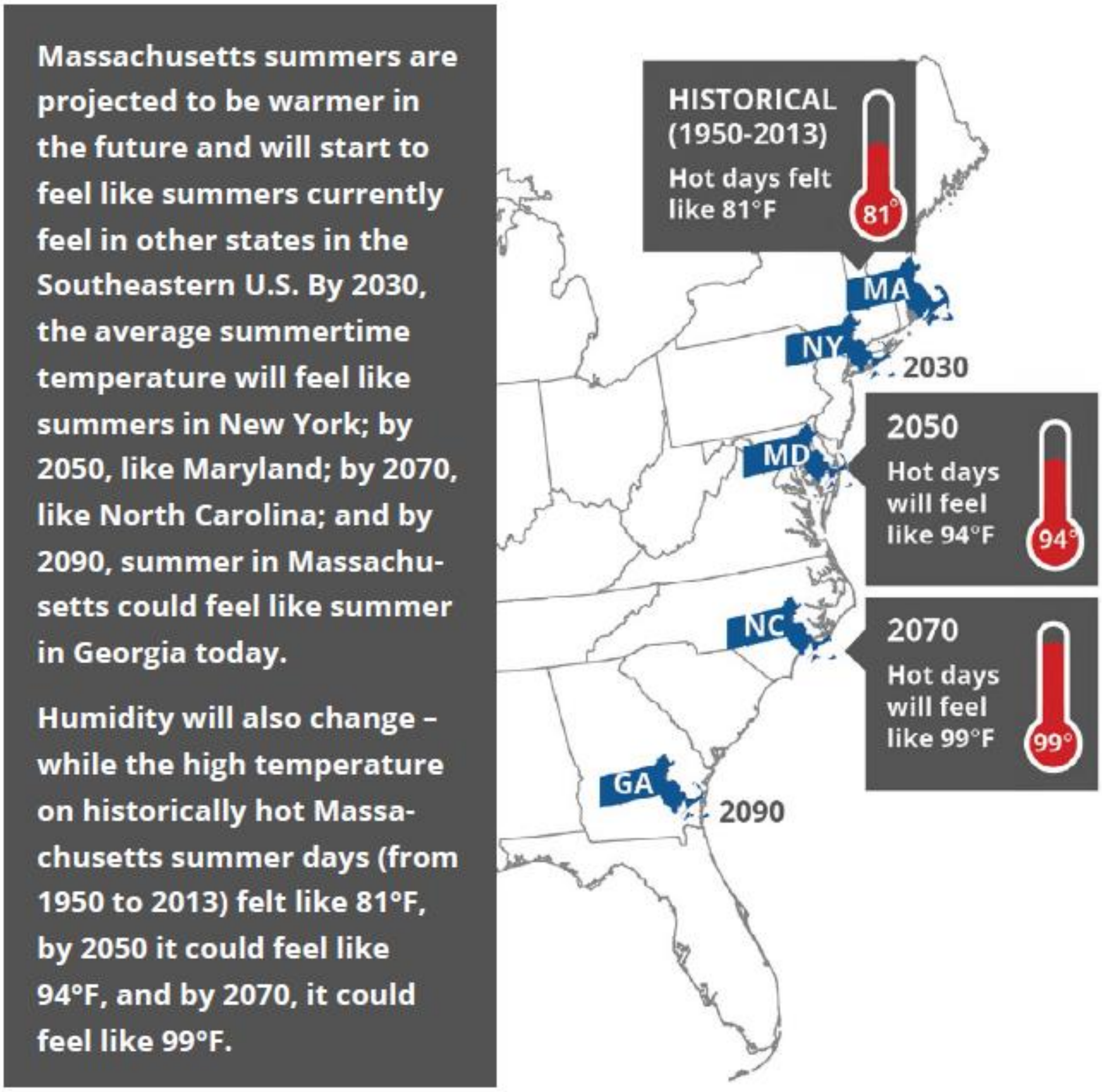
Temperature

As described in Chapter 3, warmer temperatures and more frequent heat waves are connected to impaired human health, increased droughts, reduced agriculture yields, and damaged

- [31] For more details see: https://www.climatologylab.org/maca.html infrastructure. They are also connected to increased ozone pollution; spread of invasive species; increase in wildfire potential; reduced snow cover, with implication for winter sports and an increasing temperature feedback with less sunlight reflected; and the migration of habitat for commercial ocean species such as lobster.

Figure B-5 below summarizes how summer temperature could be expected to change in Massachusetts over the next century.

Figure B-5. Change in Average Summertime Temperatures for Massachusetts



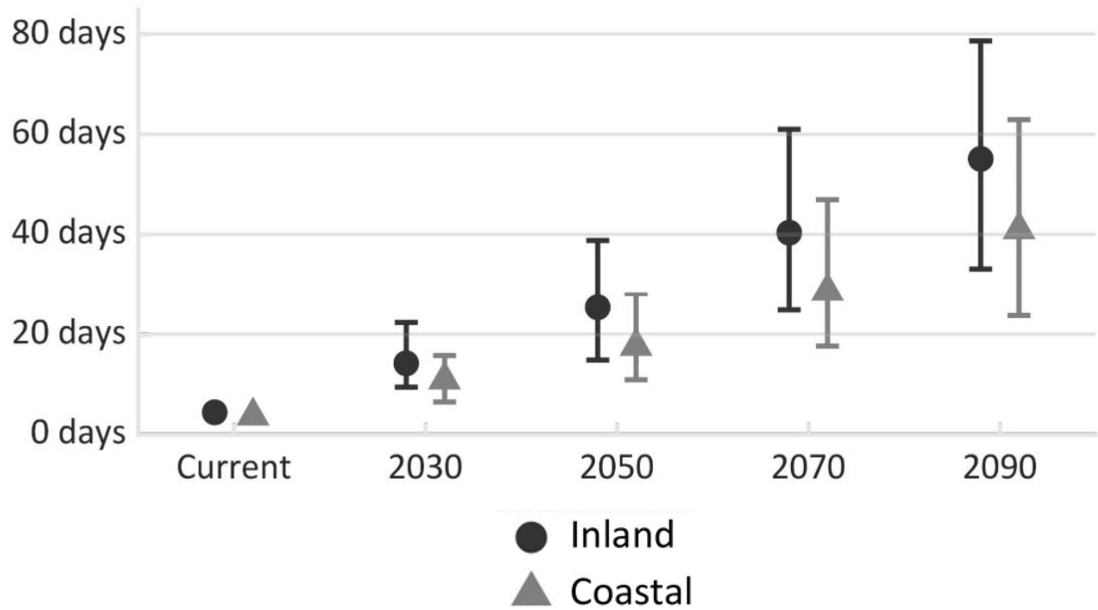
Source: Stochastic Weather Generator and analysis of LOCA GCM data outside of Massachusetts

Figure B-6 provides a different perspective, focused on the number of days per year where temperatures could exceed 90°F, or, in Panel B, could exceed 100°F, compared to current climate. The available climate model projections all show a warming trend throughout the 21st century, with inland areas warming faster than coastal areas. By mid-century, the mean projection has about 25 more days above 90°F for inland areas, and about 19 more days above 90°F for coastal areas. Overall, coastal areas would see about 25 percent more moderate increases in days per year with maximum temperatures above 90°F.

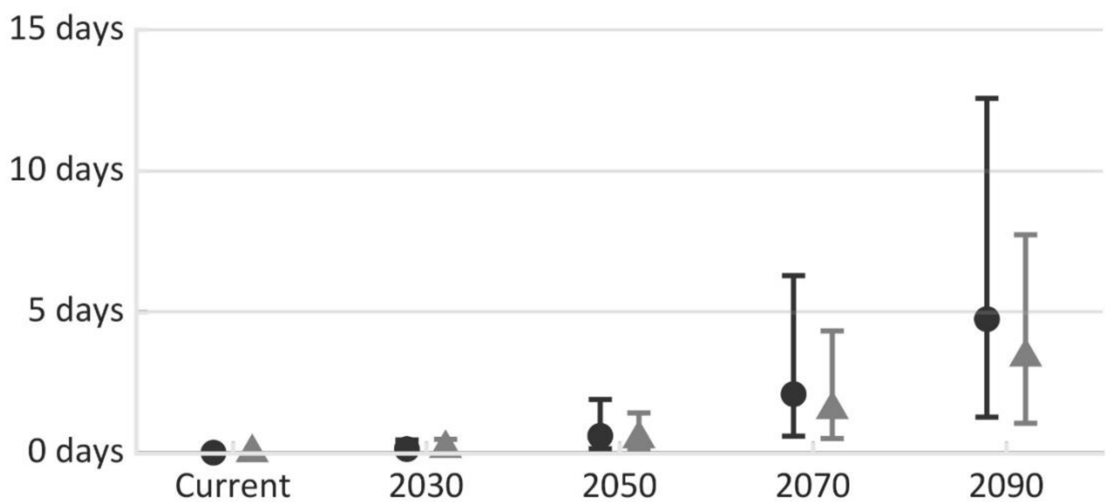
Figure B-6. Change in the Number of Days Per Year Over 90°F and 100°F Compared to Current Climate

Current climate is the 1985-2005 era, projections are for 20-year eras centered on the year shown from the Stochastic Weather Generator. Black circles represent the mean of available climate models for inland regions (Berkshires and Hilltowns, Greater Connecticut River Valley, Central, and Eastern Inland), gray triangles represent mean for coastal regions (North and South Shore, Boston Harbor, and Cape, Islands, and South Coast). The brackets show the range across available climate models, providing a measure of uncertainty in the projections.

Panel A: Days exceeding 90°F



Panel B: Days exceeding 100°F

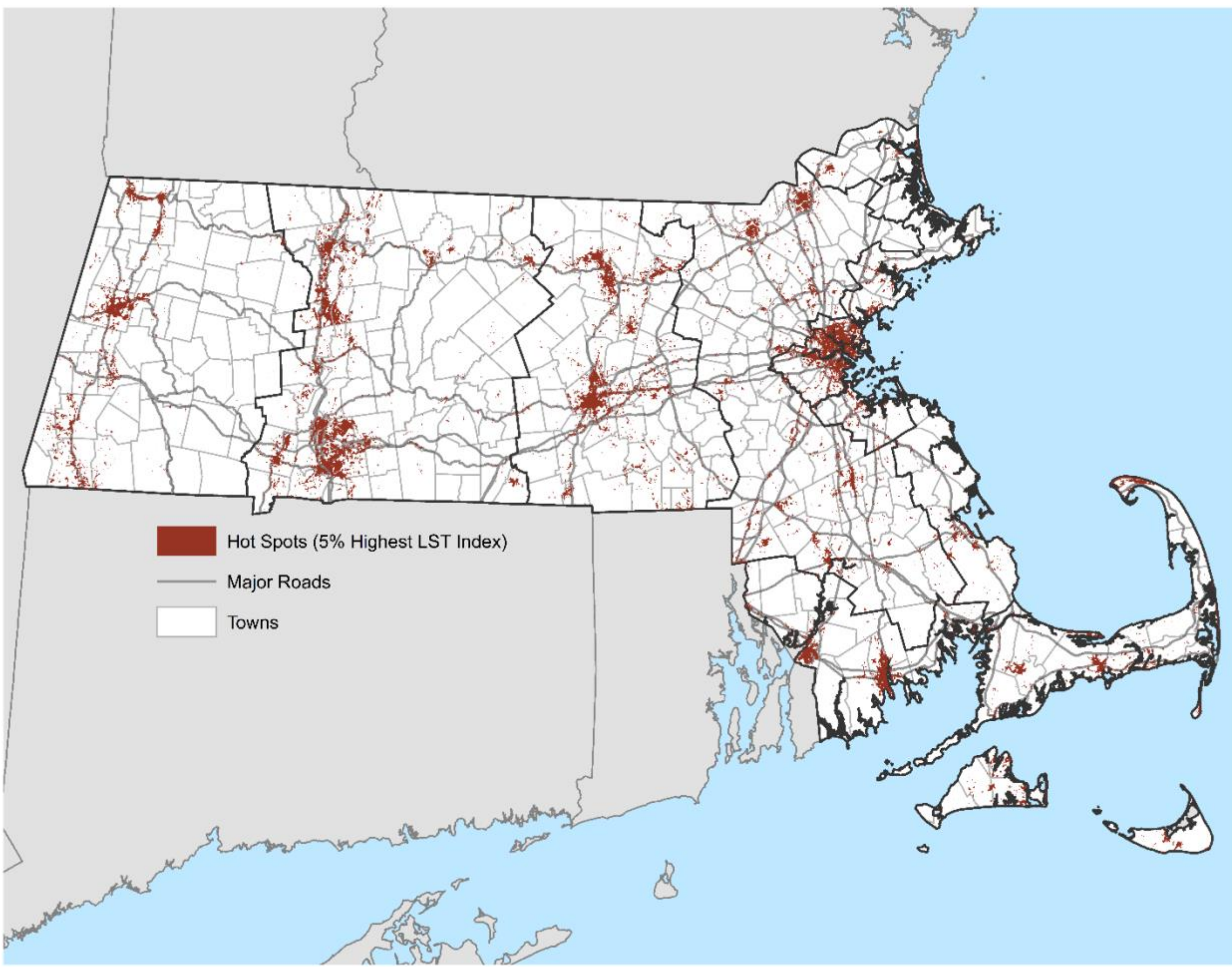


The estimates in Figure B-6 do not include the effect of changes in humidity. As temperatures rise, the air can hold more moisture – and available estimates suggest that absolute humidity will increase over time, making these temperatures feel even warmer. In other words, every 90°F or 100°F in the future could feel warmer and have a greater impact on human health for example, than current 90°F or 100°F days.

The Land Surface Temperature index also provides a measure of the distribution of high temperatures, at least for the historical record. Figure B-7 below shows relative "hot spots" in red, which represent the locations of the 5 percent highest temperature values within each of Massachusetts' 13 Regional Planning Agency (RPA) regions. Major roads and town boundaries are also shown in the Figure, for reference. As mentioned above, the composite LST values are comparable within the RPA but not the across RPA boundaries – the red areas below represent relative hot spots within each RPA only, not across the state.

Figure B-7. Locations of Relative Temperature "Hot Spots" within Regional Planning Council Regions – 5 percent Highest Land Surface Temperature Index

Black lines show regional boundaries, town boundaries and major roadways.



Source: Project Team analysis of MAPC Land Surface Temperature Index data

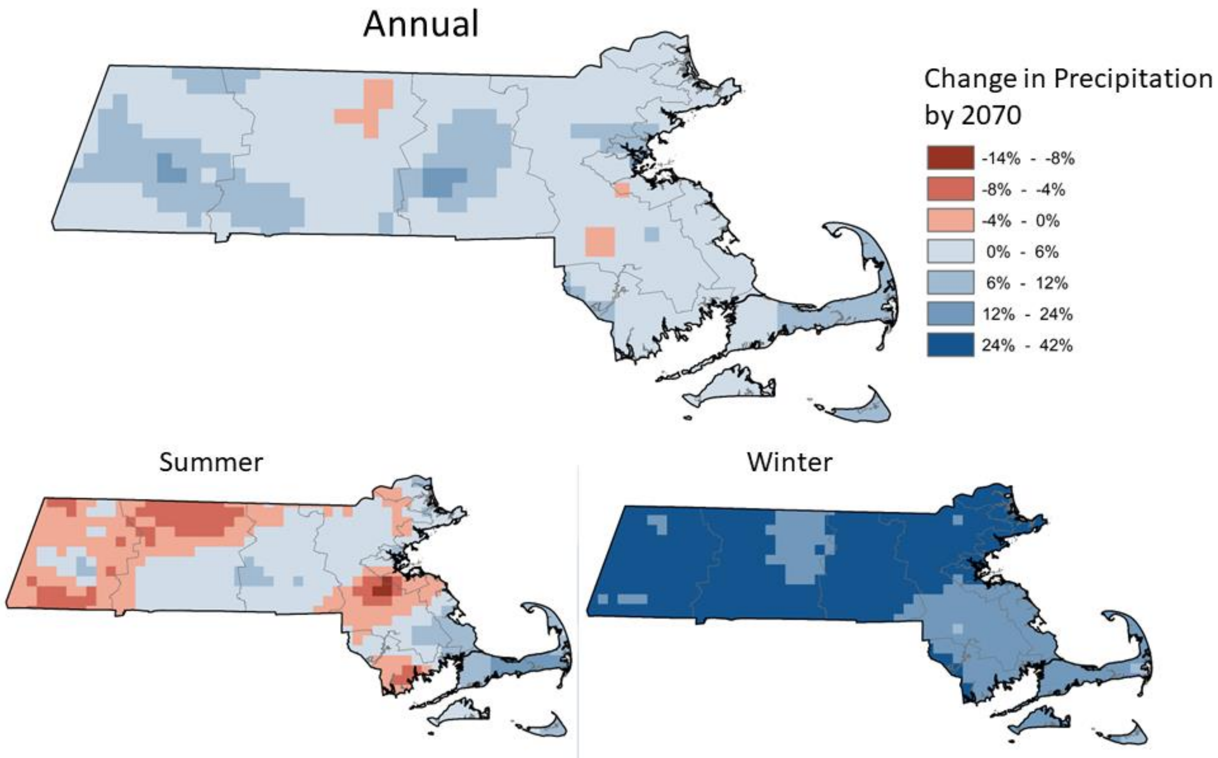
Precipitation

Forecasting precipitation under climate change is complex. In general, scientists expect that there could be more rain overall in Massachusetts, on an annual basis and in most years, as higher temperatures will mean the moisture holding capacity of the atmosphere increases. Figure B-8 is a map, derived from LOCA GCM data, which shows that most areas of Massachusetts can expect to see an increase in the annual total precipitation (increases are shown in blue). In most locations the increase in annual precipitation is less than 8 percent per year, and in a few locations (shown in red) small decreases in annual precipitation of less than 4 percent are expected. The data shown in Figure B-8 is an ensemble mean result from 20 GCMs, so individual GCM results could vary from the mean, and the variance and uncertainty in these projections would grow over time, with larger variance and uncertainty in late-century than early or mid-century.

Most of the differences in precipitation, however, are confined to differences in seasonal results. As shown in the “summer” and “winter” panels in the lower part of Figure B-8, most of these increases are expected in winter, are much larger than the annual increases, and more consistent over space. In summer, the overall state average (not shown) has little or no change from the 1986-2004 baseline period from the LOCA data, but a wide range of variation over space, with increases in the 18 to 24 percent range over Cape Cod, and decreases in the 89 to 14 percent range in the area just southwest of Boston, coupled with decreases in the Berkshire/Hilltowns and Greater Connecticut River Valley in the western part of the state.

Figure B-8. Change in Annual, Summer, and Winter Season Precipitation in 2070 Compared to Current Climate

Current climate is the 1986-2005 era, the projection for 2070 is for a 20-year era centered on 2070. Results use LOCA downscaled GCM results. Results are the 50th percentile across 20 LOCA GCMs that overlap with the GCMs used in the Stochastic Weather Generator.



In addition, the days of rainfall could be more variable, and reduced overall, implying that on those days when it does rain or snow, there will be more moisture. The reduction in days when it rains has implications for air quality, for example, generally reducing the "washout" effects that a rainy day has in reducing concentrations of soot, particulate matter, and even pollen in the atmosphere. These daily patterns could also be important for drought measures. Table B-3 shows two measures of these daily patterns – Panel A shows the number of events of consecutive dry days (of any length of number of days) derived from the Stochastic Weather Generator. Panel B show the annual total number of days without rain per year, from analysis of LOCA downscaled GCM data. Together they show consistent results, with both sources indicating an increase of about 3 percent in both the number of consecutive dry day events and the total number of days without rain statewide by 2090. The increase in dry days is somewhat larger in the Berkshire region, and somewhat smaller in the Boston Harbor region, than statewide.

Table B-3. Indicators of Drought – Consecutive Dry Day Events and Total Annual Days without Rain in Massachusetts

Future results presented for four time periods identified in the table by their central year: 2030 (near-term, 2020-2039); 2050 (mid-century, 2040-2059); 2070 (mid-late century, 2060-2079); and 2090 (end of century, 2080-2099). Values may not sum due to rounding.

