Appendix A
Global Climate Model Projections for Extreme Heat Events and Extreme Precipitation Event

Memorandum

To: Jennifer Fogliano, Jeff Perlman | North Jersey Transportation Planning Authority (NJTPA)

From: Timothy Cox, PhD PE, Lauren Miller, Melissa Harclerode, PhD BCES | CDM Smith

Date: February 23, 2018

Re: Task 2-1 Technical Memo for NJTPA Passaic River Basin Climate Resilience Plan: Global Climate Model Projections for Extreme Heat Events and Extreme Precipitation Events

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Purpose

This technical memorandum summarizes the analysis conducted for Task 2-1: Determine Climate Change Impacts in the Passaic River Basin for the Passaic River Basin Climate Resilience Plan (Plan). The purpose of this task is to quantify and summarize projected impacts of climate change in the study basin.

Climate change is predicted to occur in this part of the country in various forms. These include increased annual, seasonal, and extreme temperatures; changes in annual and seasonal precipitation; more frequent droughts; increases in intensity, duration, and frequency of extreme storms; sea level rise; and changes in the timing of peak stream flow. This memo focuses on two impacts that are expected to have consequences for transportation in the Passaic River Basin: 1) extreme heat events, and 2) extreme precipitation events. For the purposes of the Plan, these impacts are defined as the following:

- *Extreme Heat Events:* Extreme heat events will be defined for this study based on the results of this memo. The days in which the ambient temperature high is equal to or greater than 90˚F is shown in this memo as an example. This threshold was selected to represent a condition of stress on transportation assets of the basin[1].
- *Extreme Precipitation Events:* For this study, maximum annual 4-day storms, with a range of recurrence intervals, have been selected to represent extreme precipitation events. The largest of these events are known to cause flooding within the study basin presently. The frequency of such storms may be impacted by climate change. Projected changes in

[1] New Jersey TRANSIT "Resilience of NJ TRANSIT Assets to Climate Impacts" report (2012) evaluated vulnerability based on 90 degree days. It is a more conservative example than the 95 degree threshold presented in the NJTPA/Cambridge Systematics Report "Climate Change Vulnerability and Risk Assessment of New Jersey's Transportation Infrastructure" (2012).

storm event magnitude and frequency, quantified under this task, will be used in subsequent hydrologic modeling performed for this study to evaluate future flood risk of transportation assets from extreme precipitation events.

Technical Approach Overview

The methodology applied for Task 2-1 is designed to make use of the best available scientific research and data in the field of climate change. The analysis uses climate model projections released as part of the World Climate Research Programme's (WCRP's) Climate Model Intercomparison Project, Phase 5 (CMIP5). This dataset was used to inform the International Panel on Climate Change (IPCC) Fifth Assessment Report, released in 2014, and includes projections of temperature and precipitation through the end of the 21st century from a wide range of global climate models (GCMs). These models were developed by leading experts from academic and research institutes around the world. No attempt was made to assess confidence levels or relative accuracies of the models as part of this analysis. Rather, they were used to demonstrate and quantify equally plausible future climate scenarios for this region.

The IPCC GCMs use four Representative Concentration Pathway (RCP) scenarios which base climate impacts on radiative forcing values. Radiative forcing is the net amount of energy that the earth absorbs from the sun and is expressed in terms of watts per square meter ($W\ m^{-2}$). Greenhouse gases increase the amount of solar radiation in the atmosphere, which increases the net radiative forcing of the earth (the greenhouse effect). The RCP "value" indicates the level of radiative forcing assumed in the model to be reached by 2100 (i.e., RCP 2.6 is the rising radiative forcing that results in 2.6 watts per square meter by 2100). The four RCP scenarios are labeled: 2.6, 4.5, 6.0, and 8.5, representing four assumed levels of 2100 radiative forcing. Higher numbers indicate greater assumed future greenhouse gas emissions and, consequently, larger anthropogenic climate change impacts.

Daily downscaled and bias-corrected GCM projections were obtained for the study basin from the U.S. Bureau of Reclamation data portal[2]. These projections were previously downscaled to a 1/8th degree latitude/longitude grid centered over the river basin, using the bias correction corrected analogues (BCCA) method. Downscaled projections associated with the 30 overlying grid cells (**Figure 1**) were spatially averaged, with equal weighting applied for each cell. A total of 67 different projections, spanning the full range of available GCMs and assumed RCP pathways, were used for this study. Each projection includes a model hindcasting "overlap" period of 1950 to 1999 and a forecasting period of 2000 to 2100[3].

