Appendix 4

Climate Analysis & Storm Event Analysis Memo

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PREPARED BY

Brandywine Conservancy

University of Delaware Water Resources Center

Chester County Water Resources Authority

Memorandum

To: *Brandywine Conservancy*

From: *Tim Adams, Mark Maimone, CDM Smith*

Date: *January 25th, 2024*

Subject: *Precipitation Change Factors for the Brandywine River Watershed*

Introduction

As temperatures increase, the atmosphere can hold more water vapor leading to a greater potential for precipitation. There have already been noticeable changes in precipitation patterns over the past 20 years when compared to the prior century, and even more changes are projected in this century. For example, the U.S. National Climate Assessment notes that the northeastern United States has already seen, a greater increase in extreme precipitation than any other region, with a 60% increase in intense storms between 1958 and 2022. These increases in rainfall exacerbate flood risk which already has caused billions of dollars in damages across the US in recent years. Thus, it is critical for flood studies to incorporate potential changes in rainfall and streamflow into hydrologic and hydraulic modeling of streams to evaluate future risks.

This memorandum documents the methodology used to generate precipitation change factors from global climate models (GCMs). Precipitation change factors estimate the increase in precipitation that may occur in the future for storms of varying frequency and duration. CDM Smith used two different methods to calculate precipitation change factors for the Brandywine River watershed for two CMIP5 GCM scenarios (RCP4.5 and RCP8.5); the 1-, 2-, 5-, 10-, 25-, 50-, 100-, and 500-year recurrence intervals; the 1-, 2-, 3-, 6-, 12-, and 24- hour event durations; and for each decade between 2030 and 2100. These results can be found in Appendix 1 and can be used for a wide range of flood studies and applications.

Analysis

The methods used to calculate precipitation change factors for the Brandywine River are based on published research and are described in detail in the 2023 paper by Maimone et al as the “medium” and “high” methods (Maimone et al. 2023). Both methods rely on estimating increases in extreme precipitation based on projected increases in annual average temperatures. For the Brandywine River watershed, GCM data was downloaded for the watershed and changes in annual average temperatures were calculated for each decade. These results were then used to calculate the precipitation change factors using the methods described below. The sections below briefly discuss the calculations made; see Maimone et al. for further discussion of the methods, how they were derived, and the limitations of their use.

GCM Data Download

All three methods make use of Coupled Model Intercomparison Project Phase 5 (CMIP5) GCM projections based on the Local Constructed Analogs (LOCA) downscaling technique made available through the downscaled CMIP5 Climate and Hydrology Projections website: https://gdo-dcp.ucllnl.org/downscaled_cmip_projections/ for grid cells covering the City of Philadelphia. The example uses the representative concentration pathway (RCP) 8.5 emission scenario, which is the planning scenario that the city uses for many of their planning activities.

Downscaled CMIP5 Climate data was downloaded from the archive available at http://gdo-dcp.ucllnl.org/downscaled_cmip_projections/ for 32 GCM models and two representative concentration pathway (RCP) emission scenarios (RCP4.5 and RCP8.5).[1] Daily minimum and maximum temperatures were downloaded from January 1986 through December 2099 on a daily timestep for the grid cells shown in **Figure 1**. The data was filtered after download to process only those grid cells nearest to the watershed, shown as red in **Figure 1**. Data from twenty-seven grid cells were used to describe the Brandywine River watershed.

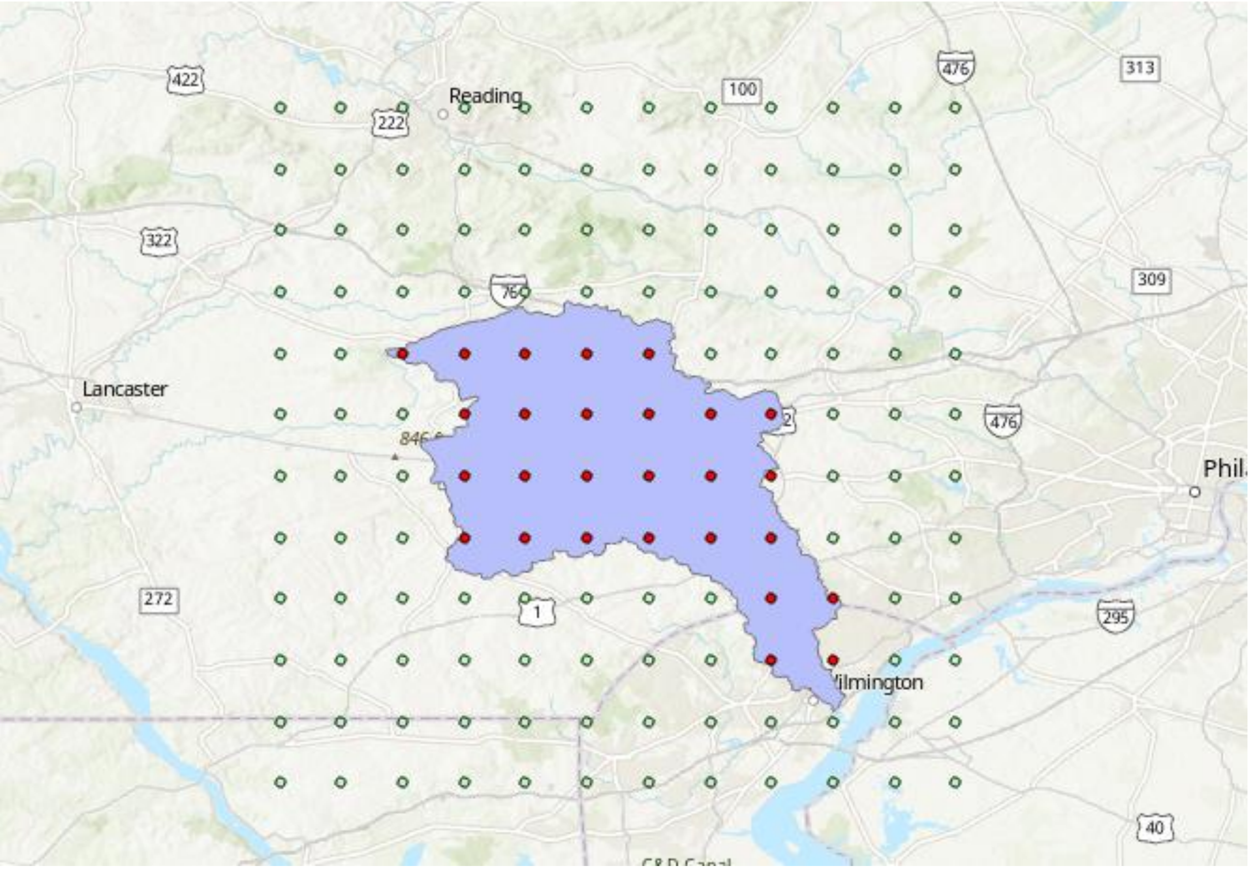

Figure 1 – Grid cells for which downscaled GCM data was downloaded

Calculation of Temperature Changes

Temperature changes were calculated for each of the 27 grid cells associated with the watershed and each of the 32 GCMs. Annual average temperatures were further averaged within 20-year rolling windows centered around each decade. The average temperature for these 20-year rolling windows

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[1] We acknowledge the World Climate Research Programme's Working Group on Coupled Modelling, which is responsible for CMIP, and we thank the climate modeling groups (listed in Appendix 2 of this paper) for producing and making available their model output. For CMIP the U.S. Department of Energy's Program for Climate Model Diagnosis and Intercomparison provides coordinating support and led development of software infrastructure in partnership with the Global Organization for Earth System Science Portals.

were compared to the average temperature for the 2020 (2010-2029 window) to obtain a projected temperature change in degrees Celsius.

