RESILIENT MASSACHUSETTS ACTION TEAM (RMAT)

DRAFT

CLIMATE RESILIENCE DESIGN STANDARDS & GUIDELINES

SECTION 3: DRAFT CLIMATE RESILIENCE DESIGN STANDARDS OVERVIEW

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RMAT CLIMATE RESILIENCE DESIGN STANDARDS AND GUIDELINES

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3. CLIMATE RESILIENCE DESIGN STANDARDS OUTPUTS AND RELATIONSHIPS

This section describes the Climate Resilience Design Standards outputs provided by the Climate Resilience Design Standards Tool (the Tool), and the relationships that inform those outputs.

3.1 CLIMATE RESILIENCE DESIGN STANDARDS OVERVIEW

3.1.1 GOALS/OBJECTIVES

The main objective of the Climate Resilience Design Standards ("Standards") is to provide a consistent basis-of-design across various projects in the Commonwealth for climate parameters: sea level rise and storm surge, extreme precipitation, and extreme heat. The term "standards" has been used in many different ways in climate resilience literature, so the RMAT developed a draft definition as follows: "***A Climate Resilience Design Standard is a scientifically based process or method that produces a consistent outcome, which uniformly guides users in the selection of planning horizons, return period, and flexible design criteria, by climate parameter***."

Many projects throughout the Commonwealth are currently using climate projections and data for design. The Standards will provide a uniform statewide methodology for consistent use of available climate projections. The Standards also bridge the gap between the climate data that have been developed and using that data for design by translating it into design criteria. The tiered methodology provided by the Standards, based on the recommended level of effort, informs users on how to calculate design criteria values for asset and project design.

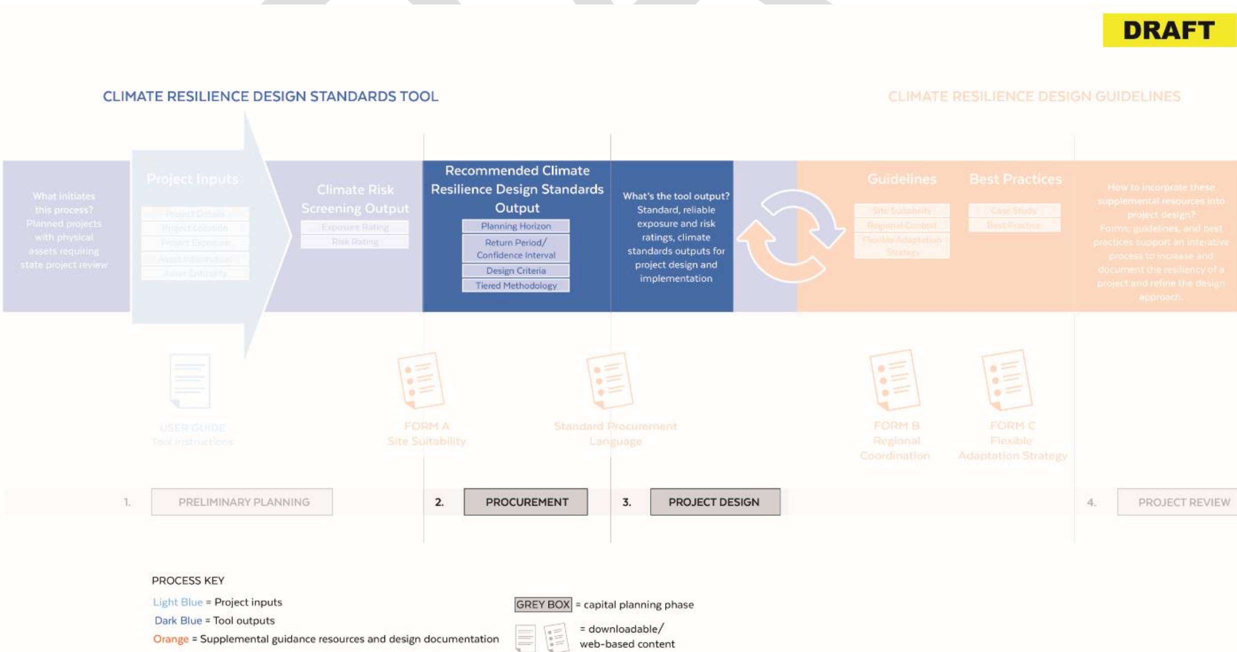

Figure 3.1. *Project Overview Emphasizing the Climate Resilience Design Standards Output from the Climate Resilience Design Standards Tool*

