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Estimating Future Changes in 100-year Floods on the Connecticut and Merrimack Rivers

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15. Abstract
This study investigates the potential impacts of climate change on future flows in the main stem of the Connecticut and Merrimack rivers within Massachusetts. The study applies two common climate projections (Representative Concentration Pathways), RCP 4.5 and RCP 8.5, to the 21st century. The authors use downscaled gridded precipitation forecasts from fourteen global circulation models (GCMs) to estimate the 100-year, 24-hour extreme precipitation events for two future time-periods: near-term (years 2021-2060) and far-term (years 2060-2099). They compare 100-year, 24-hour extreme precipitation events to extreme precipitation events during a base period (1960-1999). For many counties in Massachusetts including southern Berkshire, Hampden, southern Worcester, Norfolk, Essex, and Suffolk, future projections of 100-year, 24-hour extreme precipitation events when considering the 8.5 RCP scenario show increases of over 25% during the near-term and over 50% during the far-term. Increases also occur in 100-year, 24-hour flow estimates. The medians of the GCMs using the RCP 4.5 and RCP 8.5 suggest 2.9-8.1% (near term) and 9.0-14.1% (far-term) increases in the 100-year, 24-hour flow event in the Connecticut River, and 9.9-13.7% (near term) and 15.8-20.6% (far term) increases in the 100-year flow event in the Merrimack River. Far-term estimates for another model suggest even larger changes in the 100-year, 24-hour flow. These significant increases suggest that infrastructure whose design is based on historical hydrological events/records may not be adequate to sustain the 100-year, 24-hour flows that may occur during the latter half of this century.

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Estimating Future Changes in 100-year, 24-hour Flows on the Connecticut and Merrimack Rivers

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Disclaimer

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Executive Summary

This study of *Estimating Future Changes in 100-year, 24-hour Flows on the Connecticut and Merrimack Rivers* was undertaken as part of the Massachusetts Department of Transportation (MassDOT) Research Program. This program is funded with Federal Highway Administration (FHWA) State Planning and Research (SPR) funds. Through this program, applied research is conducted on topics of importance to the Commonwealth of Massachusetts transportation agencies.

This study investigates the potential impacts of climate change on future 100-year, 24-hour flow events in the main stems of the Connecticut and the Merrimack Rivers within Massachusetts. The study applies two commonly used Representative Concentration Pathways (RCPs) climate projections (RCP 4.5 and RCP 8.5)[1] for the 21st century. RCP 4.5 assumes that greenhouse gases stabilize near the year 2100 and RCP 8.5 assumes that greenhouse gas emissions continue to increase over time. It uses downscaled gridded precipitation forecasts from fourteen global circulation models (GCMs) to estimate gridded projections of 100-year, 24-hour precipitation events for two time-periods in the future: near-term (including the years 2021-2060) and far-term (including the years 2060-2099). The downscaling approach applied is the Localized Constructed Analog Method (LOCA). The authors then compare results to a base period (1960-1999) and later deploy downscaled precipitation and temperature values from three selected GCMs to drive a hydrology model (NOAA's Hydrology Laboratory-Research Distributed Hydrologic Model) estimating streamflow conditions and 100-year, 24-hour flows for the Connecticut and the Merrimack river basins. The authors selected three GCMs specifically to provide the median, upper 90th percentile, and lower 10th percentile of the 100-year, 24-hour flow estimates. Future projections of 100-year, 24-hour precipitation events estimated from the RCP 4.5 and RCP 8.5 show potential increases of over 25% in some counties in Massachusetts (including southern Berkshire, Hampden, southern Worcester, Norfolk, Essex, and Suffolk) for the near-term and increases of over 50% for those counties for the far-term compared to the base period. Results show that the northeastern and southwestern corners of Massachusetts will be affected by the largest percentage increases in the maximum extreme precipitation events. The results from the RCP 4.5 and RCP 8.5 projections for the 100-year, 24-hour precipitation event suggest spatially similar trends for the state. Changes in precipitation and temperature during the year will impact future 100-year, 24-hour flows in the Connecticut and Merrimack Rivers. The study estimates 100-year, 24-hour flow through the near-term (years 2021-2060) and the far-term (years 2060-2099) relative to the base period (years 1980-1999). For both the RCP 4.5 and RCP 8.5 in the near-term, the medians of the GCMs used suggest a 2.9-8.1% increase in 100-year, 24-hour flows in the Connecticut River, and a corresponding 9.0-14.1% increase in the far-term. Increases range between 9.9-13.7% in the Merrimack for the 100-year, 24-hour flows in the near-term and between 15.8-20.6% for the far-term. Overall,

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[1] RCP stands for "Representative Concentration Pathway". The RCPs were used in the Fifth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC) in 2014 as a basis for the report's findings. The numerical values of the RCPs (4.5, 6.0 and 8.5) refer to the concentrations of greenhouse gases in 2100. They make predictions of how concentrations of greenhouse gases in the atmosphere will change in future as a result of human activities.

results show that climate change impacts across all seasons are more significant in the far-term than near-term for both flooding and extreme precipitation events. The significant increase in the magnitude of the maximum 100-year, 24-hour extreme precipitation and 100-year, 24-hour flow events suggests that infrastructure designed on historical hydrological events/records may not be adequate to sustain the 100-year, 24-hour flows that may occur during the latter half of this century.

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1.0 Introduction

This study, *Estimating Future Changes in 100-year, 24-hour Flows on the Connecticut and Merrimack Rivers,* was undertaken as part of the Massachusetts Department of Transportation (MassDOT) Research Program. This program is funded with Federal Highway Administration (FHWA) State Planning and Research (SPR) funds. Through this program, applied research is conducted on topics of importance to the Commonwealth of Massachusetts transportation agencies.

1.1 Purpose

Our climate is changing due to increasing levels of carbon dioxide (CO_2) and other greenhouse gases in the atmosphere *[1], [2]*. Climate change will have significant impacts on the hydrologic cycle and those impacts are becoming more obvious over time. A warming atmosphere will influence the patterns of extreme precipitation and change regional flood behavior and risks. However, the hydrological impacts of climate change vary in different portions of the globe depending on hydroclimatic, geologic, and topographic conditions *[3]*. In the U.S. northeast, forecasted changes during the 21st century include increases in temperature, extreme precipitation, floods, droughts, and sea-level rise *[4], [5]*. Transportation agencies in the U.S. are considering future climate change impacts as they update their policies and programs for asset management *[6], [7]*. The Massachusetts Department of Transportation (MassDOT) is currently exploring the potential impacts of climate change and approaches to address transportation needs in the future given these impacts. Extreme precipitation events can disrupt Massachusetts' transportation systems and floods can pose significant risks to infrastructure such as culverts, roads, bridges, and tunnels *[8]*. MassDOT is improving its current understanding of the potential risks of the state's transportation assets and operations due to climate change and how to best plan and prepare for the future. Careful evaluations are required to understand future changes in flood characteristics and other relevant climate impacts in large rivers like the main stems of the Connecticut and the Merrimack.

This study investigates how to incorporate forecasted climate change into estimates of future 100-year, 24-hour flows (the 1% annual flow event or the annual exceedance probability). There is a relatively long history of public decision-making interest in the 100-year, 24-hour flow event. However, recognition of the impacts of climate change on extreme precipitation and floods suggests that using past stream flow events when planning for the future may no longer be appropriate *[9]*.

This study addresses future changes in the 100-year, 24-hour precipitation event across the state of Massachusetts and how these changes in precipitation and future temperature will influence 100-year, 24-hour flows in the Connecticut and Merrimack Rivers. To explore this issue, the outputs (i.e. precipitation and temperature) from fourteen general circulation models (GCMs) and two different emission scenarios [denoted as Representative Concentration Pathways (RCPs), specifically RCP 4.5 and RCP 8.5] were used to characterize changes in temperature and precipitation in Massachusetts. Based on the characteristics of those fourteen models, four were chosen to represent three different scenarios in a high-resolution, distributed hydrology model. The scenarios are: 1) a median event, 2) a 10% event – an event that represents a 10% lower bound on what might happen in the future, and 3) a 90% event – an event that represents a 90% upper bound on what might happen in the future. The four GCM models selected for the hydrologic analysis were as follows: The median conditions are represented by the GISSE2R model for the RCP 4.5 scenario and by CMCC-CMS model for the RCP 8.5 scenario. The lower 10% event is represented by the INMCM4 model for both the RCP 4.5 and RCP 8.5. The higher 90% event is represented by the GFDL-ESM2M for both RCPs scenarios. Streamflow projections obtained when outputs from these models and RCPs are incorporated into the hydrology model estimate streamflows at river cross sections along the Massachusetts portions of the Connecticut and Merrimack Rivers. These streamflow projections provide the median, the upper 90th, and the lower 10th percentile ranges of the current and future 100-year, 24-hour flows. The study addresses the following specific three important questions:

1) How will the magnitude and spatial patterns of the 100-year, 24-hour precipitation events change over time?
2) How will the 100-year, 24-hour flow event change in the future along the main stems of the Connecticut and the Merrimack Rivers in Massachusetts in the future due to changing climate? and
3) Is there a direct correlation between 100-year, 24-hour precipitation event and 100-year, 24-hour flow?

The following sections of this report present a description of the study area, the experimental methods, the results, study limitations, and the conclusions.

Although this study focuses on climate projects generated with global circulation models that forecast future events, it is important to note that there is considerable evidence that precipitation magnitudes have already changed significantly in Massachusetts. Parr and Wang *[10*] noted that the total rainfall during extreme precipitation events (which they define as the total amount of precipitation from the upper 1% of daily precipitation) in the Connecticut River basin increased by almost 240% between the years 1950-2011 and that the proportion of extreme events as a fraction of total precipitation also increased by almost 20% within the same period. Other researchers have confirmed increases in extreme precipitation in the Connecticut River basin, even though the percentage increases reported varied across a wide range [*5], [11], [12]*. For the Merrimack basin, increases in extreme precipitation are noted by Berton et al. *[13]* and Campbell et al. *[14]*. Changing precipitation characteristics are expected to influence other components of the hydrologic cycle, including runoff, soil moisture, evapotranspiration and baseflow. Peak annual discharges of rivers are often associated with extreme precipitation events, although floods also depend on many other factors (e.g. antecedent soil moisture, temperature, evapotranspiration, season, basin morphology, and snow melt) *[13]*. For instance, winter floods in snow-dominated rivers largely depend on temperature because increased temperature may result in rapid snow melt. Summer and fall flood events are often impacted by antecedent soil conditions. Hence, flooding patterns and their associated risks in the Connecticut and Merrimack rivers require detailed investigation before the precise impacts of climate change can be estimated.

1.2 Study Area

The areas of interest in this study are the main stems of the Connecticut and Merrimack Rivers (**Figure 1**). These are the two largest rivers in Massachusetts and are representative of other major rivers, streams, and tributaries that will experience the impacts of climate change in the future. Records exist of historically measured maximum average discharge rates *[15]* in both watersheds. Large portions of the watersheds are located outside of Massachusetts. The watersheds of these two rivers contain important infrastructure that could be damaged by high flow events.

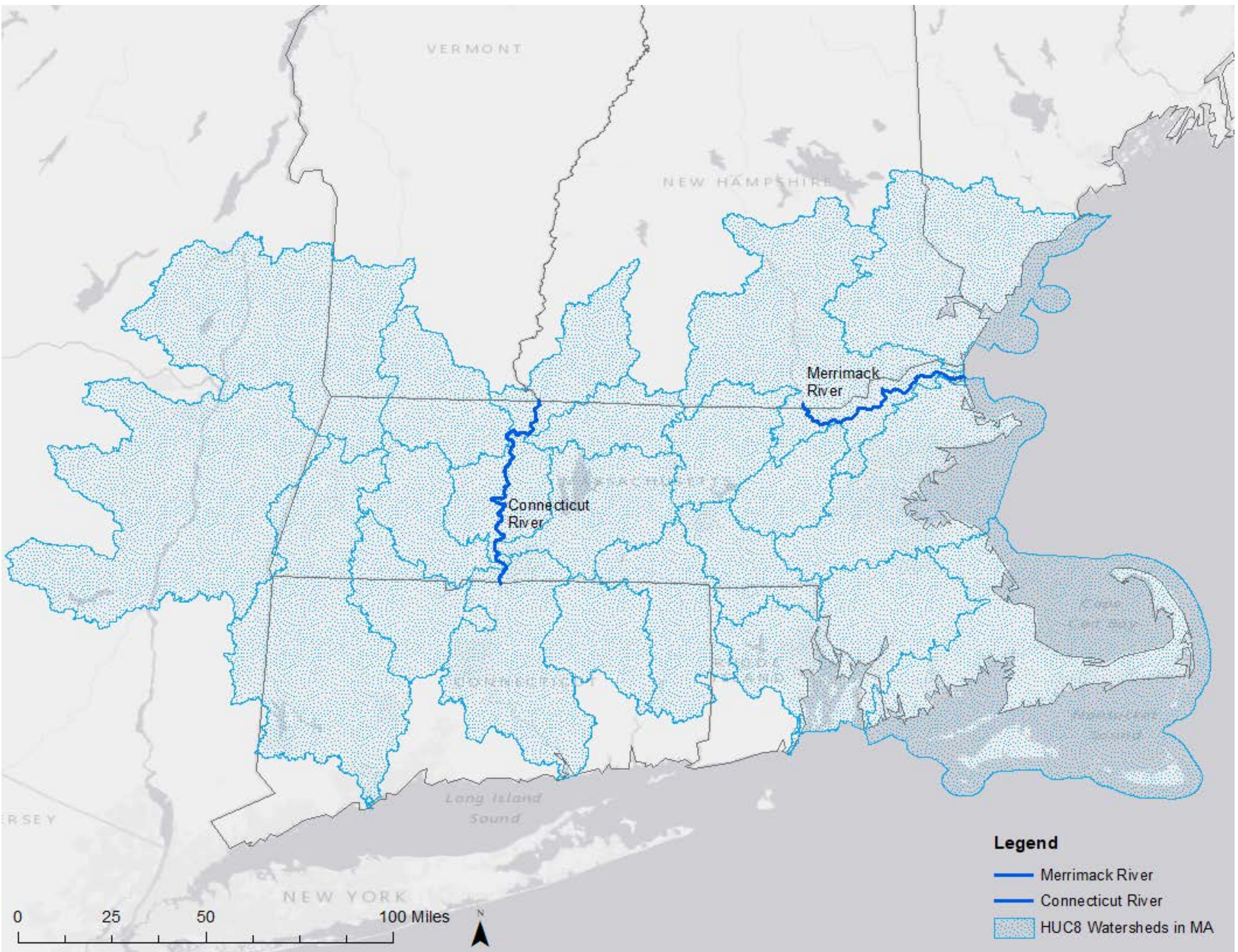

Figure 1: Study area showing parts of the main stem Connecticut River and the Merrimack River within Massachusetts

The Connecticut River basin includes portions of four states in the northeastern United States, with a drainage area of 8,147 mi^2 (21,101 km^2). With a total length of approximately 410 miles (660 kilometers), the Connecticut River is the longest river in New England and has the largest average annual flow. The Connecticut River's headwaters are located at the Fourth Connecticut Lake in New Hampshire near the Canadian border of Quebec and it discharges into Long Island Sound. The upper two-thirds of the river defines the boundary between Vermont and New Hampshire. The Connecticut River bisects central and eastern Massachusetts and Connecticut in a north/south direction. Vital to New England, the Connecticut River provides 70% of the fresh water that enters Long Island Sound. Approximately 41% of the land area of Vermont contributes flows to the Connecticut River, in addition to 33% of New Hampshire, Massachusetts, and Connecticut. The Connecticut River basin is 80% forested, representative of large portions of New England. The Connecticut River flows primarily north to south, spanning a large temperature gradient.