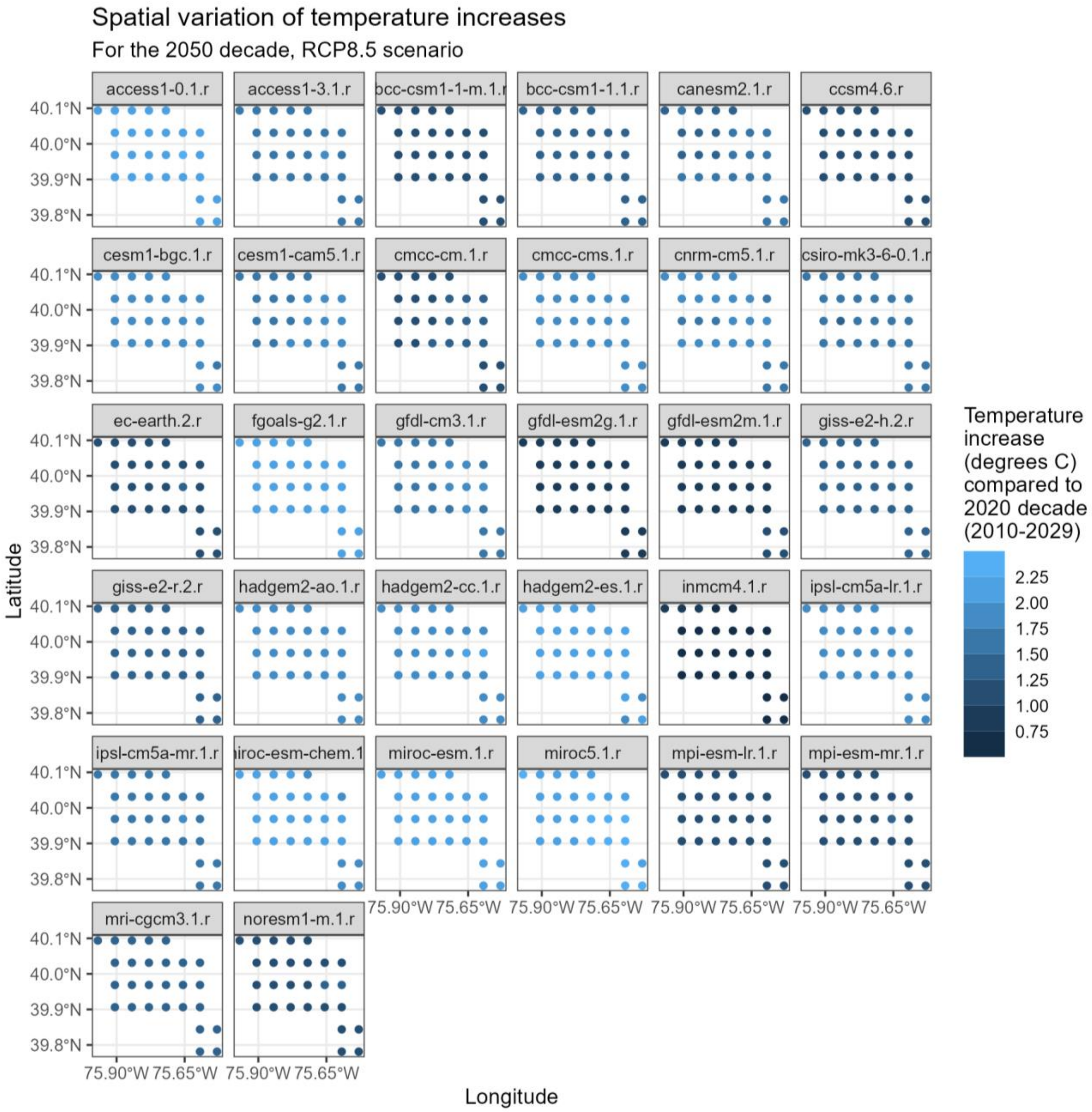

Figure 2 – Temperature increases in the 2050 decade compared to the 2020 decade, RCP8.5 scenario

Once the temperature changes were calculated for each GCM, grid cell, and RCP scenario, they were analyzed for spatial variability. **Figure 2** shows temperature changes in the 2050 decade compared to the 2020 decade for the RCP8.5 scenario. Each individual subplot shows temperature changes for one of the 32 GCM models. As can be seen, temperature changes vary little spatially, with most of the variation occurring between GCM models.

