Climate Change Analysis for Maryland

Final Report

Prepared for:

Maryland Department of the Environment - Dam Safety under
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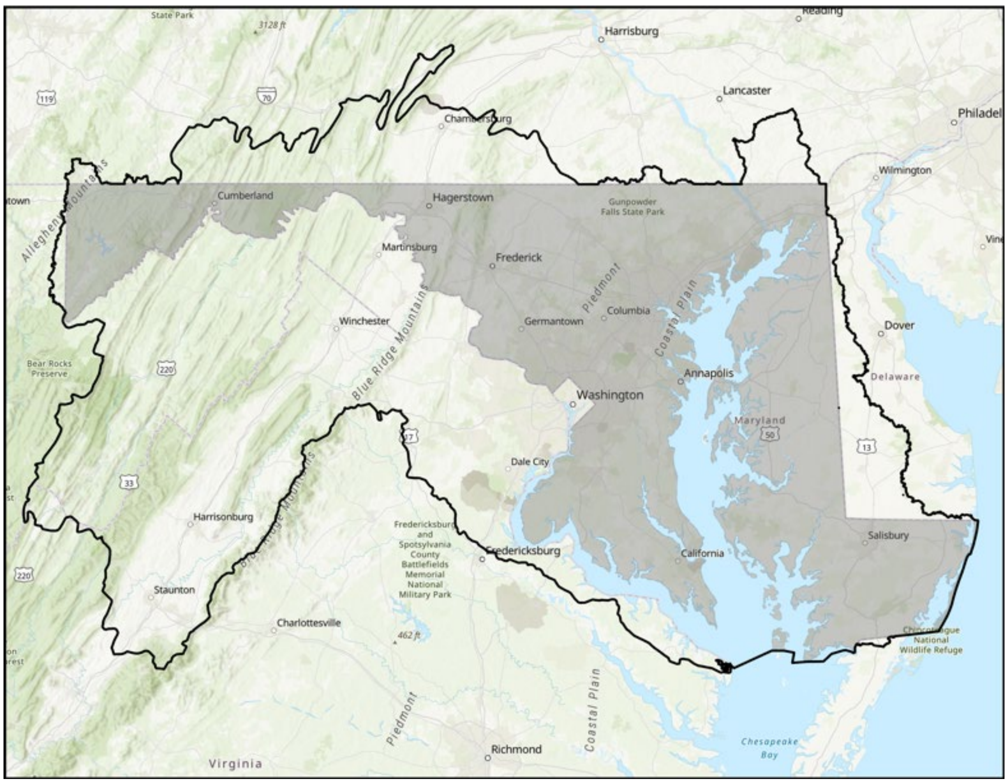

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EXECUTIVE SUMMARY

The potential effects of climate change on meteorological characterization within the study region were assessed. Future climate change projections were downloaded from Regional Downscaled Climate Model (RCM) outputs specifically evaluated for the location. The Global Climate Models (GCMs), also referred to as General Circulation Models, are developed by various governmental, academic, and research agencies around the world in coordination with the Intergovernmental Panel on Climate Change (IPCC). These are utilized to set the boundary conditions and input for the RCMs. The different emissions scenarios that are used to force the GCMs are described by Shared Socioeconomic Pathways (SSPs). SSPs are scenarios of projected socioeconomic global changes and greenhouse gas concentration trajectory that are considered possible in the future.

As part of the IPCC analysis, four pathways were applied for climate modeling: SSP 2.6, SSP 4.5, SSP 6.0, and SSP 8.5 (IPCC, 2021). The various pathways considered different climate futures, depending on the volume of greenhouse gases (GHG) emitted in the years to come. Climate change studies that evaluate future temperature and precipitation projections most often utilize the middle of the road emission scenario (SSP4.5) and the most extreme emission scenario (SSP 8.5). These provide a bracket of the projections that utilize the most likely outcome (SSP 4.5) and the most unlikely outcome (SSP 8.5).

For this study, climate model projections outputs were investigated for the three scenarios: i) historic, ii) SSP 4.5, and iii) SSP 8.5. The historical period is based on daily data from 1950 through 2014, and the SSP periods are based on daily data from 2015 through 2100. The NASA Earth Exchange Global Daily Downscaled Projections (NEX-GDDP-CMIP6) dataset, a gridded daily time-series data, which cover the study area, were extracted, aggregated, and applied for the climate change analysis. The climate model projections were used to analyze precipitation trends, precipitation frequency, and maximum precipitation for the 1-day, 3-day, and annual durations for the area covering the study region.

Results of the analysis are presented in Table E.1 through E.4 and represent the results for the four regions covering the Maryland study regions (Figure E.1). For hydrologic simulation and sensitivity, the ensemble median SSP4.5 climate change adjustments and uncertainty values for temperature and precipitation are recommended. The results are based on an evaluation of the rate of change from the current period through 2100. These values can be applied to a given period (i.e., 2050) by linearly adjusting the climate change factors.

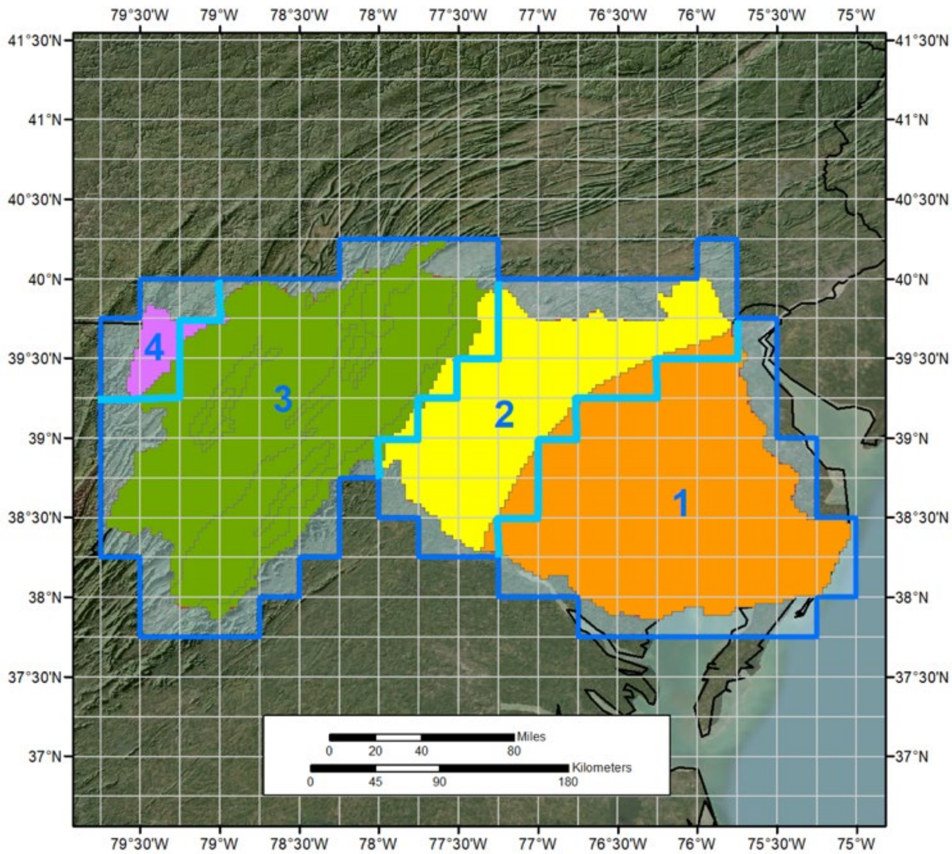

Figure E.1: Climate change regions covering the Maryland PMP study domain.

Table E.1: Climate Change Projections for Region 1 from current climate (1950-2014) through 2100.

Region 1	SSP45				SSP85			
	Mean	**Median**	**10th**	**90th**	**Mean**	**Median**	**10th**	**90th**
Temperature 1-Day; C	**2.2**	**2.1**	1.0	3.2	**5.3**	**5.0**	4.0	7.5
Temperature 1-Day Summer; C	**2.2**	**2.1**	1.0	3.2	**5.3**	**5.0**	4.0	7.5
Temperature 1-Day Winter PF; C	**2.4**	**2.4**	1.6	3.5	**5.0**	**4.9**	3.8	6.3
Precipitation 1-Day PF; %	**-2**	**-5**	-17	16	**3**	**1**	-10	20
Precipitation 1-Day Summer PF; %	**5**	**-1**	-14	21	**9**	**7**	-16	37
Precipitation 1-Day Winter PF; %	**-1**	**-2**	-12	13	**4**	**2**	-11	21
Precipitation 3-Day PF; %	**8**	**4**	-12	26	**13**	**7**	-9	36
Precipitation 3-Day Summer PF; %	**7**	**4**	-13	33	**16**	**21**	-17	53
Precipitation 3-Day Winter PF; %	**9**	**6**	-11	32	**10**	**3**	-5	32
Precipitation Annual PF; %	**12**	**13**	3	19	**13**	**14**	1	25
Moisture Maximization 1-Day, %	**No Change**				**No Change**			
Moisture Maximization 3-Day; %	**No Change**				**Potential Change**			

Table E.2: Climate Change Projections for Region 2 from current climate (1950-2014) through 2100.

Region 2	SSP45				SSP85			
	Mean	**Median**	**10th**	**90th**	**Mean**	**Median**	**10th**	**90th**
Temperature 1-Day; C	**2.4**	**2.3**	1.0	3.3	**5.7**	**5.1**	4.0	8.0
Temperature 1-Day Summer; C	**2.4**	**2.3**	1.0	3.3	**5.7**	**5.1**	4.0	8.0
Temperature 1-Day Winter PF; C	**2.5**	**2.4**	1.5	3.7	**5.3**	**5.3**	4.0	6.5
Precipitation 1-Day PF; %	**9**	**6**	-7	33	**10**	**6**	-10	36
Precipitation 1-Day Summer PF; %	**13**	**10**	-11	44	**9**	**3**	-17	45
Precipitation 1-Day Winter PF; %	**11**	**7**	-4	29	**14**	**13**	-1	32
Precipitation 3-Day PF; %	**12**	**16**	-5	26	**10**	**10**	-11	32
Precipitation 3-Day Summer PF; %	**9**	**3**	-17	45	**7**	**11**	-20	32
Precipitation 3-Day Winter PF; %	**15**	**15**	-5	36	**13**	**15**	-2	31
Precipitation Annual PF; %	**11**	**11**	5	20	**13**	**13**	3	23
Moisture Maximization 1-Day, %	**No Change**				**No Change**			
Moisture Maximization 3-Day; %	**No Change**				**No Change**			

Table E.3: Climate Change Projections for Region 3 from current climate (1950-2014) through 2100.

Region 3	SSP45				SSP85			
	Mean	**Median**	**10th**	**90th**	**Mean**	**Median**	**10th**	**90th**
Temperature 1-Day; C	**2.4**	**2.3**	1.0	3.3	**5.7**	**5.0**	3.8	8.2
Temperature 1-Day Summer; C	**2.4**	**2.3**	1.0	3.3	**5.7**	**5.0**	3.8	8.2
Temperature 1-Day Winter PF; C	**2.3**	**2.2**	1.5	3.6	**5.2**	**5.4**	3.9	6.7
Precipitation 1-Day PF; %	**8**	**6**	-9	28	**11**	**7**	-4	33
Precipitation 1-Day Summer PF; %	**10**	**9**	-10	31	**3**	**3**	-17	22
Precipitation 1-Day Winter PF; %	**10**	**7**	-6	28	**16**	**14**	5	32
Precipitation 3-Day PF; %	**11**	**14**	-10	28	**12**	**8**	-4	32
Precipitation 3-Day Summer PF; %	**7**	**4**	-15	31	**8**	**14**	-15	30
Precipitation 3-Day Winter PF; %	**12**	**12**	-3	28	**14**	**13**	0	30
Precipitation Annual PF; %	**12**	**10**	6	19	**13**	**13**	6	23
Moisture Maximization 1-Day, %	**No Change**				**No Change**			
Moisture Maximization 3-Day; %	**No Change**				**No Change**			

Table E.4: Climate Change Projections for Region 4 from current climate (1950-2014) through 2100.

Region 4	SSP45				SSP85			
	Mean	**Median**	**10th**	**90th**	**Mean**	**Median**	**10th**	**90th**
Temperature 1-Day; C	**2.4**	**2.3**	1.0	3.3	**5.7**	**5.0**	3.8	8.2
Temperature 1-Day Summer; C	**2.4**	**2.3**	1.0	3.3	**5.7**	**5.0**	3.8	8.2
Temperature 1-Day Winter PF; C	**2.3**	**2.2**	1.5	3.6	**5.2**	**5.4**	3.9	6.7
Precipitation 1-Day PF; %	**8**	**10**	-9	28	**12**	**8**	1	33
Precipitation 1-Day Summer PF; %	**10**	**9**	-10	31	**4**	**4**	-12	22
Precipitation 1-Day Winter PF; %	**9**	**7**	-6	28	**16**	**15**	5	32
Precipitation 3-Day PF; %	**12**	**15**	-10	28	**13**	**10**	-2	32
Precipitation 3-Day Summer PF; %	**7**	**4**	-15	31	**8**	**14**	-15	30
Precipitation 3-Day Winter PF; %	**13**	**13**	-3	29	**14**	**13**	0	30
Precipitation Annual PF; %	**11**	**10**	6	19	**13**	**13**	6	23
Moisture Maximization 1-Day, %	**No Change**				**No Change**			
Moisture Maximization 3-Day; %	**No Change**				**No Change**			

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Acronyms and Abbreviations

AEP	Annual Exceedance Probability
AMS	Annual Maximum Series
ARF	Areal Reduction Factor
ARI	Average Recurrence Interval
AWA	Applied Weather Associates
CDF	Cumulative Distribution Function
EVAP	Evaporation
GCM	Global Climate Model or General Circulation Model
GEV	Generalized Extreme Value distribution
GHCN	Global Historical Climatology Network
GHG	Green House Gas
GLO	Generalized Extreme Value distribution
GNO	Generalized Normal distribution
GPA	Generalized Pareto distribution
IPCC	Intergovernmental Panel on Climate Change
L-Cv	L-moment coefficient of L-variation
L-Kurtosis	L-moment ratio of kurtosis
L-Skewness	L-moment ratio of skewness
MAM	Mean Annual Maximum
MAP	Mean Annual Precipitation
NCDC	National Climate Data Center
NCEI	National Centers for Environmental Information
NOAA	National Oceanic and Atmospheric Administration
PE3	Pearson Type III distribution
PF	Precipitation-Frequency
POR	Period of Record
Ppt	Precipitation
Ppt_{adj}	Maximized Precipitation
Ppt_{max}	Largest Thirty Precipitation Events
Ppt_{pmp}	Maximum of Largest Thirty Maximized Precipitation Events
PRISM	Parameter-elevation Regressions on Independent Slopes Model
Press	Surface Pressure
QC	Quality Control
RCP	Representative Concentration Pathway
RGC	Regional Growth Curve
RH	Relative Humidity
SH	Specific Humidity
Srad	Solar Radiation
SSP	Shared Socioeconomic Pathways
Ta	Air Temperature
Td	Dew Point Temperature

1.0 INTRODUCTION

Applied Weather Associates (AWA) examined climate model projections to analyze precipitation trends, precipitation frequency, and maximum precipitation for the 1-day, 3-day, and annual durations for the region covering the Maryland regional study (Figure 1). Three different investigations were completed to evaluate the climate change projections of precipitation through time, each of which provided a different look at the climate change projections. The first method investigated station and climate projection trends using trend analysis methods based on Mann (Mann, 1945) and Hipel and McLeod (2005) utilizing the R-statistical software packages 'Kendall' developed by McLeod (2015). The second method was precipitation frequency analysis based on L-moments methods described in Hosking and Wallis (1997) and utilized the R-statistical software packages 'lmom' and 'lmomRFA' developed by Hosking (Hosking 2015a, and Hosking 2015b). The third method identified the largest precipitation events from the daily climate projections, derived monthly dew point temperature climatologies from the climate model projections and maximized the storm events through storm maximization methods (Rousseau et al., 2014; Kappel et al., 2018; Kappel et al., 2020). In addition, climate change for mean monthly and annual climatologies were derived for precipitation and temperature. It is important to note that the Maryland Department of the Environment – Dam Safety sponsored a statewide Probable Maximum Precipitation study, AWA completed the Probable Maximum Precipitation (PMP) study in 2024 (Kappel et al., 2024).

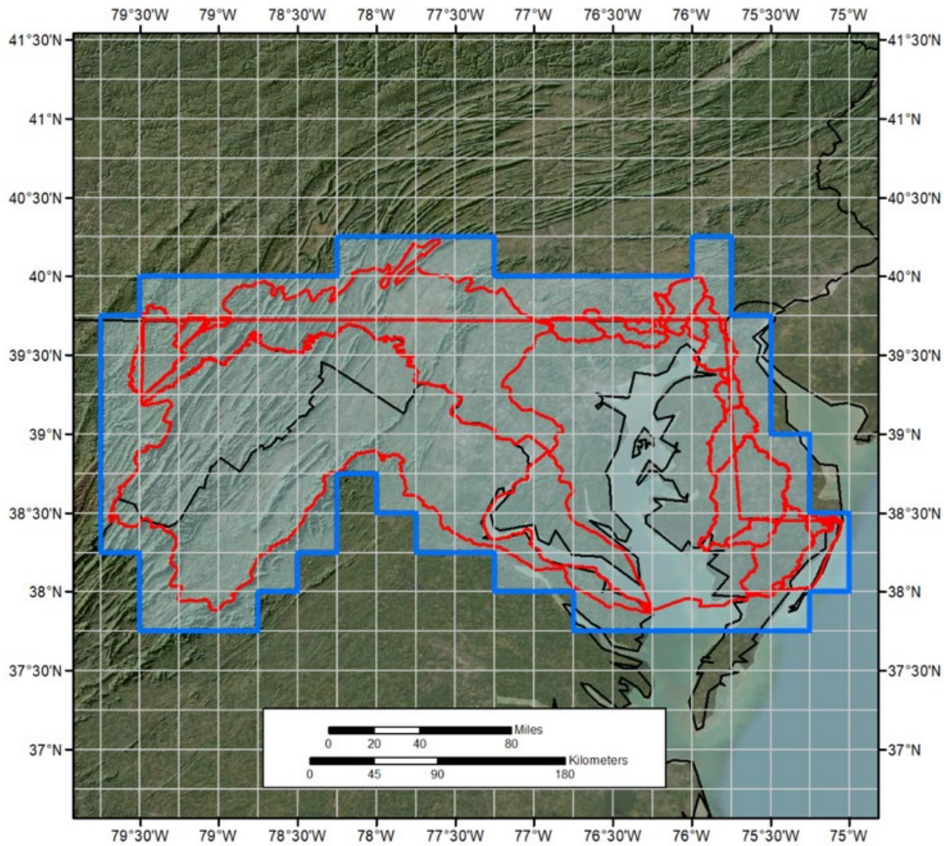

Figure 1: Location of the Maryland study region.

2.0 CLIMATE CHANGE PROJECTION BACKGROUND

Climate is changing, always has been changing, and always will change as long as the energy received from the sun across the Earth's surface and atmosphere is not distributed evenly. Evaluating climate change projections for a given location is important to reduce risk and ensure infrastructure is designed to safely handle potential future changes. Unfortunately, quantification of the amount and rate of change at any given location for any specific meteorological parameter is not explicitly quantifiable and instead has to be modeled based on our incomplete understanding of the Earth's climate system and future estimates of atmospheric composition. Therefore, model projections that utilize our current understanding of the Earth's climate system and how that climate system responds to greenhouse gases are developed. The climate projections are based on our best quantification of physical understanding of numerous atmospheric parameters and how those affect weather and climate through time and space. However, because our quantification of these parameters are incomplete (and at times inaccurate) and because we currently have a limited understanding of the various interactions and feedbacks, the climate projections represent possible outcomes. None of which can be considered truth, but instead should be treated as "what if" scenarios representing possible outcomes.

To better address these significant limitations, numerous iterations and sensitivity analyses for various atmospheric parameters are performed so that a suite of ensembles are produced to represent a wide range of potential outcomes. From this output, inferences can be made, with more confidence given when ensemble outcomes converge on a common projection.

Another layer of uncertainty within the climate change projection process relates to the assumption applied for future emissions scenarios and how those may affect the climate system. Future emissions scenarios have two major areas of uncertainty. First, our assumption that any given emission scenario will occur following a specific path through time is unknown as there are many internal and external factors that can influence emissions produced through time. Second, our understanding and quantification of how the Earth's climate will respond to any given greenhouse gas emission is limited. Both uncertainties introduce errors into the climate projections.

Finally, the Global Climate Models (GCMs) are computationally intensive and are therefore run at low resolution both in time and space. For regions like the Maryland region, the resolution of the GCMs is inadequate to capture the spatial variations. To overcome this, projections from GCMs are downscaled using a statistical process into regional downscaled model projections (RCMs). RCMs are downscaled and are what were utilized for this climate change analysis. Given all the limitations and uncertainties noted above, it is still useful to evaluate RCMs to understand the range of potential outcomes that could occur through time over the basin.

2.1 Global Climate Change Models

GCMs produce realizations of the Earth's climate on a generally coarse scale of around 1000km by 1000km. Because the scale is so coarse, a single GCM grid may cover vastly differing landscape (from very mountainous to flat coastal plains for example) with greatly varying potential for floods, droughts, or other extreme events.

2.2 Regional Downscaled Climate Change Models

RCMs and Empirical Statistical Downscaling applied over limited areas cover a much finer resolution. These are therefore able to capture the spatial and temporal variations related to a site-specific region, such as the Maryland study region. The downscaling methods are driven by GCMs, where the RCM is nested within the overall GCM and utilizes the GCM to set the initial boundary conditions. These are then downscaled using either the statistical methodology or the RCM based on a meteorological model interface. The RCM process can provide projections of future climate conditions on a much smaller scale (e.g., 25km by 25km) supporting more detailed site-specific information allowing for adaptation assessment and planning. An example of different climate model resolutions across the Maryland region are shown in Figure 2.

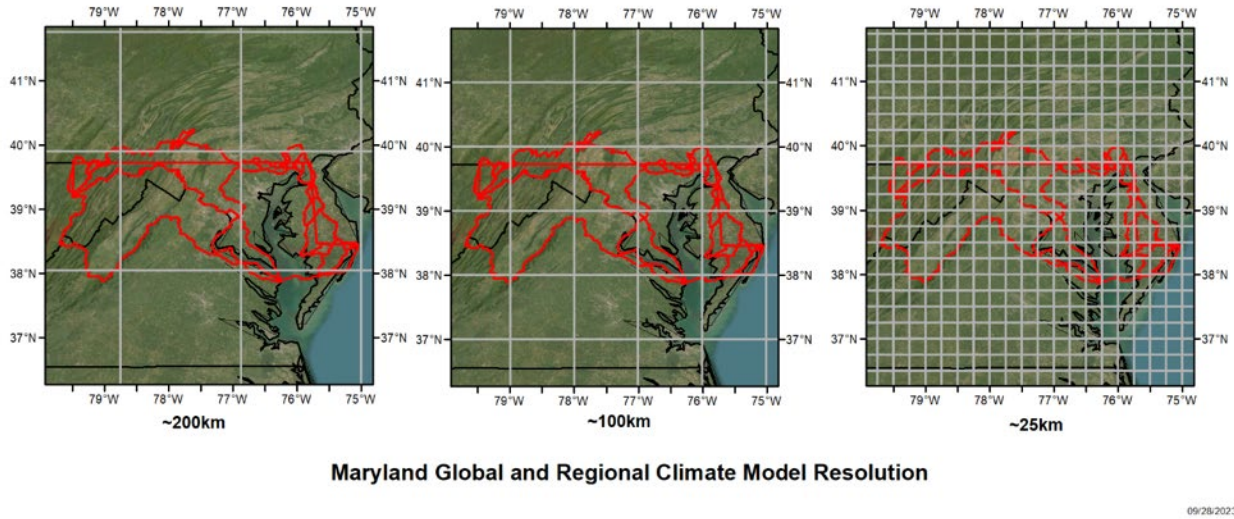

Figure 2: Example of different global and regional climate model resolutions across the Maryland region.

3.0 Climate Change Projection Analysis Methods

The Intergovernmental Panel on Climate Change (IPCC) sixth assessment report (AR6) contains Shared Socioeconomic Pathways (SCPs). SSPs are scenarios of projected socioeconomic global changes up to 2100. They are used to derive greenhouse gas emission scenarios with different climate policies. The SSPs are based on five narratives describing broad socioeconomic trends that could shape future society. These are intended to span the range of plausible futures. They include: a world of sustainability-focused growth and equality (SSP1); a "middle of the road" world where trends broadly follow their historical patterns (SSP2); a fragmented world of "resurgent nationalism" (SSP3); a world of ever-increasing inequality (SSP4); and a world of rapid and unconstrained growth in economic output and energy use (SSP5) (IPCC, 2021). The SSPs investigated; SSP1-1.9, SSP1-2.6, SSP2-4.5, SSP3-7.0, and SSP5-8.5; are labeled after a possible range of greenhouse gas emission scenarios with different climate policies through the year 2100 (Figure 3) (IPCC, 2022). The IPCC AR6 report does not estimate the likelihoods of the climate scenarios (Masson-Delmotte et al., 2021) but Hausfather and Peters (2020) concluded that SSP5-8.5 was highly unlikely, SSP3-7.0 was unlikely, and SSP2-4.5 was likely.

The NASA Earth Exchange Global Daily Downscaled Projections (NEX-GDDP-CMIP6) dataset is comprised of thirty-five global downscaled climate scenarios derived from the GCM runs conducted under the Coupled Model Intercomparison Project Phase 6 (CMIP6) and across two of the four "Tier 1" greenhouse gas emissions scenarios. The CMIP6 GCM runs were developed in support of the Sixth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC AR6) (Thrasher et. al, 2021; Thrasher et. al, 2022). The purpose of this dataset is to provide a set of global, high resolution, bias-corrected climate change projections that can be used to evaluate climate change impacts on processes that are sensitive to finer-scale climate gradients and the effects of local topography on climate conditions.

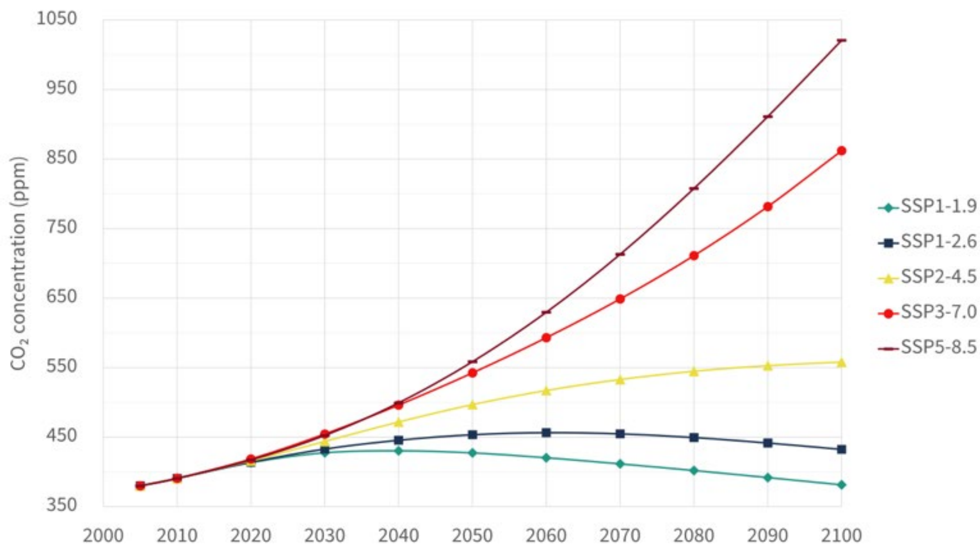

Figure 3: Shared Socioeconomic Pathways (SSP) trajectories. Reproduced from IPCC (2021).