Two different 21st century planning horizons were selected for Task 2-1: mid-century (2045) and late century (2080). For precipitation analyses, 30-year sampling bands (± 15 years) were used for each specific horizon target. This expanded sampling band was used to capture "natural"

[2] U.S. Bureau of Reclamation data portal available at: http://gdo-dcp.ucllnl.org/downscaled_cmip_projections/

[3] For more information on the dataset and downscaling method, the reader is referred to: *Bureau of Reclamation, et al. 2013. Downscaled CMIP3 and CMIP5 Climate Projections: Release of Downscaled CMIP5 Climate Projections, Comparison with Preceding Information, and Summary of User Needs.*

short timescale (year to year) variability in the climate data, while still being representative of the climate trends associated with the two planning horizons. For temperature analyses a tighter 10-year sampling band (± 5 years) was used, reflecting the lower short timescale variability associated with these projections.

GCM outputs, for each planning horizon, were grouped together into five different pools, or “ensembles”, of data for the analyses presented in the following subsections. The five ensembles include each of the four different RCP assumptions (2.6, 4.5, 6.0, and 8.5) and a comprehensive set of all the projections (“All”). For example, the RCP 2.6 ensemble for 2080 projections of precipitation includes daily projection data from 16 different GCMs for the 30-year period of 1965 – 2094; or 16 x 30 x 365 = 175,200 data points. For the “All” ensemble, there are 67 x 30 x 365 = 733,650 data points.

Note that, within each ensemble, each data point was weighted equally in the statistical analyses described below. Note also that for all calculations of percentiles, exceedance percentages, and event frequencies, the Excel *percentile* function was used, for simplicity. This function uses a non-parametric ranked order approach, with linear interpolation applied between points. Given the large number of data points associated with each ensemble, this approach is deemed appropriate. Comparable results would be expected from standard parametric (distribution fitting) options.