The Merrimack River drains 5,010 mi^2 (13,000 km^2) in New Hampshire and Massachusetts and is the fourth largest basin in New England. Most of the river's 117-mile length (188 kilometers) occurs in New Hampshire but the river flows into Massachusetts from New Hampshire prior to flowing into the Atlantic Ocean. The flows of the Merrimack River are impacted by the glaciations of the White Mountains in New Hampshire. The elevation difference between the highest and the lowest points (sea level) in the watershed is 280 feet (85 meters). The Merrimack watershed is primarily forested lands (67%) with some developed regions (16%). The impervious surfaces in the Merrimack watershed are less than 3% except in the southern, more developed regions (>9%). The Merrimack River is formed by the confluence of Pemigewasset and Winnipesaukee rivers in Franklin, New Hampshire and discharges into the Atlantic Ocean at Newburyport, Massachusetts.

2.0 Methodology

2.1 Hydrologic Model

The National Oceanic and Atmospheric Administration's (NOAA) Hydrology Laboratory-Research Distributed Hydrologic Model (HL-RDHM) is the hydrology model applied in this research (**Figure 2**). HL-RDHM employs the heat transfer version of the Sacramento Soil Moisture Accounting model (SAC-HT) for rainfall-runoff generation, as well as the SNOW-17 model to account for snow accumulation/melting. The SAC-HT is a physics-based systems model where the river network system is divided into regularly spaced, square grid cells to represent spatial heterogeneity and variability. The SNOW-17 model uses near-surface temperature to differentiate between snow accumulation and rain at each grid cell. The runoff generated at each cell is routed through channel and stream networks using hillslope and kinematic wave routing. Overall, a fully distributed HL-RDHM has been implemented at 4x4 km (16 km^2) spatial resolution. This particular hydrologic model is widely applied *[16], [17]* and is fully described in Burnash's 1995 paper "The NWS river forecast system-catchment modeling" *[18]*.

2.1.1 Calibration

HL-RDHM was calibrated by the authors for the Connecticut and Merrimack Rivers using streamflows at unregulated locations in both basins. As noted previously, calibration relies on the existence of historic streamflow gaging data at unimpaired sites. The authors carefully selected unregulated sites in the Connecticut and Merrimack river basins based on existing reports and published documents *[19], [20]*. Expert opinion was also solicited from USGS personnel familiar with the basins. After selecting appropriate sites, the authors calibrated the model parameters at the selected locations using an automatic calibration technique (Stepwise Line Search) over a period of seven years (2004-2010) after making manual adjustments. Kuzmin et al. *[21]* describes the SLS technique in detail. Six years of streamflow data (2011-2016) were used for verification.

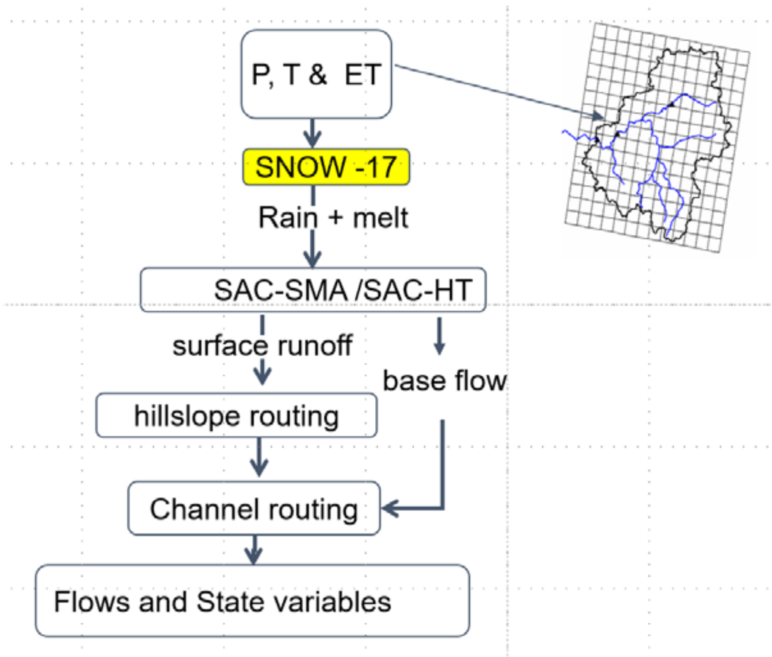

Figure 2: HL-RDHM modeling framework

2.1.2 Validation

To assess model validation performance, the study uses the following metrics: the correlation coefficient (R), percent bias (PB), and Nash-Sutcliffe efficiency (NSE). The correlation coefficient reports how strong a relationship exists between two variables (estimated flows and historic flows). The percent bias measures the average tendency of the estimated flows to be larger or smaller than their observed ones. The Nash-Sutcliffe efficiency (NSE) is used to assess the predictive power of a hydrological model, where an efficiency of 1 (NSE=1) corresponds to a perfect match of modeled flows to the observed data.

Model performance is measured using two different flow conditions: low-to-moderate flows and high flows. Low-to-moderate flows are defined as those less than the 25th percentile flow in the overall flow distribution. High flows are defined as flows greater than 90th percentile flows. Through the validation process, the authors found that the NSE for most cases ranged between 0.65 and 0.85. The PB, for most cases, ranged between 5 to 10% in absolute value. The range of correlation coefficient varies between 0.75 and 0.95. All of these performance measure values are appropriate for the standards of calibration for a physically based hydrological model. **Figure 3** provides a simple illustration of the degree to which the model captures the variability of the historic data. The statistical metrics and Figure 3 suggest that the hydrology model is capable of simulating streamflows from temperature and precipitation data and the other land-use, soil type, and vegetation data used.

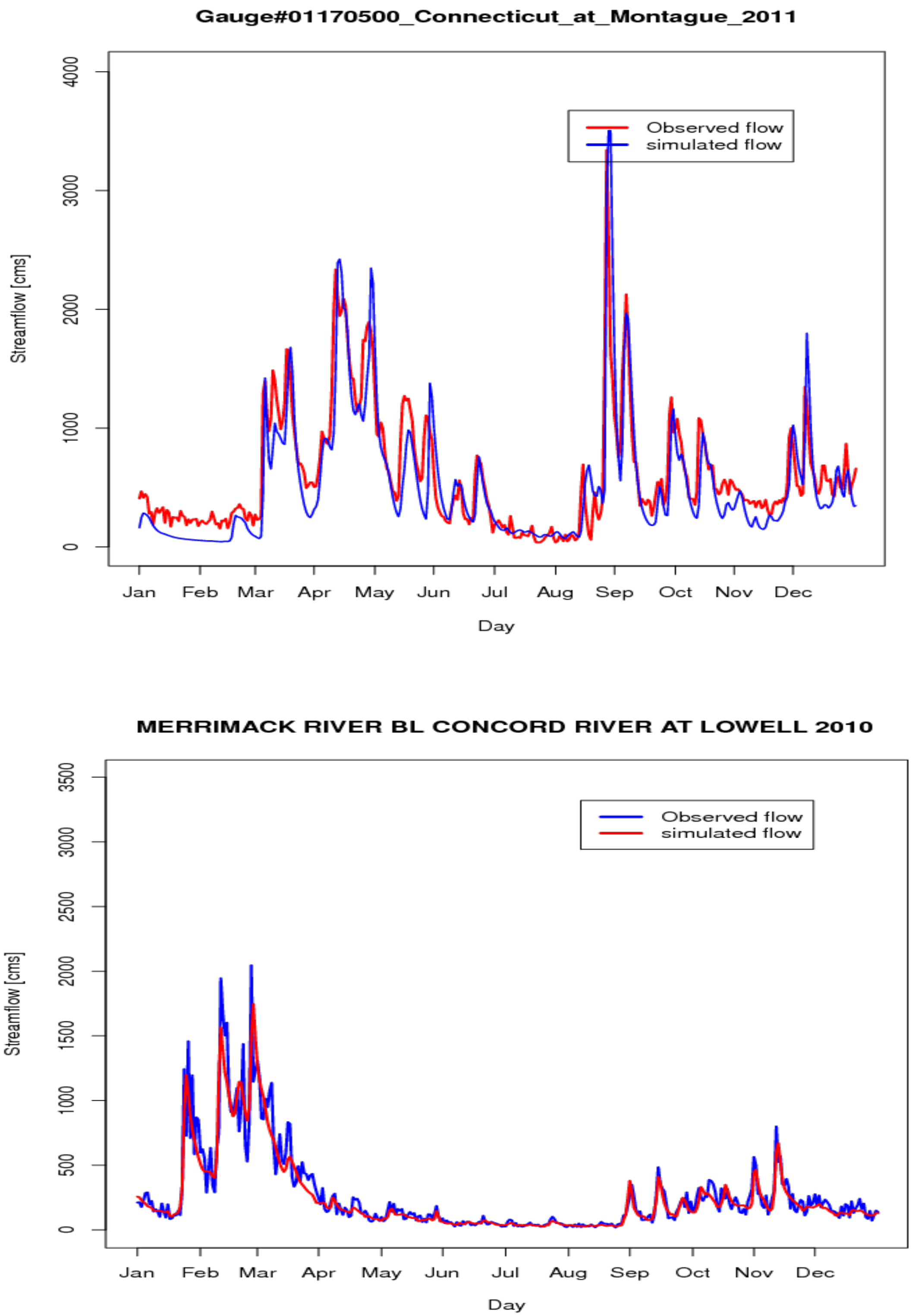

Figure 3: Model validation examples for the Connecticut (upper panel) and Merrimack (lower panel)

2.2 Estimation of 100-year, 24-hour Precipitation Event

The authors used downscaled GCM data to calculate the 100-year, 24-hour precipitation event for the state of Massachusetts. The 100-year, 24-hour precipitation event is estimated at each precipitation grid (6 kilometers x 6 kilometers) over a fixed number of years. This study uses a 40-year period to estimate the 100-year, 24-hour precipitation event in the future. Our three time-periods of interest in this study are historical (1961-1999), near-term (2021-2060), and far-term (2060-2099). For the period of 1961 and 1999 gridded data does exist—considered as observations—based on actual (historical) precipitation and temperature data from the Localized Constructed Analogs (LOCA) project *[22]*. LOCA (what stands for Localized Constructed Analogs) is a statistical downscaling technique that uses past history to add improved fine-scale detail to global climate models. These data are available for 32 global climate models from the CMIP5 archive at a 1/16th degree spatial resolution, all of the US and southern Canada. For the periods of 2021-2060 and 2060 – 2099, the gridded data come from the downscaled fourteen general GCMs used in this study (see **Table 1)**.

To estimate the 100-year, 24-hour precipitation event for the 40-year periods, the annual maximum precipitations are ranked from the climate models at each grid from highest to lowest (**Figure 4**). Next, we applied an extreme value Gumbel distribution to these data to calculate the 100-year, 24-hour precipitation event across the state. Because fourteen GCMs are applied, there are fourteen sets of 100-year, 24-hour precipitation event estimates. We estimated the 100-year, 24-hour precipitation event in two ways: 1) by determining the 100-year, 24-hour precipitation event from the "median model" and 2) by calculating the ensemble mean of 14 models. The results section includes details describing the 100-year, 24-hour precipitation event.