The key climate model parameters used in this analysis were precipitation (Ppt), air temperature (Ta), and dew point temperature (Td). The parameters of relative humidity (RH) and Ta were used to derive the estimates of dew point (Td). The NEX-GDDP-CMIP6 dataset consists of thirty-five models, of these, twenty-six models had the parameters and projections needed for the Maryland climate change analysis (Figure 4). An example of the modeled daily climate projection parameters of Ppt, Ta, and Td are shown in Figure 5 and the grid resolution covering the covering the study region are shown in Figure 6. The climate projections historical period is based on daily data from 1950 through 2014, and the future periods are based on daily data from 2015 through 2100

Model #	MODEL NAME	*Relative Humidity (hurs)* HISTORICAL	SSP45	SSP85	*Precipitation (pr)* HISTORICAL	SSP45	SSP85	*Temperature (tas)* HISTORICAL	SSP45	SSP85
1	ACCESS-CM2	1950-2014	2015-2100	2015-2100	1950-2014	2015-2100	2015-2100	1950-2014	2015-2100	2015-2100
2	ACCESS-ESM1-5	1950-2014	2015-2100	2015-2100	1950-2014	2015-2100	2015-2100	1950-2014	2015-2100	2015-2100
4	CanESM5	1950-2014	2015-2100	2015-2100	1950-2014	2015-2100	2015-2100	1950-2014	2015-2100	2015-2100
5	CESM2-WACCM	1950-2014	2015-2100	2015-2100	1950-2014	2015-2100	2015-2100	1950-2014	2015-2100	2015-2100
6	CESM2	1950-2014	2015-2100	2015-2100	1950-2014	2015-2100	2015-2100	1950-2014	2015-2100	2015-2100
7	CMCC-CM2-SR5	1950-2014	2015-2100	2015-2100	1950-2014	2015-2100	2015-2100	1950-2014	2015-2100	2015-2100
8	CMCC-ESM2	1950-2014	2015-2100	2015-2100	1950-2014	2015-2100	2015-2100	1950-2014	2015-2100	2015-2100
9	CNRM-CM6-1	1950-2014	2015-2100	2015-2100	1950-2014	2015-2100	2015-2100	1950-2014	2015-2100	2015-2100
10	CNRM-ESM2-1	1950-2014	2015-2100	2015-2100	1950-2014	2015-2100	2015-2100	1950-2014	2015-2100	2015-2100
11	EC-Earth3-Veg-LR	1950-2014	2015-2100	2015-2100	1950-2014	2015-2100	2015-2100	1950-2014	2015-2100	2015-2100
12	EC-Earth3	1950-2014	2015-2100	2015-2100	1950-2014	2015-2100	2015-2100	1950-2014	2015-2100	2015-2100
13	FGOALS-g3	1950-2014	2015-2100	2015-2100	1950-2014	2015-2100	2015-2100	1950-2014	2015-2100	2015-2100
14	GFDL-CM4_gr1	1950-2014	2015-2100	2015-2100	1950-2014	2015-2100	2015-2100	1950-2014	2015-2100	2015-2100
15	GFDL-CM4_gr2	1950-2014	2015-2100	2015-2100	1950-2014	2015-2100	2015-2100	1950-2014	2015-2100	2015-2100
16	GFDL-ESM4	1950-2014	2015-2100	2015-2100	1950-2014	2015-2100	2015-2100	1950-2014	2015-2100	2015-2100
17	GISS-E2-1-G	1950-2014	2015-2100	2015-2100	1950-2014	2015-2100	2015-2100	1950-2014	2015-2100	2015-2100
21	INM-CM4-8	1950-2014	2015-2100	2015-2100	1950-2014	2015-2100	2015-2100	1950-2014	2015-2100	2015-2100
22	INM-CM5-0	1950-2014	2015-2100	2015-2100	1950-2014	2015-2100	2015-2100	1950-2014	2015-2100	2015-2100
23	IPSL-CM6A-LR	1950-2014	2015-2100	2015-2100	1950-2014	2015-2100	2015-2100	1950-2014	2015-2100	2015-2100
26	MIROC-ES2L	1950-2014	2015-2100	2015-2100	1950-2014	2015-2100	2015-2100	1950-2014	2015-2100	2015-2100
27	MIROC6	1950-2014	2015-2100	2015-2100	1950-2014	2015-2100	2015-2100	1950-2014	2015-2100	2015-2100
28	MPI-ESM1-2-HR	1950-2014	2015-2100	2015-2100	1950-2014	2015-2100	2015-2100	1950-2014	2015-2100	2015-2100
29	MPI-ESM1-2-LR	1950-2014	2015-2100	2015-2100	1950-2014	2015-2100	2015-2100	1950-2014	2015-2100	2015-2100
30	MRI-ESM2-0	1950-2014	2015-2100	2015-2100	1950-2014	2015-2100	2015-2100	1950-2014	2015-2100	2015-2100
33	NorESM2-MM	1950-2014	2015-2100	2015-2100	1950-2014	2015-2100	2015-2100	1950-2014	2015-2100	2015-2100
34	TaiESM1	1950-2014	2015-2100	2015-2100	1950-2014	2015-2100	2015-2100	1950-2014	2015-2100	2015-2100

Figure 4: Subset of 26 CMIP6 models, the parameters, and projections used for the climate change analysis.

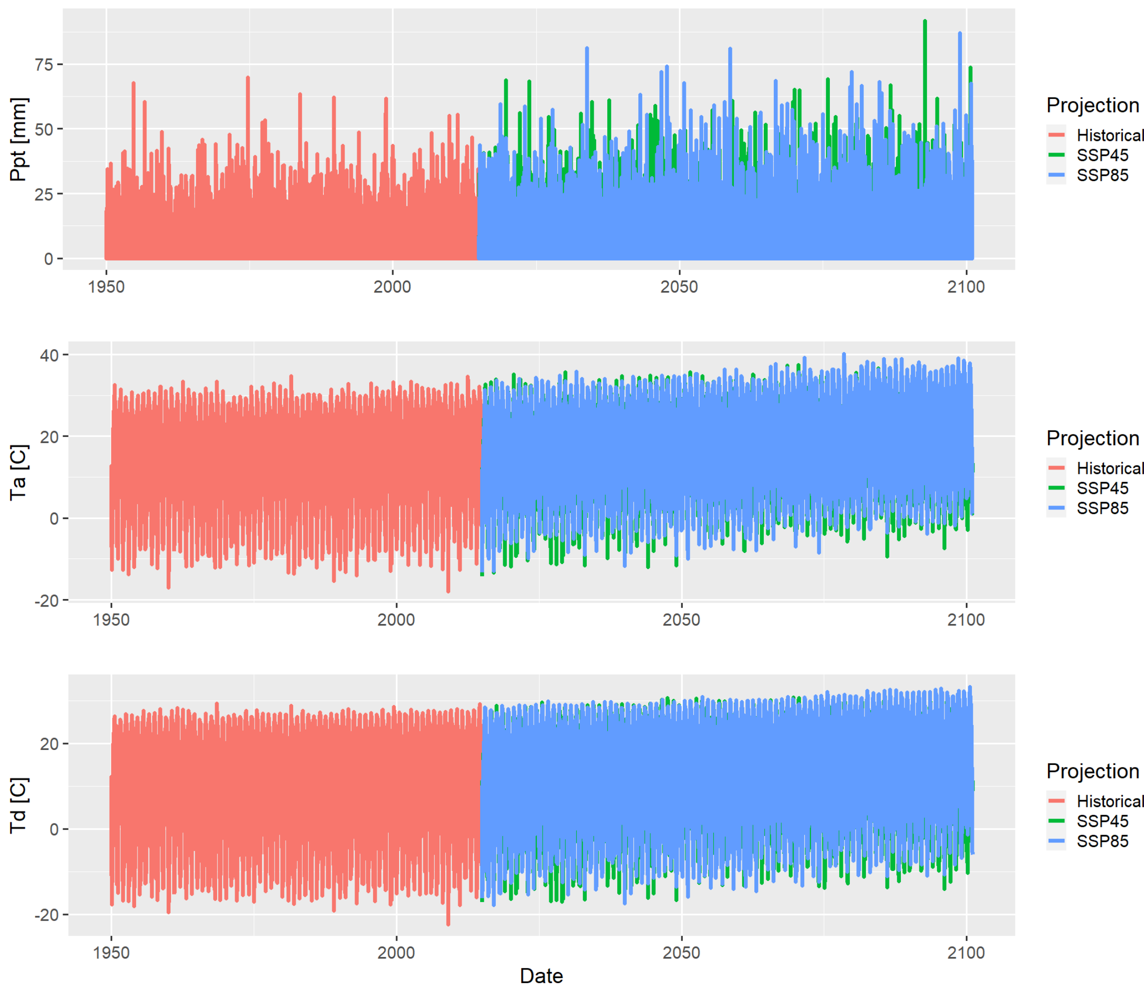

Figure 5: Climate projection parameters of Ppt, Ta, and Td from Model 1 (ACCESS-CM2)

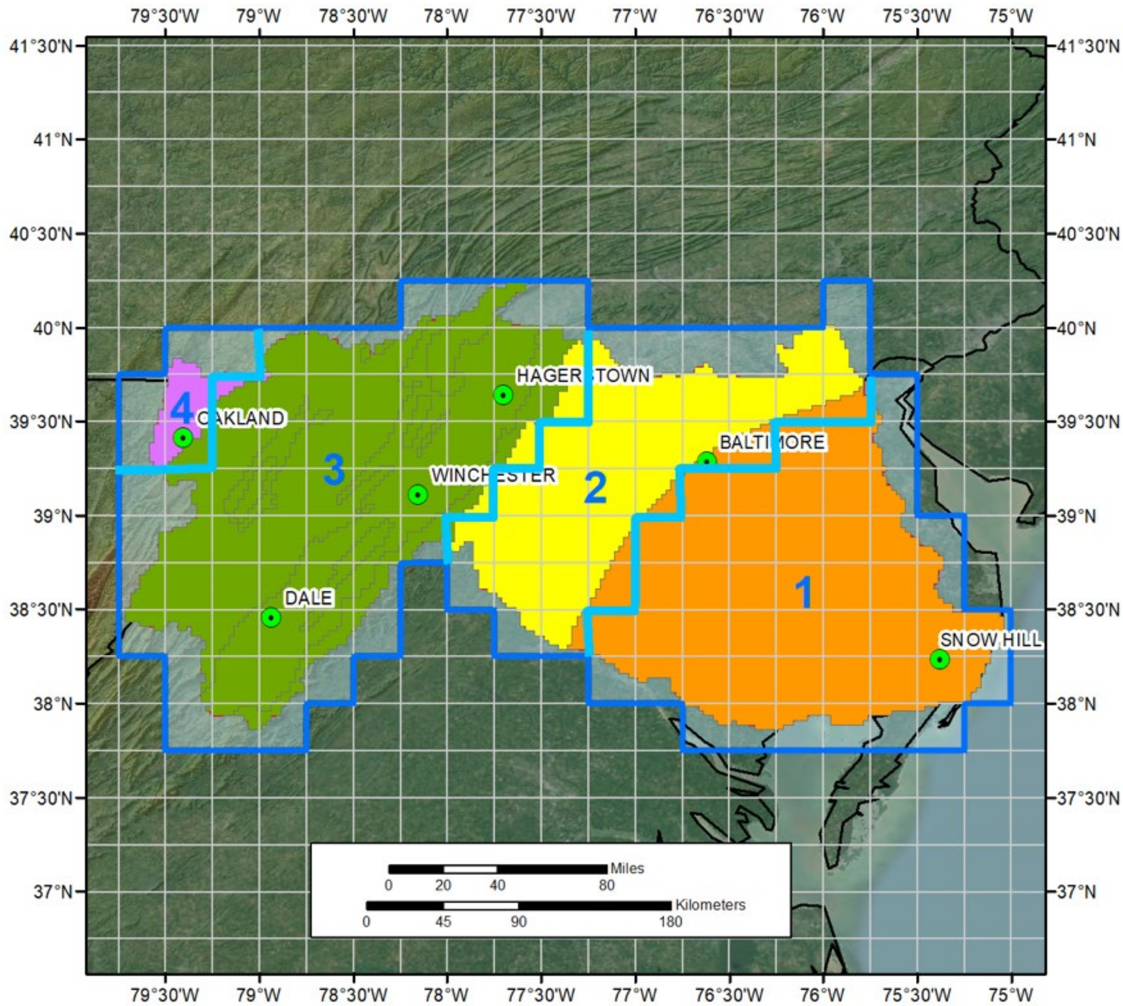

Figure 6: CMIP6 climate model grids covering Maryland. Orange, yellow, green, and purple regions represent the climate grids extracted for each domain, the grey lines represent the CMIP6 grid resolution.

3.1 Trend Analysis

Mann-Kendall trend analysis (Mann, 1945; Hipel and McLeod, 2005) was performed on six climate stations located near the mine site for 1-day, 3-day, and annual durations. Results of these station-based trend analysis are shown in Table 1. The climate station trend results were used to assess the historic model projections.

Table 1: Climate stations used for trend analysis. Trend analyses are evaluated at the 0.05 significant level.

	Precipitation 1-day	Precipitation 3-day	Precipitation Annual	Temperature 1-day
BALTIMORE, MD	no trend	no trend	no trend	increase
DALE, VA	no trend	no trend	no trend	no trend
OAKLAND, MD	no trend	no trend	no trend	no trend
SNOW HILL, MD	no trend	no trend	no trend	no trend
HAGERSTOWN, MD	no trend	no trend	increase	no trend
WINCHESTER, VA	increase	no trend	no trend	decrease

In addition, Mann-Kendall trend analysis (Mann, 1945; Hipel and McLeod, 2005) was performed on twenty-six climate model projections using the three scenarios (historic, SSP 4.5, SSP 8.5) for durations of 1-day, 3-day, and annual. Figure 7 shows an example of the results for Model 1 1-day trend analysis for the historic, SSP 4.5, and SSP 8.5 projections. Results for Region 1 climate model projection trend analyses are summarized in Table 2. Detailed results are included in Appendix B.

Table 2: Summary of climate projection trend analysis results for Region 1. Trend analyses are evaluated at the 0.05 significant level.

	Precipitation 1-day	Precipitation 3-day	Precipitation Annual	Temperature 1-day
Historic	23 – no trend 2 – increase 1 – decrease	25 – no trend 0 – increase 1 – decrease	24 – no trend 2 – increase 0 – decrease	8 – no trend 18 – increase 0 – decrease
SSP 4.5	18 – no trend 8 – increase 0 – decrease	21 – no trend 5 – increase 0 – decrease	21 – no trend 5 – increase 0 – decrease	2 – no trend 24 – increase 0 – decrease
SSP 8.5	14 – no trend 12 – increase 0 – decrease	18 – no trend 8 – increase 0 – decrease	11 – no trend 15 – increase 0 – decrease	0 – no trend 26 – increase 0 – decrease

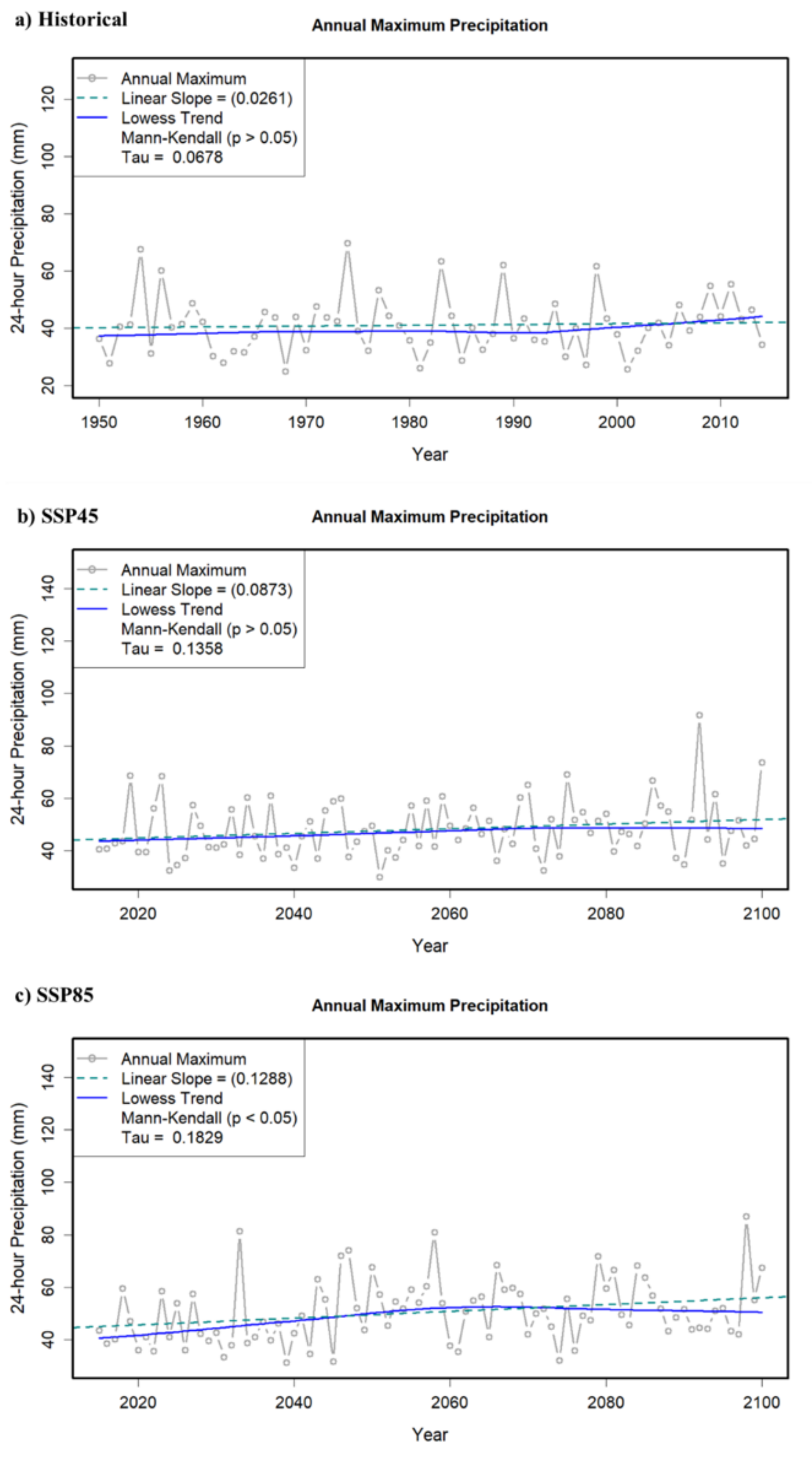

Figure 7: Example results for 1-day trend analysis for climate projection from Model 1: a) no trend for historical period, b) no trend for SSP 4.5 scenario, and c) increasing trend for SSP8.5 scenario. Blue line is Lowess trend line, dashed line is a linear trend, and Mann-Kendall p-value and Tau statistics shown in legend.

3.2 Precipitation Frequency Analysis

The precipitation frequency analysis method utilized L-moment statistics instead of product moment statistics, which decrease the uncertainty of rainfall frequency estimates for more rare events and dampens the influence of outlier precipitation amounts from extreme storms (Hosking and Wallis, 1997). Methods to account for non-stationarity in projections were not addressed, the projections were applied assuming stationarity. For the precipitation frequency analysis, AWA utilized the daily climate model projections to perform frequency analysis on the 1-day, 3-day, and annual durations.

AWA evaluates the climate change projections for the entire period available, for CMIP6 that ranges from 2015 through 2100. The changes through time reflect the entire period. However, other evaluation periods can be considered and may change the rate of change through time. For example, one may evaluate the projections through the year 2050 and then do a separate analysis for the years 2050-2100. This may result in slightly different outcomes depending on the climate change projections amount of change through time. For example, some climate change models may show minimal changes for the period 2005 through 2050, then an increasing change from 2051 through 2100. Regardless of the process utilized to evaluate the climate change projections and the increments evaluated, it is recommended that each iteration of the IPCC climate change outputs be evaluated against the previous work to check trends and changes.

AWA identified, extracted, and quality controlled maximum daily precipitation projections for the twenty-six models and three projection scenarios. The Annual Maximum Series (AMS) were then subjected to the frequency analysis methods (Hosking and Wallis, 1997). L-moment statistics were computed for annual maximum data for each projection and duration. Goodness of fit measures were evaluated for five candidate distributions: generalized logistic (GLO), generalized extreme value (GEV), generalized normal (GNO), Pearson type III (PE3), and generalized Pareto (GPA). An L-Moment Ratio Diagram was prepared based on L-Skewness and L-Kurtosis pairs for each duration (Figure 8). The weighted-average L-Skewness and L-Kurtosis pairing were found to be near the GEV distribution for all projections.

The GEV distribution was selected because: i) This is the most common distribution used for precipitation frequency studies (e.g., NOAA Atlas 14, Perica, 2015) ii) the GEV was identified on both the 1-day, 3-day, and Annual goodness-of-fit measures, and iii) using the same distribution ensures a more direct comparison to more rare values of the frequency curve. The GEV is a general mathematical form that incorporates Gumbel's Extreme Value (EV) type I, II and III distributions for maxima. The parameters of the GEV distribution are the ξ (location), α (scale), and k (shape). The Gumbel EV type I distribution is obtained when $k = 0$. For $k > 0$, the distribution has a finite upper bound at $\xi + \alpha / k$ and corresponds to the EV type III distribution for maxima that are bounded above. For $k < 0$, this corresponds to the Gumbel EV type II distribution.

The uncertainty analysis for deriving the frequency curve and uncertainty bounds were conducted as follows. The frequency distributions were randomly permuted, and data were simulated from the selected frequency distribution. The procedure is described in Hosking and Wallis (1997) and Hosking (2015b), except that the permutation of frequency distributions is a later modification, intended to give more realistic sets of simulated data (Hosking, 2015b). From each permutation the sample mean values and estimates of the quantiles of the regional growth curve, for nonexceedance probabilities are saved. From the simulated values, for each quantile specified the relative root mean square error (relative RMSE) is computed as in Hosking and Wallis (1997). The error bounds are sample quantiles of the ratio of the estimated regional growth curve to the true at-site growth curve of the ratio of the estimated to the true quantiles at individual sites (Hosking, 2015b).

In order to separate Summer season and Winter season precipitation events that are controlling of the yearly precipitation regime in the Maryland region, the 1-day and 3-day annual maximum were also extracted for Summer season (May - October) and for the Winter season (November – April). The summer and winter AMS data were used to perform L-moment frequency analysis methods as described above. Comparisons of percent change were made among model projections for 10-year through 1,000-year recurrence intervals, beyond this the uncertainty in probability distributions estimates is large. Figure 8 shows an example of the results Model 1 1-day precipitation frequency analysis for All season (mixed storm distribution), Summer/Monsoon season, and Winter season for the historic, SSP 4.5, and SSP 8.5 projections. Full results of frequency analysis are included in Appendix B.

***** 1-Day Precipitation**

	10yr	50yr	100yr	500yr	1000yr	Pct Change					Average
Historical	54.7	67.3	72.4	83.9	88.7	-	-	-	-	-	
SSP45	62.6	76.6	82.5	96.0	101.8	14%	14%	14%	14%	15%	**14%**
SSP85	66.8	81.1	86.9	99.5	104.6	22%	21%	20%	19%	18%	**20%**

***** 1-Day Summer**

	10yr	50yr	100yr	500yr	1000yr	Pct Change					Average
Historical	41.0	63.2	75.9	116.0	139.1	-	-	-	-	-	
SSP45	50.1	77.2	92.3	139.0	165.4	22%	22%	22%	20%	19%	**21%**
SSP85	47.5	61.0	66.5	79.1	84.4	16%	-4%	-12%	-32%	-39%	**-14%**

***** 1-Day Winter**

	10yr	50yr	100yr	500yr	1000yr	Pct Change					Average
Historical	52.3	64.3	69.2	80.1	84.7	-	-	-	-	-	
SSP45	57.3	67.5	71.6	80.4	84.0	10%	5%	3%	0%	-1%	**3%**
SSP85	66.2	81.8	88.2	102.7	108.8	27%	27%	28%	28%	28%	**28%**

Figure 8: Example results for 1-day precipitation frequency analysis for climate projection from Model 1.

3.3 Uncertainty

Measurement, modeling, and simulation of many meteorologic components can be highly uncertain, the main reason being the fundamental dynamics of many processes cannot be measured and modeled accurately (Kampf et al., 2020). Most meteorologic processes are not observed in detail, consequently accurate mathematical representation of the variables spatial and temporal processes, model initial boundary layer conditions, and physical processes, cannot be represented accurately. Mantovan and Tondini (2006) have identified sources of water balance uncertainties as: (i) data uncertainty, (ii) model parameter uncertainty, (iii) model structure uncertainty, and (iv) natural uncertainty.

3.3.1 Data Uncertainty

The performance of models is mainly affected by data uncertainty. This uncertainty arises from errors in the observed data, particularly data used for model calibration. The errors may be linked to the quality of the data which depends on the type and conditions of measuring instruments as well as data handling and processing. Precipitation and streamflow are usually the major sources of input and output data that are used to calibrate and evaluate model uncertainty with the spatial and temporal precipitation uncertainty being large.

3.3.2 Model Parameter Uncertainty

Model parameter uncertainty is also known as model specification uncertainty. This relates to the inability to converge to a single best parameter set using available data, which leads to parameter identifiability problems (Beven, 2001; Wagener et al., 2004). The parameters are optimized so that the model results are as good as possible (Beven, 2001; Scharffenberg et al., 2018). Uncertainty then depends on how parameters are optimized (peak flow, volume, residuals) and results are applied (Scharffenberg et al., 2018; Pokorny et al., 2021).

3.3.3 Model Structure Uncertainty

Model structure uncertainty is introduced through simplifications and/or inadequacies in the representation of physical processes in a given model. It also originates from inappropriate assumptions within the modelling procedure, inappropriate mathematical description of these processes (Beven, 2001), and the scale at which processes are represented in the model (Heuvelink, 1998; Blöschl, 1999; Koren et al., 1999). However, no matter how exact the model is calibrated, there always exists discrepancy between model outcome and observed data (Chiang et al., 2007; Beven, 2006).

3.3.4 Natural Uncertainty

Natural uncertainty arises due to the randomness of natural processes (Beven, 2001). This uncertainty can be linked to data uncertainty, whereby the quality and type of data plays a significant role in determining the amount of uncertainty. For example, the spatial and temporal randomness of rainfall can somewhat be represented explicitly when using good rain gauge networks and radar rainfall data (Segond, 2006). In addition, scaling issues, spatial representativity and interpolation methods are typically represented within natural uncertainty (Heuvelink, 1998; Blöschl, 1999).

For this study, the meaning of "within uncertainty" is considered to be within +/-20 percent and was based on several factors. This range is based on AWA's extensive professional experience evaluating each of these factors below and how they relate to the PMP calculations:

- Multiple sources of uncertainty and varying ranges of uncertainty inherent in the PMP development process and inputs
    - Gauge/Observed Precipitation
        - Point measurement 5 to 15% percent for long-term series, and as high as 75% for individual storm events
    - Frequency Analysis

        - NOAA Atlas 14 Volume 1 24-hour 100-year error bounds are approximately +/-18% (Bonin et al., 2011)
    - Climate Projections
        - Projection uncertainty for induvial regional model methods can be quite large 20 to >50% (Lehner et al., 2020)
    - Selection of the storm representative value used in the In-place Maximization Factor calculations
        - Range between 5 and 30%, with an average around 20%

4.0 RESULTS OF ANALYSIS

The modeled trends and estimated precipitation frequency results have a large variability that can be attributed to the uncertainty inherent with GCM and RCM projections. The different climate models used for the Maryland region are subject to significant components of future climate uncertainty in climate models and the uncertainty is manifested by the range of climate futures indicated by the CMIP6 ensemble of projections (McSweeney and Jones, 2016; Masson-Delmotte et al., 2021).

The Region 1 median of the 26 models project an increase in mean annual temperature (2.4 C and 3.3 C) and annual precipitation (9% and 10%). Temperature, in regard to daily maximum (frequency based) and monthly averages show an increase by 2100 for both the SSP 4.5 and SSP 8.5 projections (Figure 9 and Figure 10). Numeric values representing the change in temperature are shown in Table 3 and Table 5 under application of results. Monthly climatologies for temperature and precipitation are shown in Figure 10 and Figure 11, numeric values representing the change in temperature and precipitation are shown in Table 3 and Table 6 under application of results.

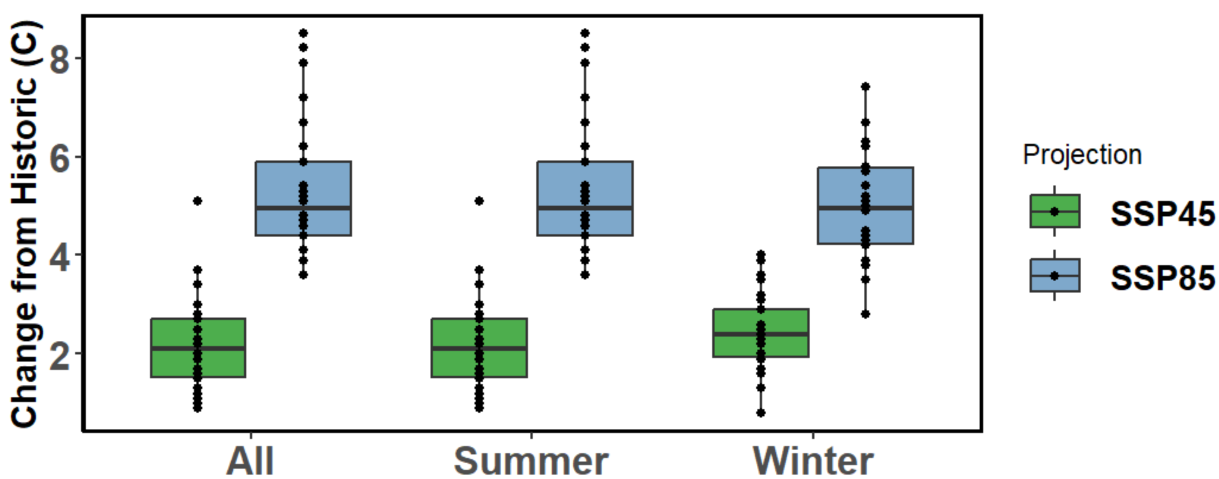

Figure 9: Change in daily maximum temperatures from current climate conditions for Region 1. Results are based on annual maximum frequency analysis.