3.1.2 APPROACH

The Climate Resilience Design Standards are one of the outputs of the online GIS-based Climate Resilience Design Standards Tool ("Tool"), the other main output of the Tool being the preliminary Climate Risk Screening Output (described in Section 2). Upon completing the necessary Project Inputs, users will first receive a preliminary Climate Risk Screening Output for their project and assets, by climate parameter (as discussed in Section 2). Users will then receive Climate Resilience Design Standards Outputs from the Tool. The Standards will be organized by climate parameter, and will include a recommended planning horizon, return period or confidence interval, design criteria, and tiered methodology for calculating design criteria values. These outputs will be automated in the web-based Tool and will include the following sections, as listed in Table 3.1.

Table 3.1. Standard Output Recommendations Provided by the Tool

Standard Output Recommendations	Example	Relationship Driving Recommendation
Planning Horizon[1]	2070	Useful Life
Return Period[2,6]	100-year (1% AEP)	Criticality[3], Asset Type, and Useful/Exposure Service Life[4]
Confidence Interval[5,6]	50th percentile	Criticality, Asset Type, and Construction Type
Design Criteria[6]	Rainfall depth, design flood elevation, cooling degree days, etc.	Asset Type and Location
Tiered Methodology[6]	Tier 3 – High Level of Effort	Criticality and Useful Life

1. Intermediate planning horizon provided for coastal climate parameters only.
2. For coastal and precipitation climate parameters only.
3. For a description of Criticality, please refer to the Glossary of Terms and Section 2.1.4.
4. Precipitation is based on useful life of asset, Coastal is based on exposure service life of asset, which is defined as number of years from when an asset is first exposed to coastal flooding to the end of its service/useful life (estimated using probability of flooding maps from the Massachusetts Coastal Flood Risk Model (MC-FRM))
5. For heat climate parameters only.
6. Return period/confidence interval, design criteria and tiered methodology are provided for each of three climate parameters: sea level rise and storm surge, precipitation, and heat.

The Standards utilize existing available climate data and provide a consistent, repeatable methodology for developing design criteria values from the data. The methodologies are structured in tiers to reflect the level of effort associated with using the climate data to generate design criteria values.

Tier 3 is the greatest level of effort and the most site-specific method to calculate design criteria values out of the tiered methodologies. There are already Tier 3 data available statewide for coastal climate parameters through the Massachusetts Coast Flood Risk Model (MC-FRM). Some communities have also developed or are in the process of developing local site-specific extreme precipitation and extreme heat data and models for planning and design, such as Cambridge, Somerville, and Boston. Once Tier 3 data are available, the level of effort for generating design criteria values is reduced significantly. Where data are not available, the Tier 3 methodology generally utilizes downscaled global climate models (GCMs) to generate design criteria values.

Tier 2 is a moderate level of effort and utilizes existing established relationships between current and future climate scenarios and current design criteria to generate future climate design criteria values. These relationships are referenced often in climate studies, such as the present-day 100-year rainfall event is similar to the 2070 25-year rainfall event. Where those relationships are not yet established for design criteria, such as the case for Heat Waves, Tier 3 or Tier 1 methods are recommended.

Tier 1 is the lowest level of effort and is only recommended for low and medium criticality assets with a useful life of less than 10 years. These projects should incorporate Tier 2 methods where feasible, but if not, should design for today and plan for resilience reinvestment in the future.

The tiered methodologies are provided with step-by-step instructions in downloadable PDFs for each climate parameter in the Tool. Users will need to follow the instructions to generate values for the recommended design criteria, using the recommended return period or confidence interval, and planning horizon. The relationships showing how tiers are determined and provided by the Tool as output, based on asset criticality and useful life, are shown in Figure 3.2, below. Please refer to Section 2 for additional information on asset criticality.