Panel A: Consecutive dry day events (number of multiple-dry-day events per year)

Region	Baseline	2030	2050	2070	2090
Berkshires & Hilltowns	29	29	30	30	31
Greater Connecticut River Valley	31	31	32	32	33
Central	32	32	32	33	33
Eastern Inland	32	32	32	33	33
Boston Harbor	31	31	32	32	33
North & South Shores	31	31	32	32	33
Cape, Islands, & S. Coast	31	31	32	32	33
Statewide	**31**	**31**	**31**	**32**	**33**
Statewide Percent Change	***0%***	***1%***	***2%***	***4%***	***6%***

Source: Stochastic Weather Generator

Panel B: Annual number of days without rain (days per year)

Region	Baseline	2030	2050	2070	2090
Berkshires & Hilltowns	159	161	165	167	170
Greater Connecticut River Valley	171	172	175	178	181
Central	180	182	185	188	192
Eastern Inland	186	181	185	188	193
Boston Harbor	192	185	192	194	198
North & South Shores	184	182	187	190	195
Cape, Islands, & S. Coast	186	182	187	191	194
Statewide	**176**	**175**	**179**	**182**	**187**
Statewide Percent Change	***0%***	***-1%***	***2%***	***3%***	***6%***

Source: Analysis of LOCA downscaled GCM data

The greater intensity of rainfall on rainy days, on the other hand, can lead to flooding, stress on built infrastructure, and consequent impacts on human health. Figure B-9 provides a sense of how precipitation intensity and frequency could change over time (i.e., future design storms), and across Massachusetts regions. The graphs show changes in rain that can be expected in the

24-hour, 10 percent chance of occurring annually rain event (or 10-year return period event). Under current climate that event is roughly 3 inches for all regions. In the future, the intensity of that event could increase by one third, to 4 inches in a day. At the same time, the frequency of the 3-inch historical event changes – the dots along the bottom of graphic show this change.

Figure B-9. Change in Intensity and Frequency of Extreme Precipitation Events: Impact of Climate Change on the 10 Percent Annual Probability (10-year return period) Historical Rainstorm

Current climate is the 1985-2005 era, projections are for 20-year eras centered on the year shown, data from analysis of Global Climate Models, downscaled using the Localized Constructed Analogs (LOCA) approach. Graph shows change in frequency of the historical 10 percent annual chance decade storm (1 in 10 year return period). Circles on the graph represent the mean of available climate models, brackets show the range across available climate models, providing a measure of uncertainty in the projections. Dots below graphs show the change in frequency of the historical 10-year 24-hour rain event. Western includes the Berkshires and Hilltowns and Greater Connecticut River Valley regions; Central includes the Central and Eastern Inland regions, and Coastal includes North and South Shore, Boston Harbor, and Cape, Islands, and South Coast regions.

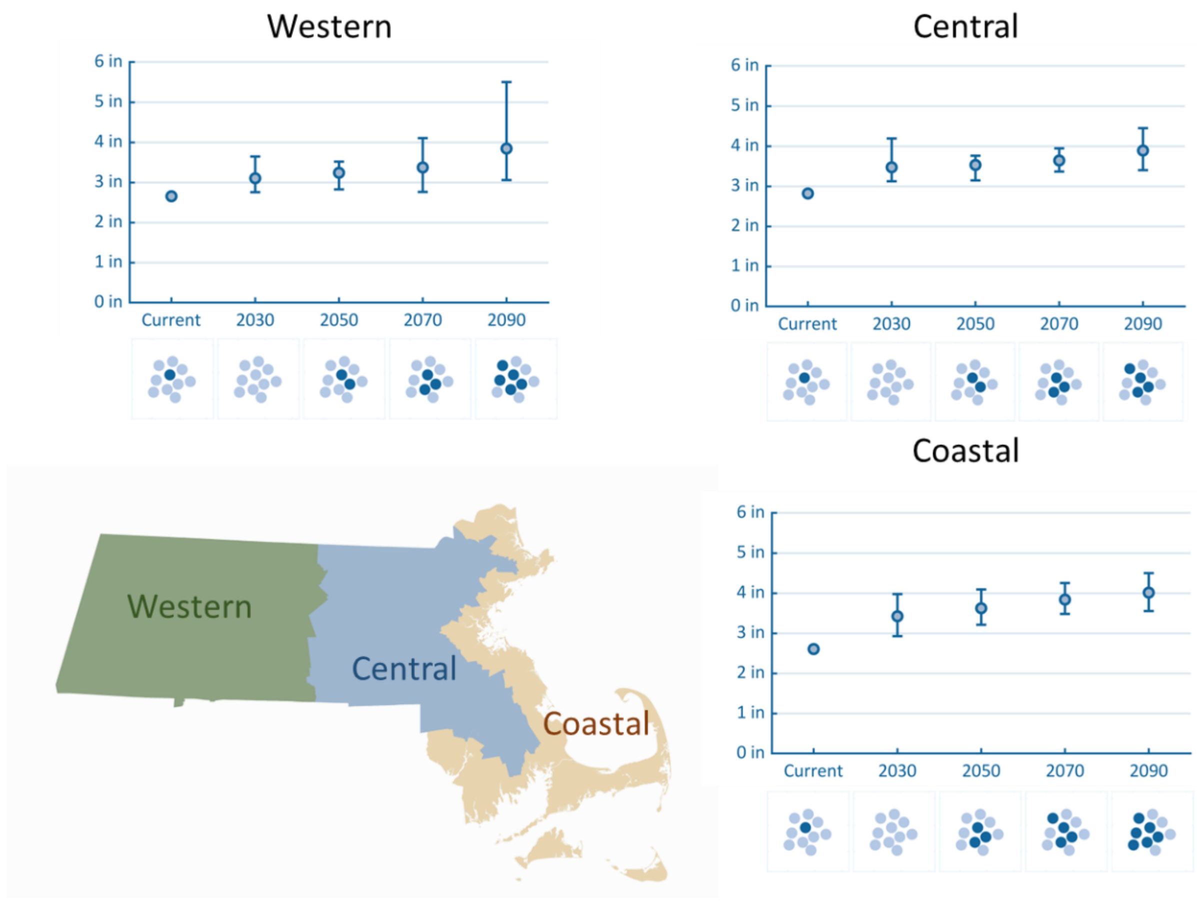
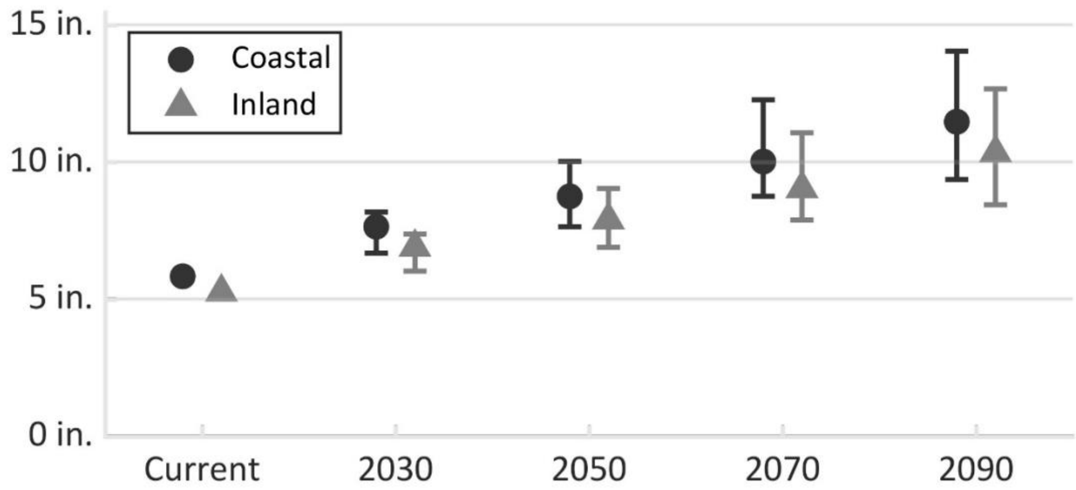


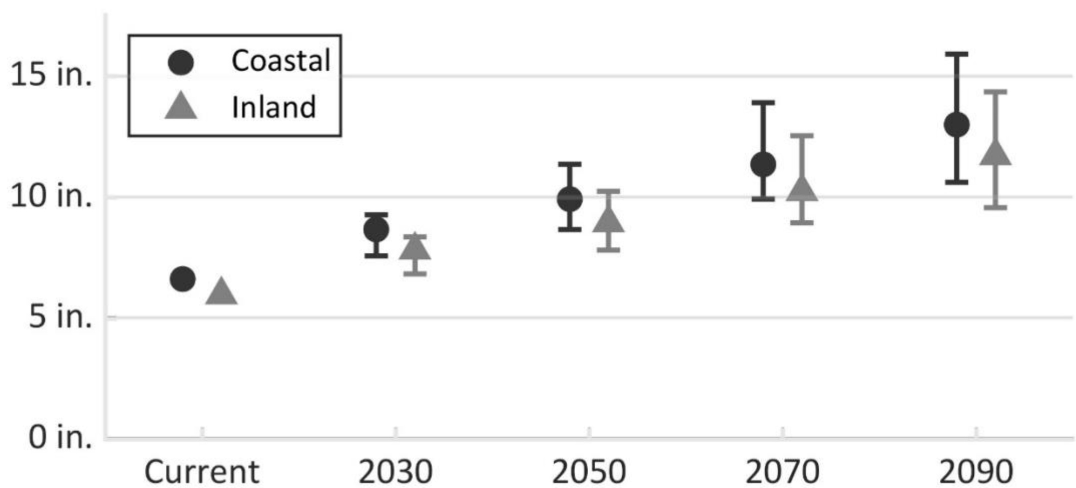
Figure B-10 provides additional data, from the same Scaled IDF curve source, but for different regions (coastal versus inland regions), and for different return-period rainfall events – the 25-yr return period (4 percent annual chance) in Panel A, the 50-year return period (2 percent annual chance) in Panel B, and the 100-year return period (1 percent annual change) in Panel C.

Figure B-10. Change in Intensity of Extreme Precipitation Events: Impact of Climate Change on the 4, 2, and 1 Percent Annual Probability (25-year, 50-year, and 100-year return period) Historical Rainstorm

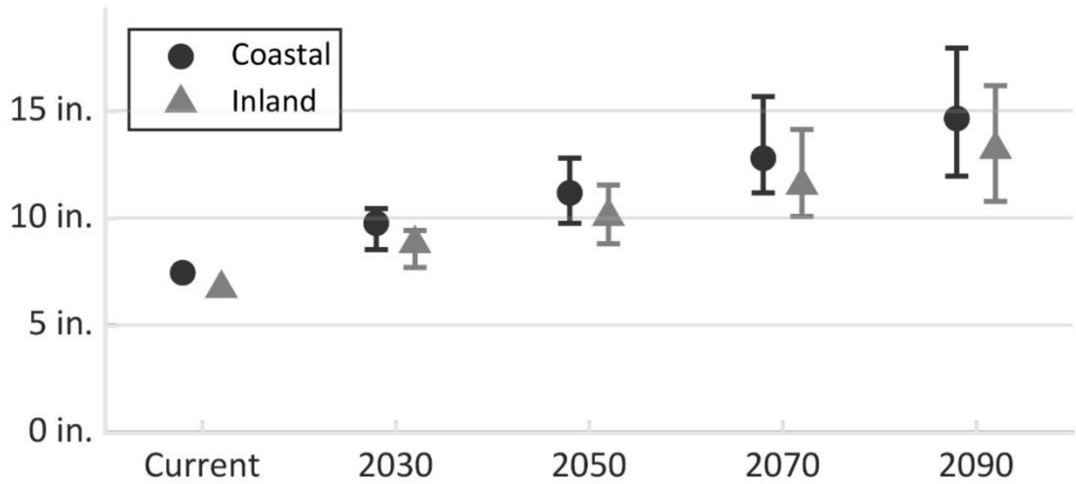
Panel A: 25-year return period, 24-hr storm



Panel B: 50-yr return period, 24-hr storm



Panel C: 100-year return period, 24-hr storm



Source: Scaled IDF Curves

Season Length

Estimating changes in season length is complicated by the lack of well-established measures for changes in seasons (other than calendar time). A complex indicator used in one of the impact analyses, exposure to certainly types of pollen (aeroallergens) is an indirect measure of changes in seasons, which reveals increase in pollen season of 10-15% over the century for selected pollen types (oak, birch, and grasses). Other physical indicators used in the Natural Environment sector, such as for forest health, may also be informative.

One commonly used measure that is temperature-based and readily available from the Stochastic Weather Generator is Growing Degree Days (GDD), which are generally used in plant phenology to estimate the growth and development of plants and insects during the growing season. The basic concept behind GDD is that plant growth will only occur if the temperature exceeds some minimum development threshold, or base temperature (T_{base}). The base temperatures can be different for each plant or insect species– the Stochastic Weather Generator uses 50°F as a base. Any temperature below T_{base} is set to T_{base} before calculating the average. The maximum temperature is capped at 86°F because many plants and insects do not grow any faster above that temperature. The accumulation of degree days is the cumulative product over the year of days times the number of degrees above T_{base} and below the cap.

Table B-4 provides these results for all regions of Massachusetts, and statewide. The results show large increases in growing-degree days relative to baseline estimates, increasing by about one-third by mid-century and by almost two-thirds by end century.

Table B-4. Changes in Growing Degree Days

Future results presented for four time periods identified in the table by their central year: 2030 (near-term, 2020-2039); 2050 (mid-century, 2040-2059); 2070 (mid-late century, 2060-2079); and 2090 (end of century, 2080-2099).

Panel A: Growing degree days (degree-days per year)

Region	Baseline	2030	2050	2070	2090
Berkshires & Hilltowns	2,586	3,160	3,613	3,970	4,329
Greater Connecticut River Valley	2,670	3,238	3,667	4,041	4,385
Central	2,882	3,488	3,870	4,289	4,624
Eastern Inland	3,018	3,658	4,017	4,494	4,869
Boston Harbor	3,083	3,730	4,066	4,585	4,944
North & South Shores	2,941	3,601	3,973	4,400	4,792
Cape, Islands, & S. Coast	2,938	3,638	4,007	4,423	4,809
Statewide	**2,818**	**3,432**	**3,831**	**4,241**	**4,602**

Panel B: Growing degree day percent change from baseline

Region	Baseline	2030	2050	2070	2090
Berkshires & Hilltowns	*0%*	*22%*	*40%*	*54%*	*67%*
Greater Connecticut River Valley	*0%*	*21%*	*37%*	*51%*	*64%*
Central	*0%*	*21%*	*34%*	*49%*	*60%*
Eastern Inland	*0%*	*21%*	*33%*	*49%*	*61%*
Boston Harbor	*0%*	*21%*	*32%*	*49%*	*60%*
North & South Shores	*0%*	*22%*	*35%*	*50%*	*63%*
Cape, Islands, & S. Coast	*0%*	*24%*	*36%*	*51%*	*64%*
Statewide	***0%***	***22%***	***36%***	***51%***	***63%***

Source: Stochastic Weather Generator

Sea Level Rise and Coastal Flooding

Please see Chapter 3 for map and data presentations on the effects of sea level rise and coastal storms on water surface elevation (corresponding to “stillwater levels” excluding wave heights) and annual exceedance probability scenario layers. The same maps are provided here in full-page format for visual clarity.

Figure B-11. Area Extent of 1 Percent Annual Chance (100-year) Flood, with Detail for Selected Areas

Spatial extent of 100-year return period flooding, which has a 1 percent probability of occurring or being exceeded in any year, and the expansion of the areal extent as sea level rises to levels expected in 2030, 2050, and 2070. Lighter blue colors show the current area within the 100-year return period coastal floodplain, and darker blue colors show how the area could expand through 2070. The insets provide additional detail for a few select coastal areas. Source: Project Team analysis of MC-FRM results.