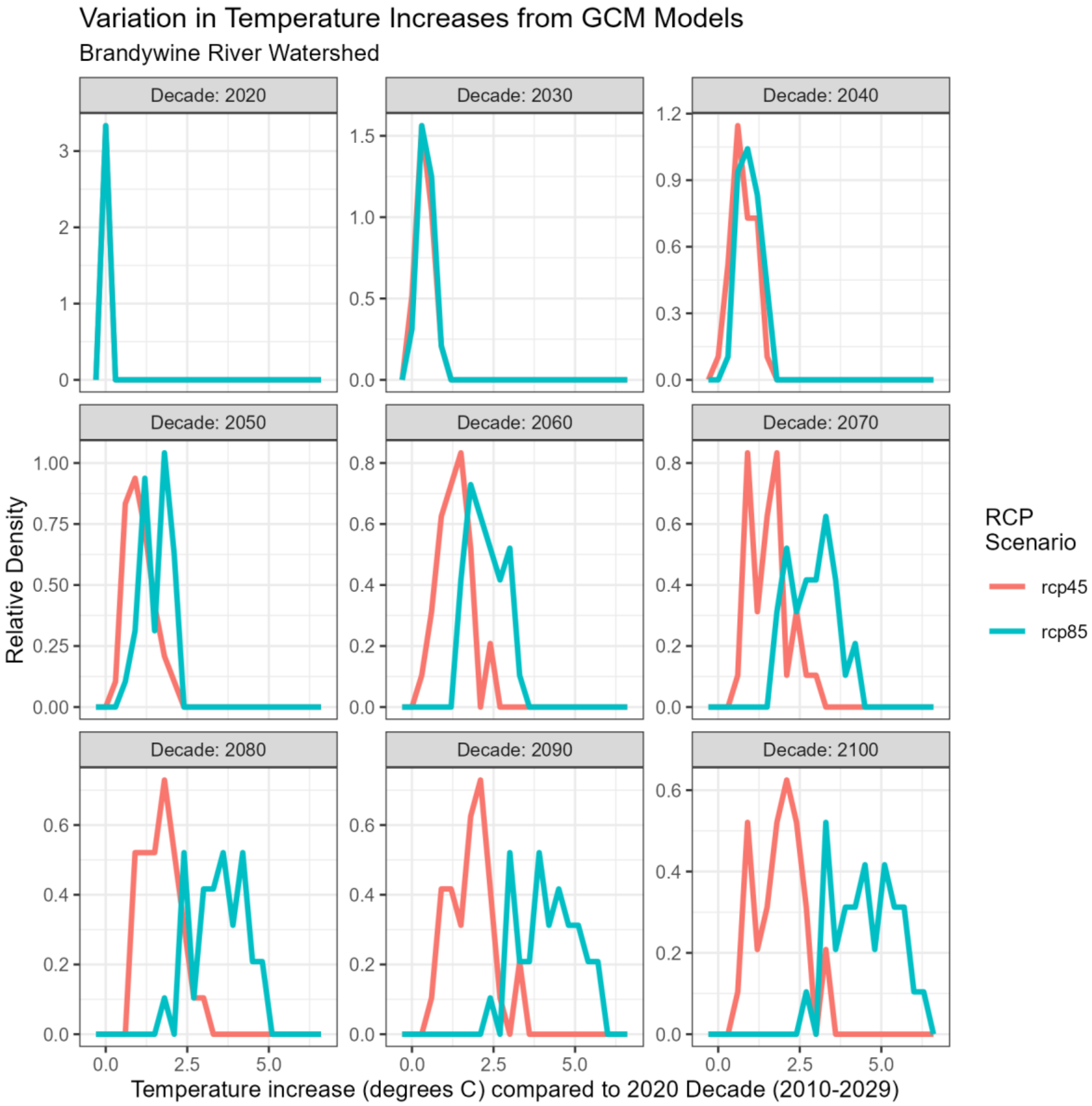

Figure 3 – Variations in temperature increases from differing GCM models

Figure 3 provides a more in-depth view of GCM model variability by showing frequency distributions of temperature changes for each decade and RCP scenario. In these subplots, each line shows the distribution of temperature changes across the 32 GCM models. As can be expected, model variation is low in earlier decades and increases in the future as uncertainty increases. Model variation is also similar between the RCP scenarios, although the more extreme RCP8.5 shows a shift towards higher temperatures as would be expected.

Based on these results, the following processing steps were taken:

1. For each GCM, decade, and RCP scenario, the spatial mean of temperature change was calculated by taking the mean of temperature change at each grid cell. Both the mean and median were tested, but due to low spatial variability there was little difference between the two.

2. For each decade and RCP scenario, the model mean of temperature change was calculated by taking the mean of temperature change for each GCM model. Using the mean is standard practice and represents the fact that it is unknown which of the GCM models is a better projection of what temperature increases would occur based on a specific emission scenario.

These steps resulted in a table of 16 values representing temperature changes for two RCP scenarios (RCP4.5 and RCP8.5) and eight 20-year periods described by their center decade (2030-2100) compared to temperatures in the 2020 decadal window (2010-2029).

Calculation of Precipitation Change Factors

Following the calculation of temperature changes, precipitation change factors were developed based on two different methods detailed in Maimone et al. 2023. Both of these methods rely on the Clausius-Clapeyron relationship, which links air temperature and atmospheric humidity when the air is saturated, giving an increase in humidity of 6–7% per degree warming (Trenberth et al. 2003).

Clausius Clapeyron 7% Method

The temperature scaling approach is based on a simple application of the Clausius-Clapeyron principal to the average annual temperature increase. The temperature changes previously calculated were multiplied by 1.07 (increase of 7%) to provide a table of precipitation change factors. These precipitation change factors were applied across all event durations and recurrence intervals. This approach provides a medium estimate of future extreme rainfall projections compared to other existing methods (Maimone et al. 2023).

Super Clausius Clapeyron 7%-12% Method

This method also relies on the application of the Clausius-Clapeyron principle; however, a more nuanced approach is taken to account for increased intensification for low-frequency, shorter duration events. The underlying assumptions are:

- The minimum increase per degree Celsius is represented by the Clausius-Clapeyron value of 7%. This is applied to the most frequent (1-year) and longest duration (24-h) event.

- The greatest increase is referred to in the literature as the super Clausius-Clapeyron value, and has been cited in the range of 12–14% per degree Celsius. A 12% increase per degree Celsius is applied to the least frequent (100-year and above) and shortest duration (1-h) duration events.

- All other percent increases at the intersects of duration and frequency are interpolated between these values following the two principles stated above.

The resulting table of applied percentage increases per degree Celsius is shown in **Table 1**. Note that this table does *not show* the final precipitation change factors derived from this method. The final precipitation change factors are found in **Appendix 1**.

Table 1 – Increases in extreme precipitation for every 1 degree Celsius increase for the super Clausius Clapeyron 7%-12% method

Event Duration	Average Recurrence Interval (years)								
	1-y	2-y	5-y	10-y	25-y	50-y	100-y	200-y	500-y
1-hour	10.0%	10.3%	10.7%	11.0%	11.3%	11.7%	12.0%	12.0%	12.0%
2-hour	9.4%	9.8%	10.1%	10.5%	10.9%	11.2%	11.6%	11.6%	11.6%
3-hour	8.8%	9.2%	9.6%	10.0%	10.4%	10.8%	11.2%	11.2%	11.2%
6-hour	8.2%	8.6%	9.1%	9.5%	9.9%	10.4%	10.8%	10.8%	10.8%
12-hour	7.6%	8.1%	8.5%	9.0%	9.5%	9.9%	10.4%	10.4%	10.4%
24-hour	7.0%	7.5%	8.0%	8.5%	9.0%	9.5%	10.0%	10.0%	10.0%

Results and Conclusions

The analysis resulted in a set of precipitation change factor tables showing increases in precipitation dependent on the change factor method, RCP scenario (4.5 or 8.5), decade, event duration, and recurrence interval in years. Change factors ranged from as low as 3% in 2030 to as high as 54% in 2100. Change factors range from 7%-19% for the 2050 decade and from 11%-42% for the 2080 decade. The appendix and the *Precipitation_Change_Factors_Brandywine.xlsx* Excel file accompanying this memo provides the precipitation change factor tables.

Comparison with National Climate Assessment

The 5th National Climate Assessment (NCA) is “the US Government’s preeminent report on climate change impacts, risks, and responses. It is a congressionally mandated interagency effort that provides the scientific foundation to support informed decision-making across the United States.” (Jay et al. 2023) The 5th NCA was released in 2023 and provides projections for many future climate variables, including extreme precipitation. **Table 2** compares precipitation change factors from the NCA for global warming levels of 2 degrees C and 3 degrees C with the results from this study. Because the NCA provides information on a per-county basis, projections for Chester County PA were used as a proxy for the Brandywine River watershed. Note that the NCA provides additional metrics that show that the number of days with extreme rainfall will increase with global warming. These metrics are not included here as they are not directly comparable to precipitation change factors, which focus on the intensity of extreme rainfall.

Table 2 – Comparison of precipitation change factors for 24-hour duration events between this study and the 5th National Climate Assessment in Chester County.

Temperature Rise Above Pre-Industrial Average (degrees C) (1851-1900)	Temperature Rise above Current Temperatures (degrees C)	NCA Description	Associated Return Interval (Years)	Precipitation Change Factors		
				From NCA (Changes are relative to the period 1991–2020)	Clausius Clapeyron 7% Method	Super Clausius Clapeyron 7%-12% Method
2	0.9	Highest daily precipitation total of the year	1	8%	7%	7%
2	0.9	Highest daily precipitation total over five years	5	9%	7%	8%
3	1.9	Highest daily precipitation total of the year	1	13%	13%	13%
3	1.9	Highest daily precipitation total over five years	5	15%	13%	15%

As can be seen, the methods used in this study ("Clausius Clapeyron 7% Method" and "Super Clausius Clapeyron 7%-12% Method") align well with the NCA for the 1-year and 5-year return intervals.

Uses and Limitations

It is important to understand that the intent of these methods is not to predict changes in future storm intensity but to provide a plausible range of climate change-related intensification for design storms and IDF curves. These methods provide medium to high changes to storm intensity and can provide critical planning information to assess future risks related to extreme storms and the accompanying flooding concerns. Actual changes to any given infrequent, extreme storm intensity are influenced by an array of factors that can include actual temperature at the moment of the storm, available water, antecedent conditions, topography, and land use.

In addition, it must be understood that the methods are designed to produce precipitation change factors that are then applied to locally based design storms. They do not directly represent design storm depths. Appendix 3 shows a simple example of how the precipitation change factors could be applied to Atlas 14 results to obtain design storm depths for future storms.