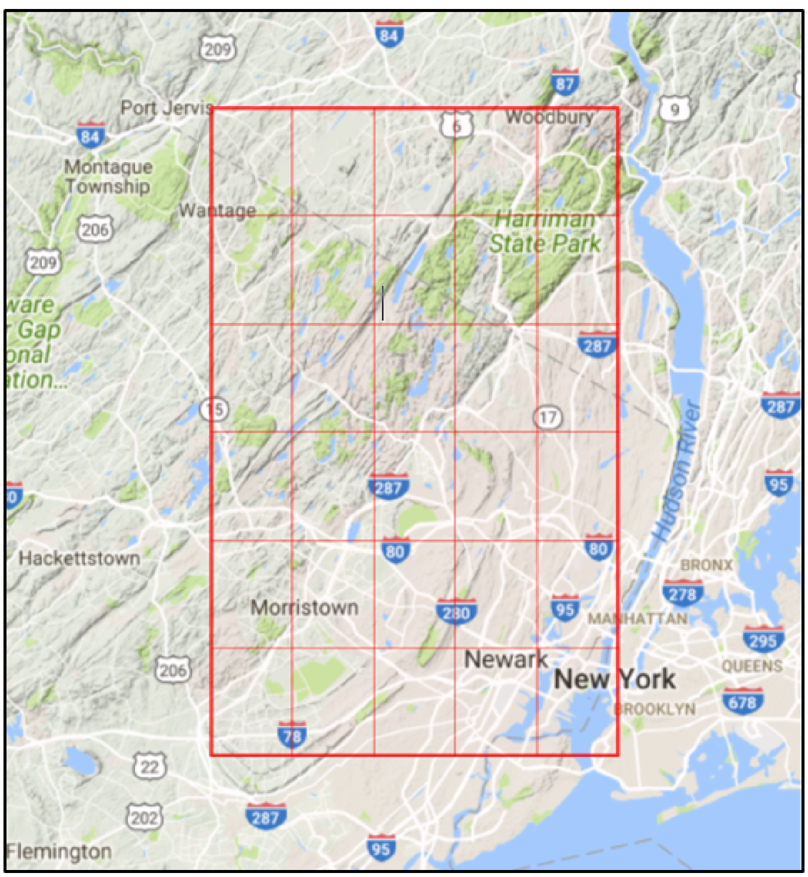


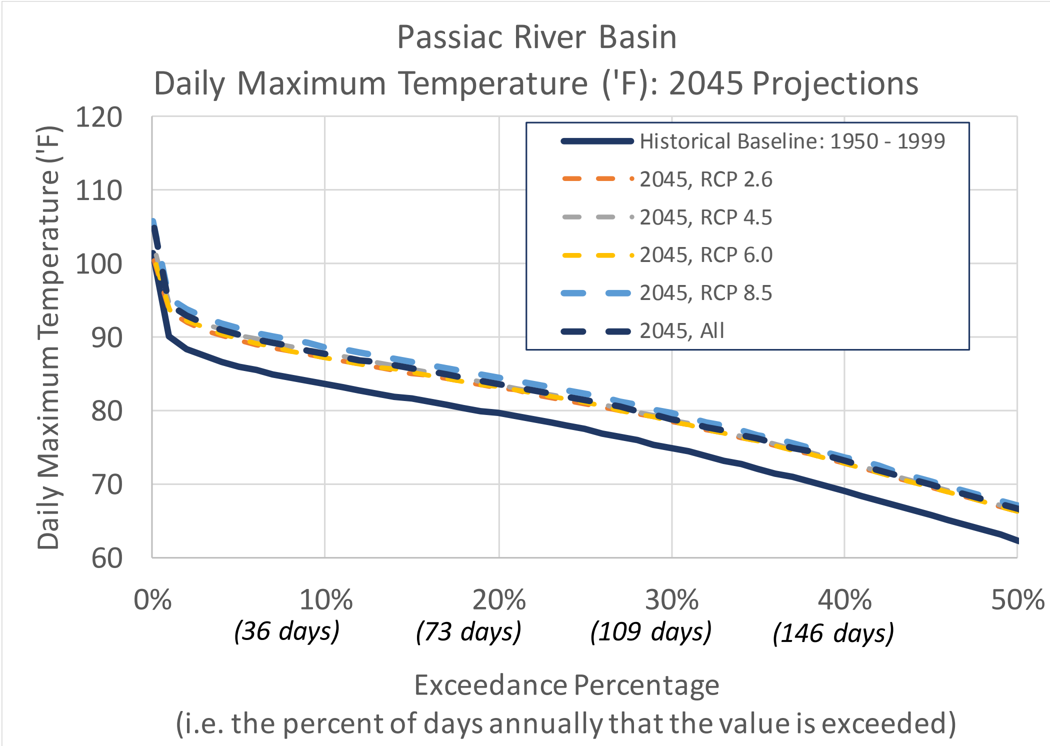
Figure 1. Downscaled GCM Spatial Grid Used for Climate Change Analysis

Extreme Heat Events

The decade of 2001-2010 was the hottest on record, and the current decade is well on its way to exceeding it, with the period 2013 - 2017 registering as the hottest five-year period on record. This trend is expected to continue. For the analysis presented here, extreme heat events are defined as days in which the daily maximum temperature is equal to or above 90˚F.

Summaries of modeled daily maximum temperature projections, for both planning horizons, are shown in **Figure 2**. Included here, for reference, are modeled hindcast projections for the baseline historical period: 1950 – 1999. This provides a convenient (modeled vs. modeled) reference for comparison that focuses on the relative changes in temperature projected by the models, rather than on the specific magnitudes of the projections. By focusing on relative (modeled vs. modeled) changes, we minimize the influence of any systematic bias in the models in our interpretation of results. Results show a clear upward shift in daily maximum temperatures for the full range of daily temperatures. The results also demonstrate the variability in projections due to future emissions assumptions (RCP scenarios), with the worst-case scenario (RCP 8.5) projecting approximately 6 degrees higher than the best base scenario (RCP 2.6), for the 2080 planning horizon. Much less variability is observed across the projection ensembles for the shorter, 2045, planning horizon. This indicates lower model sensitivity to RCP assumptions for the first half of the century. Note that the 90˚F extreme heat threshold represents approximately the upper 1st percentile of current daily maximum temperature in the basin, based on climate model hindcast projections for the period 1950 – 1999.