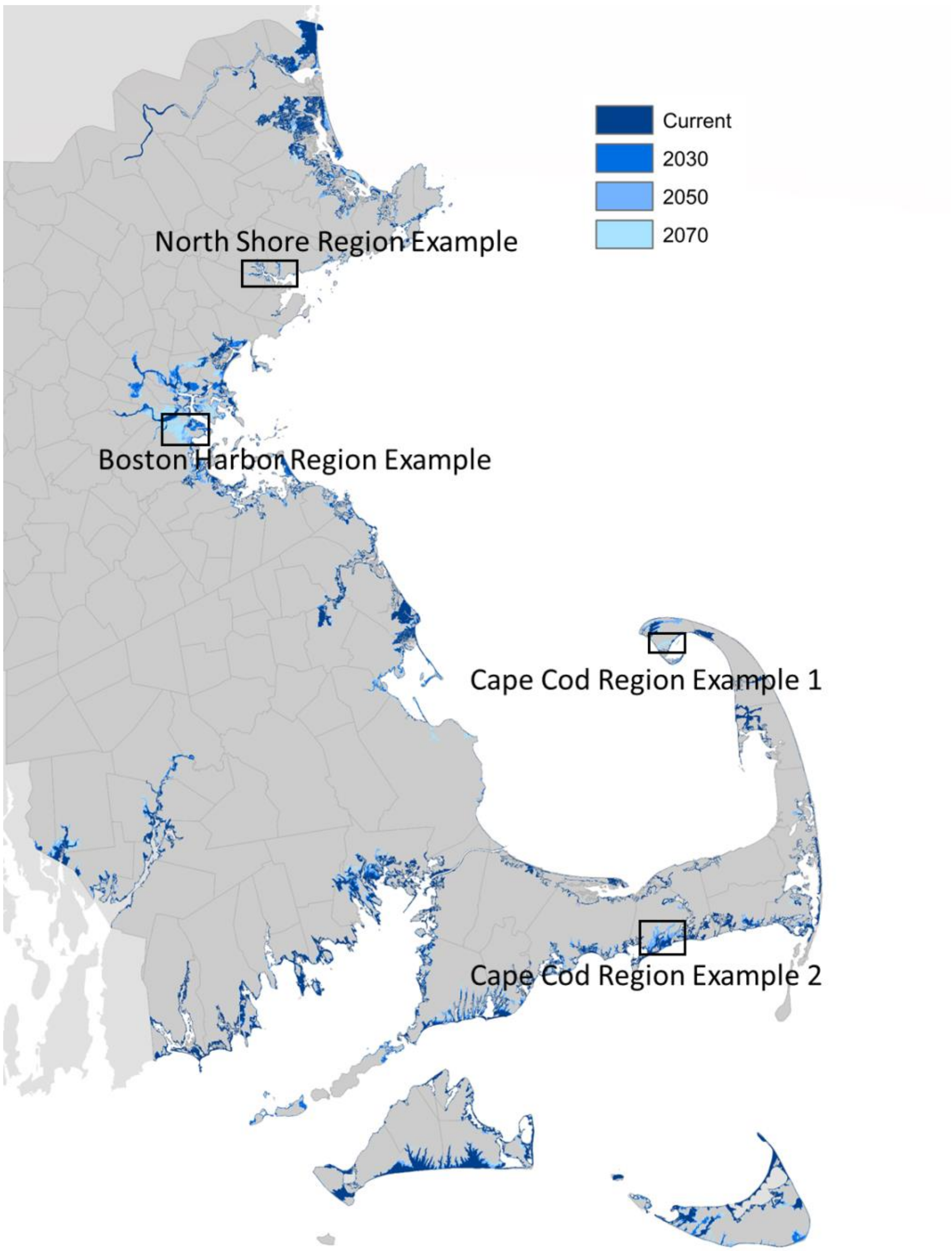
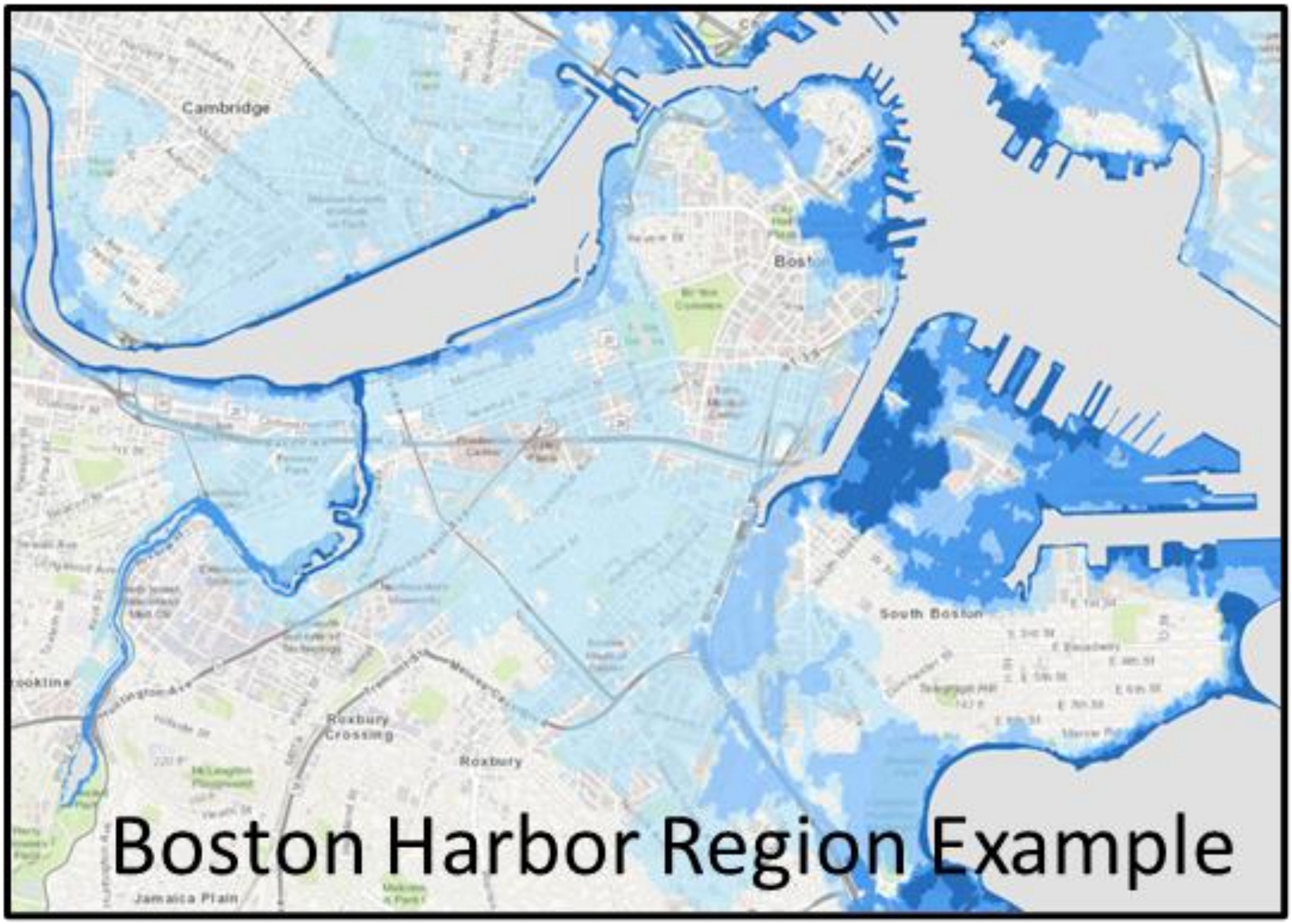
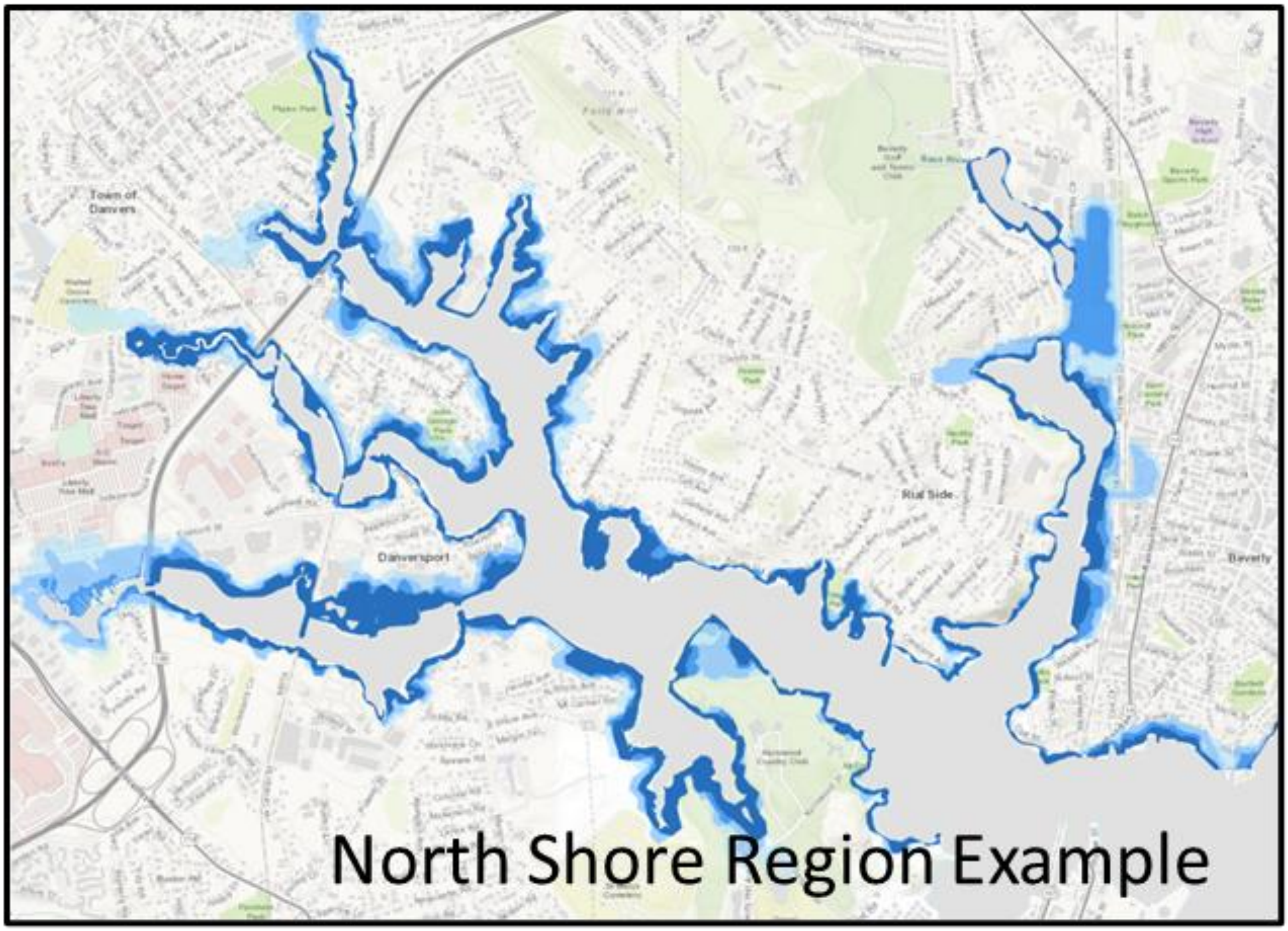
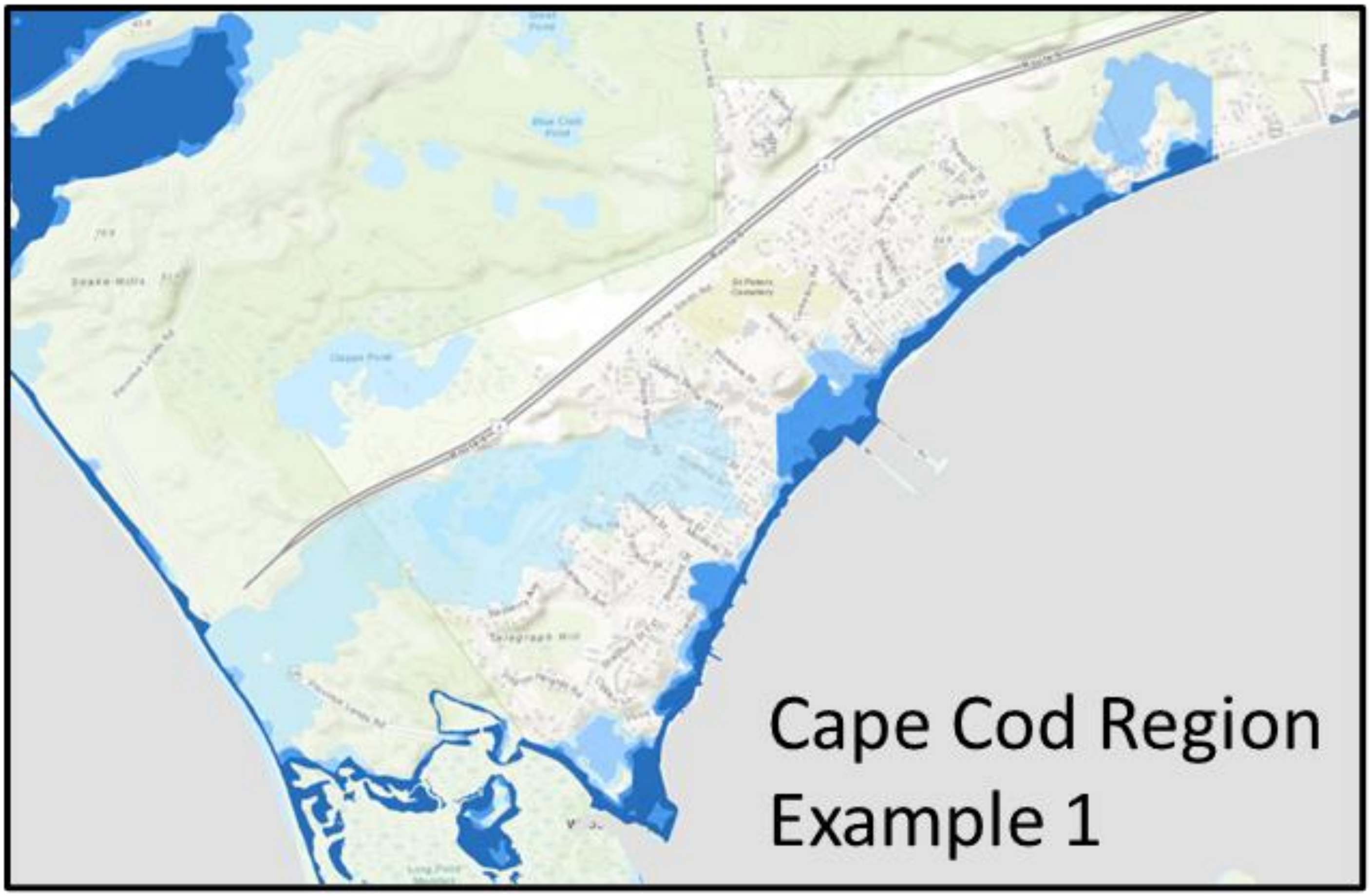
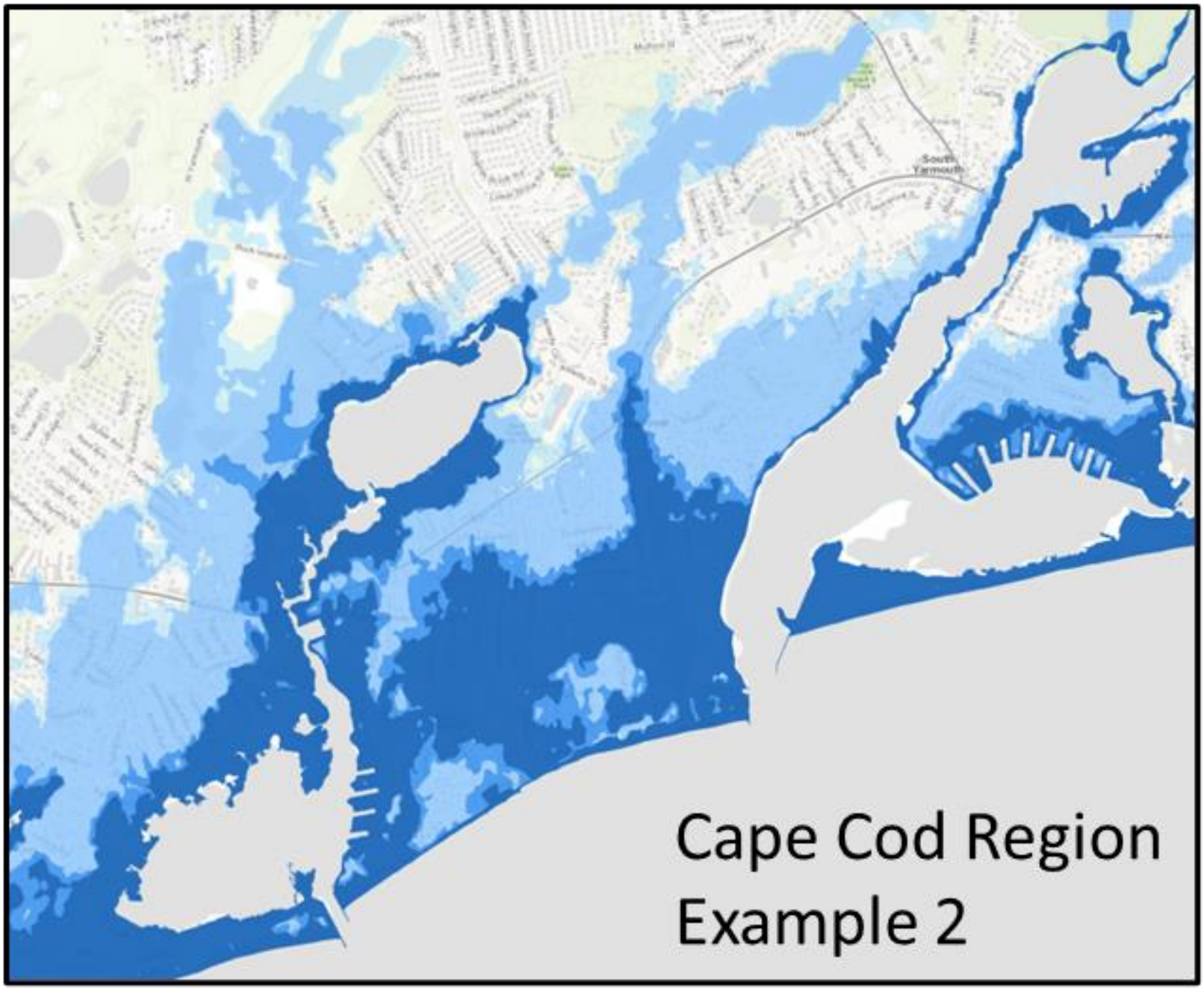


Figure B-11 (continued). Area Extent of 1 Percent Annual Chance (100-year) Flood, with Detail for Selected Areas




North Shore Region Example
Town of Danvers
Danversport
Rial Side
Beverly


Cape Cod Region
Example 1



Cape Cod Region Example 2

2. Additional Details of Assessment Methods

2.1. Organization of Detailed Methods Summary

This portion of the Appendix is designed to provide supplementary information on methods and data sources not otherwise described in other components of this report. A summary of the overall methods for conducting the Climate Assessment is included in Chapter 2 of the report, which provides an overview of how the Magnitude of Consequence, Disproportionality of Exposure, and Adaptation Gap components of the overall urgency scoring approach were conducted. In addition, each individual climate impact assessed in Chapter 4 and Appendix A of the report includes a summary of methods applied, references to peer-reviewed literature, reports, and data sources used to conduct the assessment for each component of the urgency score, and a summary of key limitations and uncertainties. This section of Appendix B supplements that information in two ways:

6. ***Assessment-Wide Methodological Details***: Section 2.2 below is designed to supplement information in Chapter 2 and the individual impact summaries for methods and assumptions that apply throughout the report, such as consistent use of population projections, data on EJ Block Groups, and economic valuation methods that apply to multiple impact categories but are not otherwise detailed in those portions of the report.
7. ***Impact Specific Methodological Details***: Section 2.3 below provides additional information on an impact-specific basis, to the extent that summary explanations and references to supporting literature in each impact write-up may not be sufficient to establish a traceable account of steps taken to quantitatively assess urgency score components.

2.2 Assessment-Wide Methods and Data Sources

This section provides a summary of methods and data sources used for current population and projections, including the use of population data for regional allocations of results in some sectors and the use of EJ Block Group designations; overarching considerations on the use of infrastructure inventories and projections; and the use of a consistent approach to valuation of avoided morbidity and mortality risks associated with climate impacts, which are mainly applied in the Human sector impacts with some components applied in the Economy sector impacts.

Population Projections and Data Sources

This Climate Assessment employs a projection of population by county that has been used in several prior climate impact analyses – U.S. EPA’s Integrated Climate and Land Use Scenarios version 2 (ICLUSv2) model.[32] This model projects total population and population by age and gender, by county, through the end of the 21st century, based on projections of future economic activity and an assumption that population generally follows economic activity. While Massachusetts-specific population projections have been developed, including a series of efforts by the UMass-Amherst Donahue Center for Public Policy, those projections and projections by the U.S. Census Bureau extend only to 2050, and are not available for the 2070 and 2090 projection periods established for the Climate Assessment. The use of the ICLUSv2 source for climate projections was originally proposed by the Project Team in December of 2021 during development of the Framework for the study and was reviewed by and discussed with the Project Working Group as part of the review of the draft and final Framework document.

Note that the ICLUS data does not consider climate-induced migration – for example, from coastal areas expected to see higher storm surge and wind risk to inland areas – or climate gentrification – for example, a process which can lead to displacement of populations as a result of property appreciation associated with adaptation investment. The Project Team is not aware of any reliable projections of climate-induced migration or climate gentrification that could be suitable for use in the Climate Assessment. The ICLUS model also does not project demographic information such as race, ethnicity, and income.

For race, ethnicity, and income demographic characteristics, which are important for the estimation of potentially disproportionate exposure to climate risk, the Climate Assessment relies on current demographic data used in the Massachusetts EJ Viewer (American Community Survey data), which is not projected over time.[33] As outlined in the main report, disproportionality scores evaluate whether areas identified as Environmental Justice (EJ) population areas are disproportionately exposed to the impact. [34] EJ population areas are identified following the EEA's June 2021 Environmental Policy. In that policy, EJ population areas are identified at the Census block group level, where Census block groups typically include between 250 and 550 households. There are approximately 5,000 block groups in the Commonwealth.

EJ block groups are defined based on the following criterion:

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[32] EPA, 2017: Updates to the Demographic and Spatial Allocation Models to Produce Integrated Climate and Land Use Scenarios (ICLUS) (Version 2). U.S. Environmental Protection Agency, Washington, DC, EPA/600/R-16/366F. Available online at https://cfpub.epa.gov/ncea/iclus/recordisplay.cfm?deid=322479 And updated version of ICLUS (from May 2020) may consider additional climate specific migration weights and will be considered as an alternative population forecast.

[33] The EJ Viewer can be found here: https://www.mass.gov/info-details/environmental-justice-populations-in-massachusetts

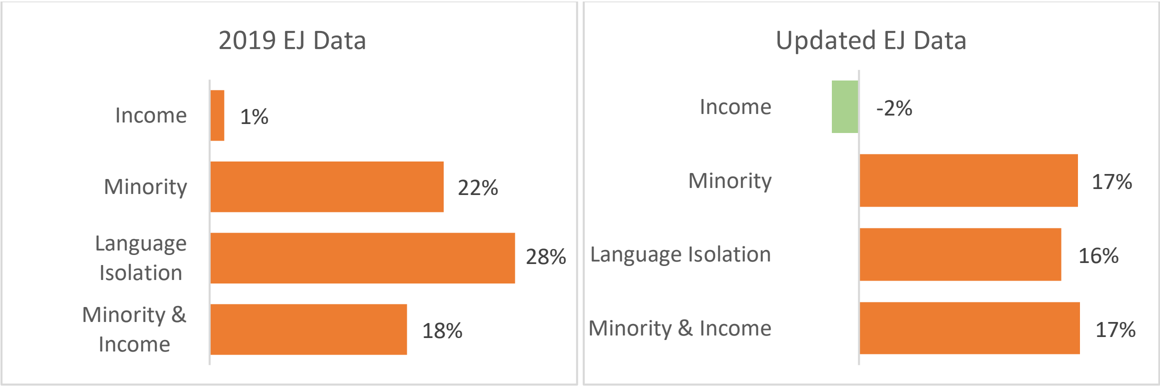
[34] As defined by the Commonwealth, "Environmental Justice (EJ) is based on the principle that all people have a right to be protected from environmental hazards and to live in and enjoy a clean and healthful environment. EJ is the equal protection and meaningful involvement of all people with respect to the development, implementation, and enforcement of environmental laws, regulations, and policies and the equitable distribution of environmental benefits." See: https://www.mass.gov/environmental-justice

- **Low-income:** the annual median household income is 65 percent or less of the statewide annual median household income
- **Minority:** minorities make up 40 percent or more of the population
- **English Isolation:** 25 percent or more of households identify as speaking English less than “very well”
- **Minority and Low-income:** minorities make up 25 percent or more of the population and the annual median household income of the municipality in which the neighborhood is located does not exceed 150 percent of the statewide annual median household income.