Some of the limitations for these methods include the following:

- The methods rely on changes to annual average temperature based on GCM projections and the selected climate change scenario. This approach does not account for the temperature and available moisture for any given storm. Thus, the temperature-based change factors are intended as a possible intensification for future storms but do not represent the temperature profile at the actual moment of any one storm.

- The methods assume that the change in moisture holding capacity will change with temperature, thus assuming that water availability is not a constraint.
- The Clausius Clapeyron 7% method does not acknowledge the body of research that suggests that shorter duration, infrequent extreme events will intensify more than longer duration, more frequent events.
- The Super Clausius Clapeyron 7%-12% method is based on research that has explored the idea that changes to storm intensity can actually exceed the physically based 7% per degree Celsius estimate, up to 12–14%. This is an area of continuing research, and its use for the high method is intended as an upper bound for risk assessments that focus on high value/critical assets in need of a reasonable margin of safety.
- The methods can use the NOAA n-minute factors to estimate sub-hourly storm intensities; however, additional research is required to assess if sub-hourly factors need to be increased further due to the shorter durations.

Despite these caveats, these results should help to understand and explain the extreme storm events that are already occurring, and to help to reset our hydrologic assumptions in the face of current and projected climate change.

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Appendix 1: Precipitation-Based Change Factors

The following pages include the change factors generated from this study. 4 tables are provided for (a) the RCP4.5 and RCP8.5 scenarios and (b) for the two different methods of deriving precipitation change factors from temperature increases (Clausius Clapeyron 7% Method, Super Clausius Clapeyron 7%-12% Method). These tables are also provided in the *Precipitation_Change_Factors_Brandywine.xlsx* Excel file.

CDM Smith Computation Metadata Summary

Client:	Brandywine Conservancy	Computation by:	*Tim Adams*	Checked by:	*Josh Soper*
Job No.:	291671	Date:	*11/17/2023*	Date Checked:	*12/1/2023*
Project:	Brandywine Creek Flood Study Support	Revision No.:	*0*	Reviewed by:	
Detail:	*Temperature-Based Precipitation Change Factors*	Revision Date:		Date Reviewed:	

Title: Temperature-Based Precipitation Change Factors for the Brandywine River Watershed

1.0 Purpose/ Objective	*This workbook contains precipitation change factors for the Brandywine River Watershed. 4 tables are provided for (a) the RCP4.5 and RCP8.5 scenarios and (b) for two different methods of deriving precipitation change factors from temperature increases*	
2.0 Procedure	*See the accompanying memo for detail on how these results were derived.*	
3.0 References/ Data Sources	*Methods are based on the published article by Maimone, Malter et al. 2023 located here: https://doi.org/10.2166/wcc.2023.420* *CMIP5 LOCA Climate Data downloaded from https://gdo-dcp.ucllnl.org/downscaled_cmip_projections/dcpInterface.html was used in this study.*	
4.0 Assumptions and Limitations	*See the accompanying memo for a and the published article linked above for key assumptions and limitiations when using these values.*	
5.0 Sheet Description	*See below for a description of the tab sheets included in this spreadsheet:*	
	Provides precipitation change factors for RCP4.5 using the clausius-clapyeron relationship (7% increase in precipitation for every one degree C increase in temperature)	*RCP45 CC 7%*
	Provides precipitation change factors for RCP4.5 using the clausius-clapyeron relationship (7% to 12% increase in precipitation for every one degree C increase in temperature, depending on event duration and recurrence interval)	*RCP45 Super CC 7-12%*
	Provides precipitation change factors for RCP8.5 using the clausius-clapyeron relationship (7% increase in precipitation for every one degree C increase in temperature)	*RCP85 CC 7%*
	Provides precipitation change factors for RCP8.5 using the clausius-clapyeron relationship (7% to 12% increase in precipitation for every one degree C increase in temperature, depending on event duration and recurrence interval)	*RCP85 Super CC 7-12%*

Clausius Clapeyron 7% Method,
RCP4.5 Scenario

					Recurrence Interval (Years)							
DCF Method	**RCP Scenario**	**Decade**	**Temperature Change (C)**	**Event Duration (Hours)**	**1-year**	**2-year**	**5-year**	**10-year**	**25-year**	**50-year**	**100-year**	**500-year**
Clausius Clapeyron 7%	rcp45	2030	0.4	1	3%	3%	3%	3%	3%	3%	3%	3%
Clausius Clapeyron 7%	rcp45	2030	0.4	2	3%	3%	3%	3%	3%	3%	3%	3%
Clausius Clapeyron 7%	rcp45	2030	0.4	3	3%	3%	3%	3%	3%	3%	3%	3%
Clausius Clapeyron 7%	rcp45	2030	0.4	6	3%	3%	3%	3%	3%	3%	3%	3%
Clausius Clapeyron 7%	rcp45	2030	0.4	12	3%	3%	3%	3%	3%	3%	3%	3%
Clausius Clapeyron 7%	rcp45	2030	0.4	24	3%	3%	3%	3%	3%	3%	3%	3%
Clausius Clapeyron 7%	rcp45	2040	0.76	1	5%	5%	5%	5%	5%	5%	5%	5%
Clausius Clapeyron 7%	rcp45	2040	0.76	2	5%	5%	5%	5%	5%	5%	5%	5%
Clausius Clapeyron 7%	rcp45	2040	0.76	3	5%	5%	5%	5%	5%	5%	5%	5%
Clausius Clapeyron 7%	rcp45	2040	0.76	6	5%	5%	5%	5%	5%	5%	5%	5%
Clausius Clapeyron 7%	rcp45	2040	0.76	12	5%	5%	5%	5%	5%	5%	5%	5%
Clausius Clapeyron 7%	rcp45	2040	0.76	24	5%	5%	5%	5%	5%	5%	5%	5%
Clausius Clapeyron 7%	rcp45	2050	1.04	1	7%	7%	7%	7%	7%	7%	7%	7%
Clausius Clapeyron 7%	rcp45	2050	1.04	2	7%	7%	7%	7%	7%	7%	7%	7%
Clausius Clapeyron 7%	rcp45	2050	1.04	3	7%	7%	7%	7%	7%	7%	7%	7%
Clausius Clapeyron 7%	rcp45	2050	1.04	6	7%	7%	7%	7%	7%	7%	7%	7%
Clausius Clapeyron 7%	rcp45	2050	1.04	12	7%	7%	7%	7%	7%	7%	7%	7%
Clausius Clapeyron 7%	rcp45	2050	1.04	24	7%	7%	7%	7%	7%	7%	7%	7%
Clausius Clapeyron 7%	rcp45	2060	1.32	1	9%	9%	9%	9%	9%	9%	9%	9%
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Clausius Clapeyron 7%	rcp45	2060	1.32	3	9%	9%	9%	9%	9%	9%	9%	9%
Clausius Clapeyron 7%	rcp45	2060	1.32	6	9%	9%	9%	9%	9%	9%	9%	9%
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Clausius Clapeyron 7%	rcp45	2060	1.32	24	9%	9%	9%	9%	9%	9%	9%	9%
Clausius Clapeyron 7%	rcp45	2070	1.52	1	11%	11%	11%	11%	11%	11%	11%	11%
Clausius Clapeyron 7%	rcp45	2070	1.52	2	11%	11%	11%	11%	11%	11%	11%	11%
Clausius Clapeyron 7%	rcp45	2070	1.52	3	11%	11%	11%	11%	11%	11%	11%	11%
Clausius Clapeyron 7%	rcp45	2070	1.52	6	11%	11%	11%	11%	11%	11%	11%	11%
Clausius Clapeyron 7%	rcp45	2070	1.52	12	11%	11%	11%	11%	11%	11%	11%	11%
Clausius Clapeyron 7%	rcp45	2070	1.52	24	11%	11%	11%	11%	11%	11%	11%	11%
Clausius Clapeyron 7%	rcp45	2080	1.65	1	12%	12%	12%	12%	12%	12%	12%	12%
Clausius Clapeyron 7%	rcp45	2080	1.65	2	12%	12%	12%	12%	12%	12%	12%	12%
Clausius Clapeyron 7%	rcp45	2080	1.65	3	12%	12%	12%	12%	12%	12%	12%	12%
Clausius Clapeyron 7%	rcp45	2080	1.65	6	12%	12%	12%	12%	12%	12%	12%	12%
Clausius Clapeyron 7%	rcp45	2080	1.65	12	12%	12%	12%	12%	12%	12%	12%	12%
Clausius Clapeyron 7%	rcp45	2080	1.65	24	12%	12%	12%	12%	12%	12%	12%	12%