The number of days equal to or above 90˚F projected by the GCMs for the two planning horizons were compared to model hindcast period results to quantify how much more frequently the basin may expect this type of extreme event in the future. The results of this analysis are summarized with percentile plots (**Figure 3**) showing levels of consensus among models, within each RCP category separately and pooled together ("All"), for the two future planning horizons. The quantified levels of consensus (x axis) can also be interpreted as relative risk levels associated with a given number of extreme heat events occurring annually for the specified planning horizon. The historical baseline curve shown on the plot summarizes the model hindcast projections of the number of annual extreme heat events for the period 1950 – 1999. For example, the results show that 1 out of 50 years (2% probability of occurrence) in the historical hindcast period (1950 – 1999) had at least 15 days with maximum temperatures over 90 ˚F. Conversely, the worst case GCM projections (RCP 8.5) predict an approximately 95% chance of the same number of extreme heat days, or more, occurring in 2080. At the highest end of the projection spectrum (1% level of consensus), GCMs project extreme heat days in the range of 60 – 100 days per year for the end of the century: a three to five-fold increase, compared to the same percentile level for the historical baseline period.



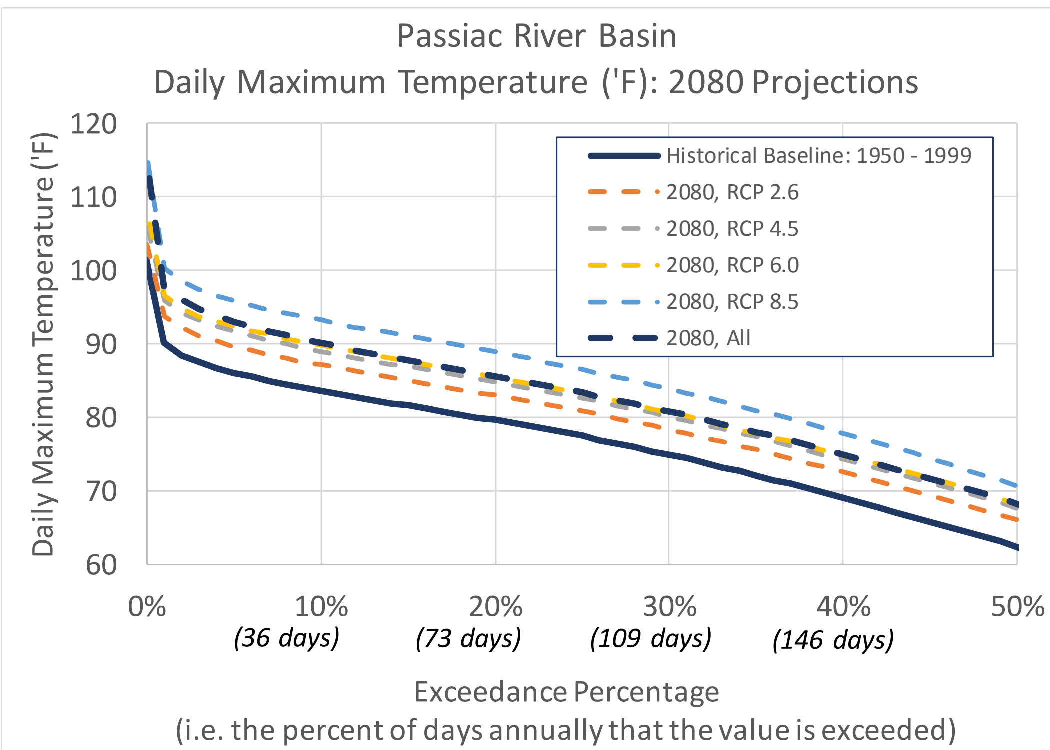
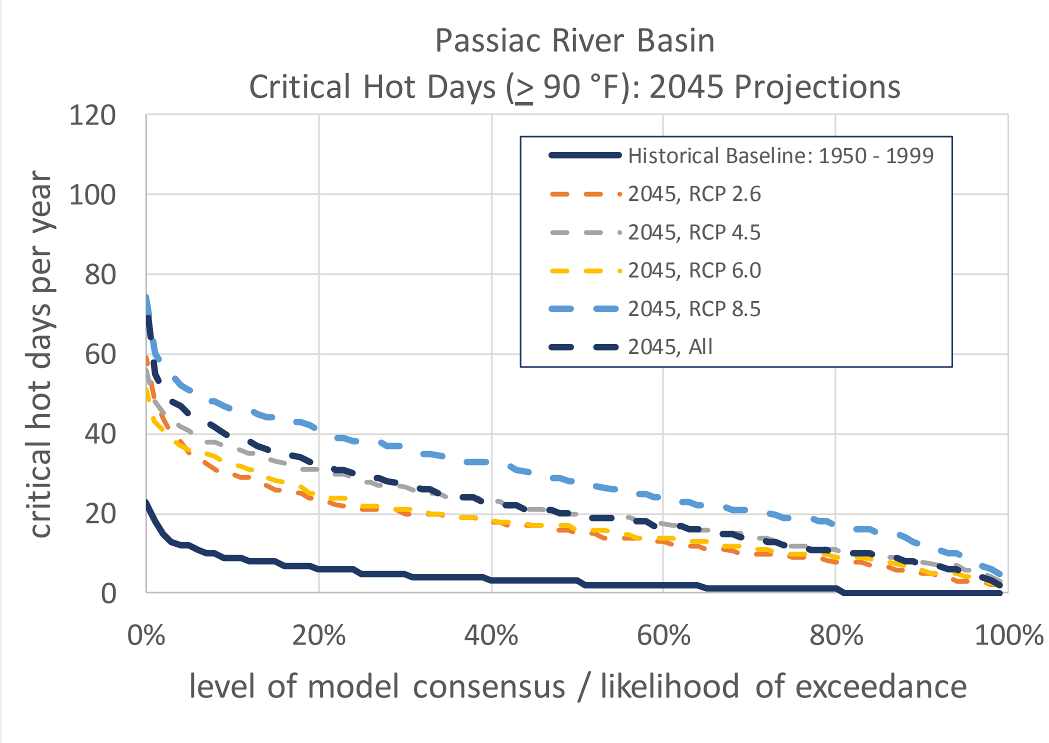