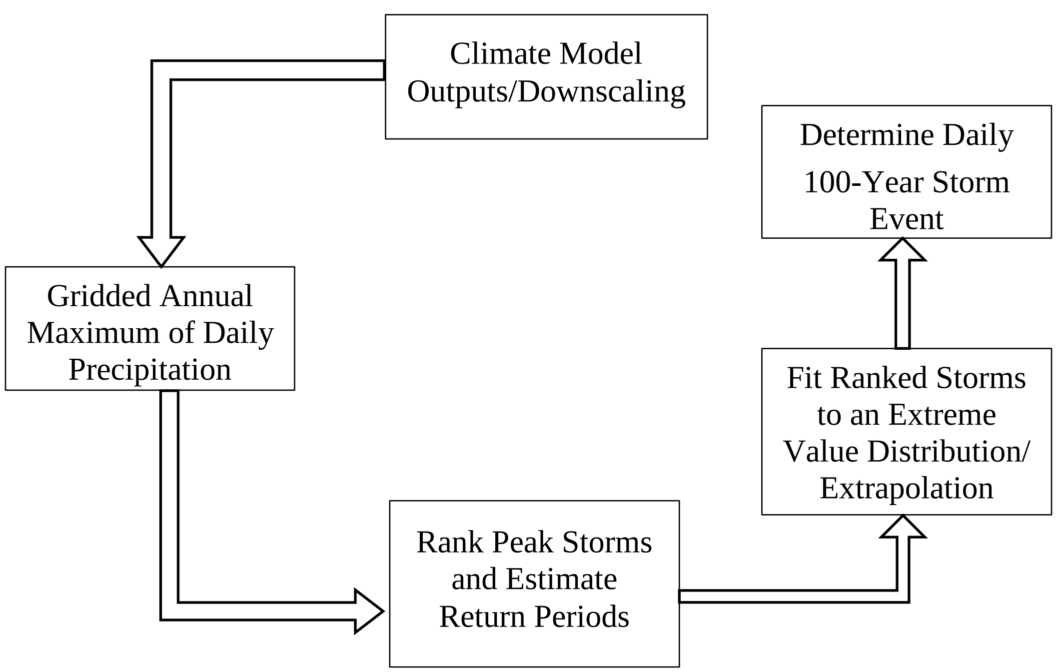

Figure 4: Flow diagram showing the estimation of 100-year, 24-hour precipitation events

2.3 Flood Frequency Analysis

Because the computational requirements associated with the HL-RDHL model are large, it is not feasible to evaluate all fourteen of the GCMs to calculate the 100-year, 24-hour flow events. The authors determined that three GCM forecasts would be evaluated in the HL-RDHL model. For the 100-year, 24-hour flow analysis, streamflows were generated using climate forcings (e.g. precipitation and temperature data taken from the downscaled GCM outputs) from four different climate models and for two emission scenarios: RCP 8.5 and RCP 4.5. The climate projections that were selected for flow analysis have shown the ability to approximate median, upper, and lower percentile estimates of 100-year, 24-hour flow in Massachusetts. This study period is divided into three different time regimes: current (1981-1999), near-term (2021-2060), and far-term (2061-2099). The authors estimated 100-year, 24-hour flows using maximum daily peaks each year for these three respective time-periods. For simplicity, they measured projected changes in 100-year, 24-hour flow using the median values, upper 90th, and lower 10th percentile projections. A previous statewide study conducted by the Massachusetts Executive Office of Energy and Environmental Affairs and the Northeast Climate Adaptation Science Center identified the median, upper, and lower quantiles of climate projection models. **Figure 5** summarizes the process for estimating the 100-year, 24-hour flow event deploying the distributed hydrological model.

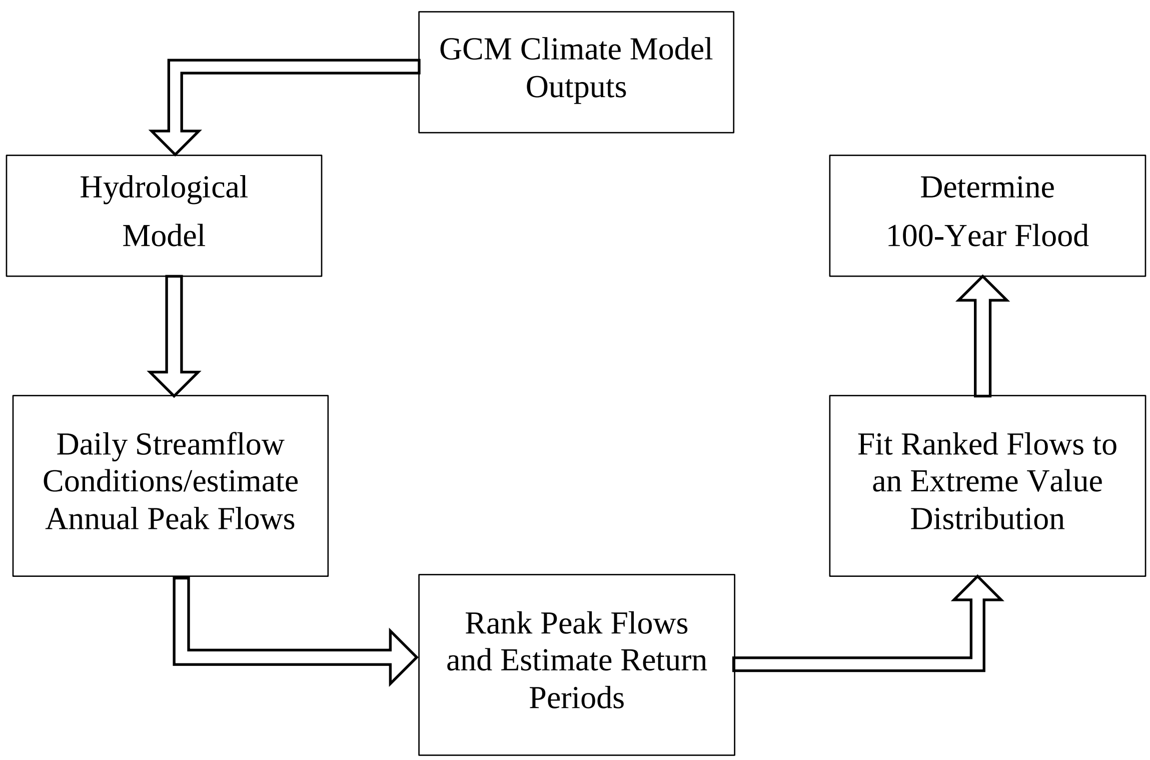

Figure 5: Flow diagram showing the estimation of 100-year, 24-hour flows

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3.0 Datasets

3.1 GCM and Downscaled Output

The authors evaluated the outputs of fourteen different climate models in preparation for the hydrological modeling effort. The fourteen models were all selected from the Coupled Model Intercomparison Project Phase 5 (CMIP5) *[23]*. **Table 1** provides a list of the model names, country of origin, the agency that developed the model, and the model's spatial resolution. The CMIP5 study examined 36 models under two scenarios: RCP 8.5 and RCP 4.5 *[24]*. While it is common to use a range of different climate models in studies of climate change and climate impacts, by combining information on model performance and similarities in their projections, it is possible to reduce the size of the ensemble without losing critical climate change information *[25]–[27]*.

Table 1: Details of the Fourteen Climate Models Applied

Model	Country	Model Agency	Atmospheric Resolution (Latitude x Longitude)
BCC-CSM1-1	China	Beijing Climate Center, China Meteorological Administration	310 km x 310 km
CanESM2	Canada	Canadian Centre for Climate Modeling and Analysis	310 km x 310 km
CESM1-BGC	USA	NSF-DOE-NCAR	130 km x 100 km
CESM1-CAM5	USA	NSF-DOE-NCAR	130 km x 100 km
CMCC-CMS	Italy	Centro Euro-Mediterraneo per i Cambiamenti Climatici, Italy	210 km x 210 km
EC-Earth	Europe	EC-Earth Consortium, Europe	120 km x 120 km
GFDL-ESM2M	USA	NOAA Geophysical Fluid Dynamics Laboratory, USA	275 km x 220 km
GISSE2R	USA	NASA Goddard Institute for Space Studies, USA	275 km x 220 km
HadGEM2-ES	United Kingdom	Met Office Hadley Center, United Kingdom	210 km x 130 km
HadGEM2-CC	United Kingdom	Met Office Hadley Center, United Kingdom	210 km x 130 km
INMCM4	Russia	Institute for Numerical Mathematics, Russia	220 km x 165 km
IPSL-CM5A-LR	France	Institut Pierre-Simon Laplace, France	410 km x 210 km
MPI-ESM-LR	Germany	Max Planck Institute for Meteorology, Germany	210 km x 210 km
MPI-ESM-MR	Germany	Max Planck Institute for Meteorology, Germany	210 km x 210 km

This study produces regional projections for the Commonwealth of Massachusetts using the downscaled counterparts of the selected models. The downscaling approach used is the Localized Constructed Analogs (LOCA) method *[22]*, a statistical downscaling method that relies on selecting appropriate analog days from observations to downscale coarse-resolution GCM data to finer spatial scales. Prior studies *[22]* have demonstrated the LOCA downscaling method improves upon the previous statistical downscaling methods (such as the bias-corrected spatial disaggregation (BCSD) method). In particular, the LOCA method produces a realistic depiction of precipitation extremes *[22*] that is lacking in other downscaling methods. The LOCA dataset is available at 6-km resolution.

3.2 Observed Meteorological and Streamflow Data

The study uses multi-sensor precipitation estimates (MPEs) as the observed precipitation data for the hydrological model calibration and validation runs. MPEs are produced hourly through the combination of multiple radars and hourly rain gauge data at 4 km x 4 km (16 km^2) grid resolution *[16], [28]*. The authors obtained the MPE product from the NOAA's Northeast River Forecasting Center (Northeast RFC); it is similar to the National Centers for Environmental Prediction (NCEP) Stage IV MPEs *[29]*. Various hydro-meteorological applications widely use gridded MPE products. The HL-RDHM *[30]* requires gridded temperature observations to obtain monthly potential evaporation and is used as an input to the Snow Accumulation and Ablation Model (SNOW-17) to determine snow accumulation and melting. The Northeast RFC provides the gridded temperature data, generated by combining data from multiple observation networks (Meteorological Aerodrome Reports, USGS stations, and National Weather Service Cooperative Observer Program). The gridded data used in the hydrology model are created using bilinear interpolation onto the regularly spaced grids (4 km x 4 km cell size) as required as input by HL-RDHM. For the verification of the streamflow simulation and forecasts, daily discharge data from the relevant USGS gages were used. In total, thirteen years (2004-2016) of streamflow observations were used for the purpose of calibration and verification.

3.3 Land Use/Land Cover and Topography Data

The basic SAC-HT model uses 16 parameters (**Table 2**). HL-RDHM retrieves these parameter values from grids for specified basins. **Table 2** lists all SAC-HT parameter grids for which *a priori* values were derived using the Digital General Soil Map of the United States (STATSGO) and the Soil Survey Geographic Database (SSURGO) *[30]*. To calculate potential evaporation (PE), the SAC-HT model uses PE adjustment factors to account for the effects of vegetation. PE demand is the product of PE and PE adjustment factors. It is common practice to use mean monthly values for PE adjustment factors, although in theory these adjustment factors can vary within a month. PE grids are thus derived by using an empirical function relating calibrated PE adjustment factors to satellite derived, green vegetation fraction data. A higher resolution digital elevation model (DEM) is used to generate the HL-RDHM grid to grid connectivity and slope.

3.4 Summary of Data Resolution, Purpose, Source, and Units

This research integrates data from a wide variety of sources into a hydrologic model. These data are made available through existing data sets from a variety of federal agencies and are in different spatial resolutions and are expressed in different units. **Table 3 s**ummarizes the types of data that are used, the purpose of these data, the data's spatial resolution and the units of the data. The data used in this research oftenrequired either disaggregation to finer spatial resolution or aggregation into coarser spatial resolution.

Table 2: List of HL-RDHM parameters

Parameter name	**Description**
UZTWM	Upper zone tension water capacity
UZFWM	Upper zone free water capacity
LZTWM	Lower zone tension water capacity
LZFSM	Lower zone supplemental free water capacity
LZFPM	Lower zone primary free water capacity
UZK	Fractional daily upper zone free water withdrawal rate
LZSK	Fractional daily supplemental withdrawal rate
LZPK	Fractional daily primary withdrawal rate
PCTIM	Minimum impervious area
ADIMP	Additional impervious area
RIVA	Riparian vegetation area
EFC	Effective forest cover
ZPERC	Maximum percolation rate
REXP	Exponent for the percolation equation
PFREE	Percent/100 of percolated water which always goes directly to lower zone free water storages
RSERV	Percent/100 of lower zone free water which cannot be transferred to lower zone tension water

Table 3: Data resolution, purpose, source, units, period of record

Name of Data	**Data Purpose**	**Data Spatial Resolution (grid size)**	**Data Source**	**Units**	**Period of Record (Begin and end year)**
Precipitation (climate)	Evaluate Changes in Precipitation/ Hydrological model forcing to generate streamflow projection	6 km x 6 km	Downscaled GCM (LOCA)	millimeter (mm)	1960-2099
Temperature (climate)	Hydrological model forcing to generate streamflow projection	6 km x 6 km	Downscaled GCM (LOCA)	Kelvin (K)	1960-2099
Precipitation (observation)	Hydrological model calibration and validation	4 km x 4 km	Multisensor precipitation estimation (National Weather Service)	millimeter (mm)	2004-2016
Temperature (observation)	Hydrological model calibration and validation	4 km x 4 km	National Weather Service	Fahrenheit (F)	2004-2016
DEMs	Use in hydrology model	30 m x 30 m	National Weather Service	meter (m)	N/A
Landcover	Use in hydrology model	1 km x 1km	STATSGO	kilometer (km)	N/A
Streamflow (observation)	Use in hydrological model calibration	N/A	USGS	Cubic meters per second (cms)	2004-2016
Hydrologic Modeling	Translate precipitation, temperature, land cover, and elevations into flow estimates	4 km x 4 km	NOAA's Hydrology Laboratory-Research Distributed Hydrologic Model	Cubic meters per second (cms)	N/A

4.0 Results

4.1 Changes in 100-year, 24-hour Precipitation Event

Downscaled outputs from fourteen GCM models were used to estimate the 100-year, 24-hour precipitation event for near-term (2021-2060) and far-term (2060-2099) for two different emission scenarios (RCP 4.5 and RCP 8.5). The term "estimate" is used here to define any statistical calculation, such as the 100-year, 24-hour event. Of the fourteen models, nine models have future increases in the 100-year, 24-hour event while five show decreases in 100-year, 24-hour precipitation event. Because the models contain variations in their projections, we investigated whether the median model projections or the fourteen ensemble mean best represents the potential changes in 100-year, 24-hour events in the future.