Clausius Clapeyron 7% Method,
RCP4.5 Scenario

					Recurrence Interval (Years)							
DCF Method	**RCP Scenario**	**Decade**	**Temperature Change (C)**	**Event Duration (Hours)**	**1-year**	**2-year**	**5-year**	**10-year**	**25-year**	**50-year**	**100-year**	**500-year**
Clausius Clapeyron 7%	rcp45	2090	1.8	1	13%	13%	13%	13%	13%	13%	13%	13%
Clausius Clapeyron 7%	rcp45	2090	1.8	2	13%	13%	13%	13%	13%	13%	13%	13%
Clausius Clapeyron 7%	rcp45	2090	1.8	3	13%	13%	13%	13%	13%	13%	13%	13%
Clausius Clapeyron 7%	rcp45	2090	1.8	6	13%	13%	13%	13%	13%	13%	13%	13%
Clausius Clapeyron 7%	rcp45	2090	1.8	12	13%	13%	13%	13%	13%	13%	13%	13%
Clausius Clapeyron 7%	rcp45	2090	1.8	24	13%	13%	13%	13%	13%	13%	13%	13%
Clausius Clapeyron 7%	rcp45	2100	1.87	1	13%	13%	13%	13%	13%	13%	13%	13%
Clausius Clapeyron 7%	rcp45	2100	1.87	2	13%	13%	13%	13%	13%	13%	13%	13%
Clausius Clapeyron 7%	rcp45	2100	1.87	3	13%	13%	13%	13%	13%	13%	13%	13%
Clausius Clapeyron 7%	rcp45	2100	1.87	6	13%	13%	13%	13%	13%	13%	13%	13%
Clausius Clapeyron 7%	rcp45	2100	1.87	12	13%	13%	13%	13%	13%	13%	13%	13%
Clausius Clapeyron 7%	rcp45	2100	1.87	24	13%	13%	13%	13%	13%	13%	13%	13%

Super Clausius Clapeyron 7%-12% Method, RCP4.5 Scenario

					Recurrence Interval (Years)							
DCF Method	**RCP Scenario**	**Decade**	**Temperature Change (C)**	**Event Duration (Hours)**	**1-year**	**2-year**	**5-year**	**10-year**	**25-year**	**50-year**	**100-year**	**500-year**
Super Clausius Clapeyron 7%-12%	rcp45	2030	0.4	1	4%	4%	4%	4%	5%	5%	5%	5%
Super Clausius Clapeyron 7%-12%	rcp45	2030	0.4	2	4%	4%	4%	4%	4%	5%	5%	5%
Super Clausius Clapeyron 7%-12%	rcp45	2030	0.4	3	4%	4%	4%	4%	4%	4%	4%	4%
Super Clausius Clapeyron 7%-12%	rcp45	2030	0.4	6	3%	3%	4%	4%	4%	4%	4%	4%
Super Clausius Clapeyron 7%-12%	rcp45	2030	0.4	12	3%	3%	3%	4%	4%	4%	4%	4%
Super Clausius Clapeyron 7%-12%	rcp45	2030	0.4	24	3%	3%	3%	3%	4%	4%	4%	4%
Super Clausius Clapeyron 7%-12%	rcp45	2040	0.76	1	8%	8%	8%	8%	9%	9%	9%	9%
Super Clausius Clapeyron 7%-12%	rcp45	2040	0.76	2	7%	7%	8%	8%	8%	8%	9%	9%
Super Clausius Clapeyron 7%-12%	rcp45	2040	0.76	3	7%	7%	7%	8%	8%	8%	8%	8%
Super Clausius Clapeyron 7%-12%	rcp45	2040	0.76	6	6%	7%	7%	7%	8%	8%	8%	8%
Super Clausius Clapeyron 7%-12%	rcp45	2040	0.76	12	6%	6%	6%	7%	7%	8%	8%	8%
Super Clausius Clapeyron 7%-12%	rcp45	2040	0.76	24	5%	6%	6%	6%	7%	7%	8%	8%
Super Clausius Clapeyron 7%-12%	rcp45	2050	1.04	1	10%	11%	11%	11%	12%	12%	13%	13%
Super Clausius Clapeyron 7%-12%	rcp45	2050	1.04	2	10%	10%	11%	11%	11%	12%	12%	12%
Super Clausius Clapeyron 7%-12%	rcp45	2050	1.04	3	9%	10%	10%	10%	11%	11%	12%	12%
Super Clausius Clapeyron 7%-12%	rcp45	2050	1.04	6	9%	9%	9%	10%	10%	11%	11%	11%
Super Clausius Clapeyron 7%-12%	rcp45	2050	1.04	12	8%	8%	9%	9%	10%	10%	11%	11%
Super Clausius Clapeyron 7%-12%	rcp45	2050	1.04	24	7%	8%	8%	9%	9%	10%	10%	10%
Super Clausius Clapeyron 7%-12%	rcp45	2060	1.32	1	13%	14%	14%	15%	15%	15%	16%	16%
Super Clausius Clapeyron 7%-12%	rcp45	2060	1.32	2	12%	13%	13%	14%	14%	15%	15%	15%
Super Clausius Clapeyron 7%-12%	rcp45	2060	1.32	3	12%	12%	13%	13%	14%	14%	15%	15%
Super Clausius Clapeyron 7%-12%	rcp45	2060	1.32	6	11%	11%	12%	13%	13%	14%	14%	14%
Super Clausius Clapeyron 7%-12%	rcp45	2060	1.32	12	10%	11%	11%	12%	13%	13%	14%	14%
Super Clausius Clapeyron 7%-12%	rcp45	2060	1.32	24	9%	10%	11%	11%	12%	13%	13%	13%
Super Clausius Clapeyron 7%-12%	rcp45	2070	1.52	1	15%	16%	16%	17%	17%	18%	18%	18%
Super Clausius Clapeyron 7%-12%	rcp45	2070	1.52	2	14%	15%	15%	16%	17%	17%	18%	18%
Super Clausius Clapeyron 7%-12%	rcp45	2070	1.52	3	13%	14%	15%	15%	16%	16%	17%	17%
Super Clausius Clapeyron 7%-12%	rcp45	2070	1.52	6	12%	13%	14%	14%	15%	16%	16%	16%
Super Clausius Clapeyron 7%-12%	rcp45	2070	1.52	12	12%	12%	13%	14%	14%	15%	16%	16%
Super Clausius Clapeyron 7%-12%	rcp45	2070	1.52	24	11%	11%	12%	13%	14%	14%	15%	15%
Super Clausius Clapeyron 7%-12%	rcp45	2080	1.65	1	17%	17%	18%	18%	19%	19%	20%	20%
Super Clausius Clapeyron 7%-12%	rcp45	2080	1.65	2	16%	16%	17%	17%	18%	19%	19%	19%
Super Clausius Clapeyron 7%-12%	rcp45	2080	1.65	3	15%	15%	16%	17%	17%	18%	19%	19%
Super Clausius Clapeyron 7%-12%	rcp45	2080	1.65	6	14%	14%	15%	16%	16%	17%	18%	18%
Super Clausius Clapeyron 7%-12%	rcp45	2080	1.65	12	13%	13%	14%	15%	16%	16%	17%	17%
Super Clausius Clapeyron 7%-12%	rcp45	2080	1.65	24	12%	12%	13%	14%	15%	16%	17%	17%