Figure 2. Daily Maximum Temperature Projections: Full Range of Temperatures



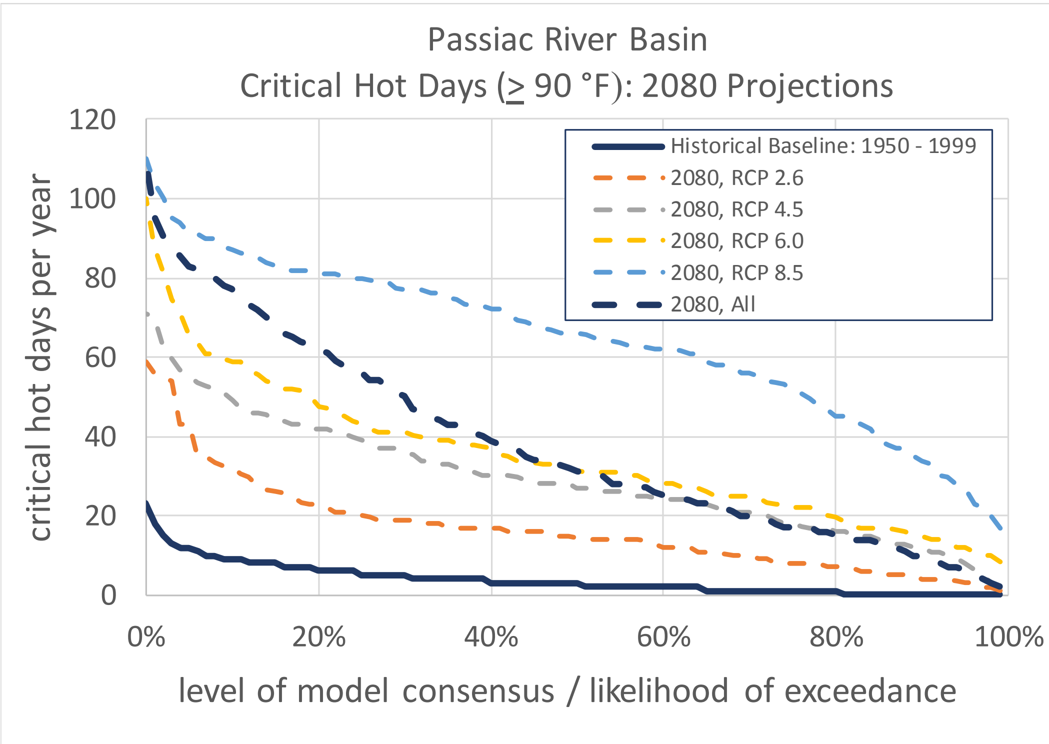


Figure 3. Daily Maximum Temperature Projections: Extreme Heat Threshold

Extreme Precipitation Events

For this study, extreme precipitation changes in the study basin were investigated using climate model projections of annual maximum 4-day storm events so they are able to be used in the hydrologic modeling which requires 4-day storm event hyetographs. The reason for this is to allow for the time it takes for the runoff to be routed through the 937-square mile watershed and accumulate at the outlet, also known as the "time of concentration" for a watershed[4].

This analysis investigated projected changes in the frequency and magnitude of such events for the two designated planning horizons, as predicted by the global climate models, and compared to historical baseline conditions. Implicit in this approach is an assumption of non-stationarity in the climate model projections of extreme precipitation events. In other words, we assume that the models predict a statistically significant change in precipitation patterns through the 21st century and that there is an underlying mechanism included in the models driving these projected changes. Otherwise, any quantified changes in storm events could simply be due to random variability or a product of the numerical methods employed. We therefore confirmed our assumption of non-stationarity by performing trend analyses on the various GCM data ensembles, described above. For each ensemble, statistically significant increasing trends ($p < 0.001$) in the annual maximum 4-day storm intensity were identified for projections through the end of the 21st century, confirming our assumption of non-stationarity.

Historical storm event statistics were obtained from the National Oceanic and Atmospheric Administration (NOAA) Climate Atlas 14 (Volume 2)[5] for the Raymond Dam (Wanaque, NJ) station. These statistics are based on data from approximately 55 years of observed record. As with extreme heat events, the future occurrence of extreme precipitation events in the basin was calculated based on the four GCM categories, included both separately and lumped together as a single group. To isolate modeled changes in storm occurrence, and to minimize the impacts of any model bias, we employed a "delta" method that normalized future model projections to model simulations of past projections. In other words, only the relative changes predicted by the climate models are used rather than directly using the actual magnitudes of projected precipitation. We calculated "change factors" as the ratio of modeled future vs. modeled past projections of rainfall intensity, for the specified recurrence intervals. We then multiplied these change factors by the actual historical storm event magnitudes to estimate storm event magnitudes reflective of future planning horizon conditions. Note that this methodology differs slightly from the approach taken for projecting extreme temperatures. Rather than only focusing on relative changes, we adjust actual measured historical data to provide specific magnitude projections, because these values are needed for subsequent hydrologic modeling projections.

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[4] See the memo submitted by CDM Smith to NJTPA on February 20, 2018: "Tasks 1 and 2 Technical Memo for NJTPA Passaic River Basin Climate Resilience Plan: Sources and Recommended Framework for Hydrologic and Hydraulic (H&H) Modeling"

[5] Precipitation-Frequency Atlas of the United States, NOAA Atlas 14, Volume 2, Geoffrey M. Bonnin, Deborah Martin, Bingzhang Lin, Tye Parzybok, Michael Yekta, David Riley, 2006.

Using this method, we calculated new 4-day precipitation magnitude values (inches) corresponding to a specific set of recurrence intervals and reflective of future (2045 and 2080) climate conditions. Additionally, linear interpolation between data points was used to estimate future recurrence intervals for the specific historical design storm magnitudes. In other words, for a given existing design storm magnitude, we calculated the projected changes in the recurrence interval of that storm for the various GCM ensembles and the two planning horizons. As an example, the magnitude of the historical 25-year 4-day design storm (7.93 inches) lies between the 10 and 15-year design storm magnitudes projected for late century (2080) conditions. Using linear interpolation, the new recurrence interval for the 7.93-inch storm, reflective of late century climate model projections, was calculated as 14 years (using the fully ensembled GCM data set).