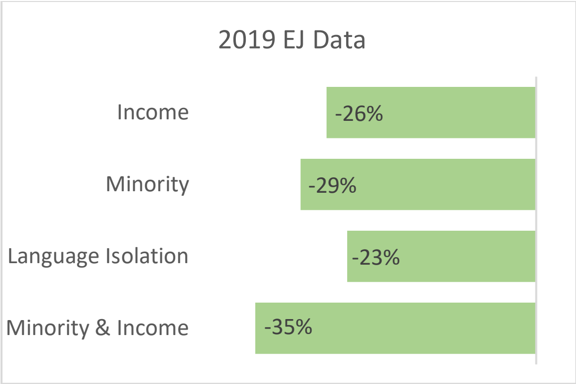
This Climate Assessment relies on the EJ Block Group designations current at the time the draft report was completed, during the Summer of 2022. As of that time, as stated on their website, the EEA used data from the 2019 American Community Survey to make EJ Block Group designations. These designations also reflect the delineation of block group boundaries based on the 2010 U.S. Census. EEA recently updated these to these EJ Block Group designations (in November 2022), but those updates were not available in time for use in the Climate Assessment. Nonetheless, preliminary draft versions of the planned updates, using 2020 Census data and updated 2020 block group boundary delineations, were shared with the Project Team to allow for sensitivity and robustness testing of the disproportionality scores for a limited set of Human and Infrastructure sector impact analyses. The results are presented in Figure B-12 below and reveal that use of the updated data would make only slight differences in the results for disproportionality of exposure scoring, none of which would be large enough to alter the disproportionality of exposures assessment scores for any of the impact sectors for the sensitivity and robustness test was conducted.

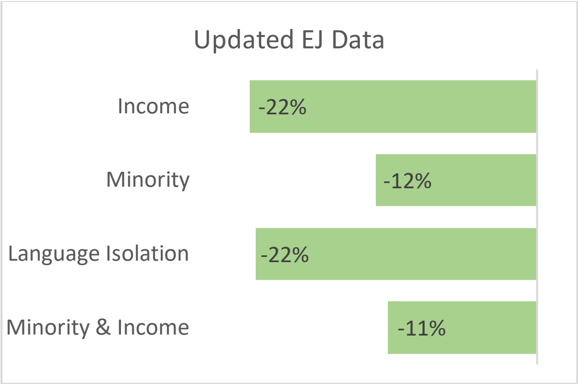
Figure B-12. Results of Sensitivity and Robustness Testing for Updated EJ Block Group Designation Data Inputs

Human Sector: Extreme Temperature Mortality

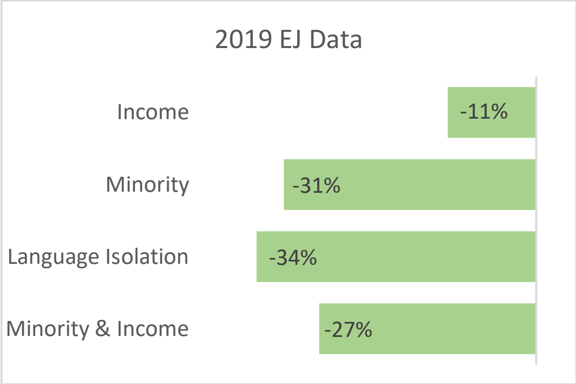


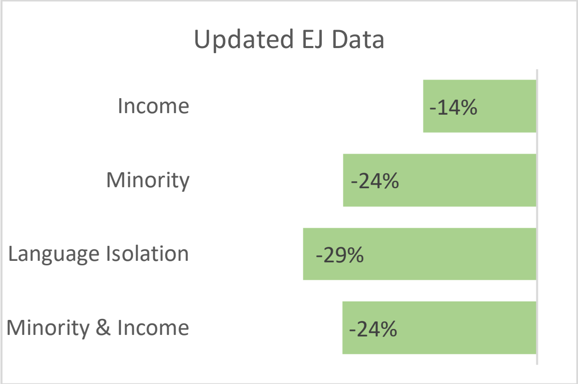
Human Sector: Increase in Vector Borne Diseases Incidence and Bacterial Infections - Vibriosis Cases



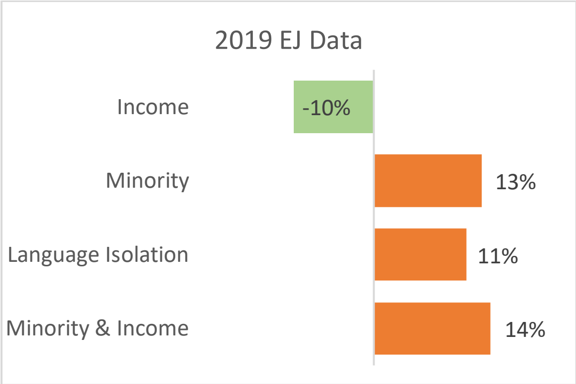


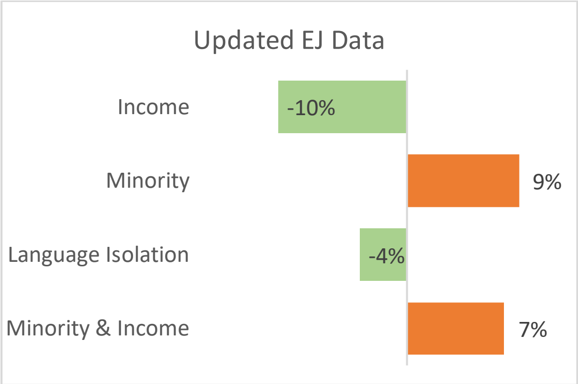
Human Sector: Increase in Vector Borne Diseases Incidence and Bacterial Infections – Lyme Disease



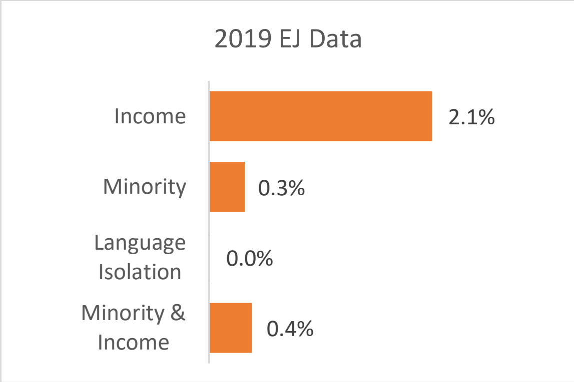


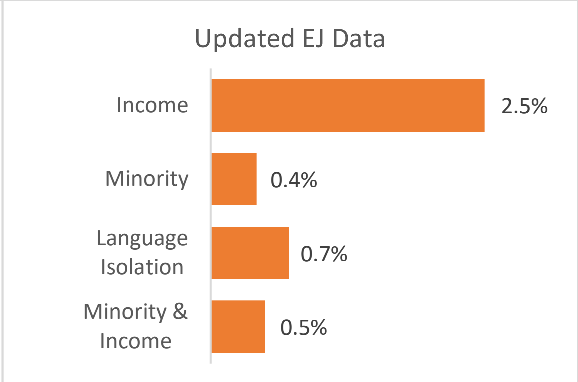
Human Sector: Increase in Vector Borne Diseases Incidence and Bacterial Infections - West Nile Virus Neuroinvasive Disease Cases



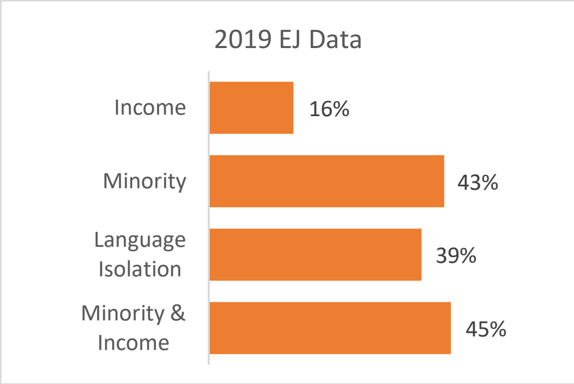


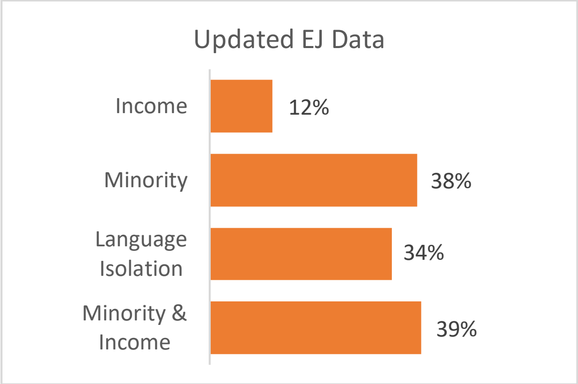
Human Sector: Health Effects from Aeroallergens and Mold – Aeroallergen-induced ED Visits





Infrastructure Sector: Loss of Urban Tree Cover





Infrastructure Inventories and Projections

For the Infrastructure sector the inventory (type, location, condition, and sometimes vintage) of potentially vulnerable assets which could be affected by climate change is a potentially important input in assessing the Magnitude of Consequence and Disproportionality of Exposure for climate stressors. For built infrastructure the default assumption for the Climate Assessment has been to model climate risks using current location and type, and to avoid projecting the location, type, or value of infrastructure into the future. The result avoids the uncertainty of projecting how infrastructure may be deployed or even abandoned in the future, although it is also clear that in some sectors in particular the type, location, and condition of infrastructure could vary substantially from the current infrastructure inventory. For these reasons, in the infrastructure impact sections, the reliance on current inventories is acknowledged as a key uncertainty in the results.

In general, it should be noted that there does not yet exist a consistent accepted or official Commonwealth forecast of changes in natural resources or infrastructure location and type over time. For example, there is no single projection of electric infrastructure (generation and transmission) from the Commonwealth which is consistent with changes anticipated in response to the Commonwealth's efforts to decarbonize and electrify transport and building infrastructure, but rather a few scenarios that span a range of future possible outcomes. While it would be desirable to assess multiple future natural resource or infrastructure scenarios, the ability to do so is limited by the broad risk and geographic scope of the Climate Assessment. To the extent possible, and where there is evidence that a particular impact is sensitive to alternative forecasts of natural resource and built infrastructure location and type (for example, the provision of electric energy may be sensitive to a forecast of future energy generation infrastructure) this is acknowledged and addressed qualitatively as part of the presentation of sensitivities and uncertainties for each impact in Chapter 4 and Appendix A.

Valuation of Avoided Risk of Mortality

Within the Human sector, some of the impact assessments estimate physical effects of future climate as “incidence counts” of excess morbidity or mortality, above baseline or current annual incidence, which can be attributed to changes in climate stressors. For morbidity, this valuation is based on estimates of direct medical costs and indirect productivity losses (for example, lost work or school days due to illness). Sources and values used for expressing morbidity incidence cases or diagnosis counts are specific to the impact categories and are sourced within each relevant Human sector impact write-up in Chapter 4 or Appendix A of the report.

In addition, for morbidity, and consistent with Federal guidance,[35] this Climate Assessment does not attempt to project changes in real medical treatment costs over time. Indirect costs for lost worker or caregiver time, are projected over time using the concept of the opportunity cost of this lost time, using the median daily wage rate in U.S.EPA’s BenMAP user manual (obtained from the US Census Bureau’s 2015 American Community Survey).[36] This rate was converted to 2018 dollars using the Employment Cost Index compiled by the U.S. Bureau of Labor Statistics and adjusted for future years using a forecast per capita GDP adjustment factor, resulting in the following daily wage values: $238.75 in 2030, $320.89 in 2050, $416.15 in 2070, and $528.39 in 2090 (in undiscounted 2018 dollars). This approach is consistent with economic analysis guidance and approaches employed by the U.S. EPA and the USDA.[371]

Several Human sector impacts also estimate avoided premature mortality, expressed as excess deaths above baseline current climate mortality, where the excess is attributed to climate stressors. More accurately, the impact of climate on mortality is a change to the annual rate of mortality among an exposed population within a given area, which can then be translated to the expected value of statistical excess deaths among the exposed population, rather than specific individual deaths. For example, a climate stressor which increases the risk of mortality

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[35] U.S. Environmental Protection Agency (EPA). (2014). Guidelines for preparing economic analyses. National Center for Environmental Economics Office of Policy, 302 pp, https://www.epa.gov/sites/production/files/2017-08/documents/ee-0568-50.pdf

[36] U.S. Environmental Protection Agency (U.S. EPA). (2021). Environmental Benefits Mapping and Analysis Program – Community Edition, User’s Manual. April 2021. Available at: https://www.epa.gov/sites/default/files/2015-04/documents/benmap-ce_user_manual_march_2015.pdf

[37] U.S. Department of Agriculture (USDA), Economic Research Service. (2021). Data Product: Cost Estimates of Foodborne Illnesses is available at: https://www.ers.usda.gov/data-products/cost-estimates-of-foodborne-illnesses/. Accessed Feb. 28, 2021.

above the baseline risk of death by 10 in 100,000 annually for an exposed population of 100,000 individuals could result in 10 excess premature deaths per year attributed to that climate stressor.

The concept of willingness to pay to avoid changes in mortality risk has been extensively studied in the literature.[38] Results expressed as "values of statistical life" are actually estimates of the tradeoffs made by individuals between money and the incremental risk of mortality. The data used in these studies is either observed and empirically estimated in real world settings (e.g., by looking at labor market outcomes where individuals, on average, demand a higher wage to accept employment with a higher risk of occupational mortality, such as mining or construction, relative to other employment opportunities with lower risk of occupational mortality) or through posing of hypothetical questions about trading income or money for mortality risk. Literature from the former sources, which extensive analysis of large data sets of labor market outcomes over many time periods and contexts, is considered more reliable and for the U.S constitutes dozens of studies by many different research groups.

The result of these types of analysis is used to value the risk of premature mortality, called the "Value of Statistical Life" (VSL), which is commonly used in U.S. Federal regulatory analyses. This Climate Assessment uses VSL values derived from the U.S.EPA's Guidelines for Preparing Economic Analyses, which recommends a mean value of $7.9 million (2008 dollars) based on 1990 incomes.[39] These values were adjusted for income growth since 1990, and forward to 2090, using a forecast of U.S. GDP from the Emissions Predictions and Policy Analysis model (version 6)[40] and accounted for population projections from ICLUS v2, a county-level population projection adopted for the Climate Assessment, as described above.[28] This procedure is outlined in more detail in the U.S. EPA's BenMAP user guide.[41] The approach employed is consistent with other studies examining the health effects of climate change, including Achakulwisut et al. (2019)[42] and Gorris et al.(2021).[43] It yielded the following VSL values: $11.7 million in 2030, $13.2 million in 2050, $14.6 million in 2070, and $16.1 million in 2090 (in undiscounted 2018 dollars).

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[38] See for example, Robinson, L.A. and J.K. Hammitt (2015). "Research Synthesis and the Value per Statistical Life," *Risk Analysis*, 35(6): 1086-1100.

[39] U.S. EPA (2014).

[40] Chen, Y.-H. H., Paltsev, S., Reilly, J.M., Morris, J.F., & Babiker, M.H. (2015). The MIT EPPA6 Model: Economic Growth, Energy Use, and Food Consumption. MIT Joint Program on the Science and Policy of Global Change, Report 278, Cambridge, MA.

[41] U.S. Environmental Protection Agency (U.S. EPA). (2021).

[42] Achakulwisut, P., S.C. Anenberg, J. E. Neumann, S.L. Penn, N. Weiss, A. Crimmins, et al. (2019). Effects of increasing aridity on ambient dust and public health in the U.S. southwest under climate change. GeoHealth, 3(5): 127–144.

[43] Gorris, M. E., Neumann, J. E., Kinney, P. L., Sheahan, M., & Sarofim, M.C. (2021). Economic Valuation of Coccidioidomycosis (Valley Fever) Projections in the United States in Response to Climate Change. Weather, Climate, and Society, 13(1), 107-123.

2.3 Impact-Specific Methods and Data Sources

In this section of the Appendix, additional methodological details are provided for specific impacts, to supplement information provided in Chapter 4 and Appendix A. The supplemental information is organized by sector.

Human Sector

IMPACT	PRIMARY QUANTITATIVE ANALYSIS SOURCE	SUPPLEMENTAL INFORMATION
Health and Cognitive Effects from Extreme Heat (MOST URGENT)	Analysis based on published sources cited in Chapter 4	Clarification of baseline incidence data sources
Health Effects from Degraded Air Quality (MOST URGENT)	Analysis based on published sources cited in Chapter 4	Clarification of baseline incidence data sources
Emergency Service Response Delays and Evacuation Disruptions (MOST URGENT)	Analysis based on published sources cited in Chapter 4	None
Reduction in Food Safety and Security	Results from Economy-Agriculture analysis, based on published sources cited in Appendix A	None
Increase in Mental Health Stressors	Analysis based on published sources cited in Appendix A	Clarification of baseline incidence data sources
Health Effects from Aeroallergens and Mold	Analysis based on published sources cited in Appendix A	Clarification of baseline incidence data sources
Health Effects of Extreme Storms and Power Outages	Analysis based on published sources cited in Appendix A	Literature review supporting qualitative analyses
Damage to Cultural Resources	Analysis based on overlays of Mass GIS data and inland and coastal flood risk analyses from Infrastructure Sector	None
Increase in Vector Borne Diseases Incidence and Bacterial Infections	Analysis based on published sources cited in Appendix A	Clarification of baseline incidence sources

Some of the impacts in the Human sector require baseline health incidence data, typically resolved to the county level. For the air quality, aeroallergens, and extreme temperature mortality impacts, baseline incidence or mortality rates are used from data in U.S. EPA's BenMAP tool.[44]

For Lyme disease, the baseline incidence rates rely on published Mass DPH data, with the relevant URL for the data source cited in Appendix A. All other impact analyses, including for

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[44] See U.S. Environmental Protection Agency (U.S. EPA). (2021). Environmental Benefits Mapping and Analysis Program – Community Edition, User's Manual. April 2021. Available at: https://www.epa.gov/sites/default/files/2015-04/documents/benmap-ce_user_manual_march_2015.pdf

mental health/suicide, West Nile virus neuroinvasive disease, and vibriosis, baseline data for Massachusetts were available from the underlying peer-reviewed study cited in either Chapter 4 or Appendix A.

Health Effects of Extreme Storms and Power Outages (literature review supporting qualitative analyses:

High heat, storms, and flooding have increased in frequency and intensity in recent years as an effect of climate change, and as a result impacted populations have faced higher incidences of power outages. In turn, literature on the effects of power outages on human health have found increased relevance in the climate change discussion (Dominianni et al. 2018). [45]Numerous studies document quantitative analyses of adverse health outcomes and mortalities linked to increased power outage; few researchers propose explanations, ranging from medical technology failure to food spoilage, depending on the health outcome. Much of this research in the United States examines the effects of power outages in New York City, particularly after the August 2003 and Hurricane Sandy blackouts.

During power outage periods in the State of New York over the course of a decade, Zhang et al. (2020) reported a rate ratio between 1.03 and 1.39 for chronic obstructive pulmonary disease (COPD), an average $4670 increase in hospital cost per case, and 1.38 more comorbidities per case.[46] Patients suffering from COPD, which claimed nearly 3000 lives in Massachusetts in 2017 as the state's fourth leading cause of death, require electricity for oxygen-supplying devices, which power outages threaten as they increase in frequency due to extreme weather events associated with climate change (CDC, 2017). Kellman et al. (2014) found that disruptions to dialysis services before, during, and following Hurricane Sandy increased New York City emergency department visits, hospitalizations, and mortalities among patients with end-stage renal disease, when compared with hurricane-unaffected renal disease populations.[47] Kidney disease was the 9th leading cause of deaths in Massachusetts in 2017, claiming over 1000 lives (CDC, 2017).