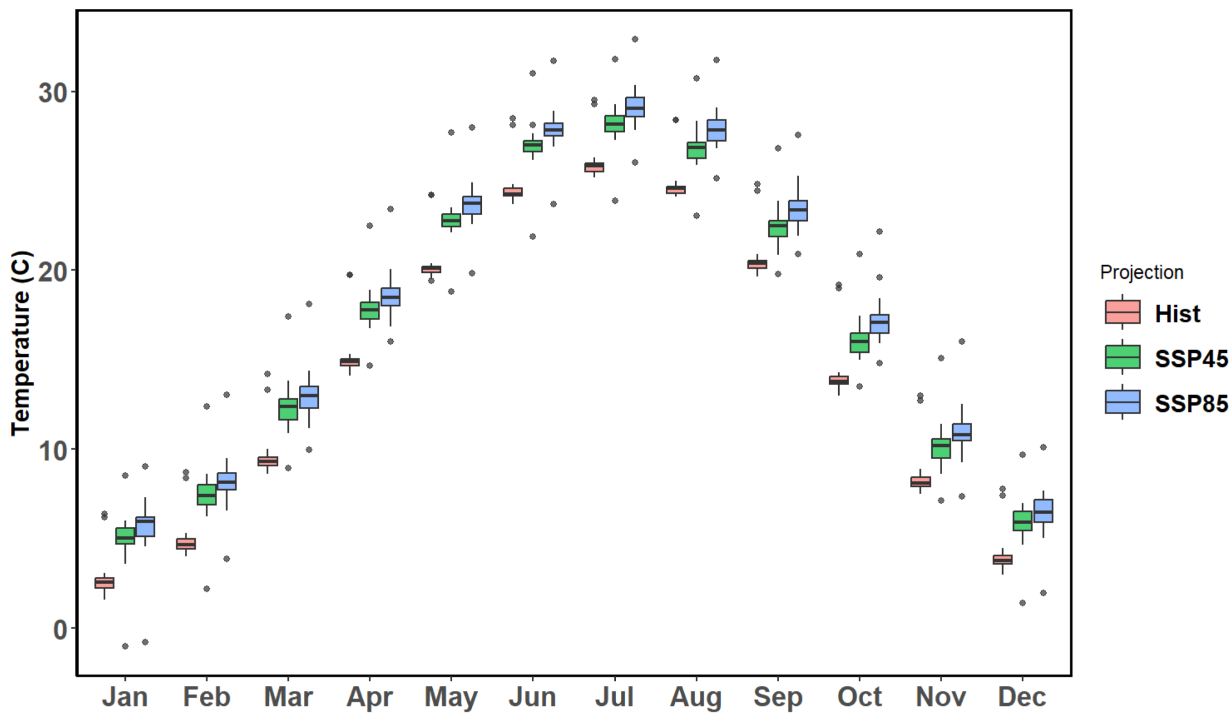

Figure 10: Monthly temperature normal compared to climate change temperature for Region 1. Results are based on daily normal calculations.

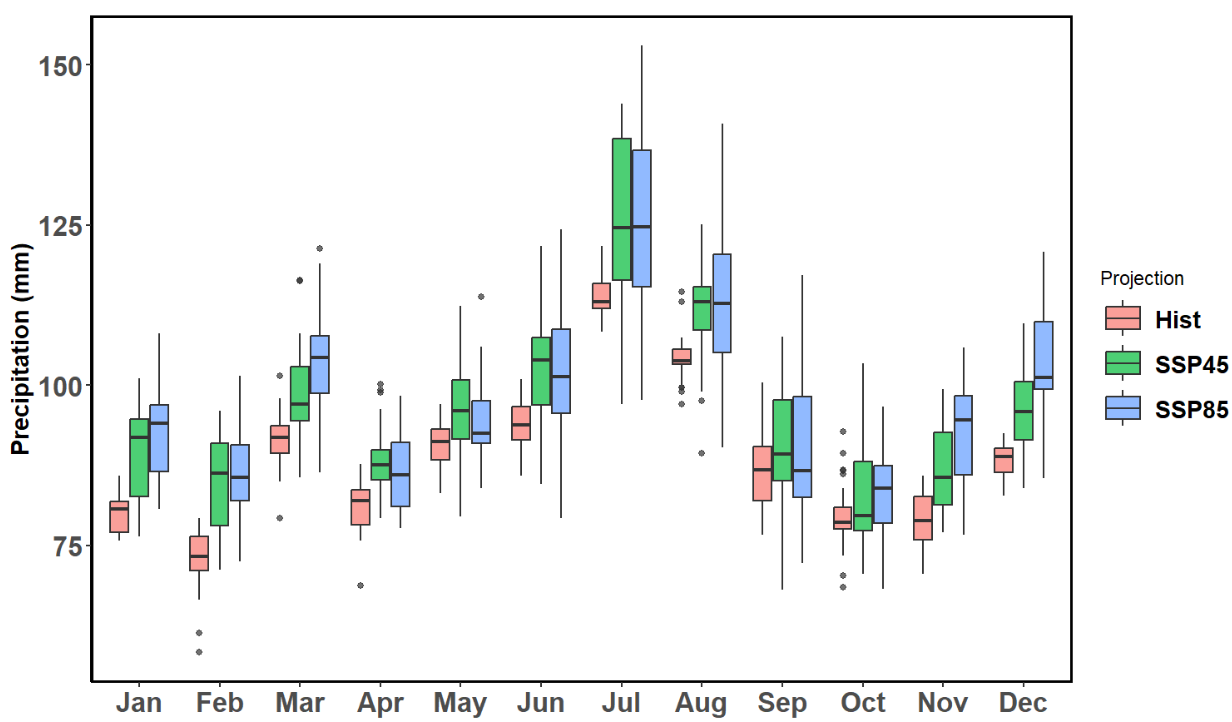

Figure 11: Monthly precipitation normal compared to climate change precipitation for Region 1. Results are based on daily normal calculations.

Precipitation frequency analysis results are summarized for 1-day, 3-day, and annual durations split by All season, Summer season and Winter season (Figure 12). Results indicate a broad range of change with the largest change for 1-day, 3-day, and annual durations, numeric values representing the change in precipitation are shown in Table 3.

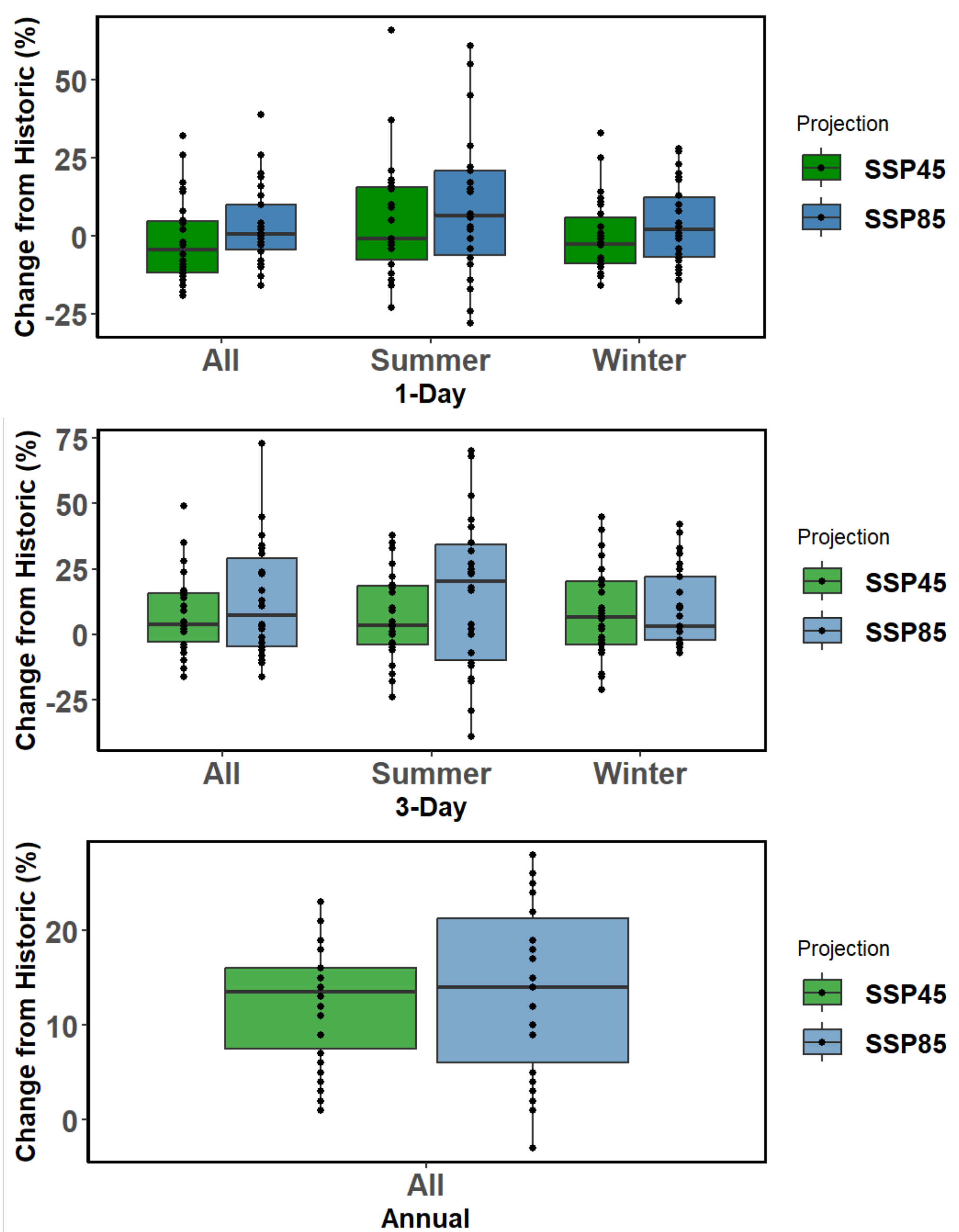

Figure 12: Change in maximum precipitation from current climate conditions for 1-day, 3-day, and annual durations for Region 1. Results are based on annual maximum frequency analysis. Note, the AMS frequency approach shows no change in annual precipitation, this is similar compared results based on the mean annual climatology method.

Results indicate no change in 1-day, 3-day, and annual precipitation (within +/-20%), and an increase in temperature in the future. The most likely outcome regarding precipitation over the basin in the climate change projections is that the mean annual precipitation and 1-day and 3-day precipitation extremes will stay the same compared to the current climate. Importantly, the climate change projections show that individual extreme events that are utilized for PMP development will stay within the range of uncertainty currently inherent in the PMP depths.

This follows expected trends in the region under a warming climate scenario. In this case, more moisture would be available from an overall perspective, and would likely affect some of the precipitation processes, but this would likely be counteracted by other processes that are required to produce precipitation at various timescales and spatial extents (Kappel et al., 2020). This is reflected in Table 3 where the SSP 4.5 and SSP 8.5 emission scenarios. This is likely a reflection of the variance in atmospheric processes that convert moisture in the atmosphere to rainfall on the ground and other factors not fully understood or quantified. These create both positive and negative feedbacks where atmospheric instability at the most extreme levels are lessened in a warming environment because the thermal contrast between airmass is lessened.

5.0 APPLICATION OF RESULTS

For hydrologic simulation and sensitivity, AWA recommends the ensemble median SSP 4.5 climate change adjustments and uncertainty values for temperature and precipitation (Table 3, Table 5, Table 6). These are based on an evaluation of rate of change from the current period through 2100 of each of the projections and taking a median of the outcomes. These values can be applied to a given period (i.e., 2050) by linearly adjusting the climate change factors. Table 4 illustrates how the recommended SSP 4.5 precipitation climate change adjustments can be scaled the linear from 2100 to 2050. Note that the median change are within the envelopment that is part of the PMP depths.

Table 3: Climate Change Projections from current climate (1950-2005) through 2100 for Region 1.

	SSP45				SSP85			
	Mean	**Median**	**10th**	**90th**	**Mean**	**Median**	**10th**	**90th**
Temperature 1-Day; C	**2.2**	**2.1**	1.0	3.2	**5.3**	**5.0**	4.0	7.5
Temperature 1-Day Summer; C	**2.2**	**2.1**	1.0	3.2	**5.3**	**5.0**	4.0	7.5
Temperature 1-Day Winter PF; C	**2.4**	**2.4**	1.6	3.5	**5.0**	**4.9**	3.8	6.3
Precipitation 1-Day PF; %	**-2**	**-5**	-17	16	**3**	**1**	-10	20
Precipitation 1-Day Summer PF; %	**5**	**-1**	-14	21	**9**	**7**	-16	37
Precipitation 1-Day Winter PF; %	**-1**	**-2**	-12	13	**4**	**2**	-11	21
Precipitation 3-Day PF; %	**8**	**4**	-12	26	**13**	**7**	-9	36
Precipitation 3-Day Summer PF; %	**7**	**4**	-13	33	**16**	**21**	-17	53
Precipitation 3-Day Winter PF; %	**9**	**6**	-11	32	**10**	**3**	-5	32
Precipitation Annual PF; %	**12**	**13**	3	19	**13**	**14**	1	25
1-Day Moisture Maximization; %	**No Change**				**No Change**			
3-Day Moisture Maximization; %	**No Change**				**Potential Change**			

* Climate Change Projections from 2005 through 2100
\+ Note, SSP8.5 represent the most extreme, unlikely climate projection scenarios

Table 4: Recommended SSP 4.5 climate change adjustments (%) for 1-day and 3-day precipitation scaled from 2100 to 2050 for Region 1.

	2050	2100
1-Day Summer PF; %	0	-1
1-Day Winter PF; %	-1	-2
3-Day Summer PF; %	2	4
3-Day Winter PF; %	4	6

Table 5: Monthly temperature (C) for current climate from 2005 through 2100 for Region 1.

	Historical		SSP45		SSP85		Mean Delta		Median Delta	
	Mean	Median	Mean	Median	Mean	Median	SSP45	SSP85	SSP45	SSP85
January	2.7	2.6	4.9	5.1	5.6	6.0	***2.2***	***2.9***	***2.5***	***3.4***
February	5.0	4.7	7.4	7.4	8.2	8.2	***2.4***	***3.2***	***2.7***	***3.5***
March	9.6	9.3	12.4	12.4	13.0	13.0	***2.8***	***3.4***	***3.1***	***3.7***
April	15.2	14.9	17.8	17.8	18.6	18.5	***2.6***	***3.4***	***2.9***	***3.6***
May	20.3	20.1	22.8	22.8	23.7	23.7	***2.5***	***3.4***	***2.7***	***3.6***
June	24.6	24.3	26.9	27.0	27.8	27.9	***2.3***	***3.3***	***2.8***	***3.6***
July	26.1	25.9	28.1	28.2	29.1	29.1	***2.1***	***3.1***	***2.3***	***3.2***
August	24.8	24.6	26.8	26.9	27.9	27.8	***2.0***	***3.0***	***2.3***	***3.2***
September	20.6	20.4	22.4	22.5	23.5	23.4	***1.8***	***2.9***	***2.1***	***3.0***
October	14.2	13.8	16.1	16.0	17.2	17.1	***1.9***	***3.0***	***2.2***	***3.3***
November	8.5	8.1	10.1	10.2	11.0	10.8	***1.7***	***2.5***	***2.1***	***2.7***
December	4.0	3.8	5.9	5.9	6.5	6.5	***1.8***	***2.4***	***2.1***	***2.7***

Table 6: Monthly precipitation (mm) for current climate from 2005 through 2100 for Region 1.

	Historical		SSP45		SSP85		Mean Delta		Median Delta	
	Mean	Median	Mean	Median	Mean	Median	SSP45	SSP85	SSP45	SSP85
January	80.0	80.7	89.4	91.9	93.4	94.1	***1.12***	***1.14***	***1.14***	***1.17***
February	72.9	73.3	84.4	86.3	85.9	85.7	***1.16***	***1.18***	***1.18***	***1.17***
March	91.5	91.8	98.9	97.0	103.7	104.4	***1.08***	***1.06***	***1.06***	***1.14***
April	80.8	82.0	88.4	87.6	86.6	86.0	***1.09***	***1.07***	***1.07***	***1.05***
May	90.9	91.2	95.9	96.1	94.6	92.5	***1.06***	***1.05***	***1.05***	***1.01***
June	94.0	93.8	103.0	103.9	101.7	101.3	***1.09***	***1.11***	***1.11***	***1.08***
July	114.1	113.0	124.8	124.6	125.5	124.8	***1.09***	***1.10***	***1.10***	***1.10***
August	104.2	103.9	111.3	113.0	112.5	112.8	***1.07***	***1.09***	***1.09***	***1.09***
September	86.9	86.9	90.8	89.2	90.3	86.7	***1.04***	***1.03***	***1.03***	***1.00***
October	79.5	78.6	81.9	79.7	83.3	83.9	***1.03***	***1.01***	***1.01***	***1.07***
November	79.0	78.9	86.9	85.6	92.3	94.6	***1.10***	***1.09***	***1.09***	***1.20***
December	88.3	88.9	95.8	95.9	103.3	101.2	***1.09***	***1.08***	***1.08***	***1.14***

5.1 Application of Results for Regions 1 through 4

AWA examined climate model projections to analyze precipitation and temperature for four regions covering Maryland (Figure 6). Results discussed in Section 5.0 represent Region 1, the north-central Maryland location. The results for all four regions are provided in digital spreadsheets Appendix A and Digital Files Appendix B and shown in Table 7 through Table 10.

Table 7: Climate Change Projections for Region 1 from current climate (1950-2014) through 2100.

Region 1	SSP45				SSP85			
	Mean	**Median**	**10th**	**90th**	**Mean**	**Median**	**10th**	**90th**
Temperature 1-Day; C	**2.2**	**2.1**	1.0	3.2	**5.3**	**5.0**	4.0	7.5
Temperature 1-Day Summer; C	**2.2**	**2.1**	1.0	3.2	**5.3**	**5.0**	4.0	7.5
Temperature 1-Day Winter PF; C	**2.4**	**2.4**	1.6	3.5	**5.0**	**4.9**	3.8	6.3
Precipitation 1-Day PF; %	**-2**	**-5**	-17	16	**3**	**1**	-10	20
Precipitation 1-Day Summer PF; %	**5**	**-1**	-14	21	**9**	**7**	-16	37
Precipitation 1-Day Winter PF; %	**-1**	**-2**	-12	13	**4**	**2**	-11	21
Precipitation 3-Day PF; %	**8**	**4**	-12	26	**13**	**7**	-9	36
Precipitation 3-Day Summer PF; %	**7**	**4**	-13	33	**16**	**21**	-17	53
Precipitation 3-Day Winter PF; %	**9**	**6**	-11	32	**10**	**3**	-5	32
Precipitation Annual PF; %	**12**	**13**	3	19	**13**	**14**	1	25
Moisture Maximization 1-Day, %	**No Change**				**No Change**			
Moisture Maximization 3-Day; %	**No Change**				**Potential Change**			

Table 8: Climate Change Projections for Region 2 from current climate (1950-2014) through 2100.

Region 2	SSP45				SSP85			
	Mean	**Median**	**10th**	**90th**	**Mean**	**Median**	**10th**	**90th**
Temperature 1-Day; C	**2.4**	**2.3**	1.0	3.3	**5.7**	**5.1**	4.0	8.0
Temperature 1-Day Summer; C	**2.4**	**2.3**	1.0	3.3	**5.7**	**5.1**	4.0	8.0
Temperature 1-Day Winter PF; C	**2.5**	**2.4**	1.5	3.7	**5.3**	**5.3**	4.0	6.5
Precipitation 1-Day PF; %	**9**	**6**	-7	33	**10**	**6**	-10	36
Precipitation 1-Day Summer PF; %	**13**	**10**	-11	44	**9**	**3**	-17	45
Precipitation 1-Day Winter PF; %	**11**	**7**	-4	29	**14**	**13**	-1	32
Precipitation 3-Day PF; %	**12**	**16**	-5	26	**10**	**10**	-11	32
Precipitation 3-Day Summer PF; %	**9**	**3**	-17	45	**7**	**11**	-20	32
Precipitation 3-Day Winter PF; %	**15**	**15**	-5	36	**13**	**15**	-2	31
Precipitation Annual PF; %	**11**	**11**	5	20	**13**	**13**	3	23
Moisture Maximization 1-Day, %	**No Change**				**No Change**			
Moisture Maximization 3-Day; %	**No Change**				**No Change**			

Table 9: Climate Change Projections for Region 3 from current climate (1950-2014) through 2100.

Region 3	SSP45				SSP85			
	Mean	Median	10th	90th	Mean	Median	10th	90th
Temperature 1-Day; C	**2.4**	**2.3**	1.0	3.3	**5.7**	**5.0**	3.8	8.2
Temperature 1-Day Summer; C	**2.4**	**2.3**	1.0	3.3	**5.7**	**5.0**	3.8	8.2
Temperature 1-Day Winter PF; C	**2.3**	**2.2**	1.5	3.6	**5.2**	**5.4**	3.9	6.7
Precipitation 1-Day PF; %	**8**	**6**	-9	28	**11**	**7**	-4	33
Precipitation 1-Day Summer PF; %	**10**	**9**	-10	31	**3**	**3**	-17	22
Precipitation 1-Day Winter PF; %	**10**	**7**	-6	28	**16**	**14**	5	32
Precipitation 3-Day PF; %	**11**	**14**	-10	28	**12**	**8**	-4	32
Precipitation 3-Day Summer PF; %	**7**	**4**	-15	31	**8**	**14**	-15	30
Precipitation 3-Day Winter PF; %	**12**	**12**	-3	28	**14**	**13**	0	30
Precipitation Annual PF; %	**12**	**10**	6	19	**13**	**13**	6	23
Moisture Maximization 1-Day, %	**No Change**				**No Change**			
Moisture Maximization 3-Day; %	**No Change**				**No Change**			

Table 10: Climate Change Projections for Region 4 from current climate (1950-2014) through 2100.

Region 4	SSP45				SSP85			
	Mean	Median	10th	90th	Mean	Median	10th	90th
Temperature 1-Day; C	**2.4**	**2.3**	1.0	3.3	**5.7**	**5.0**	3.8	8.2
Temperature 1-Day Summer; C	**2.4**	**2.3**	1.0	3.3	**5.7**	**5.0**	3.8	8.2
Temperature 1-Day Winter PF; C	**2.3**	**2.2**	1.5	3.6	**5.2**	**5.4**	3.9	6.7
Precipitation 1-Day PF; %	**8**	**10**	-9	28	**12**	**8**	1	33
Precipitation 1-Day Summer PF; %	**10**	**9**	-10	31	**4**	**4**	-12	22
Precipitation 1-Day Winter PF; %	**9**	**7**	-6	28	**16**	**15**	5	32
Precipitation 3-Day PF; %	**12**	**15**	-10	28	**13**	**10**	-2	32
Precipitation 3-Day Summer PF; %	**7**	**4**	-15	31	**8**	**14**	-15	30
Precipitation 3-Day Winter PF; %	**13**	**13**	-3	29	**14**	**13**	0	30
Precipitation Annual PF; %	**11**	**10**	6	19	**13**	**13**	6	23
Moisture Maximization 1-Day, %	**No Change**				**No Change**			
Moisture Maximization 3-Day; %	**No Change**				**No Change**			

6.0 CONCLUSIONS

The Maryland climate change analysis investigated CMIP6 projections. The projections were evaluated using several statistical methodologies to test for trends in temperature and precipitation, changes in precipitation frequency, and changes in monthly climatologies. The results have large variability that can be attributed to the uncertainties and limitations inherent in climate model projections and the physical representation of meteorological parameters such as precipitation.
The trend and frequency analysis methods provide a robust dataset to test changes in precipitation and temperature. The monthly and annual climatology analysis methods provide projections to test changes in climate normals. More confidence is given to the trend, precipitation frequency, and climatology results as compared to the moisture maximization analysis based on subjective assumptions inherent in the moisture maximization process.

The climate change analysis completed for the Maryland region was based on twenty-six CMIP6 climate model projections and three climate scenarios (historic, SSP 4.5, and SSP 8.5). A summary of the key conclusions from this study are listed below.

TREND ANALYSIS

- Most surface stations show no historic change/trend in precipitation and temperature
- Projections show increase in temperature and dew point temperature
- SSP 4.5 precipitation – most models show no trend/change at all durations
- SSP 8.5 precipitation – most models show a split between no change and an increasing trend at all durations

FREQUENCY ANALYSIS

- **1-day** – the median SSP 4.5 and SSP 8.5 results are within +/- 20% uncertainty which provide more confidence for no change in precipitation magnitude by 2100.
- **3-day** – the median SSP 4.5 and SSP 8.5 results are within +/- 20% uncertainty which provide more confidence for no change in precipitation magnitude by 2100.
- **Annual** – the median SSP 4.5 and SSP 8.5 results are larger within +/- 20% uncertainty which provide more confidence for no change in precipitation magnitude by 2100 and both have an increase in temperature by 2100.

CLIMATOLOGY

- **Monthly Climatology** – Most months show a slight increase but are +/- 20% uncertainty which provide more confidence for no change in precipitation magnitude by 2100). All months show an increase in temperature by 2100.
- **Annual Climatology** – No change in annual precipitation (within +/- 20% uncertainty). Results show an increase in annual temperature by 2100.

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Appendix A

Climate Results Spreadsheet for All Four Regions

Region 1	SSP45				SSP85			
	Mean	Median	10th	90th	Mean	Median	10th	90th
Temperature 1-Day; C	**2.2**	**2.1**	1.0	3.2	**5.3**	**5.0**	4.0	7.5
Temperature 1-Day Summer; C	**2.2**	**2.1**	1.0	3.2	**5.3**	**5.0**	4.0	7.5
Temperature 1-Day Winter PF; C	**2.4**	**2.4**	1.6	3.5	**5.0**	**4.9**	3.8	6.3
Precipitation 1-Day PF; %	**-2**	**-5**	-17	16	**3**	**1**	-10	20
Precipitation 1-Day Summer PF; %	**5**	**-1**	-14	21	**9**	**7**	-16	37
Precipitation 1-Day Winter PF; %	**-1**	**-2**	-12	13	**4**	**2**	-11	21
Precipitation 3-Day PF; %	**8**	**4**	-12	26	**13**	**7**	-9	36
Precipitation 3-Day Summer PF; %	**7**	**4**	-13	33	**16**	**21**	-17	53
Precipitation 3-Day Winter PF; %	**9**	**6**	-11	32	**10**	**3**	-5	32
Precipitation Annual PF; %	**12**	**13**	3	19	**13**	**14**	1	25
Moisture Maximization 1-Day, %	**No Change**				**No Change**			
Moisture Maximization 3-Day; %	**No Change**				**Potential Change**			

Frequency analysis climate change results for Region 1 from current climate (1950-2014) through 2100.

Region 2	SSP45				SSP85			
	Mean	Median	10th	90th	Mean	Median	10th	90th
Temperature 1-Day; C	**2.4**	**2.3**	1.0	3.3	**5.7**	**5.1**	4.0	8.0
Temperature 1-Day Summer; C	**2.4**	**2.3**	1.0	3.3	**5.7**	**5.1**	4.0	8.0
Temperature 1-Day Winter PF; C	**2.5**	**2.4**	1.5	3.7	**5.3**	**5.3**	4.0	6.5
Precipitation 1-Day PF; %	**9**	**6**	-7	33	**10**	**6**	-10	36
Precipitation 1-Day Summer PF; %	**13**	**10**	-11	44	**9**	**3**	-17	45
Precipitation 1-Day Winter PF; %	**11**	**7**	-4	29	**14**	**13**	-1	32
Precipitation 3-Day PF; %	**12**	**16**	-5	26	**10**	**10**	-11	32
Precipitation 3-Day Summer PF; %	**9**	**3**	-17	45	**7**	**11**	-20	32
Precipitation 3-Day Winter PF; %	**15**	**15**	-5	36	**13**	**15**	-2	31
Precipitation Annual PF; %	**11**	**11**	5	20	**13**	**13**	3	23
Moisture Maximization 1-Day, %	**No Change**				**No Change**			
Moisture Maximization 3-Day; %	**No Change**				**No Change**			

Frequency analysis climate change results for Region 2 from current climate (1950-2014) through 2100.