Super Clausius Clapeyron 7%-12% Method,
RCP4.5 Scenario

					Recurrence Interval (Years)							
DCF Method	**RCP Scenario**	**Decade**	**Temperature Change (C)**	**Event Duration (Hours)**	**1-year**	**2-year**	**5-year**	**10-year**	**25-year**	**50-year**	**100-year**	**500-year**
Super Clausius Clapeyron 7%-12%	rcp45	2090	1.8	1	18%	19%	19%	20%	20%	21%	22%	22%
Super Clausius Clapeyron 7%-12%	rcp45	2090	1.8	2	17%	18%	18%	19%	20%	20%	21%	21%
Super Clausius Clapeyron 7%-12%	rcp45	2090	1.8	3	16%	17%	17%	18%	19%	19%	20%	20%
Super Clausius Clapeyron 7%-12%	rcp45	2090	1.8	6	15%	16%	16%	17%	18%	19%	19%	19%
Super Clausius Clapeyron 7%-12%	rcp45	2090	1.8	12	14%	15%	15%	16%	17%	18%	19%	19%
Super Clausius Clapeyron 7%-12%	rcp45	2090	1.8	24	13%	14%	14%	15%	16%	17%	18%	18%
Super Clausius Clapeyron 7%-12%	rcp45	2100	1.87	1	19%	19%	20%	21%	21%	22%	22%	22%
Super Clausius Clapeyron 7%-12%	rcp45	2100	1.87	2	18%	18%	19%	20%	20%	21%	22%	22%
Super Clausius Clapeyron 7%-12%	rcp45	2100	1.87	3	16%	17%	18%	19%	19%	20%	21%	21%
Super Clausius Clapeyron 7%-12%	rcp45	2100	1.87	6	15%	16%	17%	18%	19%	19%	20%	20%
Super Clausius Clapeyron 7%-12%	rcp45	2100	1.87	12	14%	15%	16%	17%	18%	19%	19%	19%
Super Clausius Clapeyron 7%-12%	rcp45	2100	1.87	24	13%	14%	15%	16%	17%	18%	19%	19%

Clausius Clapeyron 7% Method,
RCP8.5 Scenario

DCF Method	RCP Scenario	Decade	Temperature Change (C)	Event Duration (Hours)	Recurrence Interval (Years) 1-year	2-year	5-year	10-year	25-year	50-year	100-year	500-year
Clausius Clapeyron 7%	rcp85	2030	0.43	1	3%	3%	3%	3%	3%	3%	3%	3%
Clausius Clapeyron 7%	rcp85	2030	0.43	2	3%	3%	3%	3%	3%	3%	3%	3%
Clausius Clapeyron 7%	rcp85	2030	0.43	3	3%	3%	3%	3%	3%	3%	3%	3%
Clausius Clapeyron 7%	rcp85	2030	0.43	6	3%	3%	3%	3%	3%	3%	3%	3%
Clausius Clapeyron 7%	rcp85	2030	0.43	12	3%	3%	3%	3%	3%	3%	3%	3%
Clausius Clapeyron 7%	rcp85	2030	0.43	24	3%	3%	3%	3%	3%	3%	3%	3%
Clausius Clapeyron 7%	rcp85	2040	0.94	1	7%	7%	7%	7%	7%	7%	7%	7%
Clausius Clapeyron 7%	rcp85	2040	0.94	2	7%	7%	7%	7%	7%	7%	7%	7%
Clausius Clapeyron 7%	rcp85	2040	0.94	3	7%	7%	7%	7%	7%	7%	7%	7%
Clausius Clapeyron 7%	rcp85	2040	0.94	6	7%	7%	7%	7%	7%	7%	7%	7%
Clausius Clapeyron 7%	rcp85	2040	0.94	12	7%	7%	7%	7%	7%	7%	7%	7%
Clausius Clapeyron 7%	rcp85	2040	0.94	24	7%	7%	7%	7%	7%	7%	7%	7%
Clausius Clapeyron 7%	rcp85	2050	1.56	1	11%	11%	11%	11%	11%	11%	11%	11%
Clausius Clapeyron 7%	rcp85	2050	1.56	2	11%	11%	11%	11%	11%	11%	11%	11%
Clausius Clapeyron 7%	rcp85	2050	1.56	3	11%	11%	11%	11%	11%	11%	11%	11%
Clausius Clapeyron 7%	rcp85	2050	1.56	6	11%	11%	11%	11%	11%	11%	11%	11%
Clausius Clapeyron 7%	rcp85	2050	1.56	12	11%	11%	11%	11%	11%	11%	11%	11%
Clausius Clapeyron 7%	rcp85	2050	1.56	24	11%	11%	11%	11%	11%	11%	11%	11%
Clausius Clapeyron 7%	rcp85	2060	2.23	1	16%	16%	16%	16%	16%	16%	16%	16%
Clausius Clapeyron 7%	rcp85	2060	2.23	2	16%	16%	16%	16%	16%	16%	16%	16%
Clausius Clapeyron 7%	rcp85	2060	2.23	3	16%	16%	16%	16%	16%	16%	16%	16%
Clausius Clapeyron 7%	rcp85	2060	2.23	6	16%	16%	16%	16%	16%	16%	16%	16%
Clausius Clapeyron 7%	rcp85	2060	2.23	12	16%	16%	16%	16%	16%	16%	16%	16%
Clausius Clapeyron 7%	rcp85	2060	2.23	24	16%	16%	16%	16%	16%	16%	16%	16%
Clausius Clapeyron 7%	rcp85	2070	2.86	1	20%	20%	20%	20%	20%	20%	20%	20%
Clausius Clapeyron 7%	rcp85	2070	2.86	2	20%	20%	20%	20%	20%	20%	20%	20%
Clausius Clapeyron 7%	rcp85	2070	2.86	3	20%	20%	20%	20%	20%	20%	20%	20%
Clausius Clapeyron 7%	rcp85	2070	2.86	6	20%	20%	20%	20%	20%	20%	20%	20%
Clausius Clapeyron 7%	rcp85	2070	2.86	12	20%	20%	20%	20%	20%	20%	20%	20%
Clausius Clapeyron 7%	rcp85	2070	2.86	24	20%	20%	20%	20%	20%	20%	20%	20%
Clausius Clapeyron 7%	rcp85	2080	3.47	1	24%	24%	24%	24%	24%	24%	24%	24%
Clausius Clapeyron 7%	rcp85	2080	3.47	2	24%	24%	24%	24%	24%	24%	24%	24%
Clausius Clapeyron 7%	rcp85	2080	3.47	3	24%	24%	24%	24%	24%	24%	24%	24%
Clausius Clapeyron 7%	rcp85	2080	3.47	6	24%	24%	24%	24%	24%	24%	24%	24%
Clausius Clapeyron 7%	rcp85	2080	3.47	12	24%	24%	24%	24%	24%	24%	24%	24%
Clausius Clapeyron 7%	rcp85	2080	3.47	24	24%	24%	24%	24%	24%	24%	24%	24%