High Criticality	TIER 2	TIER 3	TIER 3
Medium Criticality	TIER 1	TIER 2	TIER 3
Low Criticality	TIER 1	TIER 2	TIER 2
	< 10 years	10 to 50 years	50 years +

Figure 3.2. *Relationships Informing Recommended Tier Output from the Climate Resilience Design Standards Tool*

3.1.3 INTENDED USER/REVIEW

Upon completion of the Project Inputs and review of the Climate Risk Screening Output (by the State Agency Project Managers, State Agency Program Managers, and Asset Owners, during preliminary project planning), it is expected that Technical Staff will proceed with calculating design criteria values for project design based on the Standards output recommendations. Standard procurement language will be provided to solicit Technical Staff to assist with calculating design criteria values for project design. If Tier 3 methodology calculations are performed, a technical peer review is recommended to review the calculation package. The Standards and calculated design criteria values should then be considered in context of project design along with the Climate Resilience Design Guidelines (refer to Section 4).

3.1.4 WHEN TO USE THE CLIMATE RESILIENCE DESIGN STANDARDS

The Climate Resilience Design Standards are intended for use in design projects with physical assets owned and maintained by state agencies. The Standards will be accessible online and available for other projects in the Commonwealth.

The Tool should be completed as part of preliminary planning efforts before design commences. The Standards will be provided as an output from the Tool after users submit Project Inputs and receive their preliminary Climate Risk Screening Output. The Standards Output received by users should then be used to calculate design criteria values while proceeding into the project design phase.

3.1.5 LIMITATIONS

The Climate Resilience Design Standards are advisory and intended to be specific for climate resilience design of assets and consistent across agencies and municipalities. The Standards do not and are not intended to replace existing practices, regulatory requirements, codes, or existing standards required by other agencies. For example, if an asset is recommended to be designed to a 25-year return period through the Tool, but the asset is only designed to a 10-year return period based on other regulatory policy, the discrepancy should be reflected in the Forms presented as part of the Climate Design Guidelines (refer to Section 4).

The Standards provide tiered methodologies to calculate numerical values for design criteria, and those numerical values are not an output of the Tool. These methodologies are based on existing industry-accepted and scientific community-published sources, referenced in each downloadable PDF (See Section 3 Attachments).

The goal of the Standards is to provide a consistent basis-of design across various projects in the Commonwealth. There may, however, be additional asset types, design criteria, and/or climate parameters that are not included in the Standards. For example, the Commonwealth of Massachusetts is currently developing detailed precipitation and hydrologic design criteria values statewide, which would serve as Tier 3 data for precipitation design criteria, similar to how MC-FRM serves as Tier 3 data for sea level rise and storm surge design criteria. This first version of the Standards is therefore developed to be flexible and accommodate new climate parameters, data, design criteria, etc. in the future, as needed.

The Standards are not a replacement for a detailed risk and vulnerability assessment. Additional studies to evaluate climate risks and identify feasible adaptation strategies to mitigate those risks should be considered as part of design.

3.2 SEA LEVEL RISE & STORM SURGE STANDARDS OUTPUTS & RELATIONSHIPS

3.2.1 OUTPUTS OVERVIEW

Upon submission of Project Inputs and review of preliminary Climate Risk Screening Output, users will receive Standards for each climate parameter from the Tool. If users are not exposed to sea level rise/ storm surge, they will not receive Standards for this climate parameter. The Standards provided for sea level rise/ storm surge climate parameter include the following: recommended target and intermediate planning horizon, return period, design criteria, and tiered methodology to calculate design criteria values. These outputs are discussed in further detail in Sections 3.2.2 through 3.2.5, below.

3.2.2 DATA SOURCE

The Standards reference the Massachusetts Coast Flood Risk Model (MC-FRM) that is currently being developed by MassDOT. The MC-FRM is a probabilistic hydrodynamic model that uses the values for sea level rise on ResilientMA.org (RCP 8.5 scenario). The MC-FRM is capable of providing a range of design criteria outputs, including the design criteria listed in Section 3.2.6. Currently users will need to request design criteria information through the Tool, but future versions of the Tool will have some MC-FRM design criteria available directly as an output.