Region 3	SSP45				SSP85			
	Mean	Median	10th	90th	Mean	Median	10th	90th
Temperature 1-Day; C	**2.4**	**2.3**	1.0	3.3	**5.7**	**5.0**	3.8	8.2
Temperature 1-Day Summer; C	**2.4**	**2.3**	1.0	3.3	**5.7**	**5.0**	3.8	8.2
Temperature 1-Day Winter PF; C	**2.3**	**2.2**	1.5	3.6	**5.2**	**5.4**	3.9	6.7
Precipitation 1-Day PF; %	**8**	**6**	-9	28	**11**	**7**	-4	33
Precipitation 1-Day Summer PF; %	**10**	**9**	-10	31	**3**	**3**	-17	22
Precipitation 1-Day Winter PF; %	**10**	**7**	-6	28	**16**	**14**	5	32
Precipitation 3-Day PF; %	**11**	**14**	-10	28	**12**	**8**	-4	32
Precipitation 3-Day Summer PF; %	**7**	**4**	-15	31	**8**	**14**	-15	30
Precipitation 3-Day Winter PF; %	**12**	**12**	-3	28	**14**	**13**	0	30
Precipitation Annual PF; %	**12**	**10**	6	19	**13**	**13**	6	23
Moisture Maximization 1-Day, %	**No Change**				**No Change**			
Moisture Maximization 3-Day; %	**No Change**				**No Change**			

Frequency analysis climate change results for Region 3 from current climate (1950-2014) through 2100.

Region 4	SSP45				SSP85			
	Mean	Median	10th	90th	Mean	Median	10th	90th
Temperature 1-Day; C	**2.4**	**2.3**	1.0	3.3	**5.7**	**5.0**	3.8	8.2
Temperature 1-Day Summer; C	**2.4**	**2.3**	1.0	3.3	**5.7**	**5.0**	3.8	8.2
Temperature 1-Day Winter PF; C	**2.3**	**2.2**	1.5	3.6	**5.2**	**5.4**	3.9	6.7
Precipitation 1-Day PF; %	**8**	**10**	-9	28	**12**	**8**	1	33
Precipitation 1-Day Summer PF; %	**10**	**9**	-10	31	**4**	**4**	-12	22
Precipitation 1-Day Winter PF; %	**9**	**7**	-6	28	**16**	**15**	5	32
Precipitation 3-Day PF; %	**12**	**15**	-10	28	**13**	**10**	-2	32
Precipitation 3-Day Summer PF; %	**7**	**4**	-15	31	**8**	**14**	-15	30
Precipitation 3-Day Winter PF; %	**13**	**13**	-3	29	**14**	**13**	0	30
Precipitation Annual PF; %	**11**	**10**	6	19	**13**	**13**	6	23
Moisture Maximization 1-Day, %	**No Change**				**No Change**			
Moisture Maximization 3-Day; %	**No Change**				**No Change**			

Frequency analysis climate change results for Region 4 from current climate (1950-2014) through 2100.

All	SSP45				SSP85			
	Mean	Median	10th	90th	Mean	Median	10th	90th
Temperature 1-Day; C	**2.3**	**2.2**	1.0	3.3	**5.6**	**5.0**	3.8	8.2
Temperature 1-Day Summer; C	**2.3**	**2.2**	1.0	3.3	**5.6**	**5.0**	3.8	8.2
Temperature 1-Day Winter PF; C	**2.4**	**2.3**	1.5	3.7	**5.1**	**5.3**	3.8	6.7
Precipitation 1-Day PF; %	**6**	**4**	-17	33	**9**	**5**	-10	36
Precipitation 1-Day Summer PF; %	**9**	**7**	-14	44	**6**	**4**	-17	45
Precipitation 1-Day Winter PF; %	**7**	**5**	-12	29	**13**	**11**	-11	32
Precipitation 3-Day PF; %	**11**	**12**	-12	28	**12**	**9**	-11	36
Precipitation 3-Day Summer PF; %	**8**	**4**	-17	45	**10**	**15**	-20	53
Precipitation 3-Day Winter PF; %	**12**	**11**	-11	36	**13**	**11**	-5	32
Precipitation Annual PF; %	**12**	**11**	3	20	**13**	**13**	1	25
Moisture Maximization 1-Day, %	**No Change**				**No Change**			
Moisture Maximization 3-Day; %	**No Change**				**No Change**			

Frequency analysis climate change results for All Regions from current climate (1950-2014) through 2100.

Region 1		Precipitation			Temperature
		1-day	3-day	Annual	1-day
Historic	no trend	23	25	24	8
	increase	2	0	2	18
	decrease	1	1	0	0
SSP45	no trend	18	21	21	2
	increase	8	5	5	24
	decrease	0	0	0	0
SSP85	no trend	14	18	11	0
	increase	12	8	15	26
	decrease	0	0	0	0

Maryland trend analysis results from current climate (1950-2014) to 2015 through 2100 for Region 1. The numbers represent the climate models that had no trend, a significant increase or decrease trend.

Region 2		Precipitation			Temperature
		1-day	3-day	Annual	1-day
Historic	no trend	24	24	23	8
	increase	1	1	3	18
	decrease	1	1	0	0
SSP45	no trend	21	20	17	5
	increase	5	6	9	21
	decrease	0	0	0	0
SSP85	no trend	17	16	7	0
	increase	9	10	19	26
	decrease	0	0	0	0

Maryland trend analysis results from current climate (1950-2014) to 2015 through 2100 for Region 2. The numbers represent the climate models that had no trend, a significant increase or decrease trend.

Region 3		Precipitation			Temperature
		1-day	3-day	Annual	1-day
Historic	no trend	25	25	22	5
	increase	1	1	4	21
	decrease	0	0	0	0
SSP45	no trend	24	22	18	5
	increase	2	4	8	21
	decrease	0	0	0	0
SSP85	no trend	12	15	8	0
	increase	14	11	18	26
	decrease	0	0	0	0

Maryland trend analysis results from current climate (1950-2014) to 2015 through 2100 for Region 3. The numbers represent the climate models that had no trend, a significant increase or decrease trend.

gion 4		Precipitation			Temperature
		1-day	3-day	Annual	1-day
Historic	no trend	25	25	22	5
	increase	1	1	4	21
	decrease	0	0	0	0
SSP45	no trend	24	22	18	5
	increase	2	4	8	21
	decrease	0	0	0	0
SSP85	no trend	12	15	8	0
	increase	14	11	18	26
	decrease	0	0	0	0

Maryland trend analysis results from current climate (1950-2014) to 2015 through 2100 for Region 4. The numbers represent the climate models that had no trend, a significant increase or decrease trend.

Average		Precipitation			Temperature
		1-day	3-day	Annual	1-day
Historic	no trend	97	99	91	26
	increase	5	3	13	78
	decrease	2	2	0	0
SSP45	no trend	87	85	74	17
	increase	17	19	30	87
	decrease	0	0	0	0
SSP85	no trend	55	64	34	0
	increase	49	40	70	104
	decrease	0	0	0	0

Maryland trend analysis results from current climate (1950-2014) to 2015 through 2100 for All Regions (average). The numbers represent the climate models that had no trend, a significant increase or decrease trend.

Average as Percent		Precipitation			Temperature
		1-day	3-day	Annual	1-day
Historic	no trend	93%	95%	88%	25%
	increase	5%	3%	13%	75%
	decrease	2%	2%	0%	0%
SSP45	no trend	84%	82%	71%	16%
	increase	16%	18%	29%	84%
	decrease	0%	0%	0%	0%
SSP85	no trend	53%	62%	33%	0%
	increase	47%	38%	67%	100%
	decrease	0%	0%	0%	0%

Maryland trend analysis results from current climate (1950-2014) to 2015 through 2100 for All Regions (average as %). The numbers represent the climate models that had no trend, a significant increase or decrease trend.

Region 1	Historical		SSP45		SSP85		Mean Delta		Median Delta	
	Mean	Median	Mean	Median	Mean	Median	SSP45	SSP85	SSP45	SSP85
January	2.7	2.6	4.9	5.1	5.6	6.0	***2.2***	***2.9***	***2.5***	***3.4***
February	5.0	4.7	7.4	7.4	8.2	8.2	***2.4***	***3.2***	***2.7***	***3.5***
March	9.6	9.3	12.4	12.4	13.0	13.0	***2.8***	***3.4***	***3.1***	***3.7***
April	15.2	14.9	17.8	17.8	18.6	18.5	***2.6***	***3.4***	***2.9***	***3.6***
May	20.3	20.1	22.8	22.8	23.7	23.7	***2.5***	***3.4***	***2.7***	***3.6***
June	24.6	24.3	26.9	27.0	27.8	27.9	***2.3***	***3.3***	***2.8***	***3.6***
July	26.1	25.9	28.1	28.2	29.1	29.1	***2.1***	***3.1***	***2.3***	***3.2***
August	24.8	24.6	26.8	26.9	27.9	27.8	***2.0***	***3.0***	***2.3***	***3.2***
September	20.6	20.4	22.4	22.5	23.5	23.4	***1.8***	***2.9***	***2.1***	***3.0***
October	14.2	13.8	16.1	16.0	17.2	17.1	***1.9***	***3.0***	***2.2***	***3.3***
November	8.5	8.1	10.1	10.2	11.0	10.8	***1.7***	***2.5***	***2.1***	***2.7***
December	4.0	3.8	5.9	5.9	6.5	6.5	***1.8***	***2.4***	***2.1***	***2.7***

Maryland monthly temperature (C) change from current climate (1950-2014) to 2015 through 2100 for Region 1.

Region 2	Historical		SSP45		SSP85		Mean Delta		Median Delta	
	Mean	Median	Mean	Median	Mean	Median	SSP45	SSP85	SSP45	SSP85
January	1.1	0.9	3.5	3.6	4.1	4.3	***2.4***	***3.1***	***2.7***	***3.4***
February	3.6	3.3	6.2	5.9	7.0	6.9	***2.6***	***3.4***	***2.6***	***3.6***
March	8.4	8.2	11.4	11.3	12.0	11.9	***3.0***	***3.7***	***3.2***	***3.7***
April	14.3	13.9	17.0	16.8	17.9	17.8	***2.7***	***3.6***	***2.9***	***3.9***
May	19.5	19.2	22.2	22.0	23.2	23.2	***2.7***	***3.6***	***2.8***	***4.0***
June	23.9	23.5	26.4	26.4	27.4	27.3	***2.5***	***3.5***	***2.9***	***3.8***
July	25.4	25.0	27.6	27.6	28.8	28.7	***2.2***	***3.4***	***2.6***	***3.7***
August	24.1	23.8	26.3	26.1	27.5	27.3	***2.2***	***3.4***	***2.4***	***3.6***
September	19.5	19.2	21.5	21.3	22.7	22.5	***2.0***	***3.1***	***2.1***	***3.3***
October	12.8	12.5	14.8	14.8	15.9	15.8	***1.9***	***3.1***	***2.3***	***3.3***
November	6.8	6.5	8.5	8.6	9.4	9.2	***1.7***	***2.6***	***2.1***	***2.7***
December	2.4	2.1	4.1	4.2	4.8	4.8	***1.7***	***2.4***	***2.1***	***2.7***

Maryland monthly temperature (C) change from current climate (1950-2014) to 2015 through 2100 for Region 2.

Region 3	Historical		SSP45		SSP85		Mean Delta		Median Delta	
	Mean	**Median**	**Mean**	**Median**	**Mean**	**Median**	**SSP45**	**SSP85**	**SSP45**	**SSP85**
January	-0.1	-0.3	2.2	2.4	2.9	2.8	***1.5***	***2.2***	***2.6***	***3.1***
February	2.5	2.2	5.0	4.8	5.8	5.9	***1.4***	***2.2***	***2.6***	***3.7***
March	7.4	7.1	10.3	10.2	11.1	10.8	***1.4***	***2.2***	***3.2***	***3.8***
April	13.1	12.7	15.9	15.9	16.7	16.6	***1.5***	***2.3***	***3.2***	***3.9***
May	18.1	17.8	20.8	20.6	21.8	21.8	***1.6***	***2.5***	***2.8***	***4.0***
June	22.2	21.9	24.6	24.7	25.6	25.5	***1.8***	***2.7***	***2.8***	***3.7***
July	23.5	23.1	25.6	25.6	26.7	26.6	***1.7***	***2.6***	***2.5***	***3.5***
August	22.2	22.0	24.4	24.3	25.7	25.5	***1.8***	***2.7***	***2.3***	***3.5***
September	17.8	17.5	19.8	19.6	21.0	20.8	***2.0***	***2.7***	***2.1***	***3.4***
October	11.2	10.8	13.2	13.1	14.4	14.3	***1.7***	***2.5***	***2.3***	***3.5***
November	5.4	5.0	7.1	7.1	8.0	7.7	***1.5***	***2.3***	***2.0***	***2.7***
December	1.1	0.8	2.8	3.0	3.5	3.6	***1.4***	***2.2***	***2.2***	***2.8***

Maryland monthly temperature (C) change from current climate (1950-2014) to 2015 through 2100 for Region 3.

Region 4	Historical		SSP45		SSP85		Mean Delta		Median Delta	
	Mean	**Median**	**Mean**	**Median**	**Mean**	**Median**	**SSP45**	**SSP85**	**SSP45**	**SSP85**
January	-0.1	-0.3	2.2	2.4	2.9	2.8	***1.5***	***2.2***	***2.6***	***3.1***
February	2.5	2.2	5.0	4.8	5.8	5.9	***1.4***	***2.2***	***2.6***	***3.7***
March	7.4	7.1	10.3	10.2	11.1	10.8	***1.4***	***2.2***	***3.2***	***3.8***
April	13.1	12.7	15.9	15.9	16.7	16.6	***1.5***	***2.3***	***3.2***	***3.9***
May	18.1	17.8	20.8	20.6	21.8	21.8	***1.6***	***2.5***	***2.8***	***4.0***
June	22.2	21.9	24.6	24.7	25.6	25.5	***1.8***	***2.7***	***2.8***	***3.7***
July	23.5	23.1	25.6	25.6	26.7	26.6	***1.7***	***2.6***	***2.5***	***3.5***
August	22.2	22.0	24.4	24.3	25.7	25.5	***1.8***	***2.7***	***2.3***	***3.5***
September	17.8	17.5	19.8	19.6	21.0	20.8	***2.0***	***2.7***	***2.1***	***3.4***
October	11.2	10.8	13.2	13.1	14.4	14.3	***1.7***	***2.5***	***2.3***	***3.5***
November	5.4	5.0	7.1	7.1	8.0	7.7	***1.5***	***2.3***	***2.0***	***2.7***
December	1.1	0.8	2.8	3.0	3.5	3.6	***1.4***	***2.2***	***2.2***	***2.8***

Maryland monthly temperature (C) change from current climate (1950-2014) to 2015 through 2100 for Region 4.

All	Historical		SSP45		SSP85		Mean Delta		Median Delta	
	Mean	Median	Mean	Median	Mean	Median	SSP45	SSP85	SSP45	SSP85
January	0.9	0.7	3.2	3.3	3.9	4.0	***2.3***	***3.0***	***2.6***	***3.2***
February	3.4	3.1	5.9	5.7	6.7	6.7	***2.5***	***3.3***	***2.6***	***3.6***
March	8.2	7.9	11.1	11.0	11.8	11.6	***2.9***	***3.6***	***3.2***	***3.7***
April	13.9	13.6	16.6	16.6	17.5	17.4	***2.7***	***3.6***	***3.0***	***3.8***
May	19.0	18.7	21.6	21.5	22.6	22.6	***2.6***	***3.6***	***2.8***	***3.9***
June	23.2	22.9	25.6	25.7	26.6	26.6	***2.4***	***3.4***	***2.8***	***3.7***
July	24.6	24.3	26.8	26.8	27.8	27.7	***2.2***	***3.2***	***2.5***	***3.5***
August	23.3	23.1	25.5	25.4	26.7	26.5	***2.1***	***3.3***	***2.3***	***3.5***
September	18.9	18.6	20.9	20.7	22.1	21.9	***2.0***	***3.1***	***2.1***	***3.2***
October	12.4	12.0	14.3	14.2	15.5	15.4	***2.0***	***3.1***	***2.3***	***3.4***
November	6.5	6.2	8.2	8.2	9.1	8.8	***1.7***	***2.6***	***2.0***	***2.7***
December	2.2	1.9	3.9	4.0	4.5	4.6	***1.7***	***2.4***	***2.1***	***2.7***

Maryland monthly temperature (C) change from current climate (1950-2014) to 2015 through 2100 for All Regions (average).

Region 1	Historical		SSP45		SSP85		Mean Delta		Median Delta	
	Mean	Median	Mean	Median	Mean	Median	SSP45	SSP85	SSP45	SSP85
January	80.0	80.7	89.4	91.9	93.4	94.1	***1.12***	***1.14***	***1.14***	***1.17***
February	72.9	73.3	84.4	86.3	85.9	85.7	***1.16***	***1.18***	***1.18***	***1.17***
March	91.5	91.8	98.9	97.0	103.7	104.4	***1.08***	***1.06***	***1.06***	***1.14***
April	80.8	82.0	88.4	87.6	86.6	86.0	***1.09***	***1.07***	***1.07***	***1.05***
May	90.9	91.2	95.9	96.1	94.6	92.5	***1.06***	***1.05***	***1.05***	***1.01***
June	94.0	93.8	103.0	103.9	101.7	101.3	***1.09***	***1.11***	***1.11***	***1.08***
July	114.1	113.0	124.8	124.6	125.5	124.8	***1.09***	***1.10***	***1.10***	***1.10***
August	104.2	103.9	111.3	113.0	112.5	112.8	***1.07***	***1.09***	***1.09***	***1.09***
September	86.9	86.9	90.8	89.2	90.3	86.7	***1.04***	***1.03***	***1.03***	***1.00***
October	79.5	78.6	81.9	79.7	83.3	83.9	***1.03***	***1.01***	***1.01***	***1.07***
November	79.0	78.9	86.9	85.6	92.3	94.6	***1.10***	***1.09***	***1.09***	***1.20***
December	88.3	88.9	95.8	95.9	103.3	101.2	***1.09***	***1.08***	***1.08***	***1.14***

Maryland monthly precipitation (mm) change from current climate (1950-2014) to 2015 through 2100 for Region 1.

Region 2	Historical		SSP45		SSP85		Mean Delta		Median Delta	
	Mean	Median	Mean	Median	Mean	Median	SSP45	SSP85	SSP45	SSP85
January	71.8	72.0	81.9	82.0	86.2	85.5	***1.14***	***1.14***	***1.14***	***1.19***
February	66.2	66.8	78.1	78.8	78.3	77.5	***1.18***	***1.18***	***1.18***	***1.16***
March	86.8	86.2	96.1	94.0	100.5	101.7	***1.11***	***1.09***	***1.09***	***1.18***
April	83.6	83.2	94.1	93.6	92.4	93.4	***1.13***	***1.12***	***1.12***	***1.12***
May	99.3	99.1	105.4	105.9	103.6	103.9	***1.06***	***1.07***	***1.07***	***1.05***
June	96.6	96.9	103.6	104.5	101.7	99.8	***1.07***	***1.08***	***1.08***	***1.03***
July	104.0	104.1	110.5	111.0	111.3	110.3	***1.06***	***1.07***	***1.07***	***1.06***
August	92.6	92.7	99.3	99.5	100.2	97.6	***1.07***	***1.07***	***1.07***	***1.05***
September	87.1	88.1	90.6	89.6	88.4	87.2	***1.04***	***1.02***	***1.02***	***0.99***
October	80.4	79.3	82.7	80.6	83.0	84.3	***1.03***	***1.02***	***1.02***	***1.06***
November	80.9	81.1	89.2	88.1	93.2	93.0	***1.10***	***1.09***	***1.09***	***1.15***
December	81.9	82.3	89.2	89.4	95.9	95.6	***1.09***	***1.09***	***1.09***	***1.16***

Maryland monthly precipitation (mm) change from current climate (1950-2014) to 2015 through 2100 for Region 2.

Region 3	Historical		SSP45		SSP85		Mean Delta		Median Delta	
	Mean	Median	Mean	Median	Mean	Median	SSP45	SSP85	SSP45	SSP85
January	68.3	67.8	79.0	78.8	82.5	82.7	***1.16***	***1.16***	***1.16***	***1.22***
February	64.5	64.7	76.7	76.5	78.9	78.9	***1.19***	***1.18***	***1.18***	***1.22***
March	86.4	85.8	96.7	95.4	100.8	102.3	***1.12***	***1.11***	***1.11***	***1.19***
April	86.5	87.1	96.1	95.5	93.9	93.4	***1.11***	***1.10***	***1.10***	***1.07***
May	101.4	101.4	108.0	107.4	106.4	106.2	***1.06***	***1.06***	***1.06***	***1.05***
June	97.3	97.5	103.2	103.1	102.4	101.2	***1.06***	***1.06***	***1.06***	***1.04***
July	105.2	104.9	111.9	112.7	113.3	113.3	***1.06***	***1.07***	***1.07***	***1.08***
August	90.5	90.4	96.1	93.9	97.0	95.3	***1.06***	***1.04***	***1.04***	***1.05***
September	79.4	78.2	83.0	82.8	80.5	80.2	***1.05***	***1.06***	***1.06***	***1.03***
October	75.4	75.9	76.3	74.8	77.9	80.0	***1.01***	***0.99***	***0.99***	***1.05***
November	76.7	77.1	84.9	84.4	88.8	86.9	***1.11***	***1.09***	***1.09***	***1.13***
December	75.4	75.7	81.8	81.0	87.1	86.9	***1.08***	***1.07***	***1.07***	***1.15***

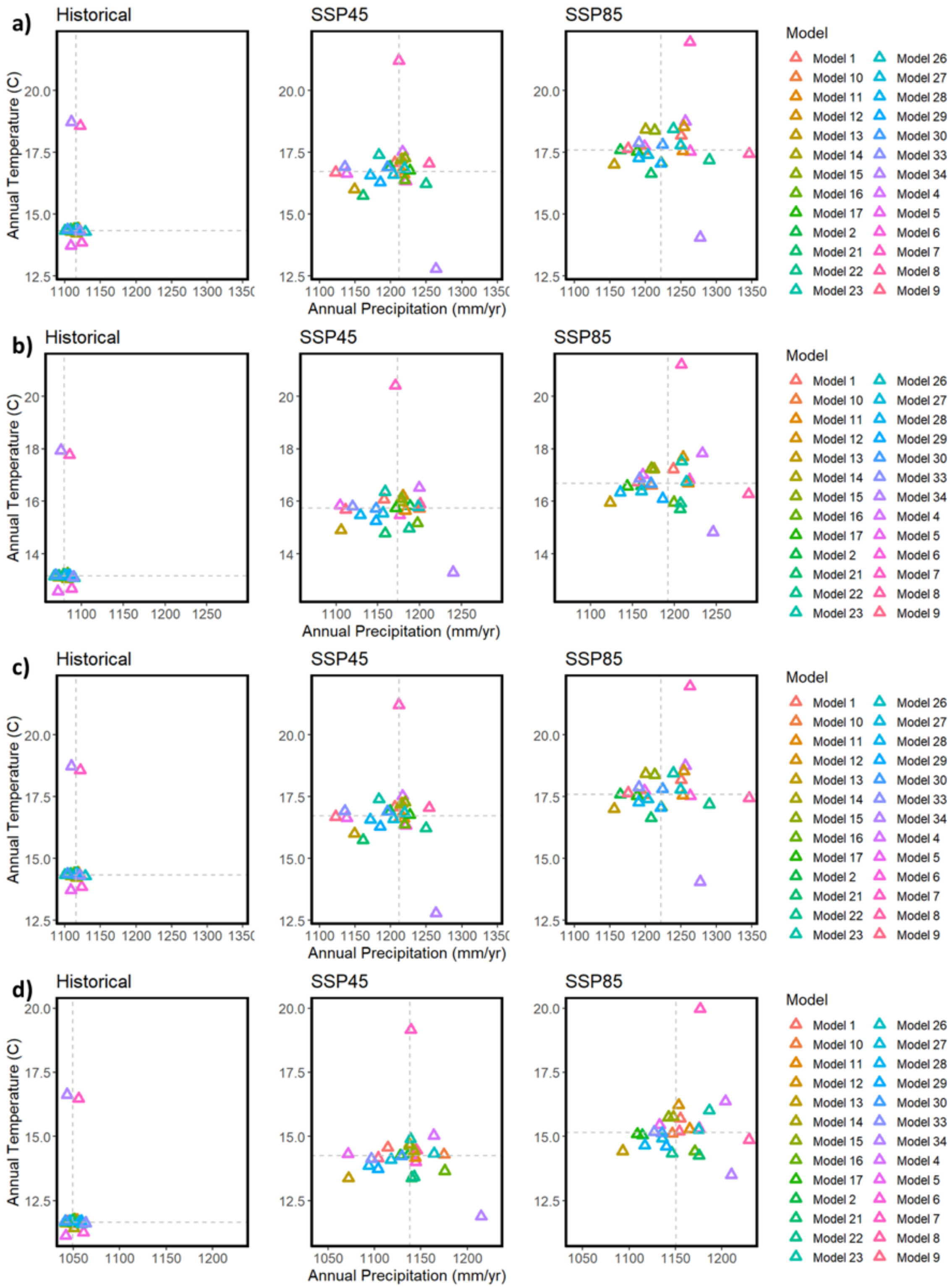
Maryland monthly precipitation (mm) change from current climate (1950-2014) to 2015 through 2100 for Region 3.

Region 4	Historical		SSP45		SSP85		Mean Delta		Median Delta	
	Mean	Median	Mean	Median	Mean	Median	SSP45	SSP85	SSP45	SSP85
January	68.3	67.8	79.0	78.8	82.5	82.7	***1.16***	***1.16***	***1.16***	***1.22***
February	64.5	64.7	76.7	76.5	78.9	78.9	***1.19***	***1.18***	***1.18***	***1.22***
March	86.4	85.8	96.7	95.4	100.8	102.3	***1.12***	***1.11***	***1.11***	***1.19***
April	86.5	87.1	96.1	95.5	93.9	93.4	***1.11***	***1.10***	***1.10***	***1.07***
May	101.4	101.4	108.0	107.4	106.4	106.2	***1.06***	***1.06***	***1.06***	***1.05***
June	97.3	97.5	103.2	103.1	102.4	101.2	***1.06***	***1.06***	***1.06***	***1.04***
July	105.2	104.9	111.9	112.7	113.3	113.3	***1.06***	***1.07***	***1.07***	***1.08***
August	90.5	90.4	96.1	93.9	97.0	95.3	***1.06***	***1.04***	***1.04***	***1.05***
September	79.4	78.2	83.0	82.8	80.5	80.2	***1.05***	***1.06***	***1.06***	***1.03***
October	75.4	75.9	76.3	74.8	77.9	80.0	***1.01***	***0.99***	***0.99***	***1.05***
November	76.7	77.1	84.9	84.4	88.8	86.9	***1.11***	***1.09***	***1.09***	***1.13***
December	75.4	75.7	81.8	81.0	87.1	86.9	***1.08***	***1.07***	***1.07***	***1.15***

Maryland monthly precipitation (mm) change from current climate (1950-2014) to 2015 through 2100 for Region 4.

All	Historical		SSP45		SSP85		Mean Delta		Median Delta	
	Mean	Median	Mean	Median	Mean	Median	SSP45	SSP85	SSP45	SSP85
January	72.1	72.1	82.3	82.8	86.1	86.3	***1.14***	***1.15***	***1.15***	***1.20***
February	67.0	67.4	79.0	79.5	80.5	80.2	***1.18***	***1.18***	***1.18***	***1.19***
March	87.8	87.4	97.1	95.4	101.4	102.6	***1.11***	***1.09***	***1.09***	***1.17***
April	84.4	84.8	93.7	93.1	91.7	91.5	***1.11***	***1.10***	***1.10***	***1.08***
May	98.2	98.3	104.3	104.2	102.7	102.2	***1.06***	***1.06***	***1.06***	***1.04***
June	96.3	96.4	103.2	103.6	102.1	100.9	***1.07***	***1.07***	***1.07***	***1.05***
July	107.1	106.7	114.8	115.2	115.9	115.4	***1.07***	***1.08***	***1.08***	***1.08***
August	94.5	94.3	100.7	100.1	101.7	100.2	***1.07***	***1.06***	***1.06***	***1.06***
September	83.2	82.8	86.8	86.1	84.9	83.6	***1.04***	***1.04***	***1.04***	***1.01***
October	77.7	77.4	79.3	77.5	80.5	82.0	***1.02***	***1.00***	***1.00***	***1.06***
November	78.3	78.5	86.5	85.6	90.8	90.3	***1.10***	***1.09***	***1.09***	***1.15***
December	80.3	80.6	87.1	86.8	93.3	92.7	***1.09***	***1.08***	***1.08***	***1.15***

Maryland monthly precipitation (mm) change from current climate (1950-2014) to 2015 through 2100 for All Regions (average).



Comparison of mean annual temperature and mean annual precipitation for the three climate projection periods for: (a) Region 1, (b) Region 2, (c) Region 3 and (d) Region 4.