Clausius Clapeyron 7% Method,
RCP8.5 Scenario

DCF Method	RCP Scenario	Decade	Temperature Change (C)	Event Duration (Hours)	Recurrence Interval (Years)							
					1-year	2-year	5-year	10-year	25-year	50-year	100-year	500-year
Clausius Clapeyron 7%	rcp85	2090	4.15	1	29%	29%	29%	29%	29%	29%	29%	29%
Clausius Clapeyron 7%	rcp85	2090	4.15	2	29%	29%	29%	29%	29%	29%	29%	29%
Clausius Clapeyron 7%	rcp85	2090	4.15	3	29%	29%	29%	29%	29%	29%	29%	29%
Clausius Clapeyron 7%	rcp85	2090	4.15	6	29%	29%	29%	29%	29%	29%	29%	29%
Clausius Clapeyron 7%	rcp85	2090	4.15	12	29%	29%	29%	29%	29%	29%	29%	29%
Clausius Clapeyron 7%	rcp85	2090	4.15	24	29%	29%	29%	29%	29%	29%	29%	29%
Clausius Clapeyron 7%	rcp85	2100	4.5	1	31%	31%	31%	31%	31%	31%	31%	31%
Clausius Clapeyron 7%	rcp85	2100	4.5	2	31%	31%	31%	31%	31%	31%	31%	31%
Clausius Clapeyron 7%	rcp85	2100	4.5	3	31%	31%	31%	31%	31%	31%	31%	31%
Clausius Clapeyron 7%	rcp85	2100	4.5	6	31%	31%	31%	31%	31%	31%	31%	31%
Clausius Clapeyron 7%	rcp85	2100	4.5	12	31%	31%	31%	31%	31%	31%	31%	31%
Clausius Clapeyron 7%	rcp85	2100	4.5	24	31%	31%	31%	31%	31%	31%	31%	31%

Super Clausius Clapeyron 7%-12% Method,
RCP8.5 Scenario

					Recurrence Interval (Years)							
DCF Method	**RCP Scenario**	**Decade**	**Temperature Change (C)**	**Event Duration (Hours)**	**1-year**	**2-year**	**5-year**	**10-year**	**25-year**	**50-year**	**100-year**	**500-year**
Super Clausius Clapeyron 7%-12%	rcp85	2030	0.43	1	4%	4%	5%	5%	5%	5%	5%	5%
Super Clausius Clapeyron 7%-12%	rcp85	2030	0.43	2	4%	4%	4%	5%	5%	5%	5%	5%
Super Clausius Clapeyron 7%-12%	rcp85	2030	0.43	3	4%	4%	4%	4%	4%	5%	5%	5%
Super Clausius Clapeyron 7%-12%	rcp85	2030	0.43	6	4%	4%	4%	4%	4%	4%	5%	5%
Super Clausius Clapeyron 7%-12%	rcp85	2030	0.43	12	3%	3%	4%	4%	4%	4%	4%	4%
Super Clausius Clapeyron 7%-12%	rcp85	2030	0.43	24	3%	3%	3%	4%	4%	4%	4%	4%
Super Clausius Clapeyron 7%-12%	rcp85	2040	0.94	1	9%	10%	10%	10%	11%	11%	11%	11%
Super Clausius Clapeyron 7%-12%	rcp85	2040	0.94	2	9%	9%	10%	10%	10%	11%	11%	11%
Super Clausius Clapeyron 7%-12%	rcp85	2040	0.94	3	8%	9%	9%	9%	10%	10%	11%	11%
Super Clausius Clapeyron 7%-12%	rcp85	2040	0.94	6	8%	8%	9%	9%	9%	10%	10%	10%
Super Clausius Clapeyron 7%-12%	rcp85	2040	0.94	12	7%	8%	8%	8%	9%	9%	10%	10%
Super Clausius Clapeyron 7%-12%	rcp85	2040	0.94	24	7%	7%	8%	8%	8%	9%	9%	9%
Super Clausius Clapeyron 7%-12%	rcp85	2050	1.56	1	16%	16%	17%	17%	18%	18%	19%	19%
Super Clausius Clapeyron 7%-12%	rcp85	2050	1.56	2	15%	15%	16%	16%	17%	17%	18%	18%
Super Clausius Clapeyron 7%-12%	rcp85	2050	1.56	3	14%	14%	15%	16%	16%	17%	17%	17%
Super Clausius Clapeyron 7%-12%	rcp85	2050	1.56	6	13%	13%	14%	15%	15%	16%	17%	17%
Super Clausius Clapeyron 7%-12%	rcp85	2050	1.56	12	12%	13%	13%	14%	15%	15%	16%	16%
Super Clausius Clapeyron 7%-12%	rcp85	2050	1.56	24	11%	12%	12%	13%	14%	15%	16%	16%
Super Clausius Clapeyron 7%-12%	rcp85	2060	2.23	1	22%	23%	24%	25%	25%	26%	27%	27%
Super Clausius Clapeyron 7%-12%	rcp85	2060	2.23	2	21%	22%	23%	23%	24%	25%	26%	26%
Super Clausius Clapeyron 7%-12%	rcp85	2060	2.23	3	20%	21%	21%	22%	23%	24%	25%	25%
Super Clausius Clapeyron 7%-12%	rcp85	2060	2.23	6	18%	19%	20%	21%	22%	23%	24%	24%
Super Clausius Clapeyron 7%-12%	rcp85	2060	2.23	12	17%	18%	19%	20%	21%	22%	23%	23%
Super Clausius Clapeyron 7%-12%	rcp85	2060	2.23	24	16%	17%	18%	19%	20%	21%	22%	22%
Super Clausius Clapeyron 7%-12%	rcp85	2070	2.86	1	29%	30%	31%	31%	32%	33%	34%	34%
Super Clausius Clapeyron 7%-12%	rcp85	2070	2.86	2	27%	28%	29%	30%	31%	32%	33%	33%
Super Clausius Clapeyron 7%-12%	rcp85	2070	2.86	3	25%	26%	27%	29%	30%	31%	32%	32%
Super Clausius Clapeyron 7%-12%	rcp85	2070	2.86	6	23%	25%	26%	27%	28%	30%	31%	31%
Super Clausius Clapeyron 7%-12%	rcp85	2070	2.86	12	22%	23%	24%	26%	27%	28%	30%	30%
Super Clausius Clapeyron 7%-12%	rcp85	2070	2.86	24	20%	21%	23%	24%	26%	27%	29%	29%
Super Clausius Clapeyron 7%-12%	rcp85	2080	3.47	1	35%	36%	37%	38%	39%	41%	42%	42%
Super Clausius Clapeyron 7%-12%	rcp85	2080	3.47	2	33%	34%	35%	36%	38%	39%	40%	40%
Super Clausius Clapeyron 7%-12%	rcp85	2080	3.47	3	31%	32%	33%	35%	36%	38%	39%	39%
Super Clausius Clapeyron 7%-12%	rcp85	2080	3.47	6	28%	30%	32%	33%	35%	36%	38%	38%
Super Clausius Clapeyron 7%-12%	rcp85	2080	3.47	12	26%	28%	30%	31%	33%	35%	36%	36%
Super Clausius Clapeyron 7%-12%	rcp85	2080	3.47	24	24%	26%	28%	30%	31%	33%	35%	35%