Xiao et al. (2021) examined pregnancy data from 8 New York counties following Hurricane-Sandy-associated power outages and reported a 16.6% increase in ED visits pertaining to pregnancy complications, a 26.7% increase in threatened and/or early delivery, and a 111.8% increase in gestational diabetes mellitus.[48] Xiao et al. then found that ED visits increased by 8.8% per level increase in ED intensity (daily maximum affected customers divided by total

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[45] Dominianni, C., Lane, K., Johnson, S., Ito, K., & Matte, T. (2018). Health Impacts of Citywide and Localized Power Outages in New York City. *Environmental health perspectives*, *126*(6), 067003.
[46] Zhang, W., Sheridan, S. C., Birkhead, G. S., Croft, D. P., Brotzge, J. A., Justino, J. G., Stuart, N. A., Du, Z., Romeiko, X. X., Ye, B., Dong, G., Hao, Y., & Lin, S. (2020). Power Outage: An Ignored Risk Factor for COPD Exacerbations. *Chest*, *158*(6), 2346–2357.
[47] Kelman, J., Finne, K., Bogdanov, A., Worrall, C., Margolis, G., Rising, K., MaCurdy, T. E., & Lurie, N. (2015). Dialysis care and death following Hurricane Sandy. *American journal of kidney diseases : the official journal of the National Kidney Foundation*, *65*(1), 109–115.
[48] Xiao, J., Zhang, W., Huang, M., Lu, Y., Lawrence, W. R., Lin, Z., Primeau, M., Dong, G., Liu, T., Tan, W., Ma, W., Meng, X., & Lin, S. (2021). Increased risk of multiple pregnancy complications following large-scale power outages during Hurricane Sandy in New York State. *The Science of the total environment*, *770*, 145359.

customers) and 1.4% per day increase in PO. Finally, the researchers noted that young adults, Black, Hispanic, and uninsured populations were at much greater risk for pregnancy complications. In Dominianni et al.'s 2018 study of broad and heat-associated, localized power outages across New York City from 1999-2014, certain power outages were associated with higher incidence of respiratory disease hospitalizations and renal disease hospitalizations, and/or all-cause mortality.

Anderson and Bell (2012) noticed a 122% increase in accidental deaths and 25% increase in non-accidental deaths in New York City following the widespread August 2003 black-out; mortality risk remained elevated for the remainder of August.[49] As a result, the researchers estimated the city incurred 90 excess deaths, 87% of which had non-accidental causes such as cardiovascular disease; they also commented on potential pathways for these mortalities, including delayed ambulance response time, food market and pharmacy closures, and difficulty contacting emergency services because of poor cell service. In certain measuring sites within New York City following the blackout, Anderson and Bell also found a non-insignificant deviation in nitrogen dioxide, sulfur dioxide, and carbon dioxide levels from baseline trends in the years prior to and following the blackout.

Also studying New York City in August 2003 following the power outages, Marx et al. (2006) examined the potential indirect impact of power outages on health via food spoilage and/or refrigeration failure.[50] The researchers reported an immediate and statistically significant increase in the (A) ratio of diarrhea-associated ED visits compared to "other-cause" visits, (B) sales of antidiarrheal medications, and (C) gastrointestinal-illness-associated employee absences. For post-blackout diarrhea patients, aged 13 and above, who agreed to participate in a survey, as well as a group of control participants, consumption of seafood (OR = 4.8; 95% CI = 1.6, 14) and non-deli, non-poultry meats (OR = 2.7, 95% CI = 1.2, 6.1) between the power outage and symptom onset was associated with diarrheal illness.

Infrastructure Sector

IMPACT	PRIMARY QUANTITATIVE ANALYSIS SOURCE	SUPPLEMENTAL INFORMATION
Damage to Inland Buildings (MOST URGENT)	Analysis based on published flood risk and data sources cited in Chapter 4	None
Damage to Electric Transmission and Distribution Infrastructure (MOST URGENT)	Analysis based on published sources cited in Chapter 4	None

[49] Anderson, G. B., & Bell, M. L. (2012). Lights out: impact of the August 2003 power outage on mortality in New York, NY. *Epidemiology (Cambridge, Mass.)*, *23*(2), 189–193.

[50] Marx, M. A., Rodriguez, C. V., Greenko, J., Das, D., Heffernan, R., Karpati, A. M., Mostashari, F., Balter, S., Layton, M., & Weiss, D. (2006). Diarrheal illness detected through syndromic surveillance after a massive power outage: New York City, August 2003. *American journal of public health*, *96*(3), 547–553.

IMPACT	PRIMARY QUANTITATIVE ANALYSIS SOURCE	SUPPLEMENTAL INFORMATION
Damage to Rails and Loss of Rail/Transit Service (MOST URGENT)	Analysis based on published sources cited in Chapter 4	Spatial results matching procedures
Loss of Urban Tree Cover	Mainly qualitative analyses	Additional data source references
Damage to Coastal Buildings and Ports	MC-FRM results and analysis based on published sources for depth-damage functions and property value at 150 meter grid scale, citations provided in Appendix A	None
Damage to Roads and Loss of Road Service	Analysis based on published sources cited in Appendix A	Spatial results matching procedures
Reduction in Clean Water Supply	Analysis based on published sources cited in Appendix A	None
Loss of Energy Production and Resources	Analysis based on published sources cited in Appendix A	None
Increased Risk of Dam Overtopping or Failure	Custom analysis of Mass GIS data on designated High or Significant Hazard dams	Additional methodological summary provided below

Damage to Rails and Loss of Rail/Transit Service:

Total impacts, assessed on a half-degree grid, are allocated first from national estimates to the state using a spatial allocation of dry land area (rail inventory from neighboring states was not used) but allocated within MA to regions using the rail inventory. Differentiations of impacts by type, ownership, and use were made using the following source for rail data: https://www.mass.gov/info-details/massgis-data-trains

Damage to Roads and Loss of Road Service:

Impacts in dollars per lane mile, which are assessed on a quarter degree grid in the underlying study, are assigned to each road by class and surface type, then the impacts are summed for each road in the region. Differentiations of impacts by type, ownership, surface, and use were made using the following road inventory data source: https://www.mass.gov/info-details/massgis-data-massachusetts-department-of-transportation-massdot-roads

The key steps in the road data analysis procedure are summarized below:

1) Calculate costs per lane mile from CIRA study (Resilient Analytics data used in latest CIRA -> Neumann et al. 2021)[51]

[51] Neumann, J.E., Chinowsky, P., Helman, J., Black, M., Fant, C., Strzepek, K., and Martinich, J. (2021) Climate effects on US infrastructure: the economics of adaptation for rail, roads, and coastal development. Climatic Change 167, 44 (2021). https://doi.org/10.1007/s10584-021-03179-w

2) Allocate costs per lane mile to census block groups
3) Calculate total costs by block group, multiplying costs per lane mile from #2 with MassDOT lane miles

MassDOT lane mile assumptions (involves three types of data: road miles, operation: one-way or two-way, and number of lanes)

1. Calculate road miles where segments were split by block group in GIS
2. Assume all roads with unclassified "operation" is 2-way
3. Assume all roads with undefined "number of lanes" is 2
4. Divided roadways note number of lanes on the given segment only but include another field with the number of lanes on the opposing side. In these cases, add together the number of lanes with the number of lanes on the opposing side.
5. land miles = length * number of lanes

Loss of Urban Tree Cover:

This data includes a designation of areas based on area determined as “Urban” according to the U.S. Census Bureau as cited in Appendix A. Other data sources are cited below.

Urban tree loss analysis data sources

Data	Description	Source
Canopy Coverage Per Land Area	Urban Tree canopy coverage 2000 in the state of Massachusetts	U.S USDA 2008. Urban Forest Data for Massachusetts - https://www.nrs.fs.fed.us/data/urban/state/?state=MA
Urban Tree coverage Change	Base rate parameters for urban tree coverage change in Massachusetts	David J Nowak, Eric J Greenfield, US Urban Forest Statistics, Values, and Projections, *Journal of Forestry*, Volume 116, Issue 2, March 2018, Pages 164–177, https://doi.org/10.1093/jofore/fvx004

Increased Risk of Dam Overtopping or Failure:

Impacts are analyzed to 1068 high and significant hazard dams, as identified by DCR. Site-analyses for flood damage, which in many instances have been conducted for Massachusetts dams, are not publicly available. It is not within the scope of this valuation exercise to conduct a new flooding impact analysis for overtopped or failed Massachusetts dams because of high precipitation events. A typical site-specific analysis would involve detailed data collection, site characterization, and hydrologic and hydraulic modeling under varying potential precipitation and flood conditions. Instead, the Project Team used historic records from the Stanford National Performance of Dams Program (NPDP) and the Association of State Dam Safety Officials’ Dam Incident Database (DID) to guide reasonable assumptions about the engineering standards that could apply to the set of dams analyzed here to estimate the future likelihood of dam overtopping and breach events. The Project Team then used a downscaled version of the

HUC level projected streamflow results of the Hydrologic and Water Quality System, as outlined in Fant et al. (2017) to simulated future hydrologic conditions at each dam site and assess the frequency of potential dam failure modes.[52]

Economic impacts representing flood damages to nearby buildings and infrastructure based on four elements of data for each dam site: (1) an average estimated area of influence for flooding associated with an overtopping event; (2) the average county level building value per acre in the area surrounding each dam in Massachusetts; (3) standard U.S. Army Corps of Engineers depth damage functions for Massachusetts that are used to estimate building damages associated with a certain freshwater flood height, and (4) estimates of the cost of dam repairs necessary after an overtopping or breach event.

Estimates of the cost of dam repairs necessary after an overtopping or breach event are developed based on NPDP[53] and DID[54] reports of dam safety incidents, characteristics, and estimated economic damage. Fifty-six and five incidents were reported in the NPDP and DID databases respectively from Massachusetts. Incidents recorded occurred between 1848 and 2015, with a majority occurring before the year 2000. The DID does not have estimates of economic damages, and only one entry from the NPDP had an economic damage estimate of one million dollars.

To estimate potential area affected and depth of potential flooding, the Project Team researched available inundation flood modeling that estimates flood area and depth of inundation for Massachusetts dams or other potentially comparable dams in the hypothesized event of dam breach or failure. Two readily available Emergency Action Plans for dams in Massachusetts that include such analysis were reviewed.[55] The results indicated that, in a breaching event, up to 36 structures might be affected by flooding, with depths of approximately 2.0 feet.

Based on the limited information available, changes in the occurrence probability of two types of events were developed: overtopping and breaching. The Project Team estimated that an

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[52] Charles Fant, Raghavan Srinivasan, Brent Boehlert, Lisa Rennels, Steven C. Chapra, Kenneth M. Strzepek, Joel Corona, Ashley Allen, and Jeremy Martinich. (2017). Climate Change Impacts on US Water Quality Using Two Models: HAWQS and US Basins. Water , 9:118-138), doi:10.3390/w9020118. The HUC-8 level results were used in this work. IEc also considered use of the Wobus et al. (2017) HUC level results, but the focus in that published work on the 100-yr flow proved too limiting for this particular application. See Wobus, Cameron, Ethan Gutmann, Russell Jones, Matthew Rissing, Naoki Mizukami, Mark Lorie, Hardee Mahoney, Andrew W. Wood, David Mills, and Jeremy Martinich. (2017). Climate change impacts on flood risk and asset damages within mapped 100-year floodplains of the contiguous United States. *Nat. Hazards Earth Syst. Sci*., 17:2199–2211.

[53] National Performance of Dams Program(NPDP), Dam Incidents Modifications/repairs, and Consequences Database, http://npdp.stanford.edu/consequences, results are based on a search of the database for all reported incidents in Massachusetts.

[54] Association of Dam Safety Officials, Dam Safety Incident Database, https://damsafety.org/incidents , results are based on a search of the database for all reported incidents in Massachusetts.

[55] IEc reviewed two publicly available Emergency Action plans, including EMERGENCY ACTION PLAN for Foster's Pond Dam; Andover, Essex County, Massachusetts; National I.D. Number: MA00153; State ID Number: 5-5-9-10; Dam Location: 42.61361º N / 71.14146º W; and EMERGENCY ACTION PLAN for Forge Pond Dam; East Bridgewater, Plymouth County, Massachusetts; National I.D. Number: MA00427; State ID Number: 7-12-83-3; Dam Location: 42.0368º N / 70.9595º W

overtopping event could result in $188,500 of damage, using the average damage per event reported from available incidence data, primarily repair costs. Breaching events are assumed to cause damage consistent with an average of 2.0 ft of standing water flood depth. To estimate structural damage, standard depth-damage functions and structure values were derived from the National Coastal Properties Model database of value for each of Massachusetts' regions.[56] This analysis assumes all non-structural damage to properties would be approximately equal to the damage to structures, consistent with the total damage from the readily available Emergency Action Plan.[4] Non-structural damage could include damage to roads or, other infrastructure; local response and cleanup costs beyond structure damage; business interruption; and traffic delays.

Based on USDA design standards, it was assumed that dams in Massachusetts were designed to the 1000-year event (0.01-percent annual likelihood event) for overtopping and 5000-year event (0.02-percent) for dam breaching. As these rare events are difficult to discern in the historical record, it is necessary to use a statistical technique to identify the flow associated with the return periods of interest. Using 20 years of historical flow data from Fant et al. (2017), the Project Team fit a Gumbel distribution (a unique form of the generalized extreme value distribution often used for extreme events of precipitation or river flow) to the available data. The same technique was applied for the projected years and compared the projected distribution for each of the future eras to the historical distribution. By comparing the number of times the flow exceeds the overtopping or dam breaching threshold in the historical period with the same estimates for the future period, an estimate was obtained of the change in expected annual impacts for the future period. For example, if a flow event in the historical period is a 1-percent flood event, and these same flows occur with 2-percent per year frequency in the future projection, annual expected damages for the future projection would be double the baseline annual expected damages.

High and Significant Hazard Dams analysis data sources

Data	Description	Source
Simulated daily river flow	Simulated daily river flows for 2,110 8-digit HUCs across the Contiguous United States, 20 of these in Massachusetts	Fant, Charles, Raghavan Srinivasan, Brent Boehlert, Lisa Rennels, Steven C. Chapra, Kenneth M. Strzepek, Joel Corona, Ashley Allen, and Jeremy Martinich. (2017). Climate Change Impacts on U.S. Water Quality Using Two Models: HAWQS and U.S. Basins. Water, 9:118-138), doi:10.3390/w9020118.

[56] See Neumann, J.E., Chinowsky, P., Helman, J., Black, M., Fant, C., Strzepek, K., and Martinich, J. (2021) Climate effects on US infrastructure: the economics of adaptation for rail, roads, and coastal development. Climatic Change 167, 44 (2021). https://doi.org/10.1007/s10584-021-03179-w

Damage per event	Approximate damage per event from two sources: Massachusetts Emergency Action Plans and the Stanford National Performance of Dams Program Database on Dam Incidents and Consequences	Massachusetts Emergency Action Plan for Foster's Pond Dam; Andover, Essex County NPDP Database- http://npdp.stanford.edu/data_library
Dam locations	Geo-located shape file of dams in Massachusetts, includes hazard classifications	MassGIS - https://www.mass.gov/orgs/massgis-bureau-of-geographic-information
Building values	Average building value by county, used for the damage of dam breaching events	Neumann, J.E., Chinowsky, P., Helman, J., Black, M., Fant, C., Strzepek, K., and Martinich, J. (2021) Climate effects on US infrastructure: the economics of adaptation for rail, roads, and coastal development. Climatic Change 167, 44 (2021). https://doi.org/10.1007/s10584-021-03179-w

Natural Environment Sector

IMPACT	PRIMARY QUANTITATIVE ANALYSIS SOURCE	SUPPLEMENTAL INFORMATION
Freshwater Ecosystem Degradation (MOST URGENT)	Analysis based on published sources cited in Chapter 4	None
Coastal Wetland Degradation (MOST URGENT)	Analysis based on published sources cited in Chapter 4	Additional documentation of SLAMM modeling effort
Marine Ecosystem Degradation (MOST URGENT)	Analysis based on published sources cited in Chapter 4	None
Forest Health Degradation	Analysis is mostly qualitative, based on published sources cited in Appendix A	None
Shifting Distribution of Native and Invasive Species	Analysis based on published sources cited in Appendix A	None
Coastal Erosion	Analysis based on published sources cited in Appendix A	Additional information on key assumptions
Soil Erosion	Analysis based on published sources cited in Appendix A	None

Coastal Wetland Degradation:

The Climate Assessment pulls from a 2016 application of Sea Level Affecting Marshes Model (SLAMM) which was run in order to determine the potential areal extent and distributions of coastal wetlands in Massachusetts as they respond to sea level rise.[57] SLAMM was developed specifically to evaluate the potential impacts to coastal wetlands from sea level rise, and incorporates important parameters, such as elevation, wetland classifications, sea level rise, tide range, and accretion and erosion rates for various habitat types. The baseline, or present day, year for this study was 2008.

SLAMM 6.7, the most current version available, was used to model coastal wetland changes for the Belle Isle Marsh study area and subsequently other areas of the Massachusetts coast.[58] Improvements made to SLAMM 6.7 since its prior iteration include the ability to utilize custom sea level rise curves, improved marsh erosion modeling, and incorporation of carbon sequestration into the model. SLAMM was designed to simulate the dominant processes involved with wetland conversion due to sea level rise.

SLAMM was chosen for this project because it utilizes the driving physical processes that result in wetland and shoreline changes predicted to occur over a long-term time frame. SLAMM utilizes a number of data inputs and parameters including LiDAR elevation data, mapped

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[57] Woods Hole Group. 2016. Modeling the Effects of Sea-Level Rise on Coastal Wetlands. Prepared for Massachusetts Office of Coastal Zone Management. November 2016. Available at: https://www.mass.gov/files/documents/2018/12/07/czm-slamm-report-nov2016.pdf

[58] Warren Pinnacle Consulting, Inc. 2016. SLAMM 6.7 Technical Documentation: Sea Level Affecting Marshes Model, Version 6.7 Beta

wetland classifications, sea level rise, tide range, accretion, and erosion rates, resulting in a more comprehensive output result compared to some other ecological models currently available. Outputs from the simulations include both graphical (map) and tabular forms.

The specific sources and vintage of LiDAR elevation data used in the SLAMM analysis is described in more detail in the 2016 coastal wetland modeling report referenced above. Some of the detail from that report is replicated below in Table B-5. LiDAR sources included a 2013/2014 USGS Sandy LiDAR flight. Omitted from the table are Boston area LiDAR sources. No single LiDAR dataset covered the entire Boston model area, so a LiDAR mosaic was created for that region by combining various datasets including the 2009 City of Boston LiDAR; 2010 Quincy LiDAR acquired by FEMA; a 2011 LiDAR for the Northeast acquired by USGS; and 2002 Boston Area LiDAR. These were utilized in order of the most recent date to ensure the fullest possible coverage.

Table B-5. Cities and Towns by Climate Assessment Region

Region	LiDAR Date	Region	LiDAR Date
Great Marsh	2011[a]	Buzzards Bay East	2011
North Shore	2011	Buzzards Bay West	2014
Boston	2010[b]	Taunton River	2011[c]
Cape Cod Bay	2011	Martha's Vineyard NE	2013
Cape Cod – Provincetown	2011	Martha's Vineyard South	2013
Cape Cod – Monomoy	2011	Martha's Vineyard NW	2013
Cape Cod – Vineyard Sound E	2011[d]	Nantucket North	2013
Cape Cod – Vineyard Sound W	2011[d]	Nantucket South	2013

Notes:

[a] The Great Marsh panel also incorporated edited LiDAR acquired from CZM.

[b] Combined 2009, 2010, 2011, and 2002 LiDAR datasets to acquire full coverage for the Boston panel, as described in text.

[c] Also included portions of the 2010 Narragansett River LiDAR

[d] Also incorporated some portions of the 2010 Dukes County LiDAR

The analysis at present combines the data from the 2016 SLAMM study, and parses these data by block group, region, and town. Within these parsed groups are information about wetland loss (demarked by wetland transition from irregularly flooded saltmarsh (High Marsh) to regularly flooded saltmarsh (Low Marsh). The focus on habitat loss targets these transitional values, in acres.