Reg1	Temp	Ppt	Delta C	Ppt %
Hist	14.3	1115		
SP45	16.7	1212	**2.4**	**9%**
SP85	17.6	1222	**3.3**	**10%**

Reg2	Temp	Ppt	Delta C	Ppt %
Hist	13.2	1080		
SP45	15.7	1174	**2.6**	**9%**
SP85	16.7	1192	**3.5**	**10%**

Reg3	Temp	Ppt	Delta C	Ppt %
Hist	11.7	1049		
SP45	14.2	1138	**2.6**	**8%**
SP85	15.2	1150	**3.5**	**10%**

Reg4	Temp	Ppt	Delta C	Ppt %
Hist	11.7	1049		
SP45	14.2	1138	**2.6**	**8%**
SP85	15.2	1150	**3.5**	**10%**

Median annual temperature and precipitation from 3 climate projections.

Appendix B

Climate Change Presentation

Climate Change Projections for New Jersey

Applied Weather Associates (AWA)

Doug Hultstrand
Bill Kappel

September 2022

1

1) Climate Model Background

- Various research groups conduct climate change modeling
  - Share data via CMIP6 group
  - Utilize same requirements to make each model comparable
- Shared Socioeconomic Pathway (SSP)
  - SSP account for unknown future GHG emissions
- SSP scenarios used as boundary conditions for CMIP6 GCMs
  - Commonly use SSP 4.5 and 8.5

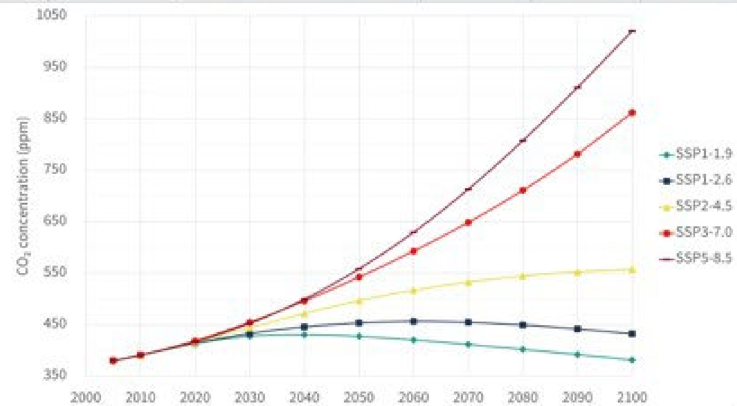
Applied Weather Associates 2

1) CMIP6 Climate Model Projections

- The **SSP 4.5** intermediate GHG emissions: CO2 emissions around current levels until 2050, then falling but not reaching net zero by 2100

- The **SSP 8.5** very high GHG emissions: CO2 emissions triple by 2075

SSP	Scenario	Estimated warming (2041–2060)	Estimated warming (2081–2100)	Very likely range in °C (2081–2100)
SSP1-1.9	very low GHG emissions: CO_2 emissions cut to net zero around 2050	1.6 °C	1.4 °C	1.0 – 1.8
SSP1-2.6	low GHG emissions: CO_2 emissions cut to net zero around 2075	1.7 °C	1.8 °C	1.3 – 2.4
SSP2-4.5	intermediate GHG emissions: CO_2 emissions around current levels until 2050, then falling but not reaching net zero by 2100	2.0 °C	2.7 °C	2.1 – 3.5
SSP3-7.0	high GHG emissions: CO_2 emissions double by 2100	2.1 °C	3.6 °C	2.8 – 4.6
SSP5-8.5	very high GHG emissions: CO_2 emissions triple by 2075	2.4 °C	4.4 °C	3.3 – 5.7



**** SP45 values are "likely" and SP85 "unlikely"*

2) “Within Uncertainty” Term

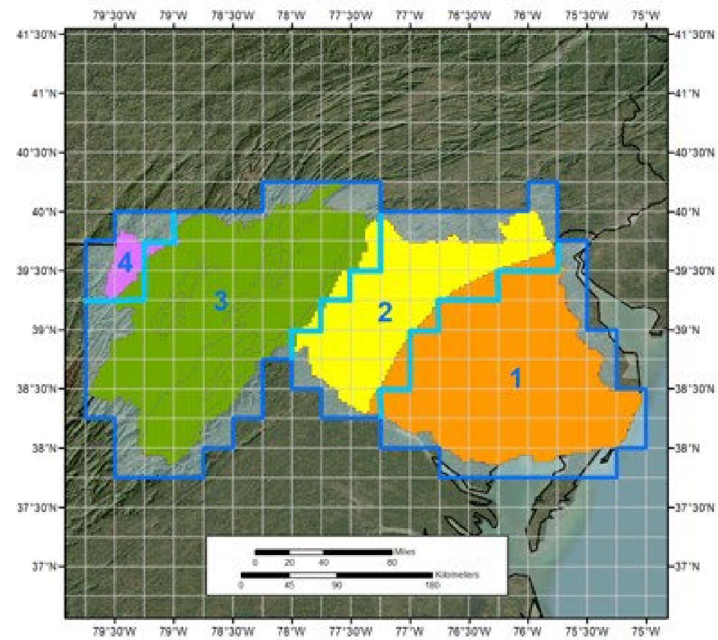
- The meaning of ***“within uncertainty”*** for this analysis
- Multiple sources of uncertainty and varying ranges of uncertainty
  - Gauge/Observed Precipitation
    - Point measurement 5 to 15% percent for long-term series, and as high as 75% for individual storm events
  - Frequency Analysis
    - Typically, 24-hour 100-year error bounds are approximately +/-18%
  - Climate Projections
    - Regional Models can be quite large 20 to >50%
  - PMP Storm In-place Maximization Factor
    - Range between 5 and 30%, with an average around 20%
- Consider +/- 20% to be within uncertainty of the analysis results.

Applied Weather Associates 4

1) CMIP6 Climate Model Projections

NASA Earth Exchange Global Daily Downscaled Projections (NEX-GDDP-CMIP6)

- Total of 35 climate models
- 9 models did not have all data
  - (6) Missing years and/or variables
  - (3) 30-days per month
- Used 26 models on daily time step
  - Temperature
  - Relative humidity
  - Precipitation



Applied Weather Associates

2) Climate Model Projections Used

- 26 models on daily time step
  - Temperature (tas)
  - Relative humidity (hurs)
  - Precipitation (pr)

Model #	MODEL NAME	*Relative Humidity (hurs)*			*Precipitation (pr)*			*Temperature (tas)*		
		HISTORICAL	SSP45	SSP85	HISTORICAL	SSP45	SSP85	HISTORICAL	SSP45	SSP85
1	ACCESS-CM2	1950-2014	2015-2100	2015-2100	1950-2014	2015-2100	2015-2100	1950-2014	2015-2100	2015-2100
2	ACCESS-ESM1-5	1950-2014	2015-2100	2015-2100	1950-2014	2015-2100	2015-2100	1950-2014	2015-2100	2015-2100
4	CanESM5	1950-2014	2015-2100	2015-2100	1950-2014	2015-2100	2015-2100	1950-2014	2015-2100	2015-2100
5	CESM2-WACCM	1950-2014	2015-2100	2015-2100	1950-2014	2015-2100	2015-2100	1950-2014	2015-2100	2015-2100
6	CESM2	1950-2014	2015-2100	2015-2100	1950-2014	2015-2100	2015-2100	1950-2014	2015-2100	2015-2100
7	CMCC-CM2-SR5	1950-2014	2015-2100	2015-2100	1950-2014	2015-2100	2015-2100	1950-2014	2015-2100	2015-2100
8	CMCC-ESM2	1950-2014	2015-2100	2015-2100	1950-2014	2015-2100	2015-2100	1950-2014	2015-2100	2015-2100
9	CNRM-CM6-1	1950-2014	2015-2100	2015-2100	1950-2014	2015-2100	2015-2100	1950-2014	2015-2100	2015-2100
10	CNRM-ESM2-1	1950-2014	2015-2100	2015-2100	1950-2014	2015-2100	2015-2100	1950-2014	2015-2100	2015-2100
11	EC-Earth3-Veg-LR	1950-2014	2015-2100	2015-2100	1950-2014	2015-2100	2015-2100	1950-2014	2015-2100	2015-2100
12	EC-Earth3	1950-2014	2015-2100	2015-2100	1950-2014	2015-2100	2015-2100	1950-2014	2015-2100	2015-2100
13	FGOALS-g3	1950-2014	2015-2100	2015-2100	1950-2014	2015-2100	2015-2100	1950-2014	2015-2100	2015-2100
14	GFDL-CM4_gr1	1950-2014	2015-2100	2015-2100	1950-2014	2015-2100	2015-2100	1950-2014	2015-2100	2015-2100
15	GFDL-CM4_gr2	1950-2014	2015-2100	2015-2100	1950-2014	2015-2100	2015-2100	1950-2014	2015-2100	2015-2100
16	GFDL-ESM4	1950-2014	2015-2100	2015-2100	1950-2014	2015-2100	2015-2100	1950-2014	2015-2100	2015-2100
17	GISS-E2-1-G	1950-2014	2015-2100	2015-2100	1950-2014	2015-2100	2015-2100	1950-2014	2015-2100	2015-2100
21	INM-CM4-8	1950-2014	2015-2100	2015-2100	1950-2014	2015-2100	2015-2100	1950-2014	2015-2100	2015-2100
22	INM-CM5-0	1950-2014	2015-2100	2015-2100	1950-2014	2015-2100	2015-2100	1950-2014	2015-2100	2015-2100
23	IPSL-CM6A-LR	1950-2014	2015-2100	2015-2100	1950-2014	2015-2100	2015-2100	1950-2014	2015-2100	2015-2100
26	MIROC-ES2L	1950-2014	2015-2100	2015-2100	1950-2014	2015-2100	2015-2100	1950-2014	2015-2100	2015-2100
27	MIROC6	1950-2014	2015-2100	2015-2100	1950-2014	2015-2100	2015-2100	1950-2014	2015-2100	2015-2100
28	MPI-ESM1-2-HR	1950-2014	2015-2100	2015-2100	1950-2014	2015-2100	2015-2100	1950-2014	2015-2100	2015-2100
29	MPI-ESM1-2-LR	1950-2014	2015-2100	2015-2100	1950-2014	2015-2100	2015-2100	1950-2014	2015-2100	2015-2100
30	MRI-ESM2-0	1950-2014	2015-2100	2015-2100	1950-2014	2015-2100	2015-2100	1950-2014	2015-2100	2015-2100
33	NorESM2-MM	1950-2014	2015-2100	2015-2100	1950-2014	2015-2100	2015-2100	1950-2014	2015-2100	2015-2100
34	TaiESM1	1950-2014	2015-2100	2015-2100	1950-2014	2015-2100	2015-2100	1950-2014	2015-2100	2015-2100

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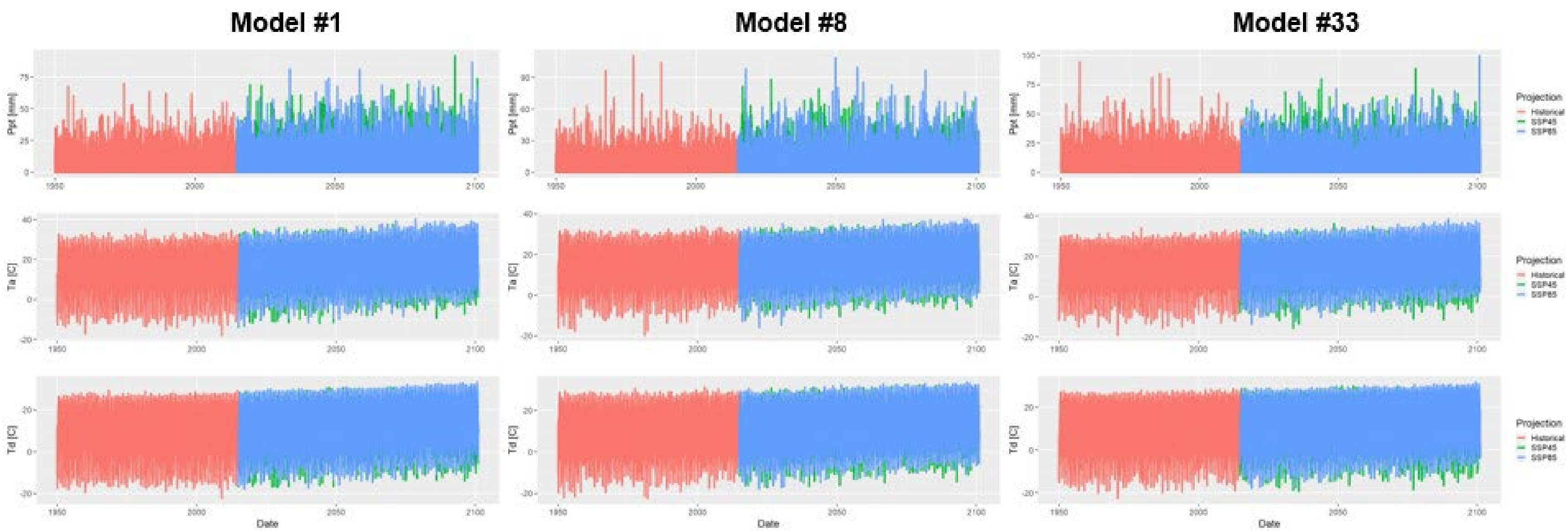
2) Climate Model Analysis Input (Model 1, 8, 33)



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3) Climate Change Analysis Methods

- **1) Trend Analysis** for 1-day, 3-day, and Annual
  - Station Data
  - Model projections (Historic, SSP45, SSP85)
- **2) Monthly and Annual Analysis**
  - Model projections (Historic, SSP45, SSP85)
- **3) Precipitation Frequency Analysis** for 1-day, 3-day, 30-day, 90-day, and Annual
  - Precipitation, Summer Period, and Winter Period
  - Model projections (Historic, SSP45, SSP85)
  - Estimate PF for 1-year through 1000-year
  - Quantify changes
- **4) Moisture Maximization Analysis** for 1-day and 3-day
  - Derive model projection monthly Td climatologies (Historic, SSP45, SSP85)
  - Quantify changes

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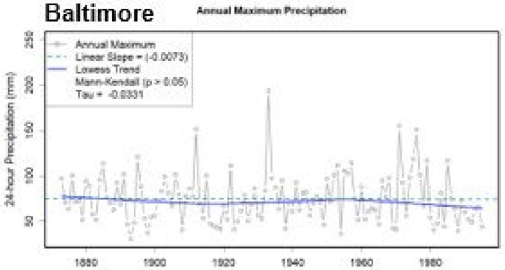
3.1) Station Trend Analysis (1-day)

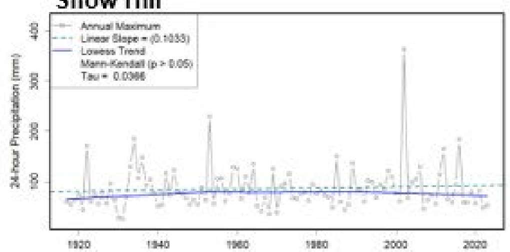
- Station 1-day AMS Trend Analysis (Mann-Kendall)

Station ID	Name	Latitude	Longitude	Elevation	POR	Trend	P-value
USW00013777	BALTIMORE, MD	39.2833	-76.6167	14	123	None	0.5892
USC00442208	DALE, VA	38.4547	-78.9352	1358	130	None	0.5091
USC00186620	OAKLAND, MD	39.4132	-79.4003	2420	120	None	0.0946
USC00188380	SNOW HILL, MD	38.2317	-75.3761	30	107	None	0.5792
USC00181790	HAGERSTOWN, MD	39.6403	-77.6978	532	124	None	0.1546
USC00449186	WINCHESTER, VA	39.1084	-78.1525	680	111	None	0.0471

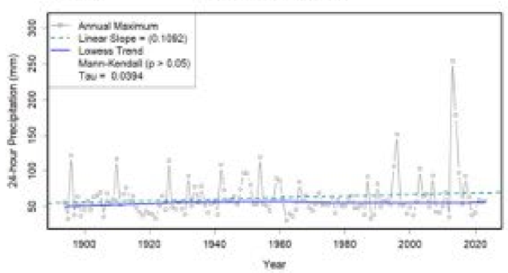
Baltimore



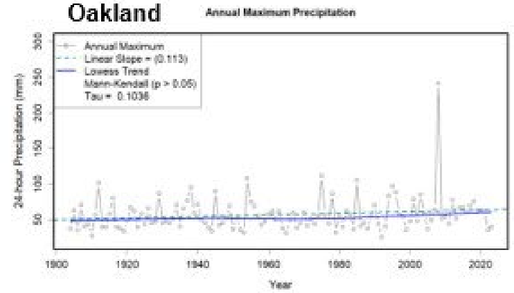
Snow Hill

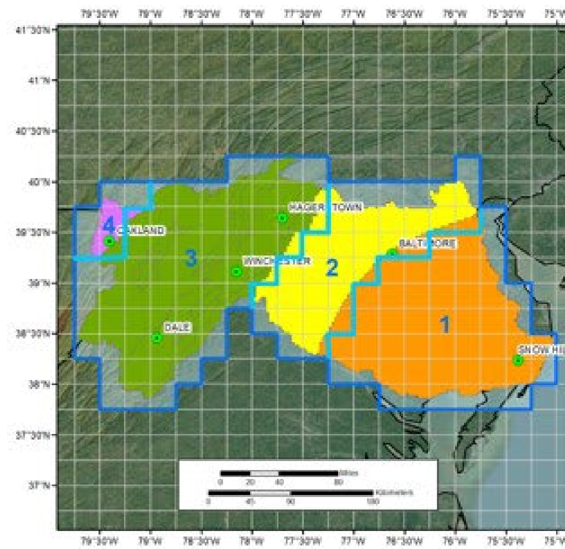


Dale



Oakland



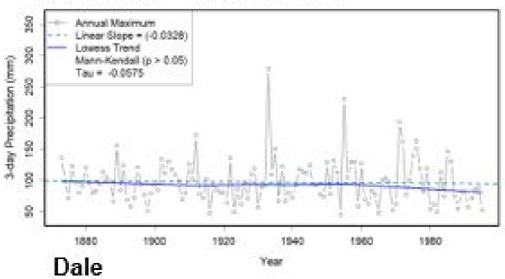


3.1) Station Trend Analysis (3-day)

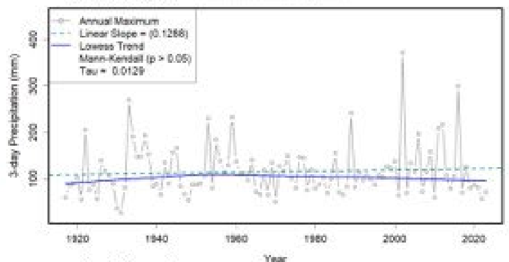
- Station 3-day AMS Trend Analysis (Mann-Kendall)

Station ID	Name	Latitude	Longitude	Elevation	POR	Trend	P-value
USW00013777	BALTIMORE, MD	39.2833	-76.6167	14	123	None	0.3472
USC00442208	DALE, VA	38.4547	-78.9352	1358	130	None	0.0739
USC00186620	OAKLAND, MD	39.4132	-79.4003	2420	120	None	0.3238
USC00188380	SNOW HILL, MD	38.2317	-75.3761	30	107	None	0.8463
USC00181790	HAGERSTOWN, MD	39.6403	-77.6978	532	124	None	0.1812
USC00449186	WINCHESTER, VA	39.1084	-78.1525	680	111	None	0.1112

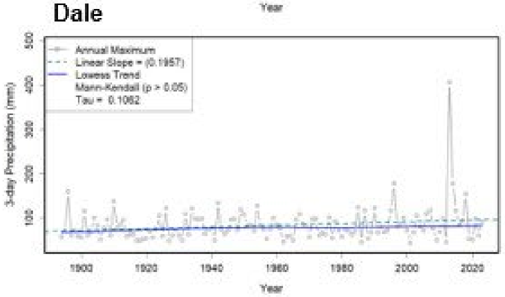
Baltimore



Snow Hill



Dale



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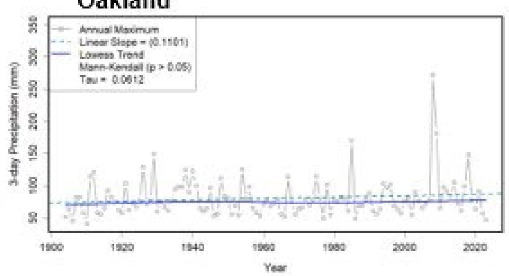

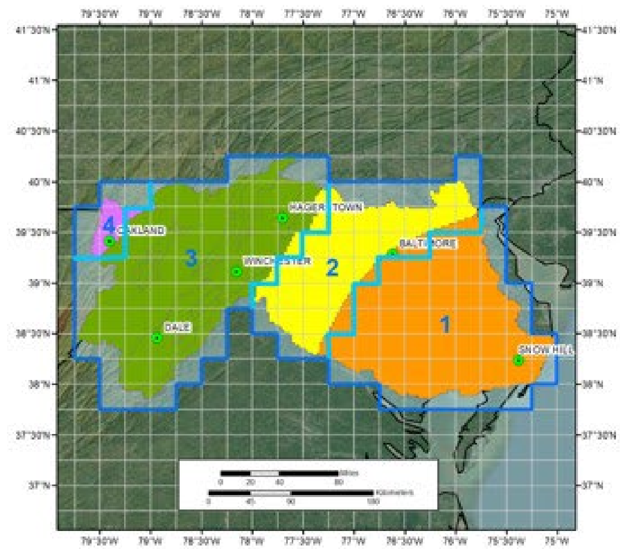

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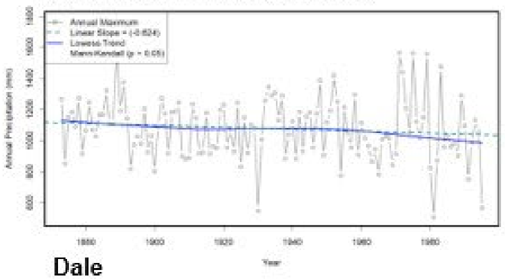
3.1) Station Trend Analysis (365-day)

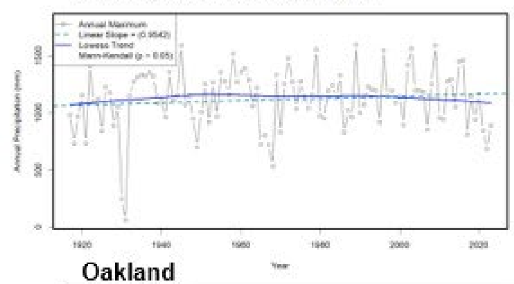
- Station 365-day AMS Trend Analysis (Mann-Kendall)

Station ID	Name	Latitude	Longitude	Elevation	POR	Trend	P-value
USW00013777	BALTIMORE, MD	39.2833	-76.6167	14	123	None	0.1802
USC00442208	DALE, VA	38.4547	-78.9352	1358	130	None	0.7444
USC00186620	OAKLAND, MD	39.4132	-79.4003	2420	120	None	0.4991
USC00188380	SNOW HILL, MD	38.2317	-75.3761	30	107	None	0.6844
USC00181790	HAGERSTOWN, MD	39.6403	-77.6978	532	124	Increase	0.0011
USC00449186	WINCHESTER, VA	39.1084	-78.1525	680	111	None	0.43102

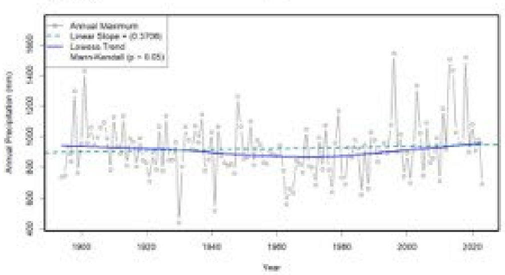
Baltimore



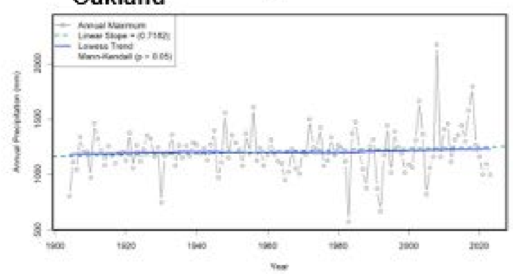
Snow Hill

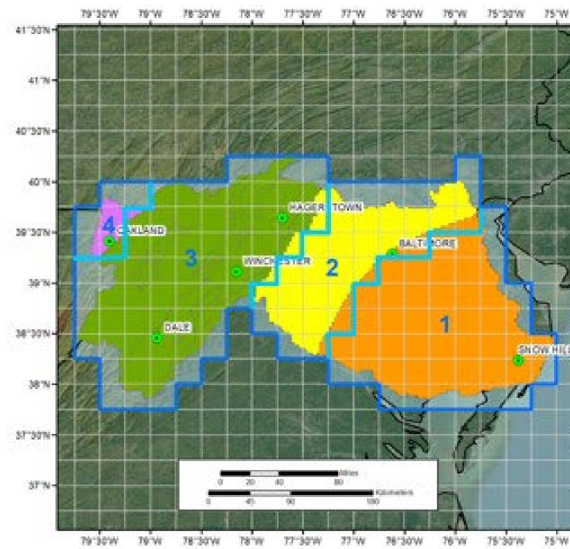


Dale



Oakland





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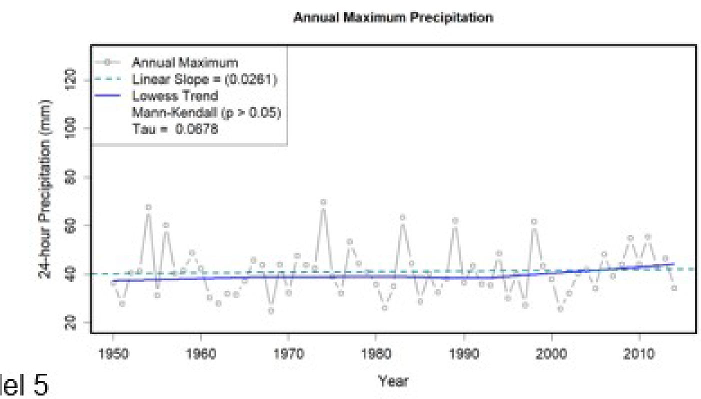
3.1) Model Trend Analysis (1-day Example)

- 1-day AMS Trend Analysis (Mann-Kendall)



- 1) Model 1
  - trend depends on period investigated
    - Historical: **no trend**
    - SP45: **no trend**
    - SP85: **increasing trend**
- 2) Model 2
  - trend depends on period investigated
    - Historical: **no trend**
    - SP45: **no trend**
    - SP85: **increasing trend**
- 3) Model 4
  - trend depends on period investigated
    - Historical: **no trend**
    - SP45: **no trend**
    - SP85: **increasing trend**
- 4) Model 5
  - trend depends on period investigated
    - Historical: **no trend**
    - SP45: **increasing trend**
    - SP85: **increasing trend**
- 5) Model 6
  - trend depends on period investigated
    - Historical: **no trend**
    - SP45: **increasing trend**
    - SP85: **no trend**

Completed for 1-day, 3-day, annual, and by season

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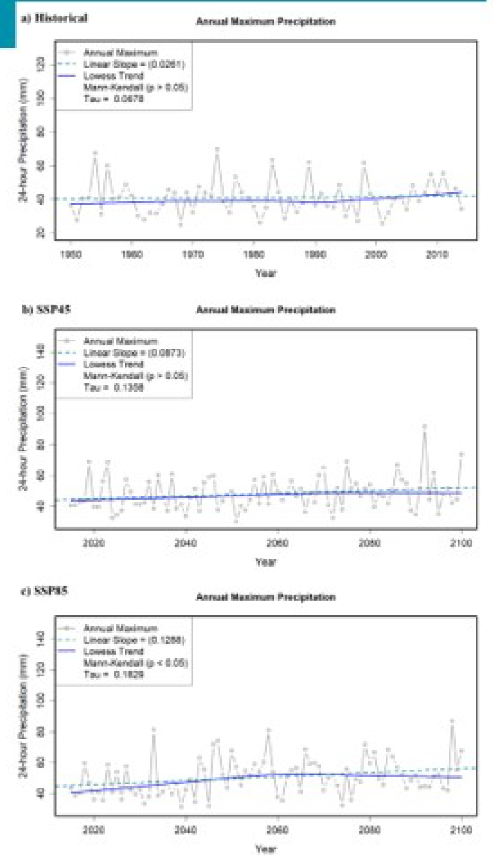
3.1) Climate Model Trend Results