First, we identified the median model by ranking averages of 100-year, 24-hour precipitation events in Massachusetts. This process identified the HadGEM2-ES model as the model that, on average, provides the median estimate of 100-year, 24-hour precipitation events in Massachusetts for both RCP 8.5 and RCP 4.5. **Figures 6a and 6b** presents the median estimates of 100-year, 24-hour design storms generated by the HadGEM2-ES model for the RCP 8.5 scenario for the periods (2021-2060) and (2060-2099) respectively. The median model showed little change between the two time-periods, near and far-term. It reported an average 7.52 inches (191 mm) estimate for 100-year, 24-hour event across near-term, whereas the average estimate near-term is approximately 7.67 inches (195 mm). However, the spatial patterns showed large differences between the two periods. More specifically, the maximum amount of the design event (> 11.8 inches or >300 mm) appeared in the northeastern and southwestern part of the state, for 2021-2060, while the areas of maximum extreme rainfall occur in the middle- to southwestern portion of the state during 2060-2099. A similar pattern exists for the RCP 4.5 scenario as well. Appendix A further demonstrates these spatial patterns. This suggests that use of any individual model, even the median, may not provide sufficient insight for use in the design of future high flow events.

Next, we used an ensemble mean of the fourteen models' projections to estimate the 100-year, 24-hour precipitation event. Other researchers have noted this approach to be a more reliable and accurate prediction of future events than a single model climate projection *[31]*. **Figure 6** presents the median and ensemble mean projection of the 100-year, 24-hour, precipitation event under RCP 8.5 for 2021-2060 and 2060-2099 (c and d), as well as the percent change over the historic period for both time-periods (e and f). During the years of 2021-2060, the largest 100-year, 24-hour precipitation event is in the range of 7.87 – 11.81 inches (200-300 mm) and the area most affected is the northeastern part of Massachusetts. The Merrimack River basin is located in this area and will be impacted by increases in these 100-year, 24-hour precipitation events. On average, the results predict that the magnitude of the 100-year, 24-hour precipitation event to be slightly higher in the eastern section of the state compared to the western section. Although there are variations in 100-year, 24-hour precipitation across the state, the ensemble mean shows maximum increases of more than 50% across eastern and western Massachusetts.

The results indicate that approximately 35% of the surface area of Massachusetts will observe larger than 50% increases in 100-year, 24-hour precipitation events in the near-term. During the far-term (2060-2099), the values for the areas that were receiving a 50% increase in the near-term will increase to 55%.

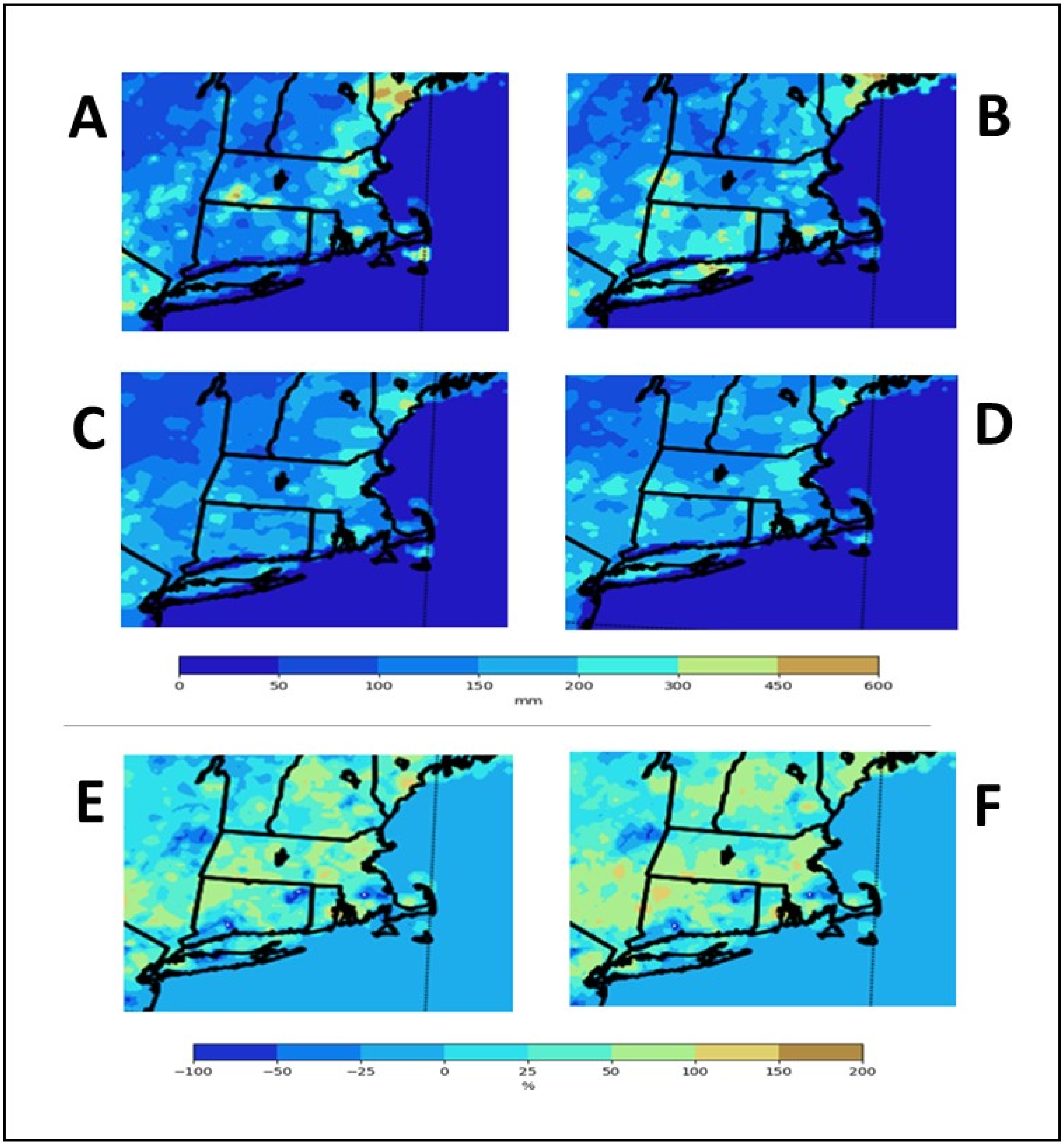

Figure 6: Model Results for 100-year, 24-hour precipitation event

Median Model Results for (a) 2021-2060 and (b) 2060-2099;
Ensemble Mean Result for (c) 2021-2060 and (d) 2060-2099;
Percent Change in Ensemble Mean for (e) 2021-2060 and (f) 2060-2099

Another area that is likely to experience increases in its 100-year, 24-hour precipitation is the southwestern part of Massachusetts. This increase is possibly related to the higher elevation areas of the Berkshires, where we expect more orographic precipitation compared to the flat land areas *[32], [33]*. The flows on the main stem of middle Connecticut River are impacted by these areas. Limited increases in 100-year, 24-hour precipitation are observed in the middle portion of Massachusetts where the land cover is mostly forested *[32], [34]*. In these areas, extreme events are defined primarily by convective rainfall that mostly occurs in the summer. Climate models are rarely capable of capturing convective rainfall due to having a coarser resolution. This is a common limitation among most of the climate model studies.

4.2 Projected Flows in the Main Stem of Connecticut River

To obtain the peak discharges along the Connecticut River, model simulations were generated for approximately 120 years (1980 to 2100) using the precipitation and temperature data from the climate models cited previously. Three climate models and two RCPs were selected based on prior studies and observations (such as the Massachusetts Executive Office of Energy and Environmental Affairs' statewide investigation of future hydrological extremes) to serve as input for the hydrology model. For comparison, we divided model simulations into three periods: historical (1981-1999), a period noted as "near- term" (2021-2060), and a period noted as "far-term" (2060-2099). The hydrologic model operated at locations less than the resolution of hydrologic model (4 km x 4 km or 16 km^2). However, we generated model flow estimates at approximately 4 km intervals to compute 100-year, 24-hour flow estimates. As discussed in Section 1.3, we then used linear interpolation to estimate flows at intermediate points between two grid cells of the hydrology model, as requested by MassDOT. The future near-term and far-term simulated streamflows are compared to simulated flow for the past. Actual USGS gaging data are not used because of the number of flood control and hydropower dams that exist in the state. Historic flows are not appropriate for use since these dams can have a significant impact on flood flows that are observed at USGS gaging stations.

The study presents the 100-year, 24-hour flow estimates at the 3,618 points along the main stem of the Connecticut River from upstream (River location 0) to downstream (River location 3618) for RCP 8.5 in **Figure 7** and RCP 4.5 in **Figure 8. Table 4** summarizes these graphs at specific locations along the Connecticut River, for the two time-periods, and for the three scenarios. The data presented in Table 4 suggest that the historic modeled 100-year flows are consistently less than the near-term (2021-2060) RCP 8.5 estimates for all three GCM scenarios. For the far-term (2060-2099), RCP 8.5 estimates the historical modeled 100-year flows are consistently less than the estimates with forecasted climate from the GCMs for the median and the 90% event. The historical estimates are less than the 10% scenario in a majority of the locations.

The data presented in Table 4 suggests that the historic modeled 100-year flood for the RCP 4.5 scenario in the near term (2021-2060) is often less than the estimates with forecasted climate from the GCMs for the median and the 90% event, but not always for the 10% event. For the RCP 4.5 for the far-term (2061-2100) the historic modeled 100-year flood is consistently less than the estimates with forecasted climate from the GCMs for the median and the 90% event but not always for the 10% event.

For RCP 4.5, the 100-year, 24-hour flow estimates are in a similar range as those for the RCP 8.5. However, there are instances for which the RCP 4.5 estimates of flows are slightly (~3-5%) less than those for the historic flows. It should be noted that, in general for a majority of the river reaches, future projected 100-year, 24-hour flows are greater than those modeled for the past. **Figure 9** shows percent differences in future flow projections (for near and far-term) compared to a base period (1981-1999). Across the three models in near-term for the RCP 8.5 scenario, the 100-year, 24-hour flow in the main stem Connecticut shows a 2-10% increase in the upstream while the increases range between 5-18% for the downstream locations. For the median estimate under RCP 8.5, the near-term showed an 11-18% increases. The flow for all percentiles indicate increases in the near and far-term when compared to the historical period. These increases in the 100-year, 24-hour flows can be associated with an increase in extreme precipitation events **(Figure 6)** for which there is an increased occurrence of 25-50% in the 100-year, 24-hour precipitation event.

4.3 Projected Flows in the Main Stem of Merrimack River

The same procedure is used to estimate the 100-year, 24-hour flows for the Merrimack River as is used for the Connecticut River. Model estimates were obtained for the Merrimack River at approximately 4 km intervals, which were then linearly interpolated to get intermediate point estimates along the river. The study estimates 2,342 flow locations along the river.

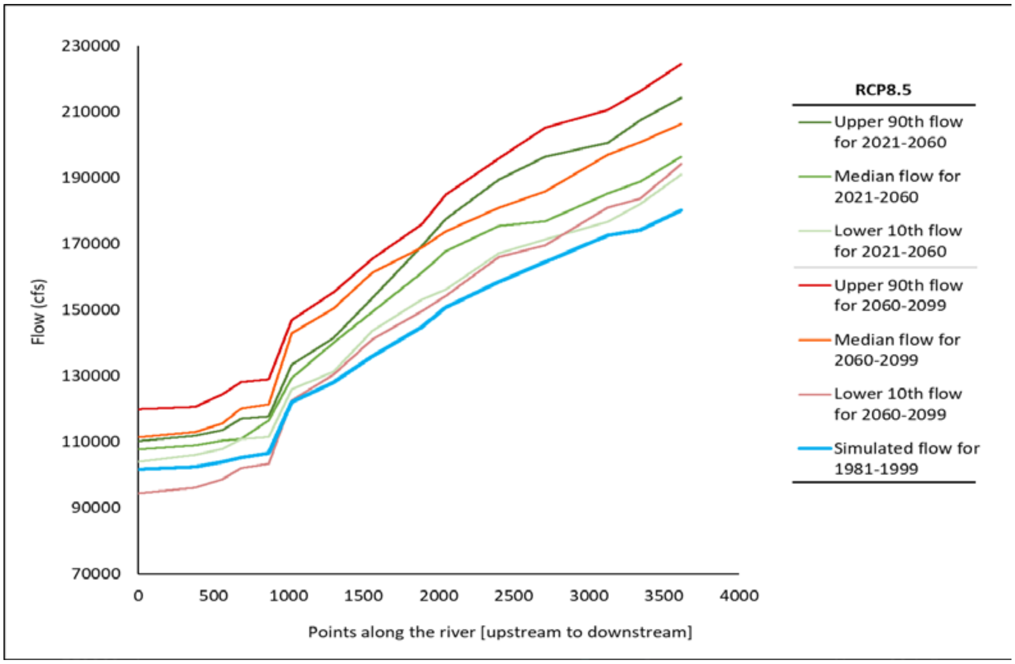

Figure 7: 100-year, 24-hour flow estimates along the Connecticut River from different climate models under RCP 8.5