Super Clausius Clapeyron 7%-12% Method,
RCP8.5 Scenario

DCF Method	RCP Scenario	Decade	Temperature Change (C)	Event Duration (Hours)	Recurrence Interval (Years)							
					1-year	2-year	5-year	10-year	25-year	50-year	100-year	500-year
Super Clausius Clapeyron 7%-12%	rcp85	2090	4.15	1	42%	43%	44%	46%	47%	48%	50%	50%
Super Clausius Clapeyron 7%-12%	rcp85	2090	4.15	2	39%	41%	42%	44%	45%	47%	48%	48%
Super Clausius Clapeyron 7%-12%	rcp85	2090	4.15	3	37%	38%	40%	42%	43%	45%	46%	46%
Super Clausius Clapeyron 7%-12%	rcp85	2090	4.15	6	34%	36%	38%	39%	41%	43%	45%	45%
Super Clausius Clapeyron 7%-12%	rcp85	2090	4.15	12	32%	33%	35%	37%	39%	41%	43%	43%
Super Clausius Clapeyron 7%-12%	rcp85	2090	4.15	24	29%	31%	33%	35%	37%	39%	42%	42%
Super Clausius Clapeyron 7%-12%	rcp85	2100	4.5	1	45%	46%	48%	49%	51%	52%	54%	54%
Super Clausius Clapeyron 7%-12%	rcp85	2100	4.5	2	42%	44%	46%	47%	49%	51%	52%	52%
Super Clausius Clapeyron 7%-12%	rcp85	2100	4.5	3	40%	41%	43%	45%	47%	49%	50%	50%
Super Clausius Clapeyron 7%-12%	rcp85	2100	4.5	6	37%	39%	41%	43%	45%	47%	49%	49%
Super Clausius Clapeyron 7%-12%	rcp85	2100	4.5	12	34%	36%	38%	40%	43%	45%	47%	47%
Super Clausius Clapeyron 7%-12%	rcp85	2100	4.5	24	31%	34%	36%	38%	40%	43%	45%	45%

Appendix 2: CMIP5 Suite of General Circulation Models (GCMs)

#	Global Climate Model (GCM)	Climate Modeling Organization
1	access1-0.1	CSIRO Climate Science Centre in Aspendale, Melbourne, Australia
2	access1-3.1	
3	bcc-csm1-1.1	Beijing Climate Center, China Meteorological Administration, China
4	bcc-csm1-1-m.1	
5	canesm2.1	Canadian Centre for Climate Modeling and Analysis
6	ccsm4.6	Community Earth System Model, National Center for Atmospheric Research (NCAR), USA
7	cesm1-bgc.1	
8	cesm1-cam5.1	
9	cmcc-cm.1	European Network of Earth System Modeling
10	cnrm-cm5.1	
11	csiro-mk3-6-0.1	CSIRO Climate Science Centre in Aspendale, Melbourne, Australia
12	ec-earth.8	European Network of Earth System Modeling
13	fgoals-g2.1	Climate Change Research Center, Chinese Academy of Sciences, Beijing, China
14	gfdl-cm3.1	National Oceanic and Atmospheric Administration (NOAA) Geophysical Fluid Dynamics Laboratory (USA)
15	gfdl-esm2g.1	
16	gfdl-esm2m.1	
17	giss-e2-r.6	National Aeronautics and Space Administration, NASA, USA
18	hadgem2-ao.1	National Meteorological Service, UK
19	hadgem2-cc.1	
20	hadgem2-es.1	
21	inmcm4.1	National Centre for Meteorological Research (CNRM), France
22	ipsl-cm5a-lr.1	Institut Pierre-Simon Laplace (France)
23	ipsl-cm5a-mr.1	
24	miroc-esm.1	Meteorological Research Institute, University of Tokyo
25	miroc-esm-chem.1	
26	miroc5.1	
27	mpi-esm-lr.1	Max Planck Institute for Meteorology (Germany)
28	mpi-esm-mr.1	
29	mri-cgcm3.1	Meteorological Research Institute of the Korea
30	noresm1-m.1	Norwegian Meteorological Institute (Norway)
31	cmcc-cms.1	European Network of Earth System Modeling
32	giss-e2-h.6	National Aeronautics and Space Administration, NASA, USA

Appendix 3: Example Application of Precipitation Change Factors to Atlas 14 Depths

Appendix 1 provides precipitation change factors tables for 8 decades (2030-2100), 2 different methods (Clausius Clapeyron 7% and Super Clausius Clapeyron 7%-12%), and 2 RCP scenarios (RCP4.5 and RCP8.5). Each table provides precipitation change factors for a number of return intervals and event durations. These tables can be used to estimate future design storm depths. This Appendix provides a simple example of this process using data from Atlas 14.

Atlas 14 provides point-based historically-based estimates of precipitation depths for a variety of return intervals and event durations. **Table 3** shows these estimates for a single point in the Brandywine River watershed.

Table 3 – Atlas 14 precipitation depths in inches (partial duration series) for an example point in the Brandywine River watershed

Event Duration	Average Recurrence Interval (years)							
	1-y	2-y	5-y	10-y	25-y	50-y	100-y	500-y
1-hour	1.2	1.5	1.8	2.1	2.4	2.6	2.9	3.4
2-hour	1.4	1.8	2.2	2.5	2.9	3.3	3.6	4.4
3-hour	1.6	1.9	2.4	2.7	3.2	3.6	4.0	4.9
6-hour	1.9	2.3	2.9	3.4	4.0	4.5	5.1	6.4
12-hour	2.4	2.8	3.6	4.1	5.0	5.7	6.5	8.6
24-hour	2.7	3.3	4.1	4.8	5.8	6.7	7.6	10.0

Depending on the application, the user may choose to apply precipitation change factors from any of the decades, methods, and RCP scenarios to the Atlas 14 data. For this representative example, the table for the RCP4.5 scenario, 2050 decade, and Super Clausius Clapeyron 7%-12% method was arbitrarily chosen, but the choice of a table will depend on the user's unique needs. **Table 4** shows the precipitation change factors for these conditions.

Table 4 – Precipitation change factors for 2050 for the RCP4.5 scenario using the Super Clausius Clapeyron 7%-12% method

Event Duration	Average Recurrence Interval (years)							
	1-y	2-y	5-y	10-y	25-y	50-y	100-y	500-y
1-hour	10%	11%	11%	11%	12%	12%	13%	13%
2-hour	10%	10%	11%	11%	11%	12%	12%	12%
3-hour	9%	10%	10%	10%	11%	11%	12%	12%
6-hour	9%	9%	9%	10%	10%	11%	11%	11%
12-hour	8%	8%	9%	9%	10%	10%	11%	11%
24-hour	7%	8%	8%	9%	9%	10%	10%	10%

To apply the precipitation change factors, simply increase the Atlas 14 depths by the appropriate percentage amount for each return interval and event duration. **Table 5** shows the new precipitation depths using the change factors.

Table 5 – Estimated future precipitation depths in inches for an example point in the Brandywine River watershed using Atlas 14 precipitation depths from Table 3 and precipitation change factors from Table 4

Event Duration	Average Recurrence Interval (years)							
	1-y	2-y	5-y	10-y	25-y	50-y	100-y	500-y
1-hour	1.3	1.6	2.0	2.3	2.7	2.9	3.2	3.8
2-hour	1.6	1.9	2.4	2.8	3.3	3.7	4.1	5.0
3-hour	1.7	2.1	2.6	3.0	3.6	4.0	4.4	5.5
6-hour	2.1	2.5	3.2	3.7	4.4	5.0	5.6	7.1
12-hour	2.5	3.1	3.9	4.5	5.5	6.3	7.2	9.5
24-hour	2.9	3.5	4.4	5.2	6.3	7.3	8.3	11.0