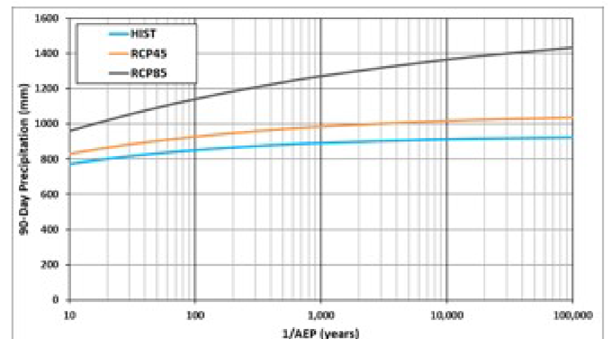
Region 1

	Precipitation			Temperature
	1-day	3-day	Annual	1-day
Historic	23 – no trend 2 – increase 1 – decrease	25 – no trend 0 – increase 1 – decrease	24 – no trend 2 – increase 0 – decrease	8 – no trend 18 – increase 0 – decrease
SSP45	18 – no trend 8 – increase 0 – decrease	21 – no trend 5 – increase 0 – decrease	21 – no trend 5 – increase 0 – decrease	2 – no trend 24 – increase 0 – decrease
SSP85	14 – no trend 12 – increase 0 – decrease	18 – no trend 8 – increase 0 – decrease	11 – no trend 15 – increase 0 – decrease	0 – no trend 26 – increase 0 – decrease



3.2) Frequency Analysis (L-moments)

- 1-day, 3-day, 365-day L-moment Frequency Analysis (Historic, SSP45, SSP85)
- All Precipitation, Summer, Winter
  - Identification of Probability Distribution
  - Goodness-of-fit measures
  - L-moment Ratio Diagram
    - The regional weighted average L-Skewness and L-Kurtosis tend to be near the GEV distribution
  - Derivation of Uncertainty bounds
    - Monte-carlo simulation
  - Point Value Annual Exceedance Estimates
  - Compare 10-, 50-, 100-, 500-, and 1000-year AEPs



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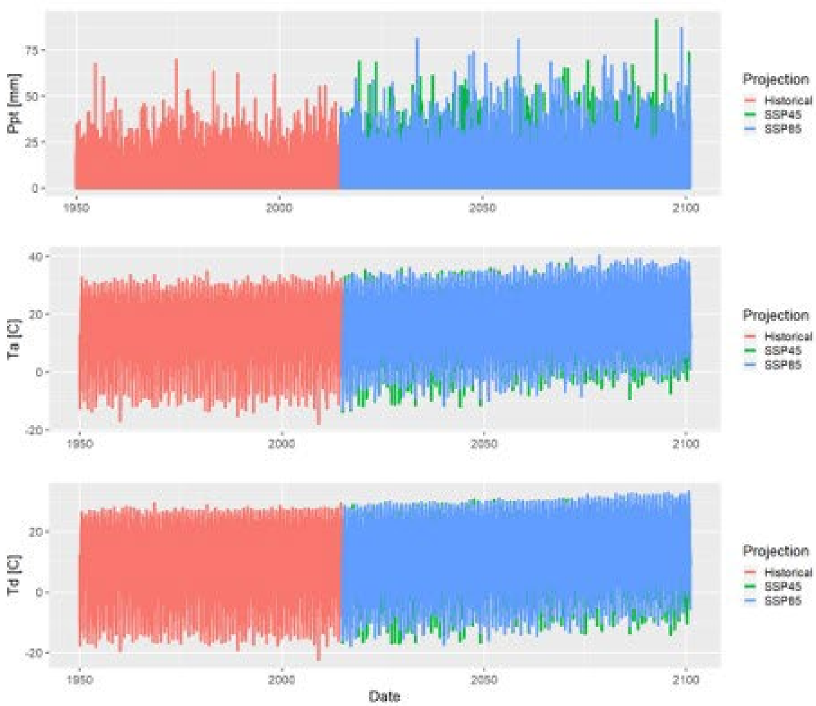
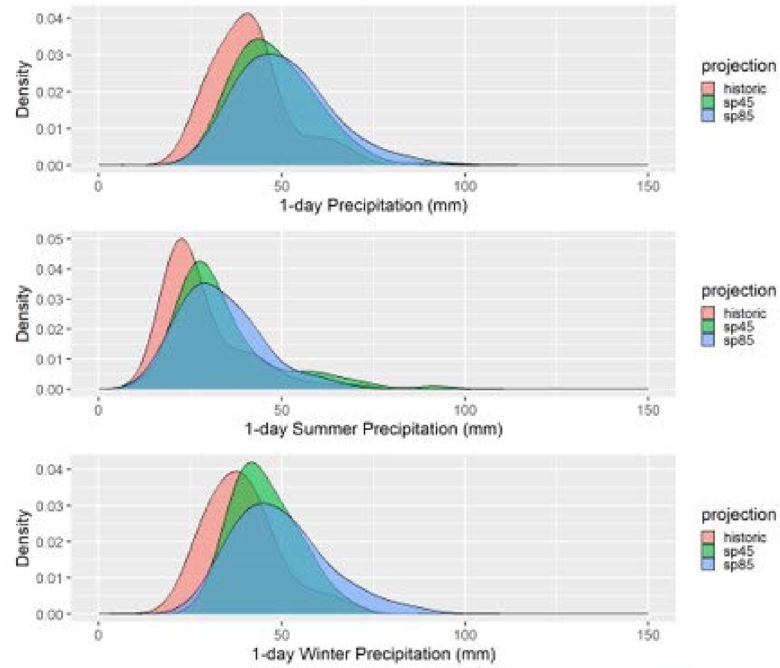
3.2) Climate Model (Model 1)





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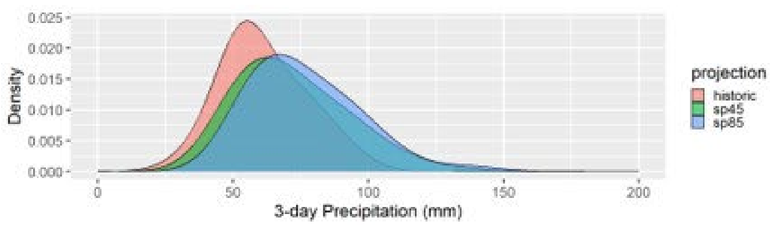
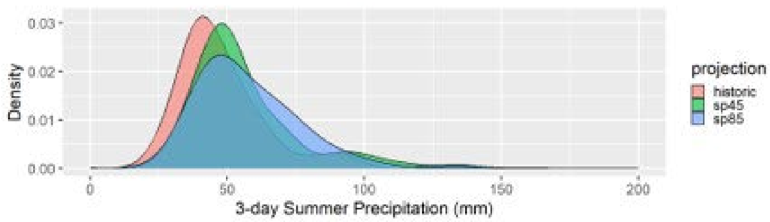
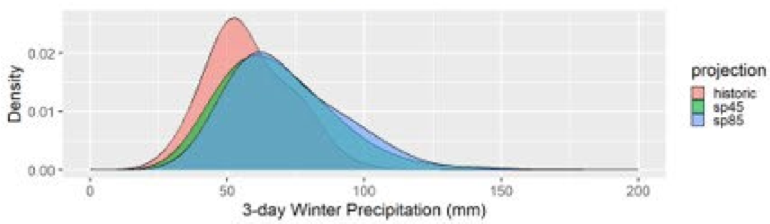
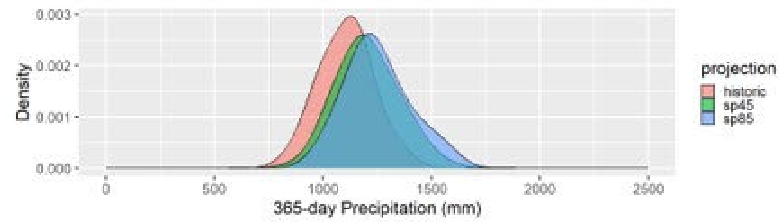
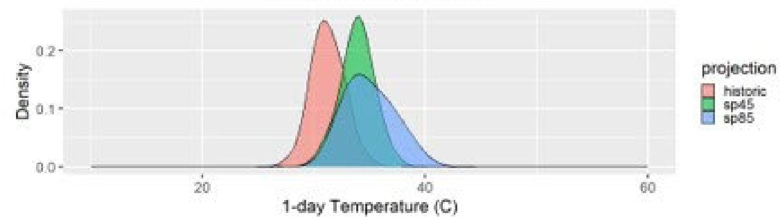
3.2) Climate Model (Model 1)

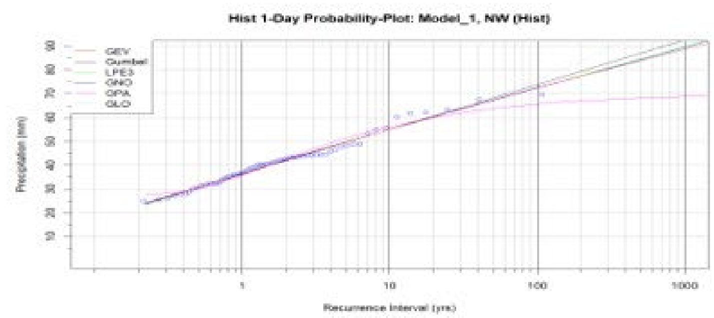












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3.2) Frequency Analysis (Model 1 Example)

*** 1-Day Precipitation

	10yr	50yr	100yr	500yr	1000yr	Pct Change					Average
Historical	54.7	67.3	72.4	83.9	88.7	-	-	-	-	-	
SSP45	62.6	76.6	82.5	96.0	101.8	14%	14%	14%	14%	15%	14%
SSP85	66.8	81.1	86.9	99.5	104.6	22%	21%	20%	19%	18%	20%

*** 1-Day Summer

	10yr	50yr	100yr	500yr	1000yr	Pct Change					Average
Historical	41.0	63.2	75.9	116.0	139.1	-	-	-	-	-	
SSP45	50.1	77.2	92.3	139.0	165.4	22%	22%	22%	20%	19%	21%
SSP85	47.5	61.0	66.5	79.1	84.4	16%	-4%	-12%	-32%	-39%	-14%

*** 1-Day Winter

	10yr	50yr	100yr	500yr	1000yr	Pct Change					Average
Historical	52.3	64.3	69.2	80.1	84.7	-	-	-	-	-	
SSP45	57.3	67.5	71.6	80.4	84.0	10%	5%	3%	0%	-1%	3%
SSP85	66.2	81.8	88.2	102.7	108.8	27%	27%	28%	28%	28%	28%

*** 3-Day Precipitation

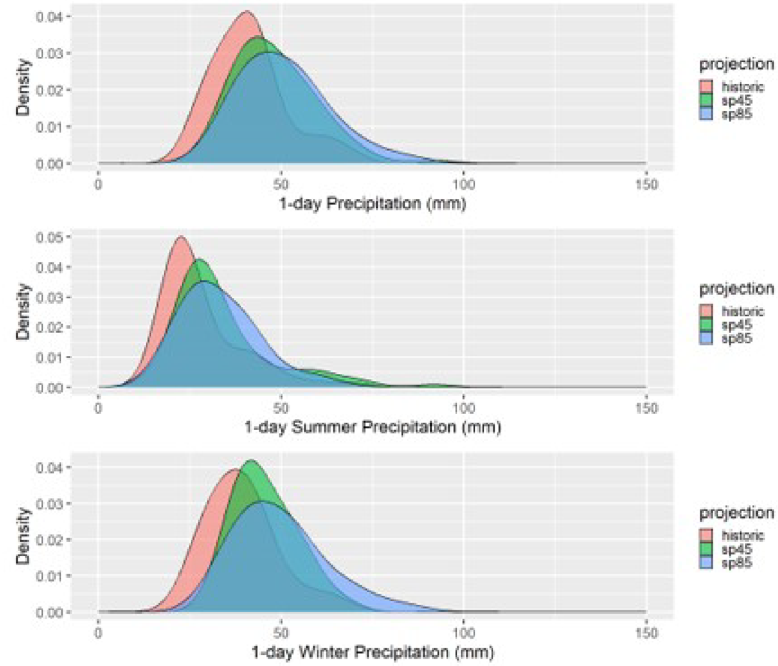
	10yr	50yr	100yr	500yr	1000yr	Pct Change					Average
Historical	81.7	98.5	104.9	118.2	123.4	-	-	-	-	-	
SSP45	98.3	123.4	133.8	157.2	167.0	20%	25%	28%	33%	35%	28%
SSP85	102.1	127.4	138.0	162.5	173.0	25%	29%	32%	37%	40%	33%

* 3-Day Summer

	10yr	50yr	100yr	500yr	1000yr	Pct Change					Average
Historical	66.7	91.1	103.0	134.7	150.4	-	-	-	-	-	
SSP45	78.7	114.5	133.9	191.5	223.1	18%	26%	30%	42%	48%	33%
SSP85	80.1	108.5	122.2	158.1	175.6	20%	19%	19%	17%	17%	18%

* 3-Day Winter

	10yr	50yr	100yr	500yr	1000yr	Pct Change					Average
Historical	77.4	92.7	98.5	110.3	114.7	-	-	-	-	-	
SSP45	93.8	117.7	127.6	149.6	158.8	21%	27%	30%	36%	38%	30%
SSP85	97.1	125.0	137.5	168.0	181.8	25%	35%	40%	52%	58%	42%



*** 365-Day

	10yr	50yr	100yr	500yr	1000yr	Pct Change					Average
Historical	1259	1339	1363	1408	1415	-	-	-	-	-	
SSP45	1391	1513	1554	1632	1658	11%	13%	14%	16%	17%	14%
SSP85	1449	1602	1658	1772	1815	15%	20%	22%	26%	28%	22%

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3.3) Moisture Maximization Ratio Analysis

- Estimate 1-day and 3-day **Ppt_{adj}** for top 30 1-day and 3-day precipitation events
  - Extracted top 30 precipitation events (**P**) and associated meteorological data
  - Derive monthly dew point (td) climatologies (Historic, SSP45, SSP85)
  - Quantified each storm events precipitable water (**Pobs**)
  - Quantified each storm events climatological maximum precipitable water (**Pw_100**)
  - Calculated each storm events maximization factor
    - (**r = PW_100 / PW_obs**)
  - Estimated **Ppt_{adj}** (~PMP) value for each event (**P * r**)

  - Slides split by two topics
    - 3a = Monthly Td analysis
    - 3b = Top 30 rainfall estimation

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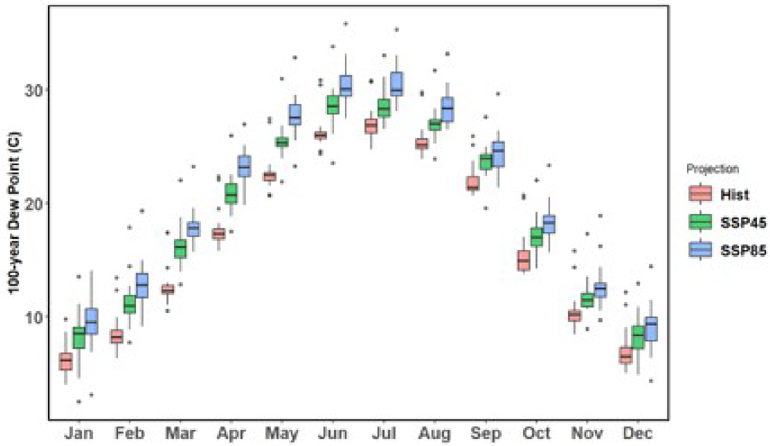
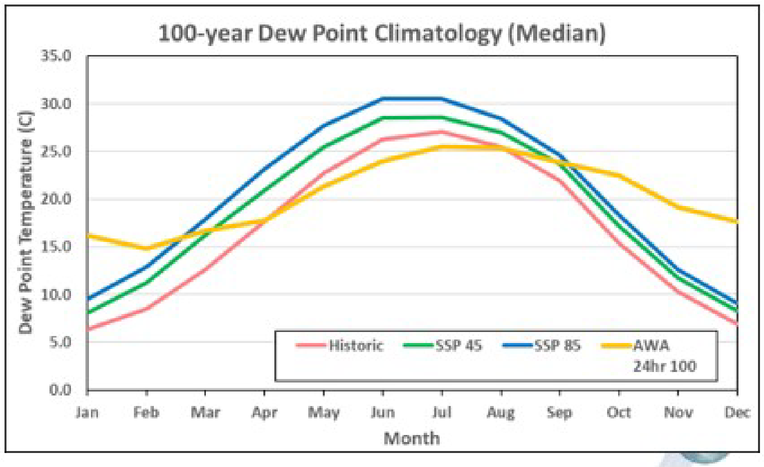
3.3) Td Analysis

- Calculate monthly dew point temperature (Td) 100-year climatology
  - all months have similar shape/seasonality
    - the **SSP 85** has largest range
  - Historic Average – 16.8 C
  - SSP45 Average – 18.9 C
  - SSP85 Average – 20.4 C





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3.3) 1-Day Ppt_{max} Analysis

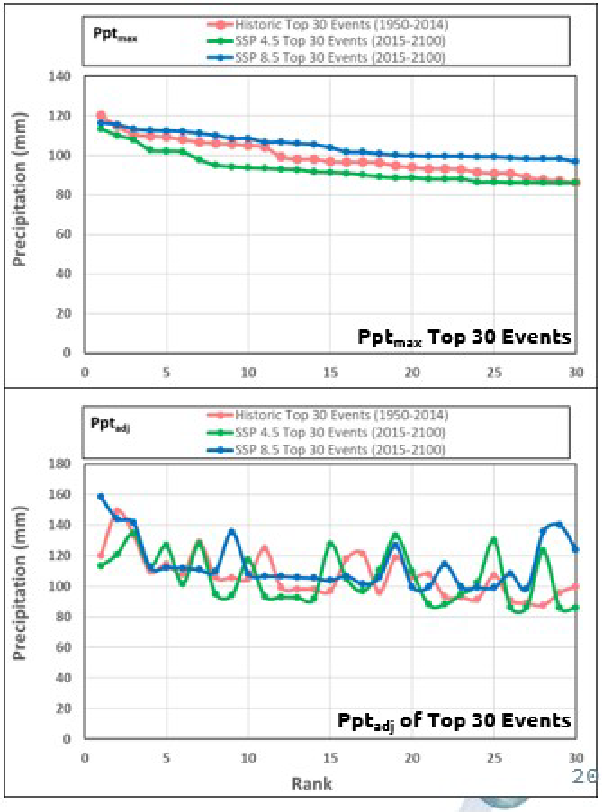
- Estimate **1-day** **Ppt_{adj}** for top 30 1-day precipitation events
  - Extracted top 30 precipitation events (**P**) and associated meteorological data
  - Quantified each storm events precipitable water (**Pobs**)
  - Quantified each storm events climatological maximum precipitable water (**Pw_100**)
  - Calculated each storm events maximization factor (**r = PW_100 / PW_obs**)
  - Estimated **Ppt_{adj}** value for each event (**P * r**)

1-Day Moisture Maximization

Ppt_{max}	(mm)	Pct Change
Historical	120	-
SSP45	113	-6%
SSP85	116	-3%

+++ values represent 1-day not 24-hour

Ppt_{adj}	(mm)	rank	Pct Change
Historical	149	2	-
SSP45	135	3	-10%
SSP85	158	1	6%



3.3) 3-Day Ppt_{max} Analysis

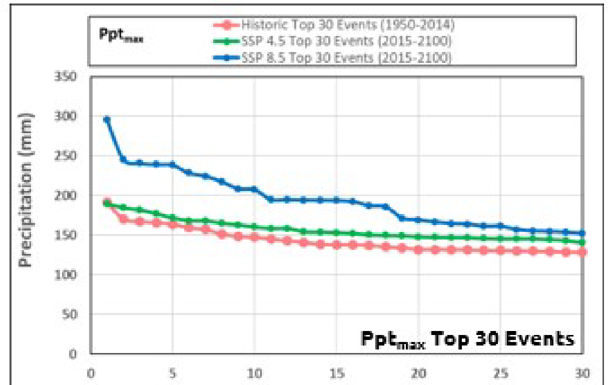
- Estimate **3-day** **Ppt_{adj}** for top 30 3-day precipitation events
  - Extracted top 30 precipitation events (**P**) and associated meteorological data
  - Quantified each storm events precipitable water (**Pobs**)
  - Quantified each storm events climatological maximum precipitable water (**Pw_100**)
  - Calculated each storm events maximization factor (**r = PW_100 / PW_obs**)
  - Estimated **Ppt_{adj}** value for each event (**P * r**)

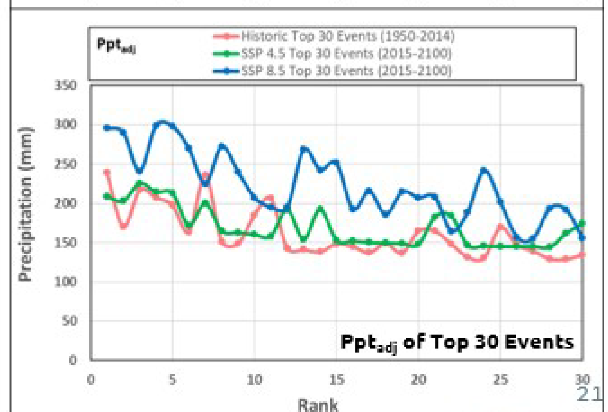
3-Day Moisture Maximization

Ppt_{max}	(mm)	Pct Change
Historical	191	-
SSP45	189	-1%
SSP85	295	54%

Ppt_{adj}	(mm)	rank	Pct Change
Historical	239	1	-
SSP45	225	3	-6%
SSP85	299	4	25%

+++ values represent 3-day not 72-hour





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4) Summary Trend Results

Region 1

	Precipitation			Temperature
	1-day	3-day	Annual	1-day
Historic	23 – no trend 2 – increase 1 – decrease	25 – no trend 0 – increase 1 – decrease	24 – no trend 2 – increase 0 – decrease	8 – no trend 18 – increase 0 – decrease
SSP45	18 – no trend 8 – increase 0 – decrease	21 – no trend 5 – increase 0 – decrease	21 – no trend 5 – increase 0 – decrease	2 – no trend 24 – increase 0 – decrease
SSP85	14 – no trend 12 – increase 0 – decrease	18 – no trend 8 – increase 0 – decrease	11 – no trend 15 – increase 0 – decrease	0 – no trend 26 – increase 0 – decrease

						PPT			TA
STID	STATION	LATITUDE	LONGITUDE	ELEVATION	POR	1-day	3-day	365-day	1-day
USW00013777	BALTIMORE, MD	39.2833	-76.6167	14	123	None	None	None	Increase
USC00442208	DALE, VA	38.4547	-78.9352	1358	130	None	None	None	None
USC00186620	OAKLAND, MD	39.4132	-79.4003	2420	120	None	None	None	None
USC00188380	SNOW HILL, MD	38.23173	-75.37606	30	107	None	None	None	None
USC00181790	HAGERSTOWN, MD	39.64034	-77.69778	532	124	None	None	Increase	None
USC00449186	WINCHESTER, VA	39.10837	-78.15252	680	111	Increase	None	None	Decrease

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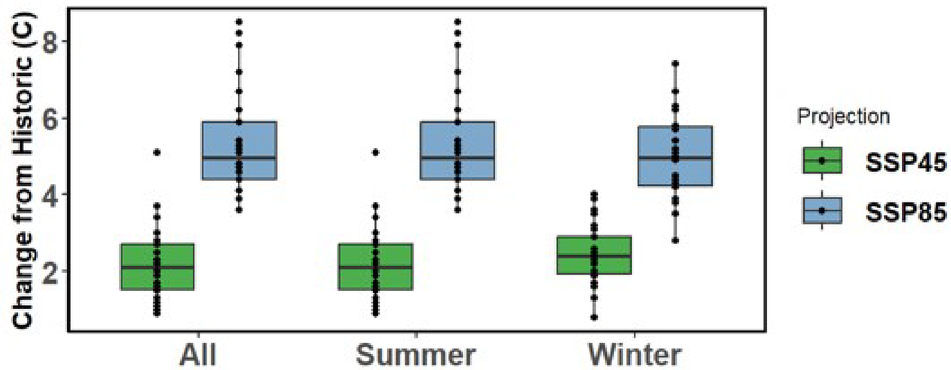
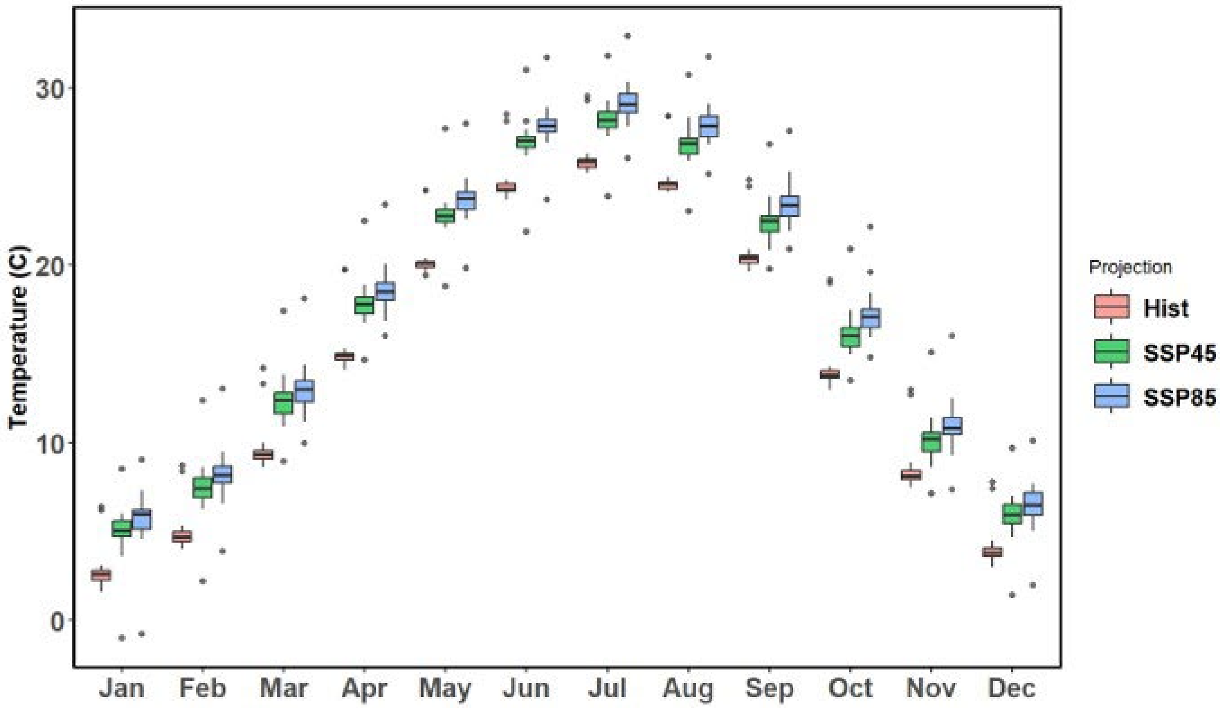
4) Summary Temperature Annual Maximum

- **1-day (ssp45; ssp85)**
  - All = 2.1 C; 5.0 C
  - Summer = 2.1 C; 5.0 C
  - Winter = 2.4 C; 4.9 C