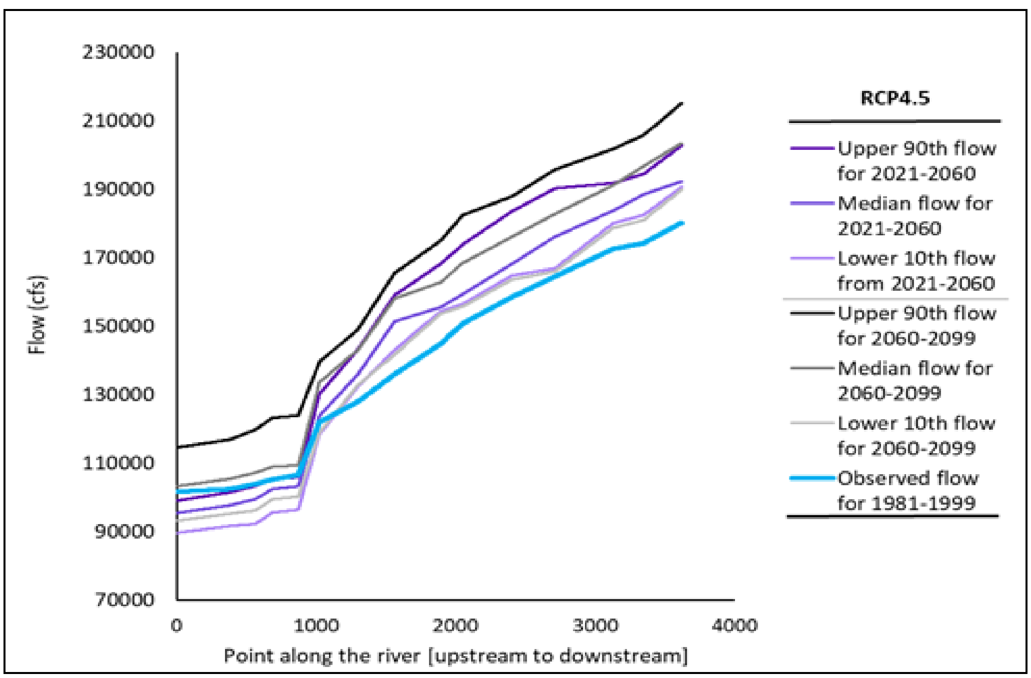

Figure 8: 100-year, 24-hour flow estimates along the Connecticut River from different climate models under RCP 4.5

Table 4: Estimates of 100-year flows on the Connecticut main-stem in the near and far-term (RCP 8.5 and RCP 4.5)

Connecticut River
100-Year Flows (cfs), RCP 8.5

Points along river, upstream to downstream	*Historical Modeled Flow (1981-1999)*	2021-2060			2060-2099		
		10th percentile	*Median*	*90th percentile*	*10th percentile*	*Median*	*90th percentile*
1	101,713	104,022	107,753	110,260	94,447	111,399	119,915
500	103,467	107,308	109,923	113,022	97,868	114,773	123,209
1000	120,047	124,078	127,725	131,381	120,053	140,121	144,595
1500	134,262	140,997	147,409	151,011	138,790	158,975	163,337
2000	149,125	155,348	166,001	175,311	152,985	172,448	182,459
2500	160,543	168,545	175,900	191,821	167,223	182,623	199,042
3000	170,241	175,140	182,845	199,391	177,725	193,813	209,013
3616	180,219	191,082	196,485	214,276	194,309	206,365	224,596

Connecticut River
100-Year Flows (cfs), RCP 4.5

Points along river, upstream to downstream	*Historical Modeled Flow (1981-1999)*	2021-2060			2060-2099		
		10th percentile	*Median*	*90th percentile*	*10th percentile*	*Median*	*90th percentile*
1	101,713	89,721	95,521	99,118	93,248	103,310	114,618
500	103,467	92,099	98,954	102,756	95,924	106,655	118,861
1000	120,047	115,663	121,201	127,097	116,587	130,598	137,550
1500	134,262	140,812	148,088	155,671	139,829	154,888	162,001
2000	149,125	155,894	158,296	172,314	155,162	166,885	180,351
2500	160,543	165,482	170,879	185,790	164,411	178,358	190,538
3000	170,241	176,262	181,514	191,327	175,025	188,733	199,996
3616	180,219	190,613	192,303	202,748	18,9824	203,423	215,054

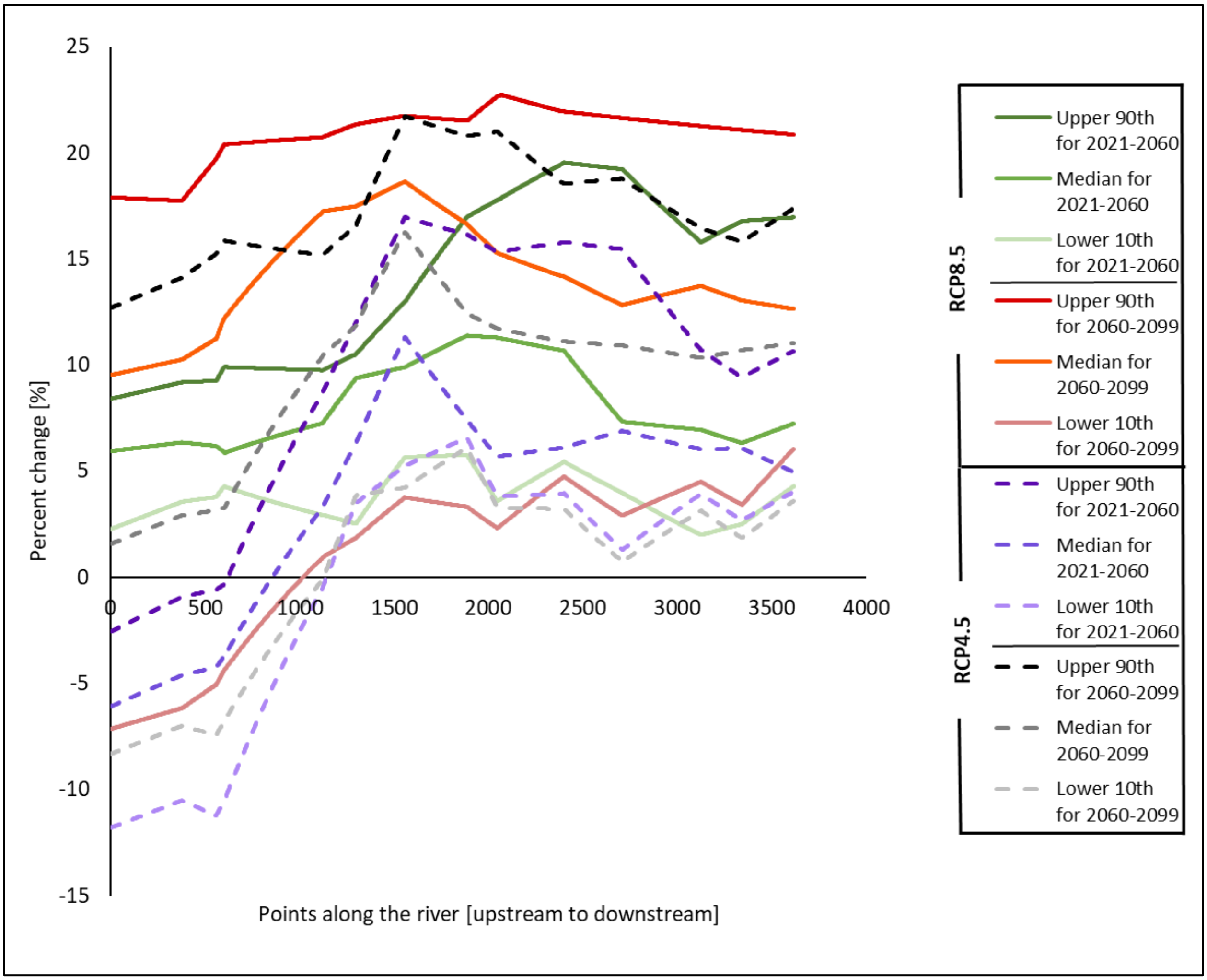

Figure 9: Percentage changes in 100-year, 24-hour flows along the Connecticut River by different percentiles flow in the near- (2021-2060) and far-term (2060-2099)

Figure 10 and **Figure 11** present the 100-year, 24-hour flow estimates for the RCP 8.5 and RCP 4.5 scenarios on the Merrimack River. The figures present data for the near-term (2021-2060) and the far-term (2060-2099) using the same GCMs that were used in the Connecticut River basin and that represent the median, upper 90th and lower 10th percentiles of the range in the future.

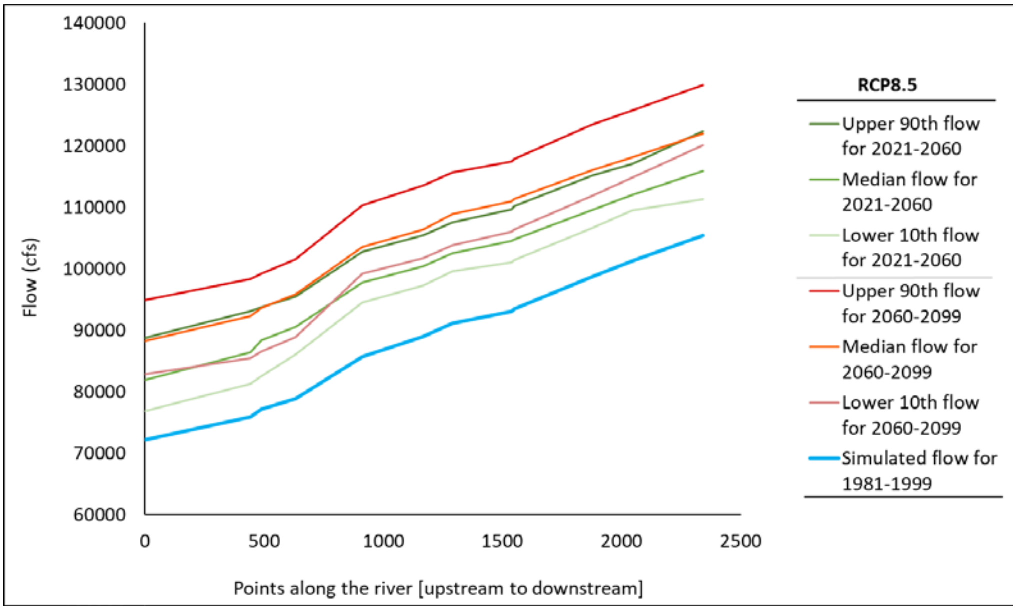

Figure 10: 100-year, 24-hour flow estimates along the Merrimack River from different climate models under RCP 8.5

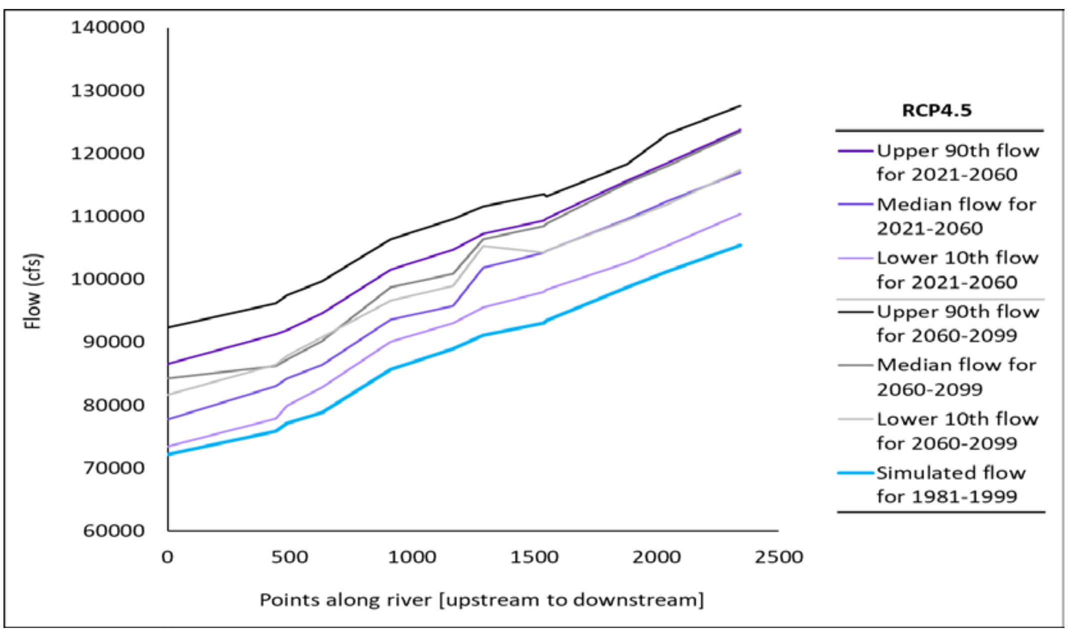

Figure 11: 100-year, 24-hour flow estimates along the Merrimack River from different climate models under RCP 4.5

Table 5 summarizes these data at specific locations along the Merrimack River, for the two time-periods and for the three scenarios. The data presented in Table 5 suggests that for the RCP 8.5 and the near-term scenario, the historic modeled 100-year flood is consistently less than the estimates for forecasted flows from the GCMs for the median, the 10% event and the 90% event. It also suggests that the historic modeled 100-year flows in the far-term (2061-2100) are consistently less than the estimates with forecasted climate from the GCMs for the median, the 10% event and the 90% event.

The data presented in Table 5 suggests that the median, 10% event, and the 90% event for RCP 4.5, when applied to the near-term scenario and the far-term scenario, are consistently greater than the historic modeled 100-year flow.