Tidal range is one of the most important parameters for determining the effect of sea level rise on coastal wetland change and as such is a highly sensitive parameter in SLAMM. Given the varied tidal ranges present in different parts of the state, it is useful to compare the general trends occurring in these different areas. Figures B-13, 14 and 15 present the trends in wetland change over the study periods for three tidal regions in the state, the macrotidal region (Great

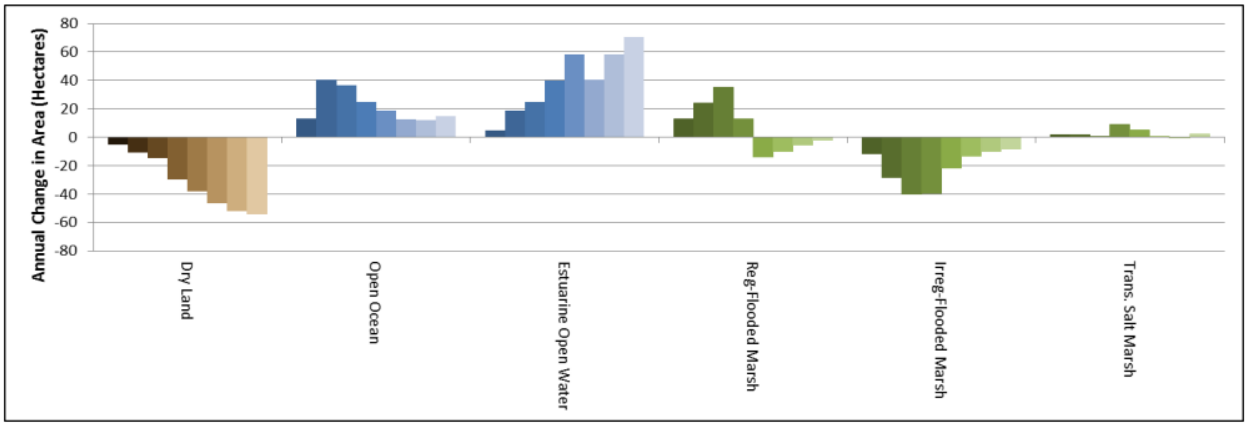
Marsh, North and South Shores of Boston, and the Northern Cape), the mesotidal region (Buzzards Bay) and the microtidal region (Nantucket Sound and the Islands). The top panel in each figure displays the wetland types broken out individually (dry land, open ocean, estuarine open water, regularly-flooded marsh, etc.), while the bottom panel for each figure shows the areas from individual wetland categories to create broader categories for simpler comparisons between map panels. The bars represent the net change in area for that wetland type for each 10-year interval (i.e., 2030 to 2040, 2040 to 2050, etc.) out to 2100, with the exception of the first interval, which represents the change occurring during the 19-year period between 2011 to 2030.

For microtidal areas, there is a consistent loss in high marsh habitat throughout the evaluation period. Low marsh increases in area until 2050, then the trend becomes negative. Combined low and high marsh suffers a minor short-term gain, then a consistent loss after 2030. Other observations include:

- Although the largest changes will occur mid- to late-century, some initial changes were relatively large in magnitude, such as the changes to open ocean and regularly- and irregularly-flooded marshes.
- Land categorized as dry land continually decreases in area throughout the entire study period, with losses of increasing magnitude at each successive time step.
- Only very minor area changes occur within the transitional salt marsh category.
- In the macrotidal regions, there is a net gain in combined saltmarsh habitat that remains relatively constant throughout the evaluation periods.
- Land categorized as dry land continually decreases in area throughout the entire study period, with losses of increasing magnitude at each successive time step.

Figure B-13 Example of Detailed SLAMM outputs: Nantucket Sound and Martha's Vineyard

Annual changes in coastal wetland areas (top panel) and combined coastal wetland areas (bottom panel) over evaluation periods for microtidal areas (Average Great Diurnal Tidal Range < 1m)



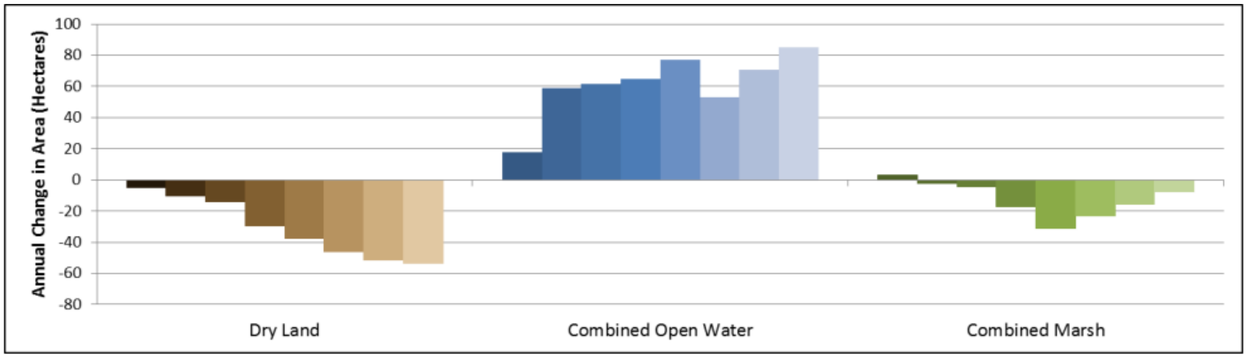
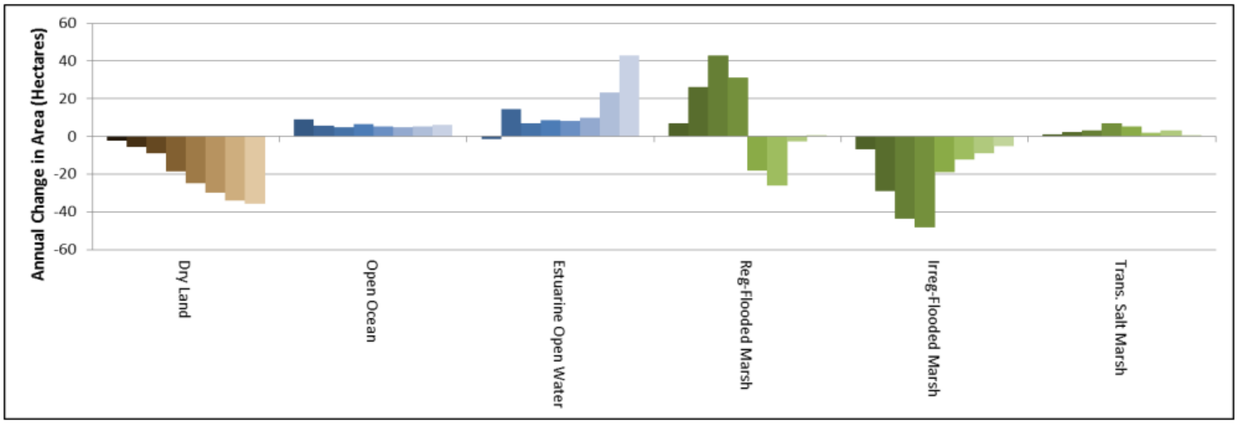


Figure B-14: Example of Detailed SLAMM outputs: Buzzards Bay and Elizabeth Islands

Annual changes in coastal wetland areas (top panel) and combined coastal wetland areas (bottom panel) over evaluation periods for mesotidal areas (Average great diurnal tidal range 1-1.5 m)



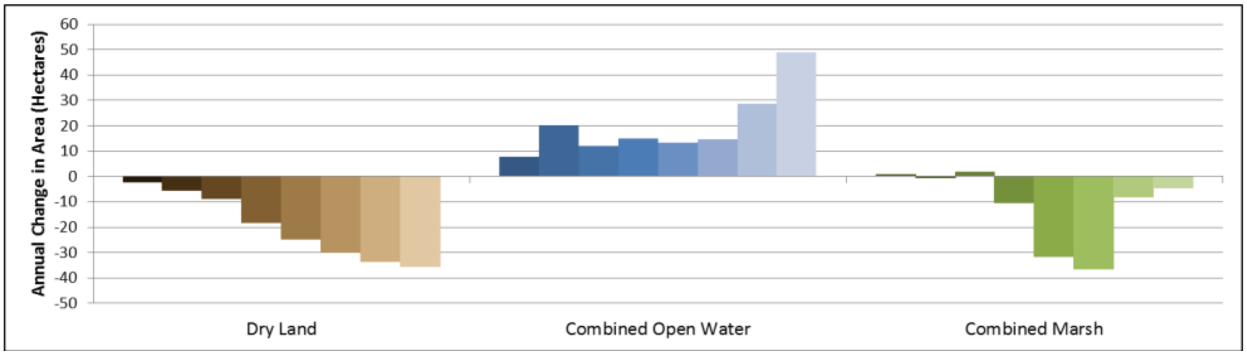
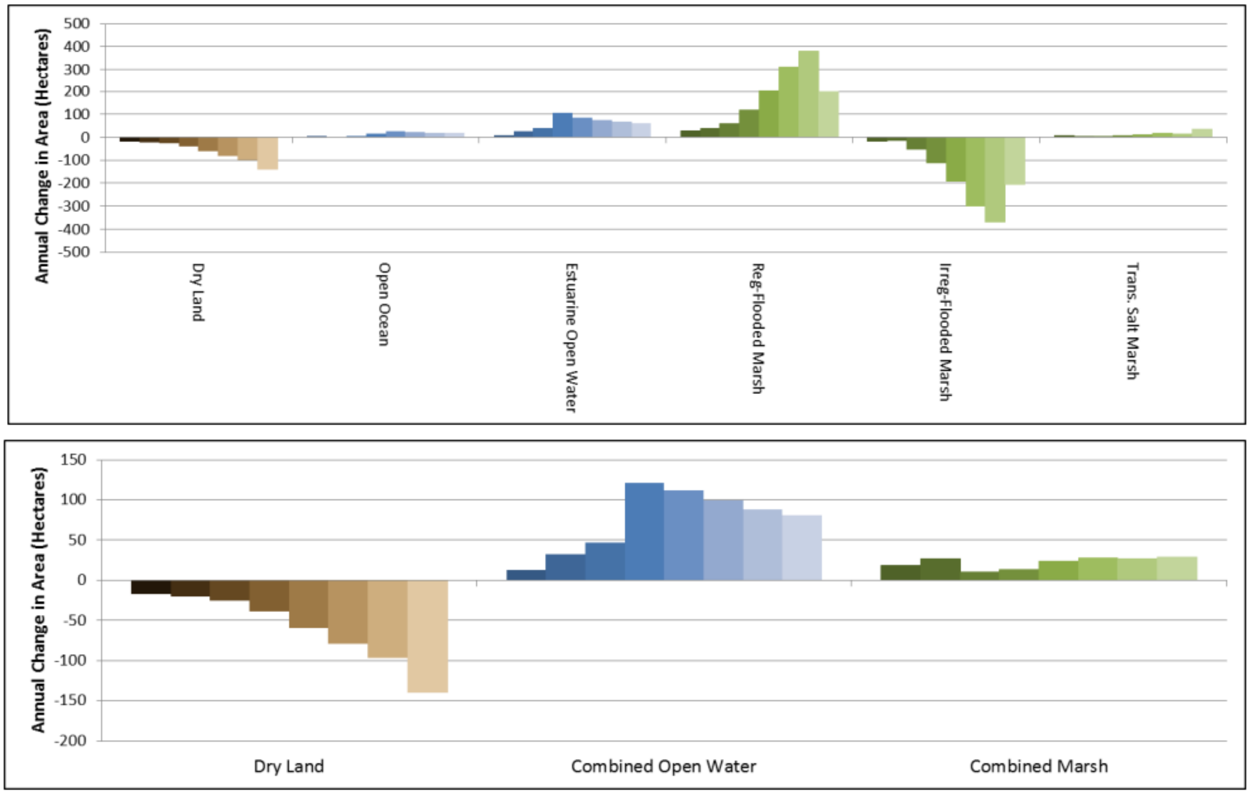


Figure B-15: Example of Detailed SLAMM outputs: Great Marsh to Provincetown, Cape Cod

Annual changes in coastal wetland areas (top panel) and combined coastal wetland areas (bottom panel) over evaluation periods for macrotidal areas (Average great diurnal tidal range > 1.5 meters)



Coastal Erosion:

For this assessment, the USGS Long Term Rates of Shoreline Change were extracted by region from the USGS database and combined to create a seamless data file for the entire Commonwealth of Massachusetts. These data were classified by rate to represent areas of erosion (negative shoreline change rates) and accretion (positive shoreline change rates) and were mapped to delineate areas of erosion > 1ft./yr. (red) erosion < 1ft./yr. (yellow), accretion < 1ft./yr. (light blue) and accretion > 1ft./yr. (dark blue).

Key assumptions that were made to project historic rates of shoreline change to the 2030, 2050, and 2070 out-years include:

- Long-term, historical rates of shoreline change were assumed to remain constant from 2021-2070, not taking into account non-linearities caused by sea level rise, increased frequency and intensity coastal storms, and changes to beach, dune, and coastal bank geomorphology.
- This analysis also assumed that historical rates of shoreline change would continue at a constant rate and that the composition of the shoreline would remain erodible over time, regardless of existing or future coastal armoring and/or hardened infrastructure.

Governance Sector

IMPACT	PRIMARY QUANTITATIVE ANALYSIS SOURCE	SUPPLEMENTAL INFORMATION
Reduction in State and Municipal Revenues (MOST URGENT)	Analysis based on published sources cited in Chapter 4	None
Increase in Costs of Responding to Climate Migration (MOST URGENT)	Mostly qualitative analysis based on publicly available data cited in Chapter 4	None
Increase in Demand for State and Municipal Government Services (MOST URGENT)	Mostly qualitative analysis based on publicly available data cited in Chapter 4	None
Damage to Coastal State and Municipal Buildings and Land	Analysis derived from Infrastructure: coastal flooding impact results, and overlay with state asset database provided to Project Team by DCAMM	None
Increase in Need for State and Municipal Policy Review and Adaptation Coordination	Analysis based on published sources cited in Appendix A	None
Damage to Inland State and Municipal Buildings and Land	Analysis derived from Infrastructure: inland flooding impact results, and overlay with state asset database provided to Project Team by DCAMM	None

Economy Sector

IMPACT	PRIMARY QUANTITATIVE ANALYSIS SOURCE	SUPPLEMENTAL INFORMATION
Reduced Ability to Work (MOST URGENT)	Analysis based on published sources cited in Chapter 4	None
Decrease in Marine Fisheries and Aquaculture Productivity (MOST URGENT)	Analysis based on published sources cited in Chapter 4	None
Reduction in the Availability of Affordably Priced Housing (MOST URGENT)	Analysis based on published sources cited in Chapter 4	None
Economic Losses from Commercial Structure Damage and Business Interruptions	Analysis derived from Infrastructure: inland flooding impact results, and from other published sources cited in Appendix A	None
Damage to Tourist Attractions and Recreation Amenities	Analysis based on published sources cited in Appendix A	None
Decrease in Agricultural Productivity	Analysis based on published sources cited in Appendix A	None

2.4 Supplemental Tables

Table B-6. Cities and Towns by Climate Assessment Region

Berkshires and Hilltowns	Central	Eastern Inland	
ADAMS	ASHBURNHAM	ABINGTON	MIDDLEBOROUGH
ALFORD	ASHBY	ACTON	MIDDLETON
ASHFIELD	ASHLAND	ANDOVER	MILLIS
BECKET	AUBURN	ARLINGTON	NATICK
BLANDFORD	AYER	ATTLEBORO	NEEDHAM
BUCKLAND	BELLINGHAM	AVON	NORFOLK
CHARLEMONT	BERLIN	BEDFORD	NORTH ANDOVER
CHESHIRE	BLACKSTONE	BELMONT	NORTH ATTLEBOROUGH
CHESTER	BOLTON	BILLERICA	NORTH READING
CHESTERFIELD	BOYLSTON	BOXBOROUGH	NORTON
CLARKSBURG	CHARLTON	BOXFORD	NORWOOD
CONWAY	CLINTON	BRIDGEWATER	PEPPERELL
CUMMINGTON	DEVENS	BROCKTON	PLAINVILLE
DALTON	DOUGLAS	BURLINGTON	PLYMPTON
EGREMONT	DUDLEY	CANTON	RANDOLPH
FLORIDA	FITCHBURG	CARLISLE	RAYNHAM
GOSHEN	FRANKLIN	CARVER	READING
GRANVILLE	GRAFTON	CHELMSFORD	ROCHESTER
GREAT BARRINGTON	GROTON	CONCORD	ROCKLAND
HANCOCK	HARVARD	DEDHAM	SHARON
HAWLEY	HOLDEN	DOVER	SHERBORN
HEATH	HOLLISTON	DRACUT	STONEHAM
HINSDALE	HOPEDALE	DUNSTABLE	STOUGHTON
HUNTINGTON	HOPKINTON	EAST BRIDGEWATER	STOW
LANESBOROUGH	HUDSON	EASTON	SUDBURY
LEE	LANCASTER	FOXBOROUGH	TAUNTON
LENOX	LEICESTER	FRAMINGHAM	TEWKSBURY
MIDDLEFIELD	LEOMINSTER	GEORGETOWN	TOPSFIELD
MONROE	LUNENBURG	HALIFAX	TYNGSBOROUGH
MONTEREY	MARLBOROUGH	HAMILTON	WAKEFIELD
MONTGOMERY	MEDWAY	HANSON	WALPOLE
MOUNT WASHINGTON	MENDON	HOLBROOK	WALTHAM
NEW ASHFORD	MILFORD	LAKEVILLE	WAYLAND
NEW MARLBOROUGH	MILLBURY	LAWRENCE	WELLESLEY
NORTH ADAMS	MILLVILLE	LEXINGTON	WENHAM
OTIS	NORTHBOROUGH	LINCOLN	WEST BRIDGEWATER
PERU	NORTHBRIDGE	LITTLETON	WESTFORD
PITTSFIELD	OXFORD	LOWELL	WESTON
PLAINFIELD	PAXTON	LYNNFIELD	WESTWOOD
RICHMOND	PRINCETON	MANSFIELD	WHITMAN
ROWE	RUTLAND	MAYNARD	WILMINGTON
RUSSELL	SHIRLEY	MEDFIELD	WINCHESTER
SANDISFIELD	SHREWSBURY	MELROSE	WOBURN
SAVOY	SOUTHBOROUGH	METHUEN	WRENTHAM
SHEFFIELD	SPENCER		
STOCKBRIDGE	STERLING	**Boston Harbor**	
TOLLAND	SUTTON	BOSTON	MEDFORD
TYRINGHAM	TOWNSEND	BRAINTREE	MILTON
WASHINGTON	UPTON	BROOKLINE	NEWTON
WEST STOCKBRIDGE	UXBRIDGE	CAMBRIDGE	QUINCY
WESTHAMPTON	WEBSTER	CHELSEA	REVERE
WILLIAMSBURG	WEST BOYLSTON	EVERETT	SOMERVILLE
WILLIAMSTOWN	WESTBOROUGH	HINGHAM	WATERTOWN
WINDSOR	WESTMINSTER	HULL	WEYMOUTH
WORTHINGTON	WORCESTER	MALDEN	WINTRHOP