*** Frequency based results, 26 RCM
+++ Boxplots based on these data

4) Summary Monthly Temperature



*** Climatology, based on 26 RCM

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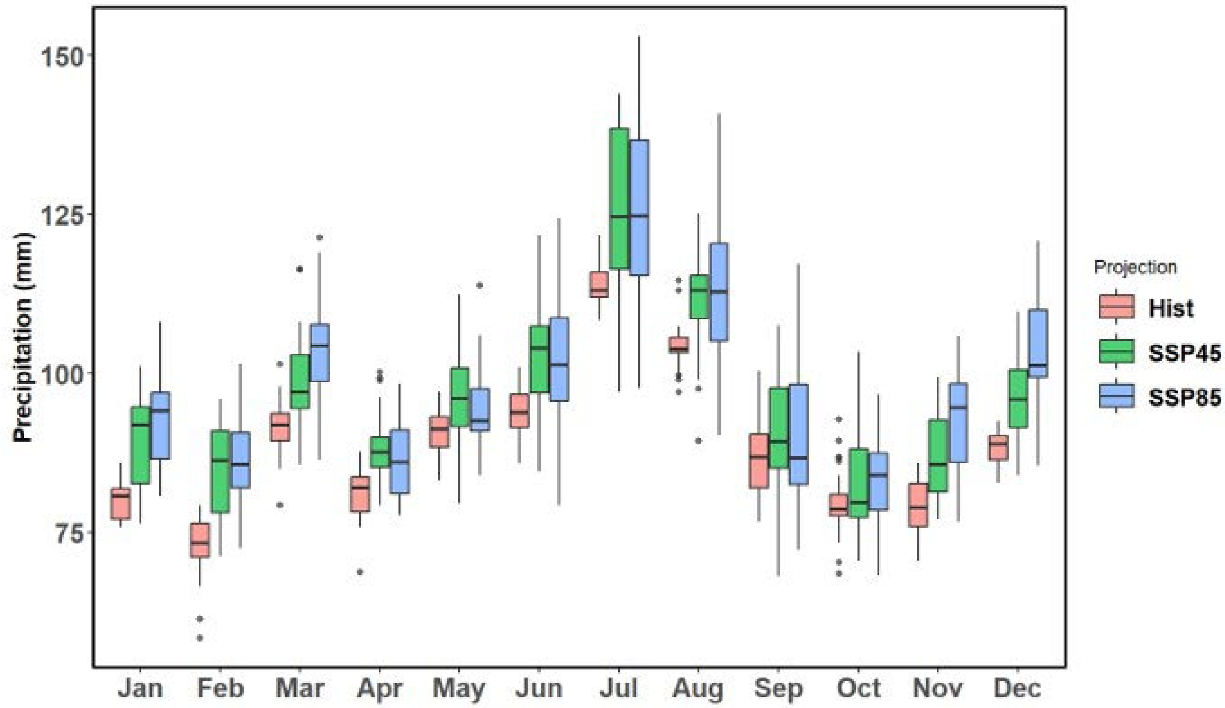
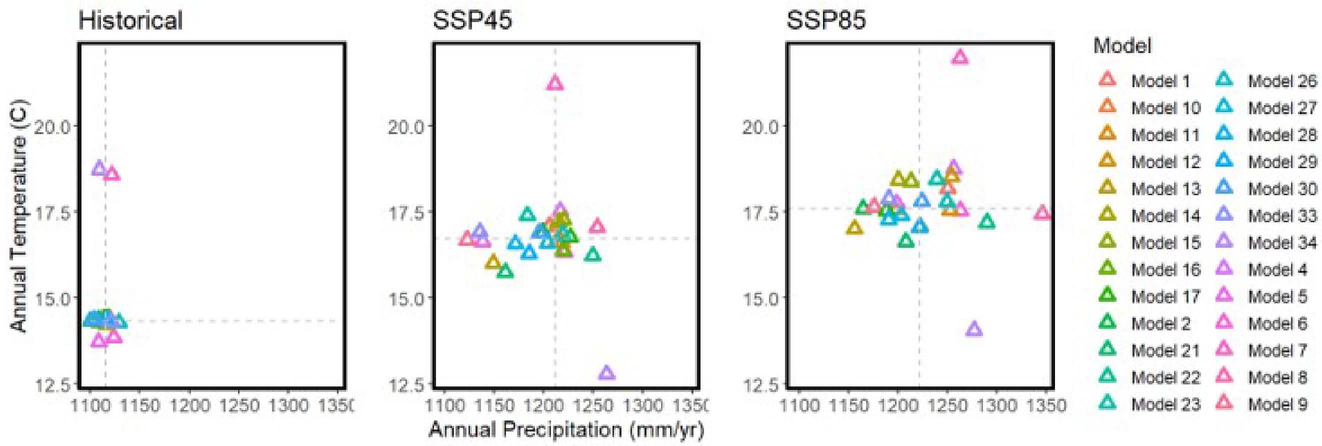
4) Summary Monthly Precipitation



*** Climatology, based on 26 RCM

4) Summary Annual Temperature and Precipitation

- **Annual Climatology (temp, ppt)**
  - Historical = 14.3 C; 1115 mm
  - SSP45 = 16.7 C; 1212 mm (2.4 C; 9%)
  - SSP85 = 17.6 C; 1222 mm (3.3 C; 10%)



*** Climatology, based on 26 RCM

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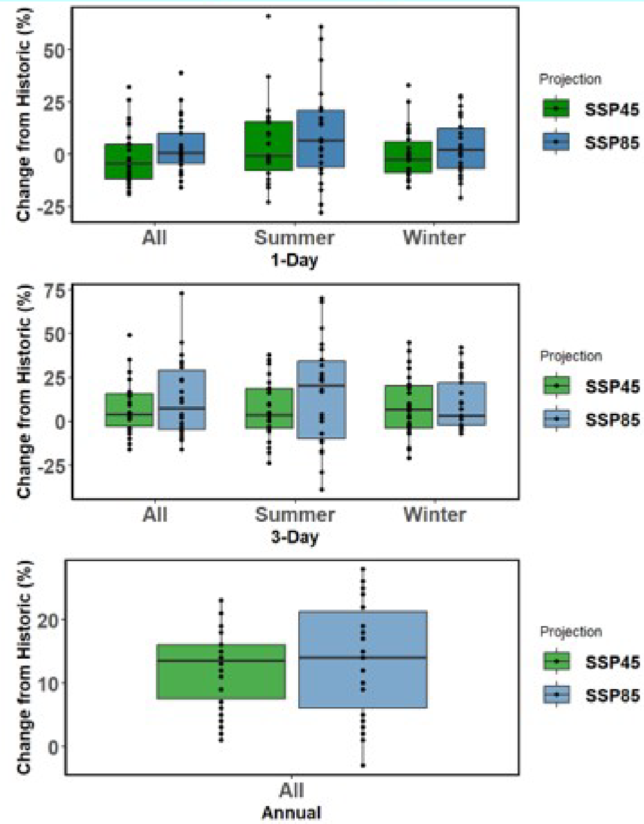
4) Summary Precipitation Frequency

- 1-day (sp45; sp85)
  - All = -5%; 1%
  - Summer = -1%; 7%
  - Winter = -2%; 2%
- 3-day
  - All = 4%; 7%
  - Summer = 4%; 21%
  - Winter = 6%; 3%
- Annual
  - All = 13%; 14%



*** Frequency based results, 26 RCM
+++ Boxplots based on these data

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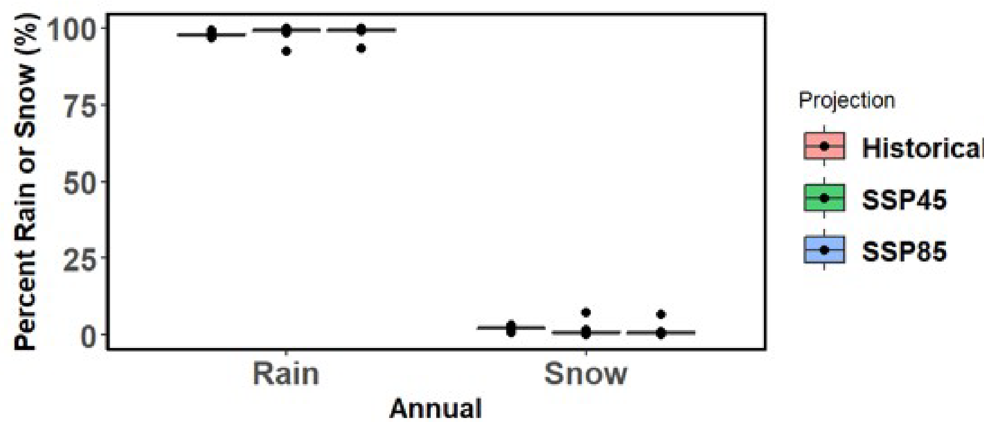
4) Summary Precipitation Type

- **Temperature Threshold 0-degree Celsius**

	Hist.	SSP45	SSP85
Rain, %	98	99	99
Snow, %	2	1	1



4) Summary Ratio Maximization (PPt_{adj})

- **Dew Point Climatologies**
  - All scenarios produce similar shape/season of monthly 100yr Td values
  - More of scaling adjustment of 1.2 C Historic to SSP 45; 2.2C for Hist to SSP85

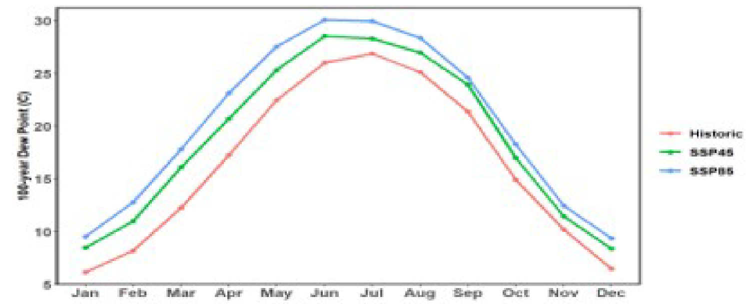
- **1-day (SSP45; SSP85)**
  - All = -10%; 6%
- **3-day**
  - All = -6%; 25%
- **Moisture Max. (SSP45; SSP85)**
  - All = 10%; 18%

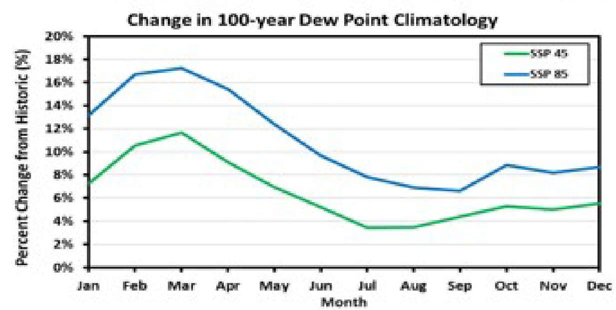
1-Day Moisture Maximization

Ppt_{max}	(mm)	Pct Change	Ppt_{adj}	(mm)	rank	Pct Change
Historical	120	-	Historical	149	2	-
SSP45	113	-6%	SSP45	135	3	-10%
SSP85	116	-3%	SSP85	158	1	6%

3-Day Moisture Maximization

Ppt_{max}	(mm)	Pct Change	Ppt_{adj}	(mm)	rank	Pct Change
Historical	191	-	Historical	239	1	-
SSP45	189	-1%	SSP45	225	3	-6%
SSP85	295	54%	SSP85	299	4	25%





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5) Application of Climate Change Results

Annual Maximum/Frequency Analysis

	SSP45				SSP85			
	Mean	**Median**	**10th**	**90th**	**Mean**	**Median**	**10th**	**90th**
Temperature 1-Day; C	**2.2**	**2.1**	1.0	3.2	**5.3**	**5.0**	4.0	7.5
Temperature 1-Day Summer; C	**2.2**	**2.1**	1.0	3.2	**5.3**	**5.0**	4.0	7.5
Temperature 1-Day Winter PF; C	**2.4**	**2.4**	1.6	3.5	**5.0**	**4.9**	3.8	6.3
Precipitation 1-Day PF; %	**-2**	-5	-17	16	**3**	**1**	-10	20
Precipitation 1-Day Summer PF; %	**5**	**-1**	-14	21	**9**	7	-16	37
Precipitation 1-Day Winter PF; %	**-1**	**-2**	-12	13	**4**	**2**	-11	21
Precipitation 3-Day PF; %	**8**	**4**	-12	26	**13**	7	-9	36
Precipitation 3-Day Summer PF; %	7	**4**	-13	33	**16**	**21**	-17	53
Precipitation 3-Day Winter PF; %	**9**	**6**	-11	32	**10**	**3**	-5	32
Precipitation Annual PF; %	**12**	**13**	3	19	**13**	**14**	1	25
1-Day Moisture Maximization; %	**No Change**				**No Change**			
3-Day Moisture Maximization; %	**No Change**				**Potential Change**			

Climate Change Projections from 2015 through 2100

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5) Application of Climate Change Results

- Results are presented as median values based on model ensemble
- Design Storm and Routing Applications
  - Recommend SSP45 climate scenario as "likely", SSP85 as "unlikely"
- Results are through 2100 and can be scaled to other periods
  - Example, for 2050 adjustment scale 2100 results by 0.59.

	2050	2100
1-Day Summer PF; %	0	-1
1-Day Winter PF; %	-1	-2
3-Day Summer PF; %	2	4
3-Day Winter PF; %	4	6

Climate Change Projections from 2015 through 2100

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5) Application of Climate Change Results

Monthly Temperature Analysis

	Historical		SSP45		SSP85		Mean Delta		Median Delta	
	Mean	Median	Mean	Median	Mean	Median	SSP45	SSP85	SSP45	SSP85
January	2.7	2.6	4.9	5.1	5.6	6.0	*2.2*	*2.9*	*2.5*	*3.4*
February	5.0	4.7	7.4	7.4	8.2	8.2	*2.4*	*3.2*	*2.7*	*3.5*
March	9.6	9.3	12.4	12.4	13.0	13.0	*2.8*	*3.4*	*3.1*	*3.7*
April	15.2	14.9	17.8	17.8	18.6	18.5	*2.6*	*3.4*	*2.9*	*3.6*
May	20.3	20.1	22.8	22.8	23.7	23.7	*2.5*	*3.4*	*2.7*	*3.6*
June	24.6	24.3	26.9	27.0	27.8	27.9	*2.3*	*3.3*	*2.8*	*3.6*
July	26.1	25.9	28.1	28.2	29.1	29.1	*2.1*	*3.1*	*2.3*	*3.2*
August	24.8	24.6	26.8	26.9	27.9	27.8	*2.0*	*3.0*	*2.3*	*3.2*
September	20.6	20.4	22.4	22.5	23.5	23.4	*1.8*	*2.9*	*2.1*	*3.0*
October	14.2	13.8	16.1	16.0	17.2	17.1	*1.9*	*3.0*	*2.2*	*3.3*
November	8.5	8.1	10.1	10.2	11.0	10.8	*1.7*	*2.5*	*2.1*	*2.7*
December	4.0	3.8	5.9	5.9	6.5	6.5	*1.8*	*2.4*	*2.1*	*2.7*

Climate Change Projections from 2015 through 2100

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5) Application of Climate Change Results

Monthly Precipitation Analysis

	Historical		SSP45		SSP85		Mean Delta		Median Delta	
	Mean	Median	Mean	Median	Mean	Median	SSP45	SSP85	SSP45	SSP85
January	80.0	80.7	89.4	91.9	93.4	94.1	*1.12*	*1.14*	*1.14*	*1.17*
February	72.9	73.3	84.4	86.3	85.9	85.7	*1.16*	*1.18*	*1.18*	*1.17*
March	91.5	91.8	98.9	97.0	103.7	104.4	*1.08*	*1.06*	*1.06*	*1.14*
April	80.8	82.0	88.4	87.6	86.6	86.0	*1.09*	*1.07*	*1.07*	*1.05*
May	90.9	91.2	95.9	96.1	94.6	92.5	*1.06*	*1.05*	*1.05*	*1.01*
June	94.0	93.8	103.0	103.9	101.7	101.3	*1.09*	*1.11*	*1.11*	*1.08*
July	114.1	113.0	124.8	124.6	125.5	124.8	*1.09*	*1.10*	*1.10*	*1.10*
August	104.2	103.9	111.3	113.0	112.5	112.8	*1.07*	*1.09*	*1.09*	*1.09*
September	86.9	86.9	90.8	89.2	90.3	86.7	*1.04*	*1.03*	*1.03*	*1.00*
October	79.5	78.6	81.9	79.7	83.3	83.9	*1.03*	*1.01*	*1.01*	*1.07*
November	79.0	78.9	86.9	85.6	92.3	94.6	*1.10*	*1.09*	*1.09*	*1.20*
December	88.3	88.9	95.8	95.9	103.3	101.2	*1.09*	*1.08*	*1.08*	*1.14*

Climate Change Projections from 2015 through 2100

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6) Conclusion

TREND

- Historical precipitation – **no change** in precipitation
- SSP45 precipitation – **no change** in precipitation
- SSP85 precipitation – mix between **no change** and an **increase** in precipitation

FREQUENCY

- 1-day – SSP45 and SPP85 median results are within +/- 20% uncertainty which provide more confidence for **no change** in precipitation magnitude by 2100
- 3-day – SSP45 and SPP85 winter median results are within +/- 20% uncertainty which provide more confidence for **no change** in precipitation magnitude by 2100. SPP85 summer median results are greater than +/- 20% uncertainty which provide more confidence for **an increase** in precipitation magnitude by 2100
- Annual – SSP45 and SPP85 median results are within +/- 20% uncertainty which provide more confidence for **no change** in precipitation magnitude by 2100

CLIMATOLOGY

- Monthly Climatology – small increase in precipitation (within +/-20%) and **increase** in temperature by 2100
- Annual Climatology – **no change** in annual precipitation (within +/-20%) and **an increase** in annual temperature by 2100

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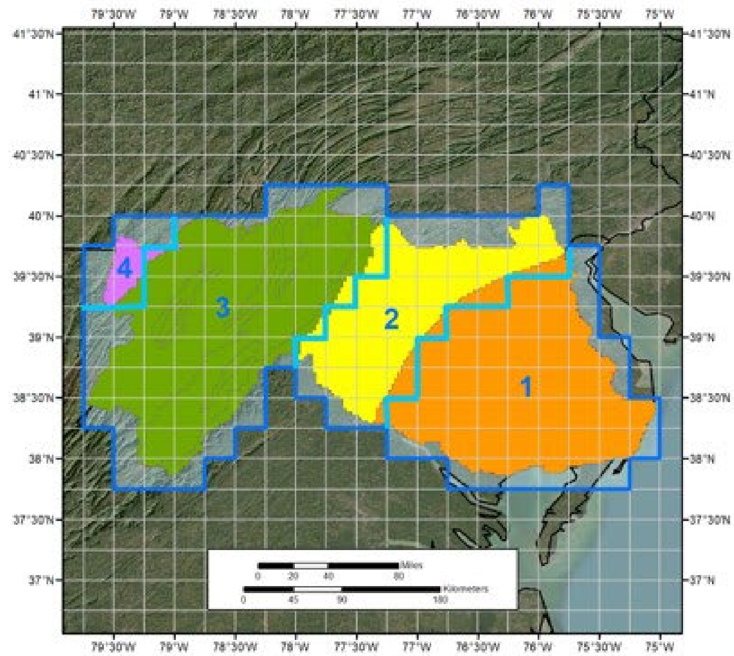
Region 2 - Climate Change Results

NASA Earth Exchange Global Daily Downscaled Projections (NEX-GDDP-CMIP6)

- Total of 35 climate models
- 9 models did not have all data
  - (6) Missing years and/or variables
  - (3) 30-days per month
- Used 26 models on daily time step
  - Temperature
  - Relative humidity
  - Precipitation



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Climate Change Analysis Methods

- **1) Trend Analysis** for 1-day, 3-day, and Annual
  - Station Data
  - Model projections (Historic, SSP45, SSP85)
- **2) Monthly and Annual Analysis**
  - Model projections (Historic, SSP45, SSP85)
- **3) Precipitation Frequency Analysis** for 1-day, 3-day, 30-day, 90-day, and Annual
  - Precipitation, Summer Period, and Winter Period
  - Model projections (Historic, SSP45, SSP85)
  - Estimate PF for 1-year through 1000-year
  - Quantify changes
- **4) Moisture Maximization Analysis** for 1-day and 3-day
  - Derive model projection monthly Td climatologies (Historic, SSP45, SSP85)
  - Quantify changes

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Region 2 - Trend Results

	Precipitation			Temperature
	1-day	3-day	Annual	1-day
Historic	24 – no trend 1 – increase 1 – decrease	24 – no trend 1 – increase 1 – decrease	23 – no trend 3 – increase 0 – decrease	8 – no trend 18 – increase 0 – decrease
SSP45	21 – no trend 5 – increase 0 – decrease	20 – no trend 6 – increase 0 – decrease	17 – no trend 9 – increase 0 – decrease	5 – no trend 21 – increase 0 – decrease
SSP85	17 – no trend 9 – increase 0 – decrease	16 – no trend 10 – increase 0 – decrease	7 – no trend 19 – increase 0 – decrease	0 – no trend 26 – increase 0 – decrease

Region 2 - Climate Change Results

Annual Maximum/Frequency Analysis

	SSP45				SSP85			
	Mean	**Median**	**10th**	**90th**	**Mean**	**Median**	**10th**	**90th**
Temperature 1-Day; C	**2.4**	**2.3**	1.0	3.3	**5.7**	**5.1**	4.0	8.0
Temperature 1-Day Summer; C	**2.4**	**2.3**	1.0	3.3	**5.7**	**5.1**	4.0	8.0
Temperature 1-Day Winter PF; C	**2.5**	**2.4**	1.5	3.7	**5.3**	**5.3**	4.0	6.5
Precipitation 1-Day PF; %	**9**	**6**	-7	33	**10**	**6**	-10	36
Precipitation 1-Day Summer PF; %	**13**	**10**	-11	44	**9**	**3**	-17	45
Precipitation 1-Day Winter PF; %	**11**	**7**	-4	29	**14**	**13**	-1	32
Precipitation 3-Day PF; %	**12**	**16**	-5	26	**10**	**10**	-11	32
Precipitation 3-Day Summer PF; %	**9**	**3**	-17	45	**7**	**11**	-20	32
Precipitation 3-Day Winter PF; %	**15**	**15**	-5	36	**13**	**15**	-2	31
Precipitation Annual PF; %	**11**	**11**	5	20	**13**	**13**	3	23
1-Day Moisture Maximization; %	**No Change**				**No Change**			
3-Day Moisture Maximization; %	**No Change**				**No Change**			

Climate Change Projections from 2015 through 2100

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Region 2 - Application of Climate Change Results

Monthly Temperature Analysis

	Historical		SSP45		SSP85		Mean Delta		Median Delta	
	Mean	**Median**	**Mean**	**Median**	**Mean**	**Median**	**SSP45**	**SSP85**	**SSP45**	**SSP85**
January	1.1	0.9	3.5	3.6	4.1	4.3	***2.4***	***3.1***	***2.7***	***3.4***
February	3.6	3.3	6.2	5.9	7.0	6.9	***2.6***	***3.4***	***2.6***	***3.6***
March	8.4	8.2	11.4	11.3	12.0	11.9	***3.0***	***3.7***	***3.2***	***3.7***
April	14.3	13.9	17.0	16.8	17.9	17.8	***2.7***	***3.6***	***2.9***	***3.9***
May	19.5	19.2	22.2	22.0	23.2	23.2	***2.7***	***3.6***	***2.8***	***4.0***
June	23.9	23.5	26.4	26.4	27.4	27.3	***2.5***	***3.5***	***2.9***	***3.8***
July	25.4	25.0	27.6	27.6	28.8	28.7	***2.2***	***3.4***	***2.6***	***3.7***
August	24.1	23.8	26.3	26.1	27.5	27.3	***2.2***	***3.4***	***2.4***	***3.6***
September	19.5	19.2	21.5	21.3	22.7	22.5	***2.0***	***3.1***	***2.1***	***3.3***
October	12.8	12.5	14.8	14.8	15.9	15.8	***1.9***	***3.1***	***2.3***	***3.3***
November	6.8	6.5	8.5	8.6	9.4	9.2	***1.7***	***2.6***	***2.1***	***2.7***
December	2.4	2.1	4.1	4.2	4.8	4.8	***1.7***	***2.4***	***2.1***	***2.7***

Climate Change Projections from 2015 through 2100

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Region 2 - Application of Climate Change Results

Monthly Precipitation Analysis

	Historical		SSP45		SSP85		Mean Delta		Median Delta	
	Mean	Median	Mean	Median	Mean	Median	SSP45	SSP85	SSP45	SSP85
January	71.8	72.0	81.9	82.0	86.2	85.5	*1.14*	*1.14*	*1.14*	*1.19*
February	66.2	66.8	78.1	78.8	78.3	77.5	*1.18*	*1.18*	*1.18*	*1.16*
March	86.8	86.2	96.1	94.0	100.5	101.7	*1.11*	*1.09*	*1.09*	*1.18*
April	83.6	83.2	94.1	93.6	92.4	93.4	*1.13*	*1.12*	*1.12*	*1.12*
May	99.3	99.1	105.4	105.9	103.6	103.9	*1.06*	*1.07*	*1.07*	*1.05*
June	96.6	96.9	103.6	104.5	101.7	99.8	*1.07*	*1.08*	*1.08*	*1.03*
July	104.0	104.1	110.5	111.0	111.3	110.3	*1.06*	*1.07*	*1.07*	*1.06*
August	92.6	92.7	99.3	99.5	100.2	97.6	*1.07*	*1.07*	*1.07*	*1.05*
September	87.1	88.1	90.6	89.6	88.4	87.2	*1.04*	*1.02*	*1.02*	*0.99*
October	80.4	79.3	82.7	80.6	83.0	84.3	*1.03*	*1.02*	*1.02*	*1.06*
November	80.9	81.1	89.2	88.1	93.2	93.0	*1.10*	*1.09*	*1.09*	*1.15*
December	81.9	82.3	89.2	89.4	95.9	95.6	*1.09*	*1.09*	*1.09*	*1.16*

Climate Change Projections from 2015 through 2100

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Region 2 Conclusion

TREND

- Historical precipitation – **no change** in precipitation
- SSP45 precipitation – **no change** in precipitation
- SSP85 precipitation – mix between **no change** and an **increase** in precipitation

FREQUENCY

- 1-day – SSP45 and SPP85 median results are within +/- 20% uncertainty which provide more confidence for **no change** in precipitation magnitude by 2100
- 3-day – SSP45 and SPP85 median results are within +/- 20% uncertainty which provide more confidence for **no change** in precipitation magnitude by 2100
- Annual – SSP45 and SPP85 median results are within +/- 20% uncertainty which provide more confidence for **no change** in precipitation magnitude by 2100

CLIMATOLOGY

- Monthly Climatology – small increase in precipitation (within +/-20%) and **increase** in temperature by 2100
- Annual Climatology – **no change** in annual precipitation (within +/-20%) and **an increase** in annual temperature by 2100

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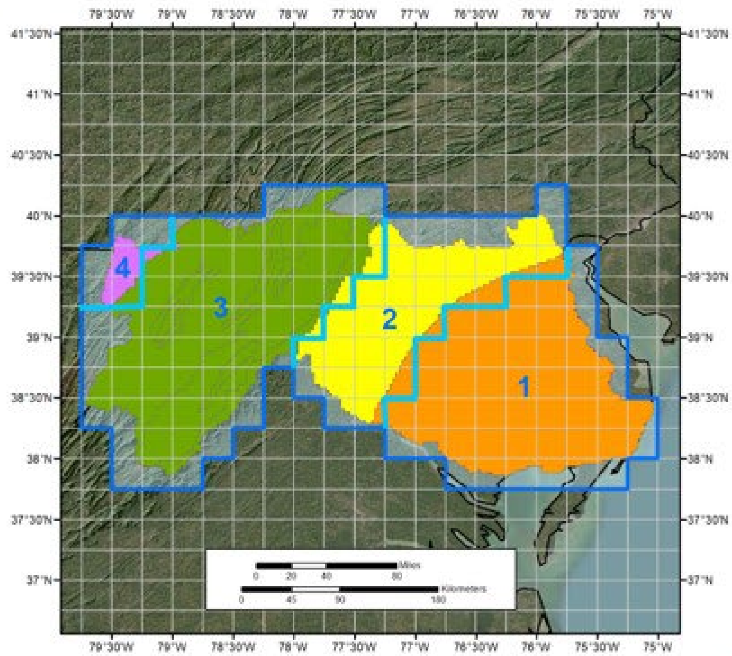
Region 3 - Climate Change Results

NASA Earth Exchange Global Daily Downscaled Projections (NEX-GDDP-CMIP6)

- Total of 35 climate models
- 9 models did not have all data
  - (6) Missing years and/or variables
  - (3) 30-days per month
- Used 26 models on daily time step
  - Temperature
  - Relative humidity
  - Precipitation



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Climate Change Analysis Methods

- **1) Trend Analysis** for 1-day, 3-day, and Annual
  - Station Data
  - Model projections (Historic, SSP45, SSP85)
- **2) Monthly and Annual Analysis**
  - Model projections (Historic, SSP45, SSP85)
- **3) Precipitation Frequency Analysis** for 1-day, 3-day, 30-day, 90-day, and Annual
  - Precipitation, Summer Period, and Winter Period
  - Model projections (Historic, SSP45, SSP85)
  - Estimate PF for 1-year through 1000-year
  - Quantify changes
- **4) Moisture Maximization Analysis** for 1-day and 3-day
  - Derive model projection monthly Td climatologies (Historic, SSP45, SSP85)
  - Quantify changes

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Region 3 - Trend Results

	Precipitation			Temperature
	1-day	3-day	Annual	1-day
Historic	25 – no trend 1 – increase 0 – decrease	25 – no trend 1 – increase 0 – decrease	22 – no trend 4 – increase 0 – decrease	5 – no trend 21 – increase 0 – decrease
SSP45	24 – no trend 2 – increase 0 – decrease	22 – no trend 4 – increase 0 – decrease	18 – no trend 8 – increase 0 – decrease	5 – no trend 21 – increase 0 – decrease
SSP85	12 – no trend 14 – increase 0 – decrease	15 – no trend 11 – increase 0 – decrease	8 – no trend 18 – increase 0 – decrease	0 – no trend 26 – increase 0 – decrease

Region 3 - Climate Change Results

Annual Maximum/Frequency Analysis

	SSP45				SSP85			
	Mean	**Median**	**10th**	**90th**	**Mean**	**Median**	**10th**	**90th**
Temperature 1-Day; C	**2.4**	**2.3**	1.0	3.3	**5.7**	**5.0**	3.8	8.2
Temperature 1-Day Summer; C	**2.4**	**2.3**	1.0	3.3	**5.7**	**5.0**	3.8	8.2
Temperature 1-Day Winter PF; C	**2.3**	**2.2**	1.5	3.6	**5.2**	**5.4**	3.9	6.7
Precipitation 1-Day PF; %	**8**	**6**	-9	28	**11**	**7**	-4	33
Precipitation 1-Day Summer PF; %	**10**	**9**	-10	31	**3**	**3**	-17	22
Precipitation 1-Day Winter PF; %	**10**	**7**	-6	28	**16**	**14**	5	32
Precipitation 3-Day PF; %	**11**	**14**	-10	28	**12**	**8**	-4	32
Precipitation 3-Day Summer PF; %	**7**	**4**	-15	31	**8**	**14**	-15	30
Precipitation 3-Day Winter PF; %	**12**	**12**	-3	28	**14**	**13**	0	30
Precipitation Annual PF; %	**12**	**10**	6	19	**13**	**13**	6	23
1-Day Moisture Maximization; %	**No Change**				**No Change**			
3-Day Moisture Maximization; %	**No Change**				**No Change**			