Table 5: Estimates of 100-year flows on the Merrimack main-stem in the near and far-term (RCP 8.5 and RCP 4.5)

Merrimack River
100 Year Flows (cfs), RCP 8.5

Points along river, upstream to downstream	*Historical Modeled Flow (1981-1999)*	2021-2060			2060-2099		
		10th percentile	*Median*	*90th percentile*	*10th percentile*	*Median*	*90th percentile*
1	72,166	76,832	81,900	88,751	82,835	88,256	94,903
500	77,288	82,812	88,546	93,883	86,728	93,813	99,401
1000	86,818	95,466	98,675	103,701	100,076	104,531	111,450
1500	92,761	100,822	104,229	109,350	105,697	110,662	117,189
2000	100,590	108,756	111,384	116,577	114,061	117,597	125,180
2341	105,418	111,316	115,914	122,398	120,116	122,016	129,917

Merrimack River
100 Year Flows (cfs), RCP 4.5

Points along river, upstream to downstream	*Historical Modeled Flow (1981-1999)*	2021-2060			2060-2099		
		10th percentile	*Median*	*90th percentile*	*10th percentile*	*Median*	*90th percentile*
1	72,166	73,442	77,745	86,561	81,659	84,270	92,336
500	77,288	80,172	84,428	92,161	88,114	87,516	97,667
1000	86,818	91,114	94,353	102,637	97,437	99,489	107,489
1500	92,761	97,635	103,862	109,024	104,416	108,153	113,250
2000	100,590	104,655	111,673	117,753	111,252	117,300	121,817
2341	105,418	110,380	116,984	123,764	117,372	123,439	127,563

The 100-year, 24-hour flow estimates under RCP 4.5 show similar trends and magnitudes as the RCP 8.5 **(Figure 10 and Figure 11)**. This is confirmed in **Figure 12,** showing the percent change by different quantiles of flood estimates in the future. The results are mixed in terms of whether the percent change in the 100-year, 24-hour flow event increases or decreases going from upstream to downstream in the Merrimack. In general, for the upper 90th percentile event, the change in percent of flow decreases going from upstream to downstream. For the lower 10th percentile event, the change in percent of flow increases slightly going from upstream to downstream.

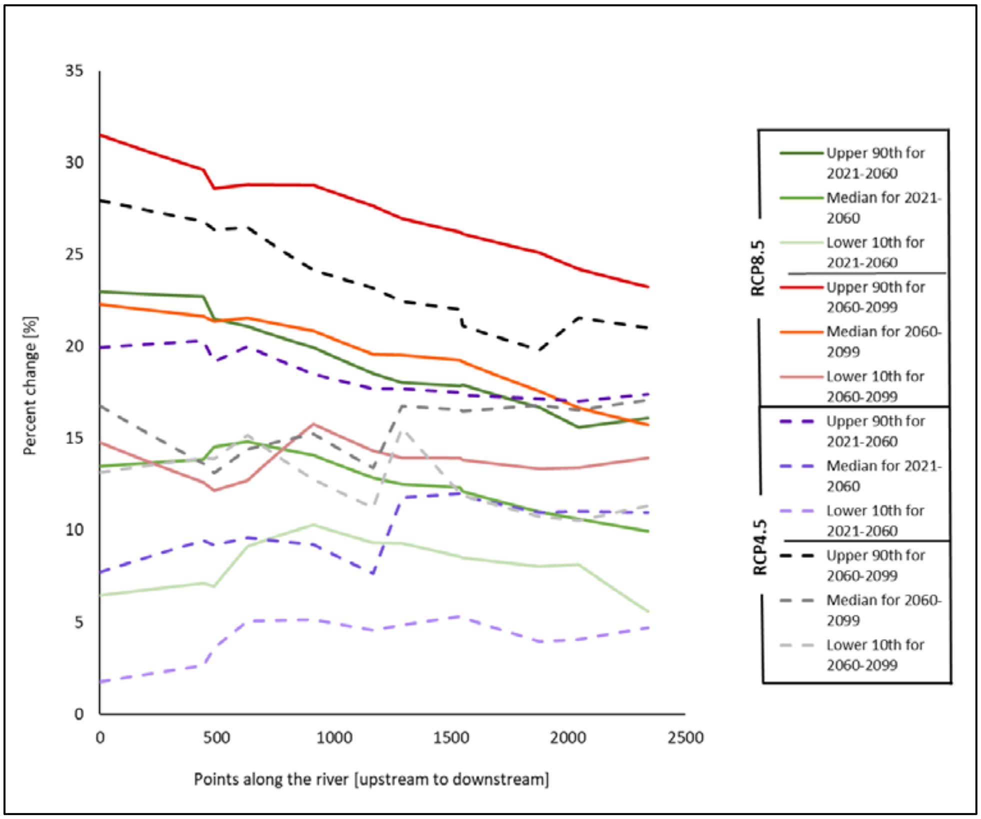

Figure 12: Percentage changes in 100-year, 24-hour flows along the Merrimack River by different percentiles flow in the near-term (2021-2060) and far-term (2060-2099)

Figure 9 and Figure 12 suggest differences between the percent changes in the 100-year, 24-hour flows along the Connecticut and Merrimack Rivers. The trend relative to the percent change in the Connecticut River (Figure 9) increases from the point 0 to point 1,500 (approximately) where the percent change is greatest; then it then slowly decreases. The percent change in the 100-year, 24-hour flows for the Merrimack (Figure 12) shows a continuous decrease throughout the range of points.

The reasons for these differences could be associated with the topographic area and slope of the rivers at the points of investigation. The elevation of the Connecticut River at the border of New Hampshire and Massachusetts (point 0, about 2.5 miles north of Northfield, Massachusetts) is approximately 200 feet and the elevation where the Connecticut River leaves Massachusetts and enters Connecticut (point 3700) is 30 feet. The elevation of the Merrimack River at the border of New Hampshire and Massachusetts (point 0, about 8 miles northwest of Lowell, Massachusetts) is approximately 95 feet and the elevation where the Merrimack River leaves Massachusetts and enters the Atlantic Ocean is at sea level. Thus, the elevation change in the Connecticut River is nearly twice that of the Merrimack River. The Connecticut River, as it flows through the state of Massachusetts, also drains some high elevation watersheds, including the Westfield and the Deerfield, and some moderately high elevation watersheds, such as the Millers and the Chicopee, as well as lower elevation areas near the main stem of the river. The Merrimack River, as it flows through Massachusetts, is already at a much lower elevation, and it drains watersheds that are at much lower elevations. The Connecticut River, downstream of the confluence of both the Millers and Deerfield Rivers, demonstrates the same general trend (a decrease in the percent change in 100-year, 24-hour flows as a function of distance downstream) as the Merrimack River.

4.4 Projected Changes in 100-year Flows, Summary

In previous portions of Section 4 of this report, the impacts of climate change on 100-year, 24 hour flows are presented. Each of the twenty-four modeling scenarios (two rivers [Connecticut River and Merrimack River], two time-periods [near-term and far-term], two emission scenarios [RCP 8.5 and RCP 4.5], and three representative GCMs) provide insight into what future 100-year flows might be. These calculated flows indicate the range of flows that might occur given the assumptions that are associated with each scenario. **Table 6** presents a summary of the estimated percent change in the 100-year, 24-hour flows for the twenty-four scenarios when averaged across the cross-sections of the river for the points identified in Table 4 and Table 5. As indicated in these previous tables, the percent of change does vary from upstream to downstream, however, it is useful to summarize the range of results to identify general trends.

Table 6: Percentage changes in 100-year, 24-hour flows

		2021-2060			2060-2099		
		10th percentile	Median	90th percentile	10th percentile	Median	90th percentile
Connecticut River	RCP 8.5	3.8%	8.1%	13.4%	0.3%	14.1%	21.2%
	RCP 4.5	-1.5%	2.9%	8.9%	-0.7%	9.0%	17.1%
Merrimack River	RCP 8.5	8.9%	13.7%	20.2%	15.1%	20.6%	28.3%
	RCP 4.5	4.1%	9.9%	18.2%	12.3%	15.8%	23.7%

The results presented in Table 6 suggest the following:

a. For the median climate model scenarios, estimated 100-year, 24 hour flows will range between increases of 2.9% and 14.1% for the Connecticut River and 9.9% and 20.6% for the Merrimack River.
b. For the 90% climate model scenarios, estimated 100-year, 24 hour flows will range between increases of 8.9% and 21.2% for the Connecticut River and 18.2% and 28.3% for the Merrimack River.

c. For the 10% climate model scenarios, estimated 100-year, 24 hour flows will range between increases of -1.5% and 3.8% for the Connecticut River and 4.1% and 15.1% for the Merrimack River.
d. In addition, Figure 9 and Figure 12 suggest that the median change at specific locations on the two rivers can be significantly larger than the overall average along the rivers.

4.5 Correlation Between 100-year, 24-hour Precipitation Events and 100-year, 24-hour Flow

Streamflow directly responds to precipitation events. However, the response is not necessarily a linear response. If the response were linear, a river basin should exhibit a similar increasing or decreasing trend in 100-year, 24-hour precipitation event and 100-year, 24-hour flow estimates. In this study, the results indicate that the relative change (increase) in the 100-year, 24-flow event is significantly less than the relative change in the 100-year, 24-hour precipitation event. For both emission scenarios, mean increases in 100-year, 24-hour flow for the near-term range between ~5-15% while increases for the far-term have shown to be within the range of ~15-30%. As noted previously in this study, approximately 35% of the surface area of Massachusetts will observe more than 50% increases in 100-year, 24-hour precipitation events in the near-term and the areas that receive a 50% increase will expand to 55%. This non-linear behavior indicates that extreme precipitation events do not translate directly to changes in the 100-year, 24-hour flow event. This is not surprising as many similar instances have been reported in other global and regional studies *[35]*, *[32]*, *[36]*. In these studies, authors have identified different rationales for these results, most related to physical processes. In fact, high flow events are influenced by the location, pattern, duration, and rarity of precipitation, as well as the state of the catchment prior to the event (wet or dry), with the streamflow response dependent on the hydraulic characteristics of the catchment, among other factors *[33]*. However, the scope of this study did include identifying which factor has been the most influential since analysis was not made of the seasonality or temperature impacts on hydrologic trends. As such, further investigation is necessary to have a clearer explanation of this topic.

5.0 Discussion of Limitations When Modeling Large Rivers

5.1 Limitations of Study

As with a study of any of major river basin using climate forecasts, there are several limitations that can be noted. These limitations include: 1) recognition of the need for ensembles of GCMs because of our inability to predict the future precisely, 2) the lack of hydrologic data that is unimpaired by infrastructure management, and 3) the challenges of hydrologic modeling.

The GCMs used in this study are highly respected and frequently applied climate models that estimate the impacts of changes in greenhouse gases on the earth's climate. They represent current state-of-the-art climate modeling. The use of an ensemble of models is also frequently applied, as they are here. However, there is great complexity in these models as they attempt to simulate the physical processes that describe our atmosphere and oceans. These models allow the user to explore potential future characteristics of climate over a century-long period. The use of "ensembles" (outputs from multiple climate models) provides the opportunity to explore a range of potential futures, but comes with computational requirements and the need to interpret multiple results. In the past, 100-year floods typically were estimated based upon existing peak annual flows at gaged sites and statistical methods to estimate extreme events from these data. The reliability of these estimates were often not associated with length of the actual record used to create the estimates. Recognition that climate change will impact extreme flows in the future suggests that the use of ensembles of estimates may help generate more realistic estimates of extreme events.

More than 30 major dams or control structures, and hundreds of smaller dams, are located in the Connecticut River basin and provide flood mitigation, water supply or hydroelectricity. The Merrimack watershed is also highly regulated with 41 major dams and hundreds of smaller dams, operating for similar purposes. In addition, water is taken for water supply and power production and either returned or lost to these watersheds. These water uses can greatly alter the natural flow regime of the river. Thus, United State Geological Survey's (USGS) gaging measurements in regulated streams do not represent natural flow conditions; it can be difficult to determine the natural flow regime of highly regulated rivers. Hydrologic modeling requires accurate flow measurements throughout the basin to calibrate model parameters.

Hydrologic models are imperfect characterizations of the complex flow of water through natural and manmade systems. The translation of precipitation, as rainfall and snow, and temperature to streamflow requires assumptions concerning the impacts of soils, land-use, and vegetation on the movement of water through the environment. Although this science has evolved dramatically during the past 40 years, models remain constrained by the quality and quantity of available data to calibrate the model. An initial goal of this study was to provide estimates of flows throughout the main stems of the Connecticut and Merrimack Rivers at frequent spatial intervals desired by MassDOT as inputs for a related effort. This goal is challenging because traditional hydrological models are not typically applied at resolutions finer than 16 km^2 resolution. For this reason, we employed linear interpolation to estimate flows at intermediate points between two grid cells of the hydrology model. For all these reasons, there are uncertainties associated with 100-year, 24-hour flow estimates generated at river cross sections.

The concept of "design storms" and 100-year, 24-hour flows, based upon historic streamflow records, have well served those planning for future infrastructure in the past. Engineers and designers are often constrained by the lack of long-term data (perhaps necessitating the estimation of a 100-year, 24-hour event with only 30 years of historic data) and they often do not have streamflow gage data in the locations they desire (necessitating the need to estimate flows at desired locations with flows at other sites). Regardless, they make the best and most informed decisions possible given the data available. Today, although we typically have longer streamflow records and more advanced techniques to estimate flows at ungaged locations, we encounter evidence that the flows of the past may not be a good indicator of future flows affected by climate change.

The insights gained from this study suggest that applying the 100-year, 24-hour precipitation event of the past in designing future infrastructure will result in underestimates of the most likely 100-year storms in the future by a significant percentage. Going forward, a discussion as to how best provide a translation of past 100-year, 24-hour flow to future floods should occur. For the two major rivers studied here, there is a clear indication that future 100-year flows will be greater than in the past. The amount of change depends somewhat on the particular river, the characteristics of its watershed, and where within the river basin the point of interest lies.