North and South Shores	Cape, Islands, and South Coast	Greater Connecticut River Valley	
AMESBURY	ACUSHNET	AGAWAM	NEW SALEM
BEVERLY	AQUINNAH	AMHERST	NORTH BROOKFIELD
COHASSET	BARNSTABLE	ATHOL	NORTHAMPTON
DANVERS	BERKLEY	BARRE	NORTHFIELD
DUXBURY	BOURNE	BELCHERTOWN	OAKHAM
ESSEX	BREWSTER	BERNARDSTON	ORANGE
GLOUCESTER	CHATHAM	BRIMFIELD	PALMER
GROVELAND	CHILMARK	BROOKFIELD	PELHAM
HANOVER	DARTMOUTH	CHICOPEE	PETERSHAM
HAVERHILL	DENNIS	COLRAIN	PHILLIPSTON
IPSWICH	DIGHTON	DEERFIELD	ROYALSTON
KINGSTON	EASTHAM	EAST BROOKFIELD	SHELBURNE
LYNN	EDGARTOWN	EAST LONGMEADOW	SHUTESBURY
MANCHESTER	FAIRHAVEN	EASTHAMPTON	SOUTH HADLEY
MARBLEHEAD	FALL RIVER	ERVING	SOUTHAMPTON
MARSHFIELD	FALMOUTH	GARDNER	SOUTHBRIDGE
MERRIMAC	FREETOWN	GILL	SOUTHWICK
NAHANT	GOSNOLD	GRANBY	SPRINGFIELD
NEWBURY	HARWICH	GREENFIELD	STURBRIDGE
NEWBURYPORT	MARION	HADLEY	SUNDERLAND
NORWELL	MASHPEE	HAMPDEN	TEMPLETON
PEABODY	MATTAPOISETT	HARDWICK	WALES
PEMBROKE	NANTUCKET	HATFIELD	WARE
PLYMOUTH	NEW BEDFORD	HOLLAND	WARREN
ROCKPORT	OAK BLUFFS	HOLYOKE	WARWICK
ROWLEY	ORLEANS	HUBBARDSTON	WENDELL
SALEM	PROVINCETOWN	LEVERETT	WEST BROOKFIELD
SALISBURY	REHOBOTH	LEYDEN	WEST SPRINGFIELD
SAUGUS	SANDWICH	LONGMEADOW	WESTFIELD
SCITUATE	SEEKONK	LUDLOW	WHATELY
SWAMPSCOTT	SOMERSET	MONSON	WILBRAHAM
WEST NEWBURY	SWANSEA	MONTAGUE	WINCHENDON
	TISBURY	NEW BRAINTREE	
	TRURO		
	WAREHAM		
	WELLFLEET		
	WEST TISBURY		
	WESTPORT		
	YARMOUTH		

Table B-7. List of Adaptation Plans Reviewed by Region

Plan Name	Plan Type
Berkshires and Hilltowns	
Assessment & Design for Adaptation & Resilience	Project Grant
Baptist Corner Road Stream Crossing Ecological Improvements	Project Grant
Churchill Brook and West Street Culvert Replacement Project	Project Grant
Climate Action, Resilience, and Equity Great Barrington (CARE GB)	Project Grant
Enhancing Flood Resiliency through Culvert Improvements along the Konkapot River in Monterey Town Center	Project Grant
Housatonic Stream Restoration for Regional Flood Resilience Project	Project Grant
Mill Street (Tel-Electric) Dam Removal Project	Project Grant
Mohawk Trail Woodland Partnership Forest Stewardship, Resilience & Climate Adaptation	Project Grant
Mohawk Trail Woodland Partnership Regional Adaptation & Resilience Project	Project Grant
Resilience Building through Community Visioning and Planning	Project Grant
Resilient Community-Driven Master Plan + Resilient Regulatory Work	Project Grant
River Road Site 1 Culvert	Project Grant
Rural Dirt Road Resilience - Assessment, Pilot Study, and Recommendations Report	Project Grant
South River Flood Resiliency Project	Project Grant
Transportation Infrastructure Improvement, Inventory, and Prioritization Plan	Project Grant
Watershed-Based Assessment and Climate Resiliency Plan for Clesson Brook	Project Grant
Boston Harbor	
Armstrong Dam and Ames Pond Dam Removal- Final Design and Permitting	Project Grant
Assessment of Shoreline Resiliency Alternatives for Marginal Road	Project Grant
Battery Storage System and Solar at Chelsea City Hall	Project Grant
Belle Isle Marsh: Evaluating Nature Based Solutions to Protect Abutting Communities and Critical Shorebird Habitat from Coastal Inundation	Project Grant
Brookline Climate Action Plan	Combined Mitigation & Adaptation Plan
Building Resilience to Climate Driven Heat in Metro Boston	Project Grant
Cambridge Climate Preparedness & Resilience Catalyst Project	Project Grant
City of Boston Climate Action Plan	Combined Mitigation & Adaptation Plan
City of Boston Heat Resilience Planning Study	Project Grant
City of Cambridge Hazard Mitigation Plan 2015 Update	Hazard Mitigation Plan
City of Newton Climate Action Plan	Combined Mitigation & Adaptation Plan
Climate Change Vulnerability Assessment, Part 1	Other
Climate Change Vulnerability Assessment, Part 2	Other
Climate Ready Boston	Adaptation Plan
Climate Ready Boston Municipal Vulnerability to Climate Change	Adaptation Plan
Climate Ready Zoning and Design Guidelines	Project Grant
Climate Resiliency Policy Audit, Amendments and LID and Design Guidelines	Project Grant
ClimateCARE	Adaptation Plan
Coastal Flood Mitigation Storm Drainage Improvements- Phase 1 - Engineering & Public Outreach	Project Grant

Plan Name	Plan Type
Coastal Resilience Feasibility Study for the Point of Pines and Riverside Area	Project Grant
Coastal Resilience Solutions for Downtown Boston and North End	Adaptation Plan
Completing a watershed-wide analysis to optimize & coordinate regional stormwater management in the Mystic River Watershed	Project Grant
Conceptualization and community building for equitable, community-driven Resilience Hubs in Medford	Project Grant
Critical Regional Infrastructure and Social Vulnerability in the Lower Mystic Watershed	Project Grant
DCR: Upgrade and strengthen control systems for both the New Charles River and Amelia Earhart dams.	Specific Action
Drainage Model & Conceptual Strategies to Reduce Future Flooding in South Medford	Project Grant
East Boston Climate Mitigation and Adaptation Planning	Combined Mitigation & Adaptation Plan
Equity-Based Community Greening Program	Project Grant
Equity-Centered Process for Climate Action and Adaptation Planning	Project Grant
Flood Mitigation Strategy Feasibility Analysis and Conceptual Design	Project Grant
Fort Point Road Coastal Infrastructure Resilience Project	Project Grant
Gibson Park Resiliency Design and Permitting	Project Grant
Greenovate Boston Climate Action Plan	Adaptation Plan
Ingleside Park Feasibility Study and Permitting	Project Grant
Island End River Flood Resilience Project	Project Grant
Island End River Flood Resilience Project Part 3	Project Grant
Keep Cool Somerville Cooling Strategies Toolkit	Adaptation Plan
Keeping Metro Boston Cool, A Regional Heat Preparedness and Adaptation Plan	Adaptation Plan
Malden River Works	Project Grant
Malden River Works for Waterfront Equity and Resilience	Project Grant
Massachusetts Port Authority Floodproofing Design Guide	Other
MassDOT-FHWA Pilot Project - Climate Change and Extreme Weather Vulnerability Assessments and Adaptation Options of the Central Artery	Adaptation Plan
Medford Climate Action and Adaptation Plan Draft	Combined Mitigation & Adaptation Plan
Medford Open Space Plan Update Part 1	Project Grant
Medford Open Space Plan Update Part 2	Project Grant
Medford Open Space Plan Update Part 3	Project Grant
Medford Open Space Plan Update Part 4	Project Grant
Metro Boston Regional Climate Change Adaptation Strategy Report	Adaptation Plan
MMC Heat Preparedness, Community and Social Cohesion Pathway Brief	Adaptation Plan
MMC Heat Preparedness, Employment Pathway Brief	Adaptation Plan
MMC Heat Preparedness, Housing Pathway Brief	Adaptation Plan
MMC Heat Preparedness, Open Space and Recreation Pathway Brief	Adaptation Plan
MMC Heat Preparedness, School Buildings and Education Pathway Brief	Adaptation Plan
MMC Heat Preparedness, Transportation Research Pathway Brief	Adaptation Plan
Moakley Park - Resilience Preliminary Design, Technical Analysis, and Pre-Permitting	Project Grant
Monatiquot River Restoration – Construction	Project Grant
Preparing for the Rising Tide	Adaptation Plan
Recommendations for Adaptation to Climate Change	Adaptation Plan

Plan Name	Plan Type
Resilient Boston - An Equitable and Connected City	Adaptation Plan
Resilient Cambridge	Adaptation Plan
Smith Beach Green Infrastructure Project	Project Grant
Somerville Climate Forward - Somerville's Community Climate Change Plan	Adaptation Plan
Somerville Climate Forward Program 2020 Progress Report	Combined Mitigation & Adaptation Plan
Somerville Stormwater System Modeling for Improved Communications and Development of Green Infrastructure	Project Grant
Suitability Assessment for Equitable, Community-Driven Resilience Hubs	Project Grant
Town of Braintree Climate Vulnerability Assessment and Action Plan	Combined Mitigation & Adaptation Plan
Urban Forest Climate Resiliency Master Plan	Project Grant
Urban Heat Island Mitigation Project	Project Grant
Winthrop Climate Resilient Land Use and Zoning	Project Grant
Cape, Islands, and South Coast	
Assess and Plan for Climate Threats to East Beach Corridor	Project Grant
Climate Change Flood Vulnerability Assessment and Adaption Planning	Project Grant
Climate Change Vulnerability Assessment and Adaptation Planning Study for Water Quality Infrastructure in New Bedford, Fairhaven and Acushnet	Adaptation Plan
Coastal Resiliency Planning for the Surf Drive Area	Project Grant
Comprehensive Climate Adaptation and Resilience Action Plan and Interactive Community Dashboard	Project Grant
Conceptual Design of Flood-Resiliency Improvements for Sewer Infrastructure	Project Grant
Coonamessett River Restoration Project - Construction of Phase 2	Project Grant
Culvert and Green Infrastructure Concept Design and Dam Resiliency Assessment	Project Grant
Cuttyhunk Land Conservation Project	Project Grant
Development of an Island-Wide Specific Adaptation Strategy	Project Grant
Edgartown Climate Change Flood Vulnerability Assessment and Adaptation Planning	Project Grant
Energy Resiliency for Mission-Critical Facilities	Project Grant
Herring River Restoration Project Phase 1 Final Construction Plans and Bid Specifications	Project Grant
Martha's Vineyard and Gosnold Climate Action Plan, Phase II	Project Grant
New Bedford Green Infrastructure Master Strategy and Implementation Roadmap	Project Grant
New Bedford Harbor MC-FRM Evaluation and Resilience Design Guideline Development	Project Grant
North Bluff Preservation Project	Project Grant
Permit Level Design of the Ryder Street Outfall Relocation and Drainage Improvements	Project Grant
Pine Island Watershed Lands Project	Project Grant
Planning for a Shifting Shoreline and Coastal Storms Chapter, Buzzards Bay Comprehensive Conservation and Management Plan	Adaptation Plan
Pound Pond, Dennis- Flood Mitigation and Storm Drainage Improvements	Project Grant
Public Water Supply Infrastructure Vulnerability Assessment	Project Grant
Regional Emergency Water System Interconnectivity Analysis	Project Grant
Regional Low Lying Road Assessment and Feasibility	Project Grant
Resilient Nantucket - Designed for Adaptation	Project Grant
Resilient Nantucket: Flooding Adaptation & Building Elevation Design Guidelines	Adaptation Plan

Plan Name	Plan Type
Water Supply Risk & Resilience Assessment (RRA) and Distribution System	Project Grant
Watershed-based Solutions to Increase Resilience to Harmful Algal Blooms in Santuit Pond in a Warmer and Wetter Climate	Project Grant
Central	
Apple Country Ecological Climate Resiliency and Carbon Planning Assessment	Project Grant
Armory Village Green Infrastructure Project	Project Grant
Armory Village Green Infrastructure Project - Phase II	Project Grant
Armory Village Green Infrastructure Project - Phase III	Project Grant
Bolstering Public and Private Action to Improve Flood Resilience in Baker Brook	Project Grant
Carpenter Road Causeway Alternatives Analysis and Source Water Green Infrastructure Protection Plan	Project Grant
Community Climate Action & Land Stewardship Plan	Project Grant
Develop Protection Measures for Vulnerable Drinking Water Supply Areas and Evaluate Green Bridge Design	Project Grant
Devens Climate Action and Resilience Plan	Project Grant
Green Infrastructure Implementation in Downtown Spencer, Mechanic Street Parking Lot	Project Grant
Green Stormwater Infrastructure in Milford Town Park	Project Grant
Green Worcester Plan	Combined Mitigation & Adaptation Plan
Integrated Vector-borne Disease Control Program	Project Grant
Integrated Water Infrastructure Vulnerability Assessment and Climate Resiliency Plan	Project Grant
Integration of Low Impact Development Standards into Local Bylaws & Subdivision Regulations	Project Grant
John Fitch Highway – A Resilient Road Corridor	Project Grant
Leesville Pond Water Quality Protection and Community-Wide Resiliency Improvements	Project Grant
MassWildlife - Dam removals at the Merrill Ponds Wildlife Management Area	Specific Action
Mendon Town Hall Campus Green Stormwater Infrastructure: Design through Contractor Mobilization	Project Grant
Microgrid Feasibility Study	Project Grant
Monoosnoc Brook Bank Stabilization Project Part 1	Project Grant
Monoosnoc Brook Bank Stabilization Project Part 2	Project Grant
Nashua River Communities Resilient Lands Management Project	Project Grant
Planimetric Impervious Surface Mapping Project	Project Grant
Regulatory Updates to Support Climate Resiliency	Project Grant
Sustainable Franklin County	Combined Mitigation & Adaptation Plan
Uxbridge Integrated Water Infrastructure Vulnerability Assessment and Climate Resiliency Plan	Project Grant
Water and Sewer Infrastructure Green Emergency Power Supply	Project Grant
Worcester Hazard Mitigation Plan	Hazard Mitigation Plan
Worcester Senior Center Parking Lot – Nature-Based Solutions	Project Grant
Greater Connecticut River Valley	
Agawam Stormwater Master Plan	Project Grant
Cherry Street Green Infrastructure and Slope Restoration Construction	Project Grant
City of Springfield Hazard Mitigation Plan	Hazard Mitigation Plan
Climate Action, Adaptation and Resilience Plan	Project Grant
Climate Resilient South Hadley	Project Grant

Plan Name	Plan Type
Community Resilience Through Urban Forestry - Improving Emergency Response and Environmental Conditions in Springfield Massachusetts	Project Grant
Comprehensive Master Plan	Project Grant
Energy Resiliency for Town Hall-EOC-Police HQ Facility	Project Grant
Enhancing Water Supply Reliability - Resilient Water Storage & Water Conservation Planning	Project Grant
Enhancing Water Supply Reliability - Resilient Water Storage and Water Conservation – Design & Implementation	Project Grant
Flood Resiliency Through Green Infrastructure in Deerfield	Project Grant
Green Infrastructure Planning and Resiliency Design for Cherry Street	Project Grant
Greening Lord Pond Plaza Phase 2	Project Grant
Hampden and East Longmeadow Infrastructure Assessment and Prioritization of Nature-Based Solutions and Public Outreach and Participation	Project Grant
Healthy Soils, Green Infrastructure Policy and Climate Resiliency Public Engagement in Deerfield	Project Grant
Holyoke Urban Forest Equity Plan	Project Grant
Impervious Surface Mapping for Resiliency Planning and Implementation	Project Grant
Klaus Anderson Road Johnson Brook Road-Stream Crossing Redesign, Floodplain Restoration and Green Stormwater Management	Project Grant
Klaus Anderson Road/Johnson Brook Replacement Culvert and Green Infrastructure	Project Grant
Land Conservation and Restoration of the Scarborough Brook Headwaters for Climate Resilience	Project Grant
Lord Pond Plaza Improvement Project	Project Grant
MassDOT: Pilot Deerfield Watershed Stream Crossing Resilience Project.	Specific Action
Meeting an Immediate Need by Learning from Hurricane Maria Survivors in Holyoke	Project Grant
Montague City Road Flooding Protection Project - Design and Permitting	Project Grant
Municipal Vulnerability Preparedness Plan Implementation	Project Grant
Northampton Designs with Nature to Reduce Storm Damage	Project Grant
Palmer Comprehensive Master Plan	Project Grant
Pelham Severe Weather Mitigation Project	Project Grant
People-focused Resilient Redesign and Retrofits for community and civic Infrastructure and critical facilities in Springfield MA (improving communication/building trust and advancing Microgrids)	Project Grant
Pioneer Valley Climate Action and Clean Energy Plan	Combined Hazard Mitigation & Adaptation Plan
Protecting Downtown - Northampton’s Flood Control Levees	Project Grant
Queensville Dam Removal Feasibility Study and Buttery Brook Watershed Enhancement	Project Grant
Reducing Flooding Vulnerability in Deerfield	Project Grant
Resilient Pelham	Project Grant
Resilient Regulatory Work + Refocusing on Climate Resilience Pathway in Master Plan	Project Grant
Restoring the Pine Grove Golf Course for Climate Resiliency	Project Grant
RT 181 Culvert Replacement & Culvert Infrastructure Assessment	Project Grant
Shutesbury Road Culvert Enhancement	Project Grant
Springfield Climate Action & Resiliency Plan Vulnerability and Resilience	Adaptation Plan
Town-wide Road Stream Crossing Assessment and Climate Change Adaptation Plan	Project Grant
Trees, Homes, and People - Creating a More Resilient Living Environment	Project Grant
Wheelock Culvert Repair and Replacement and Data Redundancy	Project Grant

Plan Name	Plan Type
Eastern Inland	
53 River Street Dam Removal	Project Grant
Advancing Green Infrastructure in Foxborough for Enhancing Climate Resilience through Planning and Design	Project Grant
Assawompset Ponds Complex Watershed Management and Climate Action Plan	Project Grant
Assessing the Health of Lake Boon – a Key to Climate Resiliency in Stow & Hudson, MA – and beyond	Project Grant
Bringing Climate Resilience to Beaver Brook	Project Grant
Building a Municipal Resilience Portfolio - Assessment of Critical Land in the Winnetuxet River Corridor	Project Grant
Building Relationships and Resilience with MetroWest Environmental Justice Neighborhoods	Project Grant
Building Resilience Across the Charles River Watershed	Project Grant
Building Resilience Across the Charles River Watershed Phase II	Project Grant
City Hall Parking Lot Green Infrastructure Project	Project Grant
City of Framingham Climate Change and Hazard Planning	Combined Hazard Mitigation & Adaptation Plan
City of Lowell Municipal Vulnerability Preparedness and Hazard Mitigation Plan	Hazard Mitigation Plan
Claypit Brook Climate Resilience Stormwater Management Capital Improvement Plan	Project Grant
Climate Action Plan and Electrification Roadmap	Project Grant
Climate Change Vulnerability and Resiliency Assessment Study	Project Grant
Climate Change Water Resource Vulnerability and Adaptation Strategy Assessment	Project Grant
Climate Resilience and Low Impact Development Regulatory Integration and Green Infrastructure Master Plan	Project Grant
Concord Climate Action & Resilience Plan	Project Grant
Culvert Assessment and Green Infrastructure Survey, Walpole, MA	Project Grant
Dedham Climate Action & Resilience Plan	Project Grant
Dunshire Drive Culvert Replacement & Deep Brook Stream Restoration - Phase I	Project Grant
Eagle Dam Removal	Project Grant
Flood Resiliency Plan	Project Grant
Flood Study and DPW Yard Adaptation Plan	Project Grant
Groundwork Lawrence DPW Flood Assessment & Adaptation Plan	Adaptation Plan
High Street Dam Removal	Project Grant
Horn Pond Brook Improved Fisheries Habitat and Flood Control	Project Grant
Increasing Regional Flood Resiliency through Re-Designing Culverts in the Howlett Brook Watershed	Project Grant
Integrated Water Infrastructure Vulnerability Assessment & Economic Development Plan for Climate Resiliency	Project Grant
Low Impact Development Regulation Development and Zoning Bylaw Inclusion	Project Grant
MAGIC Climate Change Resiliency Plan, Vulnerability Assessment, Pt. 1	Adaptation Plan
Melrose, Malden, and Medford Building Resilience, Efficiency, and Affordability Project	Project Grant
Merrimack River Watershed Comprehensive Plan for Diadromous Fishes	Adaptation Plan
Mill Brook Corridor Flood Management Demonstration Project - Pilot Study & Implementation	Project Grant
Reforestation and Municipal Tree Resilience	Project Grant
Richardson Green Conservation Acquisition	Project Grant
Searles Pond/Bloody Brook Corridor Resilience Planning	Project Grant