Results of this analysis (**Figure 4** and **Table 1**) show that recurrence intervals associated with the selected extreme storm events are consistently predicted to decrease in the future, for both planning horizons. For example, a 4-day storm event producing 9.1 inches of rain has a historical recurrence interval of 100-years. By 2045, a storm event producing the same level of precipitation over 4-days has a projected recurrence interval of 54-years (across all four RCPs). This means that the likelihood of extreme events of a specific magnitude occurring in the future is predicted to increase compared to the recent past.

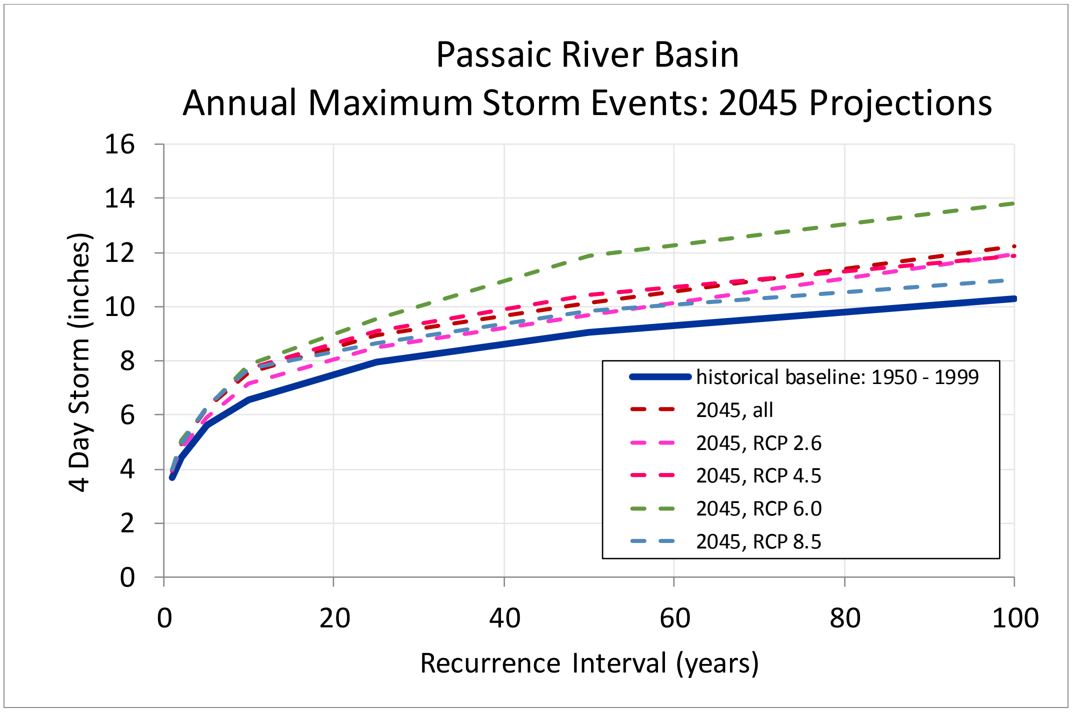
Storm events are projected to increase in intensity and frequency in the future, for this location. There is 100% consensus across GCMs that full range of storm events will increase in magnitude in the future (**Figure 4**). The magnitudes of projected changes do vary across models and model ensembles. For example, late century projections of the changes in the 25-year 4-day storm range from an increase of 0.6 inches to an increase of 1.8 inches, across the five ensembles. Mid-century projected increases for the same event range from 0.6 inches to 1.6 inches.

The tabular results provide a more detailed view of discrete projected changes in recurrence intervals for specific storm magnitudes. Results show, for example, that the current 10-year, 4-day storm event is projected to change to a 5 to 7-year event, and the 25-year event to a 13 to 18-year, by late century.

It should also be noted that there is generally less certainty associated with GCM precipitation projections compared to temperature projections. Therefore, we can surmise that the levels of uncertainty associated with results presented here are greater than those presented for extreme heat forecasts. We have not attempted to quantify this uncertainty in the results presented in Table 1. However, the range of results calculated across the five ensembles do demonstrate some of this uncertainty. In fact, the bands of storm projection results (Figure 4) are best viewed as reflective of overall GCM uncertainty rather than as conveying any meaningful stories about differences between RCP scenarios. The comparison of RCP scenarios is clouded by the fact that each RCP ensemble includes a different number of models (i.e. different sample sizes). Not all models simulated all four of the RCP pathways, and therefore specific GCM-RCP combinations were not always available. It is recommended that the full ensemble of GCM projections (“All”) be used for subsequent hydrologic analyses.