5.2 Impacts of Infrastructure on Flows

The Connecticut and the Merrimack are two of the largest rivers in Massachusetts and they have a long history of dam construction for various purposes. Although the precise numbers are difficult to establish, it is estimated that there are approximately 850 dams on the Merrimack River basin and more than 3,000 dams in the Connecticut River basin. Thus, flows are highly regulated in these streams. The construction of these control structures impair the natural flow regime, making flow modeling extremely difficult. Hydrologic model parameters need to be calibrated using accurate measurements at stream gages, which becomes a challenge in regulated rivers, as natural flow traces are generally not represented. Transferring parameters from adjacent streams that are not impaired may work to some extent, although they may not be fully accurate. For these reasons, model flow estimates at regulated streams can at times prove to be highly uncertain and should not be used for design purposes at a specific location. Although flood estimates could be uncertain, the comparative studies are expected to give us an idea about future trends of floods and other extreme events at different past and future time-periods and locations. As such, this study can be used to guide policy makers to develop strategies against climate change for asset management in the floodplains of the Connecticut and Merrimack River.

5.3 Spatial Scale and Limitations

The original spatial resolution of climate models was generally coarse (>500 km on a side); today, the spatial resolution has decreased further (<100 km on a side). To perform hydrologic modeling, a downscaling technique transforms the climate data from the GCMs into a much finer resolution was necessary (6 x 6 km). The authors use these high-resolution climate model estimates to obtain 100-year, 24-hour precipitation estimates. The hydrological model applied requires climate data at a higher resolution (4 km x 4 km), which was obtained by employing bilinear interpolation. Thus, rescaling and resampling climate data between different resolutions bring additional uncertainties to our estimates. In addition, we applied linear interpolation to obtain intermediate flow estimates between locations along the main stem of the rivers. Thus, uncertainties can also be associated with flood estimates that were obtained for point cross-sections along the main stems of the Connecticut and the Merrimack.

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6.0 Conclusions

In this study, the authors estimated 100-year, 24-hour precipitation events across the Commonwealth of Massachusetts by employing high resolution downscaled precipitation projections from fourteen different climate models under RCP 8.5 and RCP 4.5 emission scenarios. The authors computed precipitation events for two future time-periods, near-term (2021-2060) and far-term (2060-2099), and then compared those to historical 100-year, 24-hour precipitation events estimated over a base period (1960-1999). To calculate the estimated medians of future precipitation events, the researchers averaged the gridded value of all fourteen models within Massachusetts. Since median estimates for 100-year, 24 hour precipitation events are not spatiotemporally consistent, we estimated the ensemble mean of all fourteen model estimates to show future changes in 100-year, 24-hour events. These results are presented in Section 4 of this report and summarized succinctly in Figure 6. For both RCP scenarios, the ensemble mean of the design storm showed more than a 35% increase across near-term in many parts of the Massachusetts, while the increase for the far-term crosses beyond the 50% mark. Specifically, the northeastern and southwestern parts of Massachusetts are expected to be the most affected regions in the future due to increases in extreme precipitation events. We observed that the areas of increases cover parts of the Connecticut River Valley and the Merrimack River basin.

From the fourteen climate models, we selected four models to provide a range of potential future flood estimates. These included the median, the upper 90th percentile, and lower 10th percentile. We carefully observed results from previous studies and investigations in order to select these climate models. We incorporated precipitation and temperature from the selected climate models into a high resolution distributed hydrological model to generate daily streamflow estimates. The study generates 100-year, 24-hour flow estimates by using annual peak flows for near-term (2021-2060) and far-term (2060-2099) and then compares these to historical flow trends estimated over the base period (1980-1999). The study generates flow estimates at 3,618 points along the main stem of the Connecticut and 2,342 points along the main stem of the Merrimack River.

The percent changes in 100-year, 24-hour flows are summarized in Table 6 for combinations of the two rivers, different RCPs, and different time-periods, and different percentile levels. The 90% model suggests that the 100-year, 24-hour flows will increase between 8.9% and 21.2% for the Connecticut River and between 18.2% and 28.3% for the Merrimack River depending on the future time-period and the RCP applied. The median model suggests that the 100-year, 24-hour flows will increase between 2.9% and 14.1% for the Connecticut River and between 9.9% and 20.6% for the Merrimack River depending on the future time-period and the RCP applied. These increases could be the direct response of increased 100-year, 24-hour precipitation events in these two river basins, in combination of changes in temperature patterns. In future work, a full exploration of the uncertainties associated with both the hydrologic modeling and the output from the GCMs would provide better understanding and more accurate estimations of the floods and extreme precipitation events.

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7.0 References

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Appendix: Supplemental Figures of Estimates of 100-year, 24-hour Precipitation Events and 100-year, 24-hour Flow Events

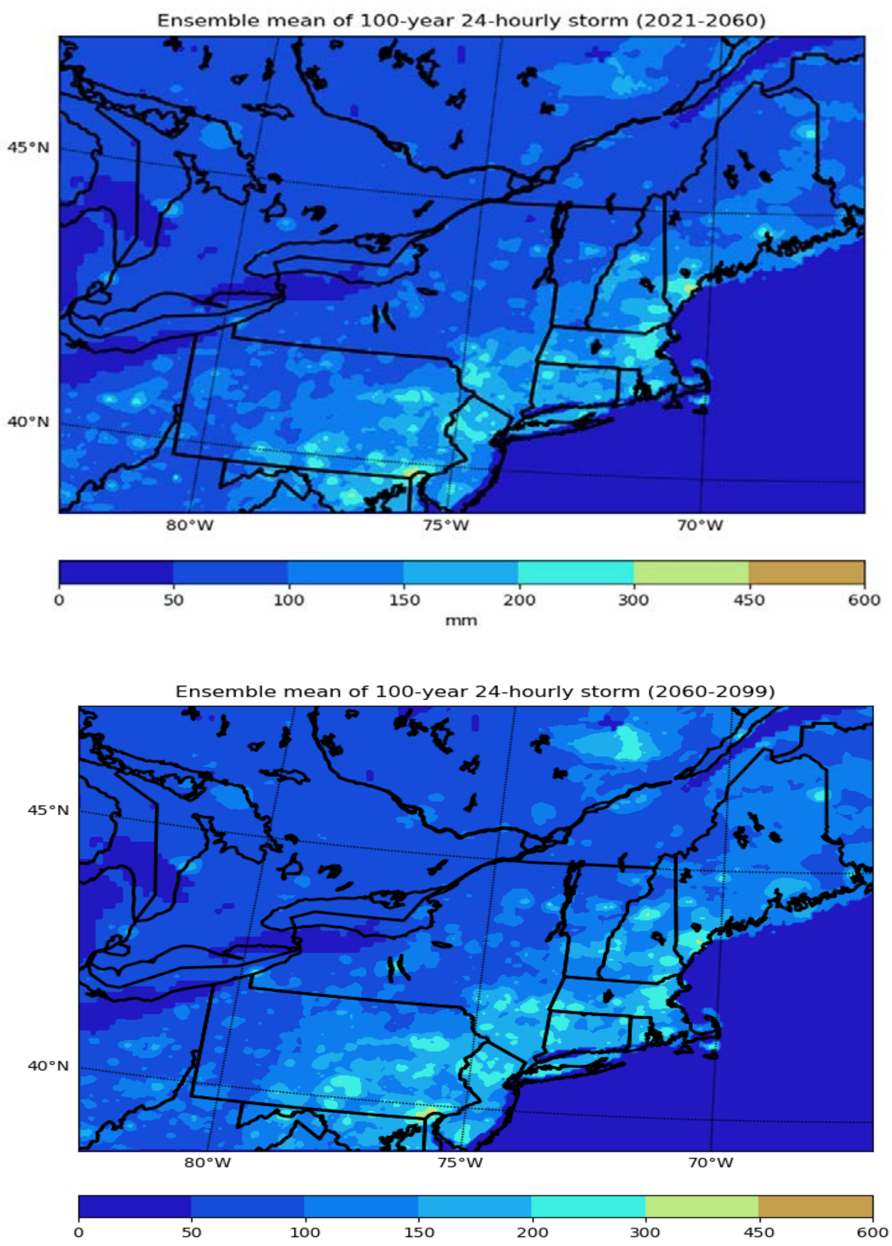

Figure A.1: The ensemble mean estimate showing 100-year, 24-hour precipitation estimate for near- (2021-2060) (upper panel) and far-term (2060-2099) (lower panel) under RCP 8.5

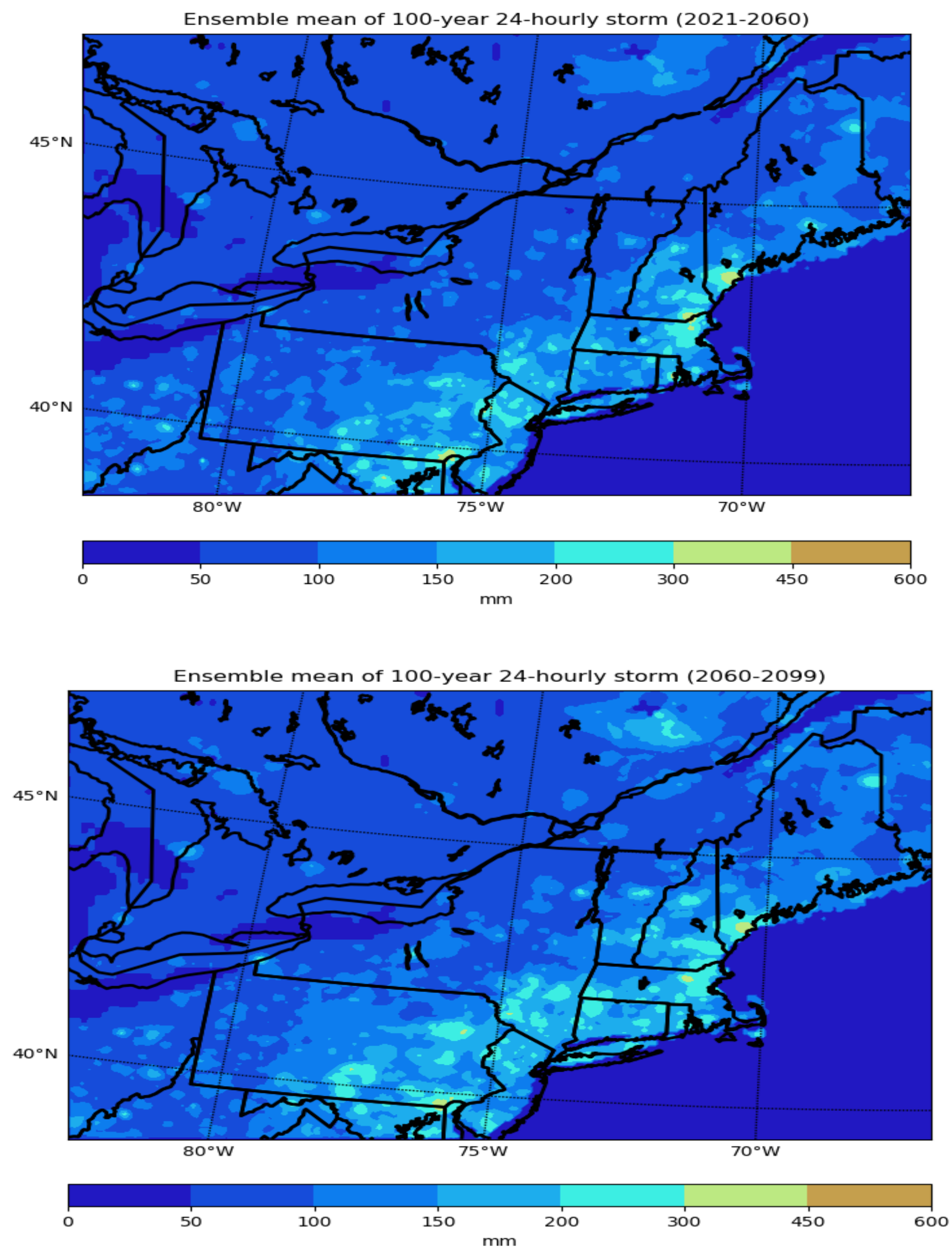

Figure A.2: The ensemble mean showing 100-year, 24-hour precipitation estimate for near- (2021-2060) (upper panel) and far-term (2060-2099) (lower panel) under RCP 4.5.