Plan Name	Plan Type
Shaker Glen Restoration and Flood Mitigation	Project Grant
Shawsheen River Watershed Land Conservation Planning and Prioritization for Climate Resilience and Environmental Justice	Project Grant
Stormwater Analysis for Nature-Based Solutions and Community Co-Benefits	Project Grant
Stormwater Flood Reduction and Climate Resilience Capital Improvement Plan	Project Grant
Sucker Brook Continuity Restoration	Project Grant
Traphole Brook Flood Prevention and Stream Restoration Project	Project Grant
Tree Planting Plan to Mitigate Heat Islands and Reduce Runoff	Project Grant
Upper Mystic River Watershed Regional Stormwater Wetlands	Project Grant
Vine Brook Watershed and Urban Heat Island Assessment	Project Grant
Walnut Street Neighborhood Flood Mitigation - Design & Permitting	Project Grant
Walnut Street Neighborhood Flood Mitigation & City Stormwater Utility Feasibility Studies	Project Grant
Waltham Resilient Stormwater Management and Implementation Plan	Project Grant
Water Conservation Campaign	Project Grant
Watershed Protection for Climate Resiliency- Brown's Woods Acquisition	Project Grant
Westford Tree and Invasive Species Inventory and Management Plan with Tree Planting Plan	Project Grant
Weston Climate Action & Resiliency Plan	Project Grant
Wetland Restoration- Removal of Abandoned Structures	Project Grant
Wicked Hot Mystic	Project Grant
Working Across Boundaries to Minimize Stormwater Flood Damage in the Upper Mystic Watershed	Project Grant
North and South Shores	
Assessing storm energy reduction by the vegetated salt marsh platform	Project Grant
Barry Park Green Infrastructure Project	Project Grant
Beach Access Resiliency and Accessibility Improvements	Project Grant
Beverly & Salem Climate Action and Resilience Plan	Project Grant
Building a Resilient Scituate	Adaptation Plan
City of Salem Hazard Mitigation Plan	Hazard Mitigation Plan
Climate Change Adaptation, Master Plan Chapter	Adaptation Plan
Climate Change Vulnerability Assessment and Adaptation Planning for the Town of Sandwich	Project Grant
Communicating the Local Benefits of a Resilient Coast	Project Grant
Comprehensive Wastewater Treatment Resilience Feasibility Study	Project Grant
Controlling Flooding and Addressing Future Climate Impacts through the Replacement of the Orchard Street Culvert	Project Grant
Documenting Effects of a Large-Scale, Natural Sediment Event on Salt Marsh Resiliency in the Great Marsh Estuary	Project Grant
Duxbury Climate Change Flood Vulnerability Assessment and Adaptation Planning	Project Grant
Dynamic Adaptation Pathways and Prioritized Resilient Design Solutions for Historic Sandwich Village	Project Grant
Feasibility Study for an Essex Bay Living Shoreline	Project Grant
Gloucester Climate Action and Resilience Plan (CARP)	Project Grant
Green Infrastructure for Stormwater Management in City Projects	Project Grant
Impacts of future storminess, greater wave energy, and increased sediment transport	Project Grant
Increasing the Resiliency of Short Beach on Nahant to Sea Level Rise - Access Point Restoration and Modification Plan	Project Grant

Plan Name	Plan Type
Ipswich River Sewer Interceptor and Siphon Risk Mitigation and Resiliency Improvements	Project Grant
Ipswich River Sewer Interceptor Bank Biostabilization Project	Project Grant
Johnson Creek Watershed Flood Resiliency Project	Project Grant
Lawrence Brook Watershed Flood Mitigation and Water Quality Improvement	Project Grant
Little River Dam Removal and River Restoration	Project Grant
Little River Dam Removal Feasibility Study	Project Grant
Mapping Storm Tide Pathways in Scituate & Cohasset - Assessing Coastal Vulnerability to Storms & Sea Level Rise	Project Grant
Marshfield Long-term Coastal Resiliency Plan	Project Grant
North River Canal Resilient Wall, Riverwalk and Park	Project Grant
Ocean Ave. West Pump Station Flood Mitigation – Preliminary Design	Project Grant
Open Space and Recreation Plan Update	Project Grant
Peabody-Salem Resilient North River Corridor & Riverwalk Project	Project Grant
Plum Island Cost/Benefit Analysis	Project Grant
Ready for Tomorrow - The City of Salem Climate Change Vulnerability Assessment and Adaptation Plan	Adaptation Plan
Resilient Critical Infrastructure - Adapting a Wastewater Treatment Facility, Underground Electric Lines and Public Rail Trail to Future Sea Level Rise and Storm Surge Part 1	Project Grant
Resilient Critical Infrastructure - Adapting a Wastewater Treatment Facility, Underground Electric Lines and Public Rail Trail to Future Sea Level Rise and Storm Surge Part 2	Project Grant
Resilient North River Canal Corridor– Phase 2 Part 1	Project Grant
Resilient North River Canal Corridor– Phase 2 Part 2	Project Grant
Resilient Ring's Island - Preventing a Neighborhood from Being Stranded by Flooding	Project Grant
Resilient Ring's Island - Preventing a Neighborhood from Being Stranded by Flooding Phase 2	Project Grant
Salem Sanitary Sewer Trunk Line Relocation Assessment	Project Grant
Saugus Climate Adaptation and Resilience Plan	Project Grant
Sawmill Brook Central Pond Restoration Design	Project Grant
Sawmill Brook Central Pond Restoration Project Phase 2 - Permitting and Final Design	Project Grant
Scituate/Duxbury Coastal Climate Resiliency Plan	Adaptation Plan
Strawberry Brook Green Infrastructure Implementation	Project Grant
Strawberry Brook Resilient Stormwater Management and Implementation Plan	Project Grant
Subterranean Resiliency: Predicting, Assessing and Mitigating Saltwater Intrusion	Project Grant
Town of Duxbury Climate Vulnerability Assessment and Action Plan	Adaptation Plan
Wastewater Treatment Plant Climate Resilience	Project Grant
Watershed and Water Supply Vulnerability, Risk Assessment and Management Strategy	Project Grant
Coastal (Multi-Region)	
DCR: Work in strong coordination with EOEEA to monitor coastal shoreline sediment migration.	Specific Action
DER: Restore Coastal Wetlands - Prioritize, develop, and implement coastal wetland restoration projects that improve ecological health and increase the climate resilience of human and natural communities.	Specific Action
Massachusetts Coastal Erosion Commission	Adaptation Plan
Massachusetts Ocean Resource Information System	Other
MassDOT: Expand and improve the Boston Harbor Flood Risk Model to create the Massachusetts Coastal Flood Risk Model.	Specific Action

Plan Name	Plan Type
MassWildlife: In partnership with CZM, improve management of beach nourishment projects and other shoreline protection strategies and incorporate habitat considerations into coastal storm disaster response habitat and infrastructure on barrier beaches.	Specific Action
Preparing for the Storm - Recommendations for Management of Risk from Coastal Hazards in Massachusetts	Adaptation Plan
Statewide	
A&F: Budgeting, coordinating administrative functions, and planning.	Specific Action
Addressing climate-related asthma prevalence	Other
Building retrofit standards adapted to consider climate change resilience and health	Specific Action
Caring for Your Woods: Adapting to Changing Conditions	Adaptation Plan
Caring for Your Woods: Managing for Forest Carbon	Combined Mitigation & Adaptation Plan
Climate Resilience Design Standards Tool	Other
Co-benefits of emissions reductions	Other
DCAMM: Incorporate hazard and climate change vulnerability into capital planning, master planning, and facilities management functions.	Specific Action
DCR Watershed Management Plans	Adaptation Plan
DCR: Develop strategy to implement priority DCR infrastructure projects in its Coastal Inventory.	Specific Action
DCR: Incorporate climate vulnerability in all planning efforts.	Specific Action
DCR: Revise current review procedures for DCR-managed dams and other flood control structures to incorporate climate change data.	Specific Action
DCR: Track and assess asset vulnerability by adding climate change/resiliency categories as part of the Asset Management Modernization Project.	Specific Action
DCR: Update the State Forest Action Plan to enhance climate change mitigation and adaptation strategies.	Specific Action
DEP: Demand strategies educational campaign.	Specific Action
DEP: Develop a Statewide River Hydraulic Model.	Specific Action
DEP: Develop Future Extreme River Flow Projections.	Specific Action
DEP: Enhance the Water Utility Resilience Program (WURP).	Specific Action
DEP: Implement Updated Stream crossing culvert replacement guidance.	Specific Action
DEP: Improve Mapping to Enhance Resilience and Emergency Preparedness of Water Utilities.	Specific Action
DEP: Promulgate wetlands regulations to establish performance standards for work in land subject to coastal storm flowage.	Specific Action
DEP: Regional water quality monitoring initiative.	Specific Action
DEP: Resiliency Grants for Water Infrastructure.	Specific Action
DEP: Update precipitation data used by wetlands program.	Specific Action
DEP: Vulnerability assessment of hazardous waste sites.	Specific Action
DER: Restore Water Quality - Develop and implement priority water quality restoration projects that improve ecological health and increase the climate resilience of human and natural communities.	Specific Action
DER: Build Regional Restoration Capacity - Develop and implement a Regional Restoration Partnerships Program that builds the capacity of regional organizations to help communities plan and implement climate adaptation and ecological restoration actions.	Specific Action
DER: Develop a Dam Removal Decision Support Tool - Develop and share a web-based tool that evaluates the potential removal of any dam for hazard reduction and ecological and climate resilience benefits.	Specific Action
DER: Remove Barriers From Cold Water Streams - Develop and implement priority restoration projects on cold water streams to reduce public hazards, improve ecological health, and increase the climate resilience of human and natural communities.	Specific Action
DER: Remove Municipal and Other Dams Statewide - Remove unwanted, obsolete municipal and other dams to reduce public hazards, improve ecological health, and increase the climate resilience of human and natural communities.	Specific Action

Plan Name	Plan Type
DER: Remove State-owned Dams - Remove unwanted, obsolete state-owned dams to reduce public hazards, improve ecological health, and increase the climate resilience of human and natural communities.	Specific Action
DER: Restore Streamflow - Develop and implement priority streamflow restoration projects that improve ecological health and increase the climate resilience of human and natural communities.	Specific Action
DER: Restore Wetlands and Streams Within Retired Cranberry Bogs - Develop and implement priority restoration projects within retired cranberry bogs to improve ecological health, protect open space, and increase the climate resilience of human and natural communities.	Specific Action
DER: Upgrade Municipal Culverts - Build municipal capacity to replace undersized, deteriorated culverts with larger, safer structures that reduce public hazards, improve ecological health, and increase the climate resilience of human and natural communities.	Specific Action
DHCD: Facilitate and coordinate development of guidelines and best practices for climate change adaptation and resilience for state-aided housing development.	Specific Action
DLS: Review and consider updates to MASSsafetyWorks! resources given increased expectations of extreme weather events.	Specific Action
DOER: Build energy resiliency.	Specific Action
DPH: Provide support and direct care to vulnerable populations susceptible to climate change impacts.	Specific Action
DPH: Strengthen DPH health care systems and services to prepare for climate impacts.	Specific Action
DPH: Strengthen environmental health programs to respond to climate-related impacts.	Specific Action
DPH: Update and expand DPH and DPH provider/vendor Emergency Operations Plans (EOPs) and Continuity of Operations Plans (COOPs) to address climate impacts.	Specific Action
DPU: Facilitate a program for sharing resources between municipalities for tree maintenance.	Specific Action
DPU: Power system planning that incorporates climate change risk.	Specific Action
DPU: Regional power grid planning and incorporation of climate change data.	Specific Action
DPU: Review storm preparedness best practices from other regional distribution systems.	Specific Action
EOE: Review and recommend changes to regulations and policy related to determine if changes are needed to address resiliency planning for the sites and providers who are licensed by the Commonwealth to care for children.	Specific Action
EOEEA: Accelerate implementation of priority actions identified through the Municipal Vulnerability Preparedness (MVP) program, increase municipal participation in planning program, conduct program review and revise planning and action grant program as needed.	Specific Action
EOEEA: Based on results of vulnerability assessment for EOEEA properties and vulnerability assessments from other agencies, use climate change projections to develop stormwater management actions and projects.	Specific Action
EOEEA: Create and deploy a SHMCAP project database.	Specific Action
EOEEA: Develop and implement a communications strategy to build state agency, municipal and public awareness of climate change resiliency issues and adaptation strategies.	Specific Action
EOEEA: In consultation with DCAMM, MassDOT, and EOHED develop climate change design standards.	Specific Action
EOEEA: Incorporate information on climate change risk and vulnerability from the SHMCAP and subsequent studies into all capital budget planning.	Specific Action
EOEEA: Maintain and enhance climate change projections and specific climate change data sets to support different groups of end users.	Specific Action
EOEEA: Review habitat management, land stewardship, coastal zone management, agricultural and invasive species programs and policies to develop strategies that promote coordination among agencies and support climate change adaptation and mitigation goals.	Specific Action
EOEEA: Review, evaluate, and implement revisions as needed to environmental and energy policies, regulations, and plans.	Specific Action
EOEEA: Update and maintain the resilientMA.org climate change clearinghouse site to include a Vulnerability Assessment Wizard for MVP communities, a clearinghouse to grant programs to fund MVP actions, and a dynamic version of the SHMCAP.	Specific Action
EOEEA: Utilize available climate change projections and risk assessment data to assess vulnerabilities of all EOEEA properties. Support efforts across the administration to assess facilities held by other Executive Offices.	Specific Action
EOHED: Incorporate climate change resilience/adaptation standards into grant programs including MassWorks.	Specific Action

Plan Name	Plan Type
EOPSS: Create a statewide Threat and Hazard Identification and Risk Assessment (THIRA). In conjunction with the development of the THIRA conduct a statewide capabilities gap assessment.	Specific Action
EOPSS: Incorporate climate change resilience into business continuity planning for state government.	Specific Action
EOTSS: For Registry of Motor Vehicle systems that must remain on-premises (not cloud), evaluate migration options or relocations to third party on premises.	Specific Action
EOTSS: Migrate Beacon, Meditech and FamilyNet to the cloud.	Specific Action
EOTSS: Migrate CommVault to the cloud.	Specific Action
EOTSS: Migrate critical operational systems to the cloud; move critical communications infrastructure to 3rd party provider - off site from MITC	Specific Action
EOTSS: Migrate email to the cloud.	Specific Action
EOTSS: Migrate HRCMS/MMARS to the cloud.	Specific Action
EOTSS: Re-platform MA21 and MMIS to enable cloud migration.	Specific Action
Greening the Gateway Cities Program	Specific Action
HRD: Incorporate hazard and climate change vulnerability into personnel and workplace policies, training, and guidance as appropriate.	Specific Action
Increasing Forest Resiliency for an Uncertain Future	Adaptation Plan
Massachusetts 2022 Vibrio parahaemolyticus Control Plan	Adaptation Plan
Massachusetts Clean Water Trust Green Bonds	Other
Massachusetts Climate Change Adaptation Report	Adaptation Plan
Massachusetts H 4835 - An Act Promoting Climate Change Adaptation, Environmental and Natural Resource Protection and Investment in Recreational Assets and Opportunity	Adaptation Plan
Massachusetts State Hazard Mitigation and Climate Adaptation Plan	Combined Hazard Mitigation & Adaptation Plan
Massachusetts States Forest Action Plan	Combined Mitigation & Adaptation Plan
Massachusetts StormSmart Coasts Program	Other
Massachusetts Wildlife Climate Action Tool	Other
MassDOT: Assess the feasibility of recommendations from the Commission on the Future of Transportation in the Commonwealth.	Specific Action
MassDOT: Capture and document institutional knowledge on vulnerabilities from staff using the Mapping Our Vulnerable Infrastructure Tool (MOVIT).	Specific Action
MassDOT: Coordinate with state and federal agencies to evaluate environmental regulation and permitting processes to address current roadblocks in climate change.	Specific Action
MassDOT: Develop climate change adaptation design guidance and provide resources and training for project managers and design teams on bridge and culvert design interaction with emerging fluvial geomorphology practices.	Specific Action
MassDOT: Establish training to incorporate climate change awareness into project design, operations, and maintenance functions.	Specific Action
MassDOT: Incorporate climate change adaptation into the MassDOT Highway Division Transportation Asset Management Plan and coordinate Asset Management across divisions and partner agencies.	Specific Action
MassDOT: Incorporate climate resiliency into capital planning activities.	Specific Action
MassDOT: Incorporate resiliency review items into the Early Environmental Coordination Checklist.	Specific Action
MassDOT: Incremental Development of Resiliency-Oriented Design Guidelines.	Specific Action
MassDOT: State-wide Transportation Asset Vulnerability Assessment (inland flooding).	Specific Action
MassWildlife: Evaluation of climate change impacts on common species.	Specific Action
MassWildlife: Evaluation of shifts in habitats and species distributions.	Specific Action
MassWildlife: Great Marsh Pilot Ditch Remediation Project.	Specific Action
MassWildlife: Identification of areas with high native aquatic biodiversity to help prioritize aquatic adaptation actions as the climate changes.	Specific Action

Plan Name	Plan Type
MassWildlife: Identification of cold water climate refugia and transitional waters for protections of CFRs.	Specific Action
MassWildlife: Mapping and control of invasive plant species.	Specific Action
MassWildlife: Study impact of climate change on fish hatcheries held by MassWildlife.	Specific Action
MassWildlife: Updates to BioMap2.	Specific Action
MassWildlife: Work with MassDOT to incorporate habitat and cold water fisheries considerations into MassDOT climate vulnerability assessments, adaptation projects, and community planning tools.	Specific Action
MBTA: Complete system-wide vulnerability assessment.	Specific Action
MBTA: Incorporate climate resiliency into capital planning activities.	Specific Action
MEMA: Apply for available federal HMA funding to implement and update the completed and approved multi-jurisdictional and local hazard mitigation plans.	Specific Action
MEMA: Build out a mechanism to incorporate new data and recommendations from the FEMA-approved regional and local mitigation plans into the SHMCAP, ArcGIS online and/or Climate Clearinghouse, especially locations of critical facilities and assessments of vulnerability and estimates of potential losses by jurisdiction.	Specific Action
MEMA: Create an Earthquake Risk Reduction Program.	Specific Action
MEMA: Develop Disaster Survivor Assistance Plans.	Specific Action
MEMA: Encourage state granting agencies in the Commonwealth, such as the Massachusetts Department of Housing and Community Development's review of Community Development Block Grants, to work together with MEMA to assist in providing the Non-federal cost share in Disaster Recovery and Hazard Mitigation Grants to maximize the federal funding available to the Commonwealth and its communities.	Specific Action
MEMA: Enhance the effectiveness of 406 funding by working to further integrate mitigation into the FEMA Public Assistance Program.	Specific Action
MEMA: Improved Local Comprehensive Emergency Management Plan (CEMP) Program.	Specific Action
MEMA: Partner with stakeholders in Massachusetts to develop and implement regional and local multi-hazard mitigation plans by providing training and technical assistance.	Specific Action
MEMA: Perform a statewide risk analysis for all hazards to include in future updates to this state hazard mitigation plan and other related plans. Address data deficiencies and improve analysis, when available, by partnering with federal, state, local, and other subject matter experts.	Specific Action
MEMA: Plan and host hazard mitigation grant workshops for state agencies and local governments after natural disasters, especially immediately following Presidential Disaster Declarations.	Specific Action
MEMA: Prepare hazard mitigation best practices and case studies.	Specific Action
MEMA: Technical assistance and support for FEMA's Hazard Mitigation Assistance programs to maximize HMA Advance Assistance and project funding.	Specific Action
MEMA: Update the State Hazard Mitigation and Climate Adaptation Plan and submit for FEMA review and approval every 5 years.	Specific Action
MEMA: Work with communities to implement cost-effective, environmentally sound, and feasible mitigation projects to severe repetitive loss properties.	Specific Action
MOTT: Research and assess and potential effects of climate change on Commonwealth travel and tourism industry and assets.	Specific Action
MPRO: Review Chapter 40A and existing regulatory framework to evaluate incorporation of feasibility and practicality of climate change hazard mitigation measures.	Specific Action
Municipal Vulnerability Preparedness Program Action Grant Projects	Other
OPSI: Review the state building code to assess feasibility of incorporating hazard mitigation and resilience.	Specific Action
OPSI: Voluntary resilience audits for private property.	Specific Action
Reassess and develop a climate change resiliency framework and criteria for all EOEEA agency land acquisition and grant funding for land acquisition to support natural resource conservation, wildlife, human health and public safety.	Specific Action
Recommendations of the Mosquito Control for the Twenty-First Century Task Force	Adaptation Plan
Resilient MA Climate Change Clearinghouse for the Commonwealth	Other
Roadmap for Behavioral Health Reform	Adaptation Plan
State Forest Resource Management Plans	Adaptation Plan