Table 1. Projected Changes in 4-Day Storm Event Recurrence Intervals

Storm Size (in)	Reported Historical Recurrence Interval (yrs)	Projected Future Recurrence Interval, All (yrs)	Projected Future Recurrence Interval, RCP 2.6 (yrs)	Projected Future Recurrence Interval, RCP 4.5 (yrs)	Projected Future Recurrence Interval, RCP 6.0 (yrs)	Projected Future Recurrence Interval, RCP 8.5 (yrs)
		2045 Planning Horizon:				
3.7	2	2	2	2	1	1
4.4	5	4	4	3	3	3
5.6	10	6	8	6	6	6
6.6	25	14	19	12	11	14
7.9	50	27	37	24	20	34
9.1	100	54	64	47	33	70
		2080 Planning Horizon:				
3.7	2	1	2	1	1	1
4.4	5	3	4	3	3	3
5.6	10	6	7	6	6	5
6.6	25	14	14	13	18	13
7.9	50	27	16	28	36	30
9.1	100	53	33	58	70	54



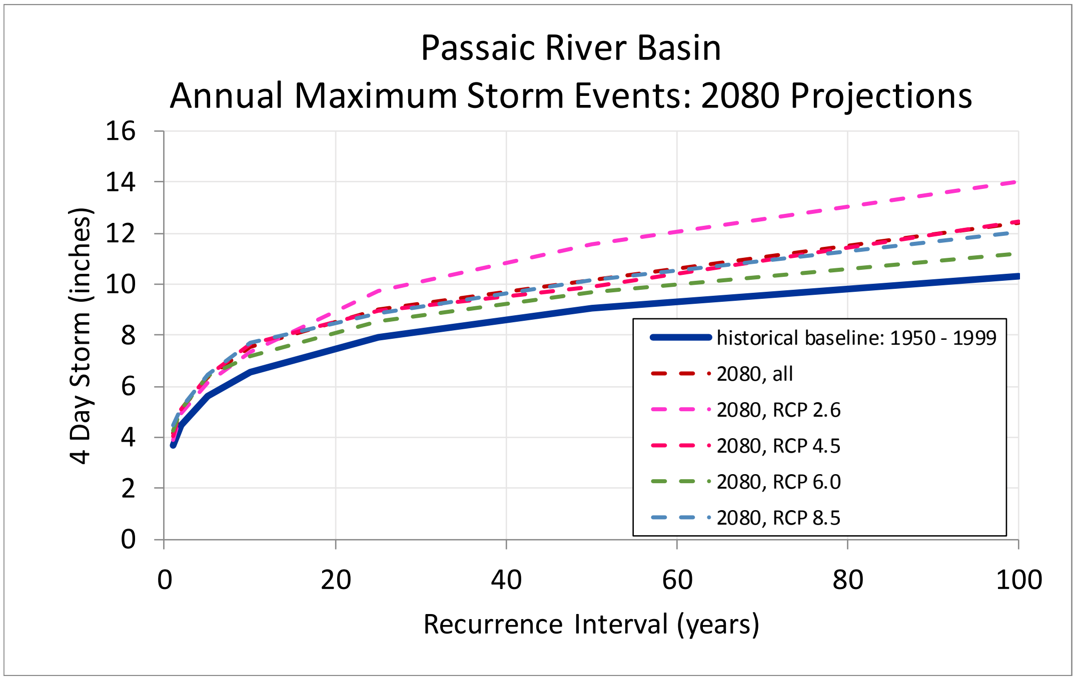


Figure 4. Annual Maximum 4-Day Storm Event Projections

Summary

This memo summarizes the potential range of impacts of extreme heat events and extreme precipitation events that may affect the Passaic River Basin and other coastal transportation assets. CDM Smith recommends that the that the full ensemble of GCM projections (“All”) be used in this study.

CDM Smith will work with NJTPA to determine the appropriate heat and precipitation events from the full ensemble of GCM projections for both planning time horizons to be included as part of this study. The results from this consensus on precipitation will then be considered during the next steps of hydrologic and hydraulic modeling efforts.