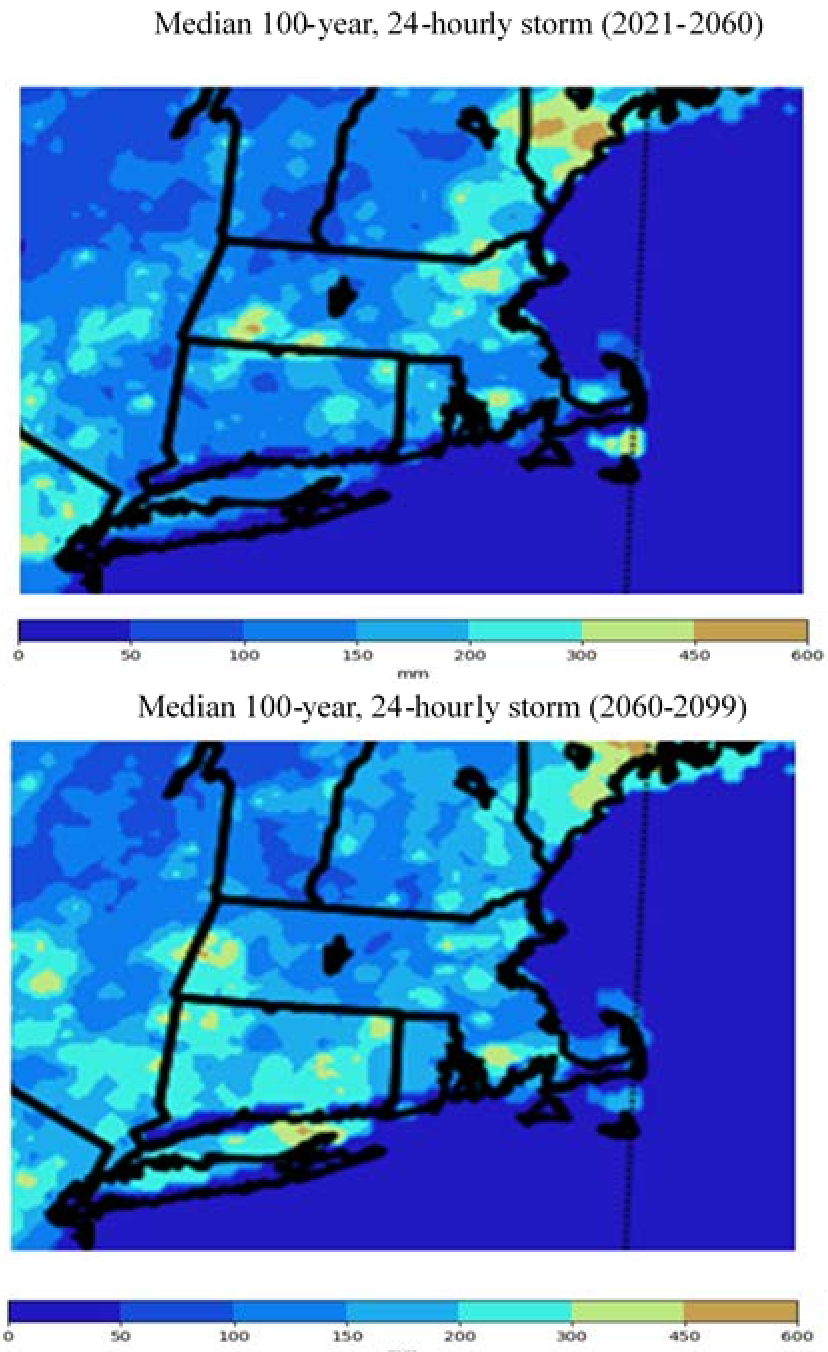

Figure A.3: The median model estimate showing 100-year, 24-hour precipitation estimate for near- (2021-2060) (upper panel) and far-term (2060-2099) (lower panel) under RCP 8.5.

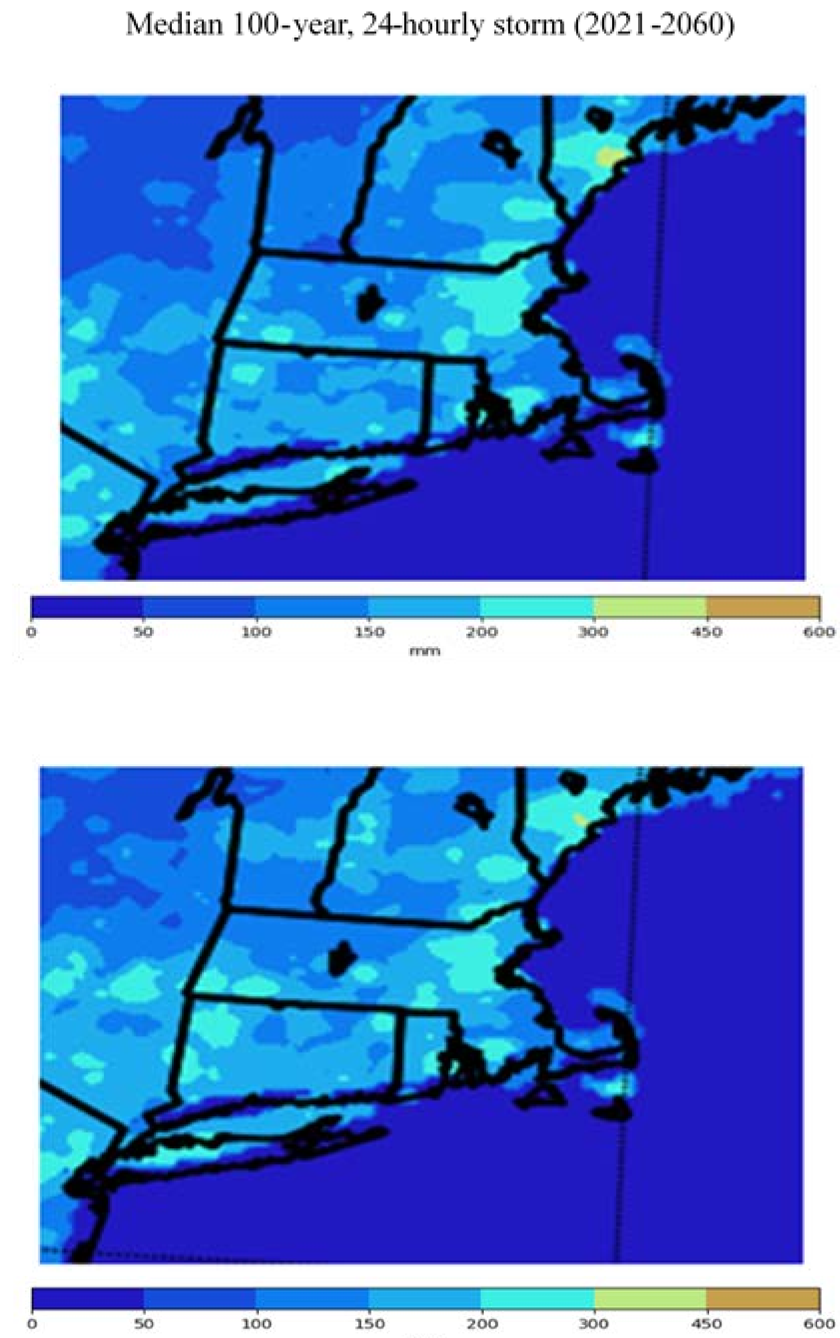

Figure A.4: The median model estimate showing 100-year, 24-hour precipitation estimate for near- (2021-2060) (upper panel) and far-term (2060-2099) (lower panel) under RCP 4.5.

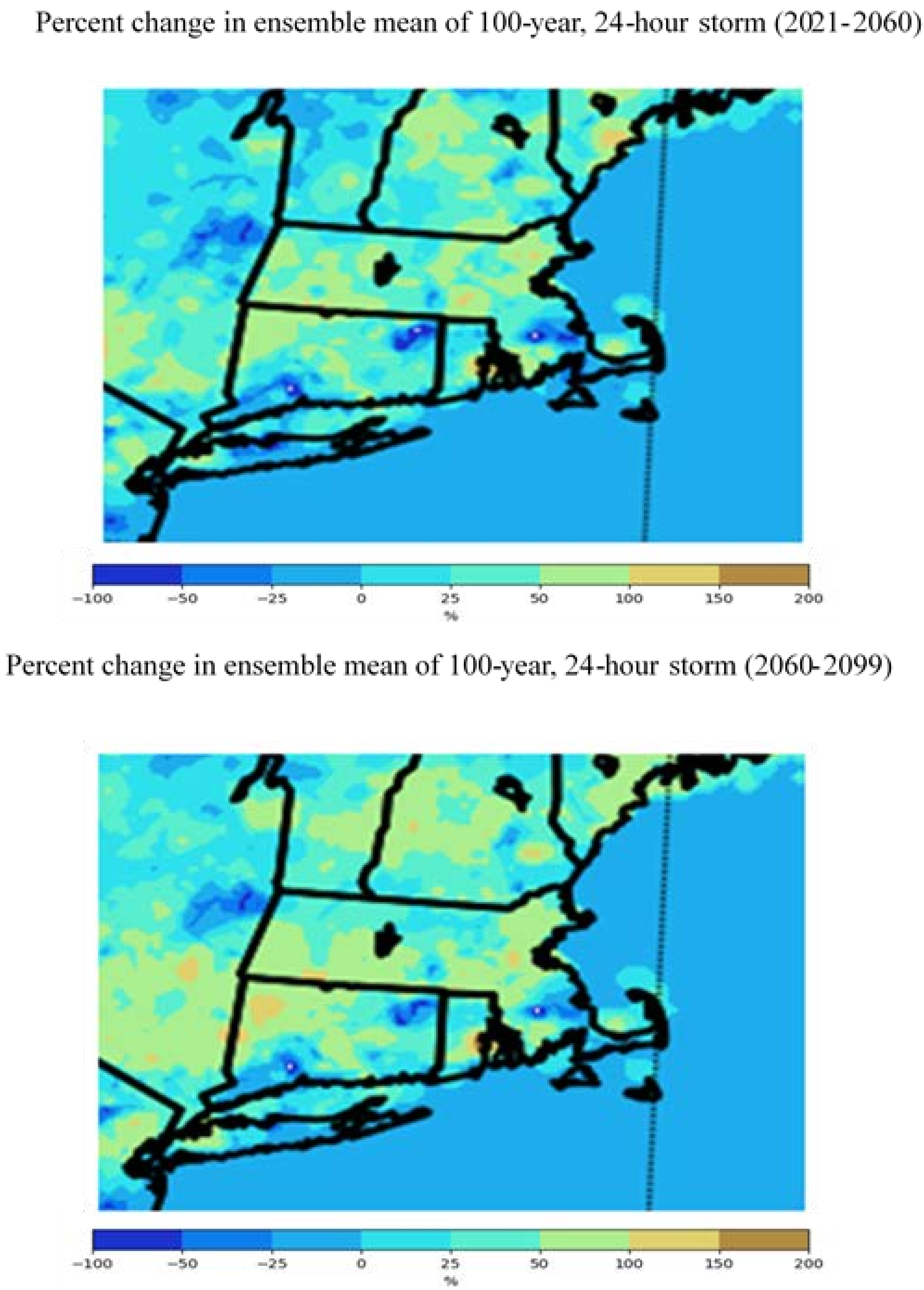

Figure A.5: Percentage changes by the ensemble mean estimate showing 100-year, 24-hour storm estimate for near- (2021-2060) (upper panel) and far-term (2060-2099) (lower panel) under RCP 8.5 compared to the base period (1960-1999)

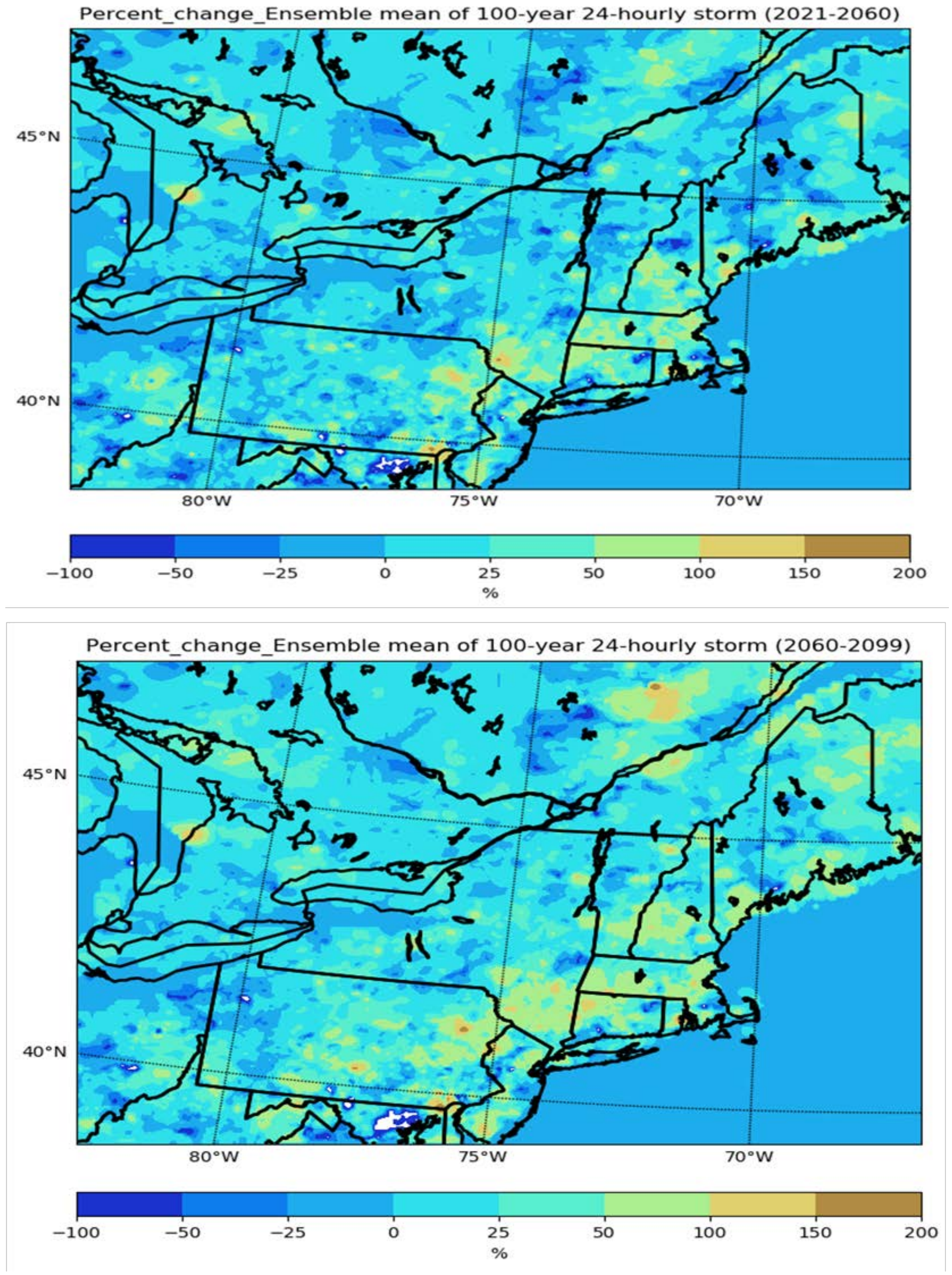

Figure A.6: Percentage changes by the ensemble mean estimate showing 100-year storm estimate for near- (2021-2060) (upper panel) and far-term (2060-2099) (lower panel) under RCP 4.5 compared to the base period (1960-1999)