3.2.3 PLANNING HORIZONS

A planning horizon is defined as a future time period to which a project is recommended to be designed for, which allows the project to incorporate anticipated climate change projections. The Tool will provide two planning horizons for the project: Target and Intermediate. The Target Planning Horizon refers to the recommended planning horizon for incorporating climate resilience in the design of the asset. The Intermediate Planning Horizon is provided as an interim planning horizon if the Target Planning Horizon is not achievable in design. Recommended planning horizons provided by the Tool do not vary based on climate parameter but may vary by asset. However, the Intermediate Planning Horizon is only applicable for sea level rise and storm surge parameter, not for extreme precipitation and heat.

The recommended planning horizons are informed by the useful life of each asset, as indicated in Project Inputs. The relationships used to provide the recommended Target Planning Horizon and the recommended Intermediate Planning Horizon are based on asset useful life, as indicated in Table 3.2. For assets with useful life greater than or equal to 31 years (2050 and beyond), an Intermediate Planning Horizon of 2050 will be provided for flexible adaptation design considerations.

Table 3.2. Recommended Target Planning Horizons Provided by the Tool, based on Asset Useful Life

ASSET USEFUL LIFE	RECOMMENDED TARGET PLANNING HORIZON[1] OUTPUT	RECOMMENDED INTERMEDIATE PLANNING HORIZON OUTPUT
0 to 10 years	**2030[2]**	**Not Applicable**
11 years to 20 years	**2050[3]**	**Not Applicable**
21 years to 30 years	**2050[3]**	**Not Applicable**
31 years to 40 years	**2070[4]**	**2050**
41 years to 50 years	**2070[4]**	**2050**
51 years to 60 years	**2070[4]**	**2050**
61 years to 75 years	**2090[5]**	**2050**
Greater than 75 years	**2090[5]**	**2050**

1. The bounding years for the planning horizons are consistent with the SHMCAP and ResilientMA.org.
2. The bounding years for the 2030 planning horizon are 2020 through 2049.
3. The bounding years for the 2050 planning horizon are 2040 through 2069.
4. The bounding years for the 2070 planning horizon are 2060 through 2089.
5. The bounding years for the 2090 planning horizon are 2080 through 2099.

3.2.4 RETURN PERIOD

A return period is defined as the annual probability of occurrence of an event (also known as a recurrence interval). The Tool will provide a recommended return period for each asset in a project. The recommended return period will also be provided in terms of percent annual exceedance probability (% AEP or “annual probability”). This distinction is based on industry practice and is described in further detail in the Glossary of Terminology, Section 1.6. Different State Agencies and municipalities may have their own standards for return periods. The recommended return periods provided by the Tool are advisory and do not replace regulatory requirements. These recommended return periods for each climate parameter are based on industry standards and professional judgment, asset criticality, and useful life. For sea level rise/ storm surge, the recommended return periods for each Asset Category are shown in Table 3.3, below.

Table 3.3. Recommended Return Periods Provided by the Tool for the Sea Level Rise & Storm Surge Climate Parameter