Climate Change Projections from 2015 through 2100

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Region 3 - Application of Climate Change Results

Monthly Temperature Analysis

	Historical		SSP45		SSP85		Mean Delta		Median Delta	
	Mean	Median	Mean	Median	Mean	Median	SSP45	SSP85	SSP45	SSP85
January	-0.1	-0.3	2.2	2.4	2.9	2.8	***2.3***	***3.0***	***2.6***	***3.1***
February	2.5	2.2	5.0	4.8	5.8	5.9	***2.5***	***3.4***	***2.6***	***3.7***
March	7.4	7.1	10.3	10.2	11.1	10.8	***3.0***	***3.7***	***3.2***	***3.8***
April	13.1	12.7	15.9	15.9	16.7	16.6	***2.8***	***3.6***	***3.2***	***3.9***
May	18.1	17.8	20.8	20.6	21.8	21.8	***2.6***	***3.6***	***2.8***	***4.0***
June	22.2	21.9	24.6	24.7	25.6	25.5	***2.4***	***3.4***	***2.8***	***3.7***
July	23.5	23.1	25.6	25.6	26.7	26.6	***2.2***	***3.3***	***2.5***	***3.5***
August	22.2	22.0	24.4	24.3	25.7	25.5	***2.1***	***3.4***	***2.3***	***3.5***
September	17.8	17.5	19.8	19.6	21.0	20.8	***2.0***	***3.3***	***2.1***	***3.4***
October	11.2	10.8	13.2	13.1	14.4	14.3	***2.0***	***3.1***	***2.3***	***3.5***
November	5.4	5.0	7.1	7.1	8.0	7.7	***1.8***	***2.6***	***2.0***	***2.7***
December	1.1	0.8	2.8	3.0	3.5	3.6	***1.7***	***2.4***	***2.2***	***2.8***

Climate Change Projections from 2015 through 2100

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Region 3 - Application of Climate Change Results

Monthly Precipitation Analysis

	Historical		SSP45		SSP85		Mean Delta		Median Delta	
	Mean	Median	Mean	Median	Mean	Median	SSP45	SSP85	SSP45	SSP85
January	68.3	67.8	79.0	78.8	82.5	82.7	*1.16*	*1.16*	*1.16*	*1.22*
February	64.5	64.7	76.7	76.5	78.9	78.9	*1.19*	*1.18*	*1.18*	*1.22*
March	86.4	85.8	96.7	95.4	100.8	102.3	*1.12*	*1.11*	*1.11*	*1.19*
April	86.5	87.1	96.1	95.5	93.9	93.4	*1.11*	*1.10*	*1.10*	*1.07*
May	101.4	101.4	108.0	107.4	106.4	106.2	*1.06*	*1.06*	*1.06*	*1.05*
June	97.3	97.5	103.2	103.1	102.4	101.2	*1.06*	*1.06*	*1.06*	*1.04*
July	105.2	104.9	111.9	112.7	113.3	113.3	*1.06*	*1.07*	*1.07*	*1.08*
August	90.5	90.4	96.1	93.9	97.0	95.3	*1.06*	*1.04*	*1.04*	*1.05*
September	79.4	78.2	83.0	82.8	80.5	80.2	*1.05*	*1.06*	*1.06*	*1.03*
October	75.4	75.9	76.3	74.8	77.9	80.0	*1.01*	*0.99*	*0.99*	*1.05*
November	76.7	77.1	84.9	84.4	88.8	86.9	*1.11*	*1.09*	*1.09*	*1.13*
December	75.4	75.7	81.8	81.0	87.1	86.9	*1.08*	*1.07*	*1.07*	*1.15*

Climate Change Projections from 2015 through 2100

Region 3 Conclusion

TREND

- Historical precipitation – **no change** in precipitation
- SSP45 precipitation – **no change** in precipitation
- SSP85 precipitation – mix between **no change** and an **increase** in precipitation

FREQUENCY

- 1-day – SSP45 and SPP85 median results are within +/- 20% uncertainty which provide more confidence for **no change** in precipitation magnitude by 2100
- 3-day – SSP45 and SPP85 median results are within +/- 20% uncertainty which provide more confidence for **no change** in precipitation magnitude by 2100
- Annual – SSP45 and SPP85 median results are within +/- 20% uncertainty which provide more confidence for **no change** in precipitation magnitude by 2100

CLIMATOLOGY

- Monthly Climatology – small increase in precipitation (within +/-20%) and **increase** in temperature by 2100
- Annual Climatology – **no change** in annual precipitation (within +/-20%) and **an increase** in annual temperature by 2100

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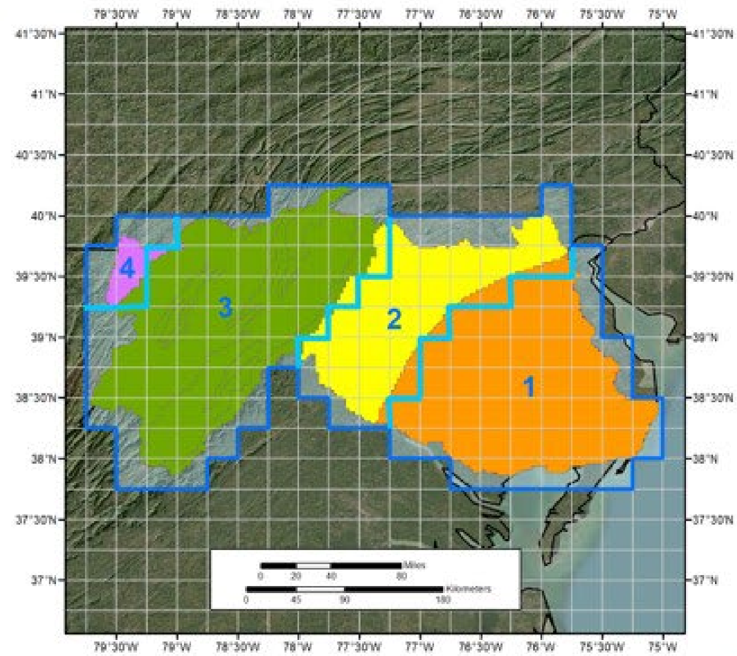
Region 4 - Climate Change Results

NASA Earth Exchange Global Daily Downscaled Projections (NEX-GDDP-CMIP6)

- Total of 35 climate models

- 9 models did not have all data
  - (6) Missing years and/or variables
  - (3) 30-days per month

- Used 26 models on daily time step
  - Temperature
  - Relative humidity
  - Precipitation



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Climate Change Analysis Methods

- **1) Trend Analysis** for 1-day, 3-day, and Annual
  - Station Data
  - Model projections (Historic, SSP45, SSP85)
- **2) Monthly and Annual Analysis**
  - Model projections (Historic, SSP45, SSP85)
- **3) Precipitation Frequency Analysis** for 1-day, 3-day, 30-day, 90-day, and Annual
  - Precipitation, Summer Period, and Winter Period
  - Model projections (Historic, SSP45, SSP85)
  - Estimate PF for 1-year through 1000-year
  - Quantify changes
- **4) Moisture Maximization Analysis** for 1-day and 3-day
  - Derive model projection monthly Td climatologies (Historic, SSP45, SSP85)
  - Quantify changes

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Region 4 - Trend Results

	Precipitation			Temperature
	1-day	3-day	Annual	1-day
Historic	25 – no trend 1 – increase 0 – decrease	25 – no trend 1 – increase 0 – decrease	22 – no trend 4 – increase 0 – decrease	5 – no trend 21 – increase 0 – decrease
SSP45	24 – no trend 2 – increase 0 – decrease	22 – no trend 4 – increase 0 – decrease	18 – no trend 8 – increase 0 – decrease	5 – no trend 21 – increase 0 – decrease
SSP85	12 – no trend 14 – increase 0 – decrease	15 – no trend 11 – increase 0 – decrease	8 – no trend 18 – increase 0 – decrease	0 – no trend 26 – increase 0 – decrease

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Region 4 - Climate Change Results

Annual Maximum/Frequency Analysis

	SSP45				SSP85			
	Mean	**Median**	**10th**	**90th**	**Mean**	**Median**	**10th**	**90th**
Temperature 1-Day; C	**2.4**	**2.3**	1.0	3.3	5.7	**5.0**	3.8	8.2
Temperature 1-Day Summer; C	**2.4**	**2.3**	1.0	3.3	5.7	**5.0**	3.8	8.2
Temperature 1-Day Winter PF; C	**2.3**	**2.2**	1.5	3.6	5.2	**5.4**	3.9	6.7
Precipitation 1-Day PF; %	**8**	**10**	-9	28	**12**	**8**	1	33
Precipitation 1-Day Summer PF; %	**10**	**9**	-10	31	**4**	**4**	-12	22
Precipitation 1-Day Winter PF; %	**9**	7	-6	28	**16**	**15**	5	32
Precipitation 3-Day PF; %	**12**	**15**	-10	28	**13**	**10**	-2	32
Precipitation 3-Day Summer PF; %	7	**4**	-15	31	**8**	**14**	-15	30
Precipitation 3-Day Winter PF; %	**13**	**13**	-3	29	**14**	**13**	0	30
Precipitation Annual PF; %	**11**	**10**	6	19	**13**	**13**	6	23
1-Day Moisture Maximization; %	**No Change**				**No Change**			
3-Day Moisture Maximization; %	**No Change**				**No Change**			

Climate Change Projections from 2015 through 2100

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Region 4 - Application of Climate Change Results

Monthly Temperature Analysis

	Historical		SSP45		SSP85		Mean Delta		Median Delta	
	Mean	Median	Mean	Median	Mean	Median	SSP45	SSP85	SSP45	SSP85
January	-0.1	-0.3	2.2	2.4	2.9	2.8	***2.3***	***3.0***	***2.6***	***3.1***
February	2.5	2.2	5.0	4.8	5.8	5.9	***2.5***	***3.4***	***2.6***	***3.7***
March	7.4	7.1	10.3	10.2	11.1	10.8	***3.0***	***3.7***	***3.2***	***3.8***
April	13.1	12.7	15.9	15.9	16.7	16.6	***2.8***	***3.6***	***3.2***	***3.9***
May	18.1	17.8	20.8	20.6	21.8	21.8	***2.6***	***3.6***	***2.8***	***4.0***
June	22.2	21.9	24.6	24.7	25.6	25.5	***2.4***	***3.4***	***2.8***	***3.7***
July	23.5	23.1	25.6	25.6	26.7	26.6	***2.2***	***3.3***	***2.5***	***3.5***
August	22.2	22.0	24.4	24.3	25.7	25.5	***2.1***	***3.4***	***2.3***	***3.5***
September	17.8	17.5	19.8	19.6	21.0	20.8	***2.0***	***3.3***	***2.1***	***3.4***
October	11.2	10.8	13.2	13.1	14.4	14.3	***2.0***	***3.1***	***2.3***	***3.5***
November	5.4	5.0	7.1	7.1	8.0	7.7	***1.8***	***2.6***	***2.0***	***2.7***
December	1.1	0.8	2.8	3.0	3.5	3.6	***1.7***	***2.4***	***2.2***	***2.8***

Climate Change Projections from 2015 through 2100

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Region 4 - Application of Climate Change Results

Monthly Precipitation Analysis

	Historical		SSP45		SSP85		Mean Delta		Median Delta	
	Mean	Median	Mean	Median	Mean	Median	SSP45	SSP85	SSP45	SSP85
January	68.3	67.8	79.0	78.8	82.5	82.7	*1.16*	*1.16*	*1.16*	*1.22*
February	64.5	64.7	76.7	76.5	78.9	78.9	*1.19*	*1.18*	*1.18*	*1.22*
March	86.4	85.8	96.7	95.4	100.8	102.3	*1.12*	*1.11*	*1.11*	*1.19*
April	86.5	87.1	96.1	95.5	93.9	93.4	*1.11*	*1.10*	*1.10*	*1.07*
May	101.4	101.4	108.0	107.4	106.4	106.2	*1.06*	*1.06*	*1.06*	*1.05*
June	97.3	97.5	103.2	103.1	102.4	101.2	*1.06*	*1.06*	*1.06*	*1.04*
July	105.2	104.9	111.9	112.7	113.3	113.3	*1.06*	*1.07*	*1.07*	*1.08*
August	90.5	90.4	96.1	93.9	97.0	95.3	*1.06*	*1.04*	*1.04*	*1.05*
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Climate Change Projections from 2015 through 2100

Region 4 Conclusion

TREND

- Historical precipitation – **no change** in precipitation
- SSP45 precipitation – **no change** in precipitation
- SSP85 precipitation – mix between **no change** and an **increase** in precipitation

FREQUENCY

- 1-day – SSP45 and SPP85 median results are within +/- 20% uncertainty which provide more confidence for **no change** in precipitation magnitude by 2100
- 3-day – SSP45 and SPP85 median results are within +/- 20% uncertainty which provide more confidence for **no change** in precipitation magnitude by 2100
- Annual – SSP45 and SPP85 median results are within +/- 20% uncertainty which provide more confidence for **no change** in precipitation magnitude by 2100

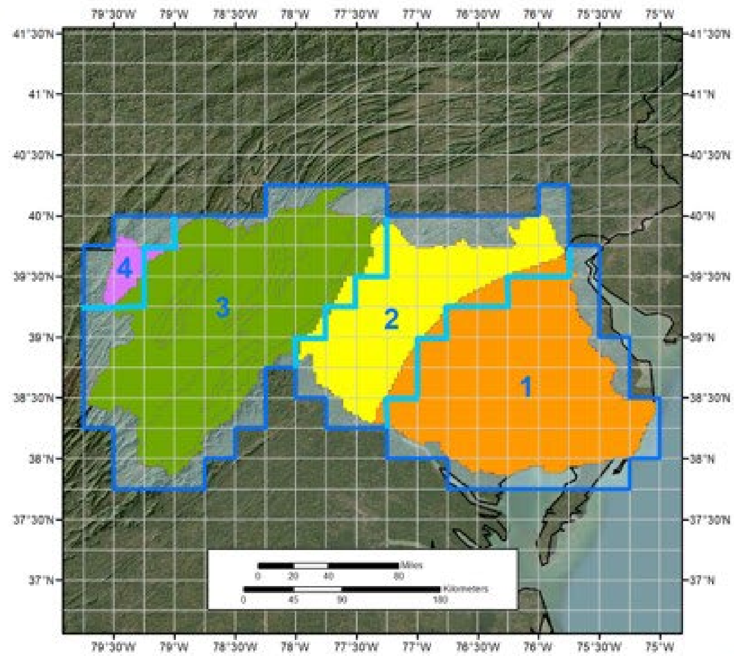
CLIMATOLOGY

- Monthly Climatology – small increase in precipitation (within +/-20%) and **increase** in temperature by 2100
- Annual Climatology – **no change** in annual precipitation (within +/-20%) and **an increase** in annual temperature by 2100

All Regions - Climate Change Results

NASA Earth Exchange Global Daily Downscaled Projections (NEX-GDDP-CMIP6)

- Total of 35 climate models
- 9 models did not have all data
  - (6) Missing years and/or variables
  - (3) 30-days per month
- Used 26 models on daily time step
  - Temperature
  - Relative humidity
  - Precipitation



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Climate Change Analysis Methods

- **1) Trend Analysis** for 1-day, 3-day, and Annual
  - Station Data
  - Model projections (Historic, SSP45, SSP85)
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  - Model projections (Historic, SSP45, SSP85)
  - Estimate PF for 1-year through 1000-year
  - Quantify changes
- **4) Moisture Maximization Analysis** for 1-day and 3-day
  - Derive model projection monthly Td climatologies (Historic, SSP45, SSP85)
  - Quantify changes

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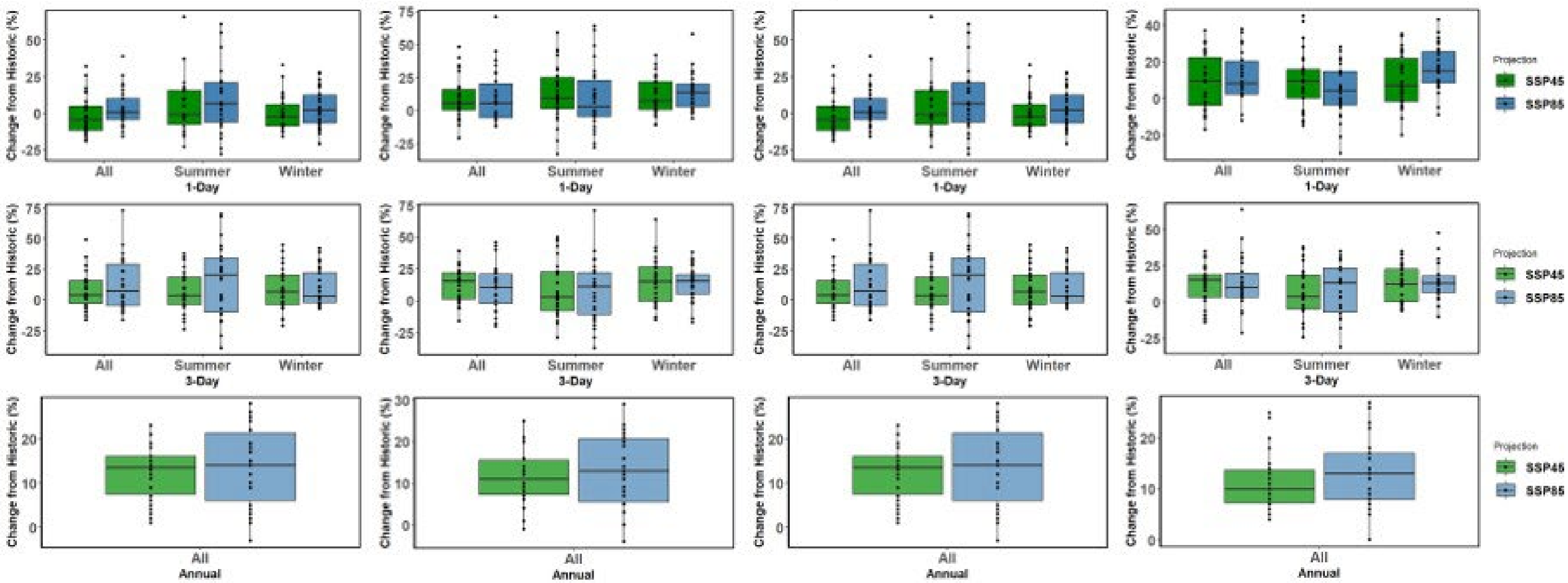
All Regions - Trend Results

Average as Percent		Precipitation			Temperature
		1-day	3-day	Annual	1-day
Historic	no trend	93%	95%	88%	25%
	increase	5%	3%	13%	75%
	decrease	2%	2%	0%	0%
SSP45	no trend	84%	82%	71%	16%
	increase	16%	18%	29%	84%
	decrease	0%	0%	0%	0%
SSP85	no trend	53%	62%	33%	0%
	increase	47%	38%	67%	100%
	decrease	0%	0%	0%	0%

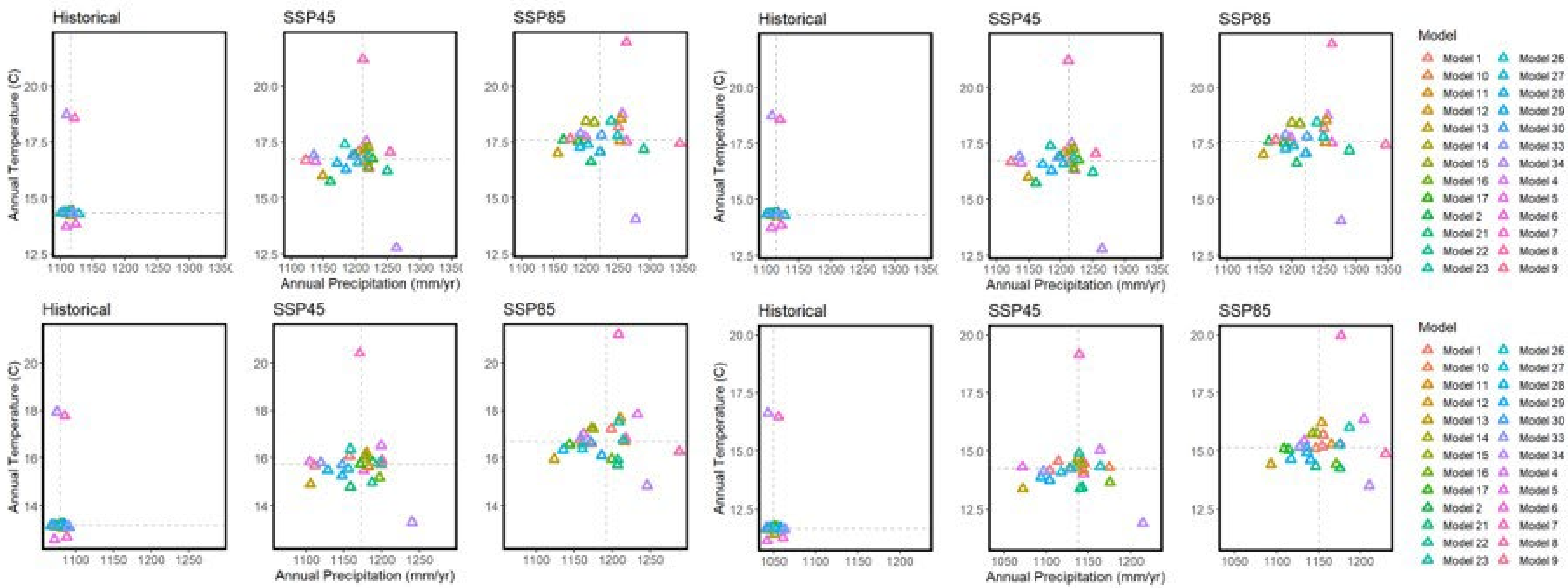
All Regions - Climate Change Results

- 1-day (ssp45; ssp85)
  - All = 4%; 5%
  - Summer = 7%; 4%
  - Winter = 5%; 11%
- 3-day
  - All = 12%; 9%
  - Summer = 4%; 15%
  - Winter = 11%; 11%
- Annual
  - All = 11%; 13%



All Regions - Summary Annual Ta and Ppt

- **Annual Climatology (temp, ppt)**
  - Historical = 12.7 C; 1073 mm
  - SSP45 = 15.2 C; 1166 mm (2.5 C; 9%)
  - SSP85 = 16.2 C; 1179 mm (3.4 C; 10%)



All Regions - Climate Change Results

Annual Maximum/Frequency Analysis

All	SSP45				SSP85			
	Mean	**Median**	**10th**	**90th**	**Mean**	**Median**	**10th**	**90th**
Temperature 1-Day; C	**2.3**	**2.2**	1.0	3.3	**5.6**	**5.0**	3.8	8.2
Temperature 1-Day Summer; C	**2.3**	**2.2**	1.0	3.3	**5.6**	**5.0**	3.8	8.2
Temperature 1-Day Winter PF; C	**2.4**	**2.3**	1.5	3.7	**5.1**	**5.3**	3.8	6.7
Precipitation 1-Day PF; %	**6**	**4**	-17	33	**9**	**5**	-10	36
Precipitation 1-Day Summer PF; %	**9**	7	-14	44	**6**	**4**	-17	45
Precipitation 1-Day Winter PF; %	7	5	-12	29	**13**	**11**	-11	32
Precipitation 3-Day PF; %	**11**	**12**	-12	28	**12**	**9**	-11	36
Precipitation 3-Day Summer PF; %	**8**	**4**	-17	45	**10**	**15**	-20	53
Precipitation 3-Day Winter PF; %	**12**	**11**	-11	36	**13**	**11**	-5	32
Precipitation Annual PF; %	**12**	**11**	3	20	**13**	**13**	1	25
Moisture Maximization 1-Day, %		**No Change**				**No Change**		
Moisture Maximization 3-Day; %		**No Change**				**No Change**		

Climate Change Projections from 2015 through 2100

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All Regions – App. of Climate Change Results

Monthly Temperature Analysis

All	Historical		SSP45		SSP85		Mean Delta		Median Delta	
	Mean	Median	Mean	Median	Mean	Median	SSP45	SSP85	SSP45	SSP85
January	0.9	0.7	3.2	3.3	3.9	4.0	***2.3***	***3.0***	***2.6***	***3.2***
February	3.4	3.1	5.9	5.7	6.7	6.7	***2.5***	***3.3***	***2.6***	***3.6***
March	8.2	7.9	11.1	11.0	11.8	11.6	***2.9***	***3.6***	***3.2***	***3.7***
April	13.9	13.6	16.6	16.6	17.5	17.4	***2.7***	***3.6***	***3.0***	***3.8***
May	19.0	18.7	21.6	21.5	22.6	22.6	***2.6***	***3.6***	***2.8***	***3.9***
June	23.2	22.9	25.6	25.7	26.6	26.6	***2.4***	***3.4***	***2.8***	***3.7***
July	24.6	24.3	26.8	26.8	27.8	27.7	***2.2***	***3.2***	***2.5***	***3.5***
August	23.3	23.1	25.5	25.4	26.7	26.5	***2.1***	***3.3***	***2.3***	***3.5***
September	18.9	18.6	20.9	20.7	22.1	21.9	***2.0***	***3.1***	***2.1***	***3.2***
October	12.4	12.0	14.3	14.2	15.5	15.4	***2.0***	***3.1***	***2.3***	***3.4***
November	6.5	6.2	8.2	8.2	9.1	8.8	***1.7***	***2.6***	***2.0***	***2.7***
December	2.2	1.9	3.9	4.0	4.5	4.6	***1.7***	***2.4***	***2.1***	***2.7***

Climate Change Projections from 2015 through 2100

SSP45 Mean = 2.5 C
SSP85 Mean = 3.4 C

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All Regions – App. of Climate Change Results

Monthly Precipitation Analysis

All	Historical		SSP45		SSP85		Mean Delta		Median Delta	
	Mean	Median	Mean	Median	Mean	Median	SSP45	SSP85	SSP45	SSP85
January	72.1	72.1	82.3	82.8	86.1	86.3	*1.14*	*1.15*	*1.15*	*1.20*
February	67.0	67.4	79.0	79.5	80.5	80.2	*1.18*	*1.18*	*1.18*	*1.19*
March	87.8	87.4	97.1	95.4	101.4	102.6	*1.11*	*1.09*	*1.09*	*1.17*
April	84.4	84.8	93.7	93.1	91.7	91.5	*1.11*	*1.10*	*1.10*	*1.08*
May	98.2	98.3	104.3	104.2	102.7	102.2	*1.06*	*1.06*	*1.06*	*1.04*
June	96.3	96.4	103.2	103.6	102.1	100.9	*1.07*	*1.07*	*1.07*	*1.05*
July	107.1	106.7	114.8	115.2	115.9	115.4	*1.07*	*1.08*	*1.08*	*1.08*
August	94.5	94.3	100.7	100.1	101.7	100.2	*1.07*	*1.06*	*1.06*	*1.06*
September	83.2	82.8	86.8	86.1	84.9	83.6	*1.04*	*1.04*	*1.04*	*1.01*
October	77.7	77.4	79.3	77.5	80.5	82.0	*1.02*	*1.00*	*1.00*	*1.06*
November	78.3	78.5	86.5	85.6	90.8	90.3	*1.10*	*1.09*	*1.09*	*1.15*
December	80.3	80.6	87.1	86.8	93.3	92.7	*1.09*	*1.08*	*1.08*	*1.15*

Climate Change Projections from 2015 through 2100

SSP45 Mean = 8%
SSP85 Mean = 10%

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All Regions Conclusion

TREND

- Historical precipitation – **no change** in precipitation
- SSP45 precipitation – **no change** in precipitation
- SSP85 precipitation – mix between **no change** and an **increase** in precipitation

FREQUENCY

- 1-day – SSP45 and SPP85 median results are within +/- 20% uncertainty which provide more confidence for **no change** in precipitation magnitude by 2100
- 3-day – SSP45 and SPP85 median results are within +/- 20% uncertainty which provide more confidence for **no change** in precipitation magnitude by 2100
- Annual – SSP45 and SPP85 median results are within +/- 20% uncertainty which provide more confidence for **no change** in precipitation magnitude by 2100

CLIMATOLOGY

- Monthly Climatology – small increase in precipitation (within +/-20%) and **increase** in temperature by 2100
- Annual Climatology – **no change** in annual precipitation (within +/-20%) and **an increase** in annual temperature by 2100

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Questions

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