SEA LEVEL RISE & STORM SURGE

Criticality[1]	Exposure Service Life[1]	Buildings/ Facilities	Infrastructure				Natural Resources	
			Transportation	*Flood Control*	*Utilities*	*Solid/Haz. Waste*	*Coastal Ecosystems*	*Other*
		Return Period (% AEP)	**Return Period (% AEP)**	**Return Period (% AEP)**	**Return Period (% AEP)**	**Return Period (% AEP)**	**Return Period (% AEP)**	**Return Period (% AEP)**
High	50-100 years	**500-yr (0.2%)**	**1000-yr (0.1%)**	**500-yr (0.2%)**	**500-yr (0.2%)**	**1000-yr (0.1%)**	**Tidal Benchmarks[2]**	**200-yr (0.5%)**
Medium	50-100 years	**200-yr (0.5%)**	**200-yr (0.5%)**	**200-yr (0.5%)**	**200-yr (0.5%)**	**200-yr (0.5%)**	**Tidal Benchmarks[2]**	**100-yr (1%)**
Low	50-100 years	**100-yr (1%)**	**100-yr (1%)**	**100-yr (1%)**	**100-yr (1%)**	**100-yr (1%)**	**Tidal Benchmarks[2]**	**100-yr (1%)**
High	10-50 years	**200-yr (0.5%)**	**500-yr (0.2%)**	**200-yr (0.5%)**	**200-yr (0.5%)**	**500-yr (0.2%)**	**Tidal Benchmarks[2]**	**100-yr (1%)**
Medium	10-50 years	**100-yr (1%)**	**200-yr (0.5%)**	**100-yr (1%)**	**100-yr (1%)**	**200-yr (0.5%)**	**Tidal Benchmarks[2]**	**50-yr (2%)**
Low	10-50 years	**50-yr (2%)**	**100-yr (1%)**	**50-yr (2%)**	**50-yr (2%)**	**100-yr (1%)**	**Tidal Benchmarks[2]**	**50-yr (2%)**
High	10 years or less	**100-yr (1%)**	**100-yr (1%)**	**100-yr (1%)**	**100-yr (1%)**	**100-yr (1%)**	**Tidal Benchmarks[2]**	**100-yr (1%)**
Medium	10 years or less	**50-yr (2%)**	**50-yr (2%)**	**50-yr (2%)**	**50-yr (2%)**	**50-yr (2%)**	**Tidal Benchmarks[2]**	**50-yr (2%)**
Low	10 years or less	**20-yr (5%)**	**20-yr (5%)**	**20-yr (5%)**	**20-yr (5%)**	**20-yr (5%)**	**Tidal Benchmarks[2]**	**20-yr (5%)**

1. Criticality and Exposure Service Life are not outputs, but the relationship informs the recommended return period from the Tool.
2. Tidal datums are standard elevations defined by a certain phase of the tide and are used as reference to measure local water levels. Such datums are referenced to known fixed points called tidal benchmarks. Tidal benchmarks corresponding to present and future tidal elevations are outputs of MC-FRM. Tidal benchmarks are recommended for design of coastal ecosystems in lieu of return periods, since coastal ecosystems rely on daily tide cycles.

3.2.5 CUMULATIVE PROBABILITY

> Cumulative probability is defined as the measure of the total probability that a certain event will happen during a given period of time. Cumulative probability is calculated based on the equation:
>
> $$p_n = 1 - (1-p)^n$$
>
> where 'p_n' equals the cumulative probability over 'n' number of years and 'p' equals annual probability, which is not constant due to climate change.

As described in Section 3.2.4, recommended return periods for assets by climate parameter are based on industry standards and professional judgment, asset criticality, and useful life. However, the recommended return period output from the Tool is also informed by an asset's cumulative probability of being exposed to a climate event. The median cumulative probability from sea level rise and storm surge for an asset can be calculated based on the asset's recommended planning horizon and site-specific projected flood elevation from sea level rise and storm surge. The projected sea level rise and storm surge elevations for a site corresponding to different annual probabilities by planning horizon can be obtained from the Massachusetts Coast Flood Risk Model (MC-FRM), and are referred to as the "Probability of Exceedance (PEx)" output[1].

An example of how the recommended return periods relate to cumulative probabilities for a site for sea level rise/ storm surge over the intended useful life of a Flood Control Asset Type is shown in Table 3.4. An example site-specific PEx output table that shows projected flood elevations from sea level rise and storm surge corresponding to different annual exceedance probabilities by planning horizon is shown in Table 3.5.

Table 3.4. Draft Example of Cumulative Probability Informing the Recommended Return Periods for Sea Level Rise and Storm Surge Climate Parameter Output from the Tool

			INFRASTRUCTURE			
			Flood Control			
				Example Site – Boston, MA		
	Criticality	**Exposure Service Life**	**Return Period (% AEP)**	***Target Planning Horizon[1]***	***Base Flood Elevation (ft-BCB)[1]***	***Median Cumulative Probability[1]***
SEA LEVEL RISE/STORM SURGE	High	50-100 years	**500-yr (0.2%)**	2070	21.7	2%
	Medium	50-100 years	**100-yr (1%)**	2070	21.0	5%
	Low	50-100 years	**50-yr (2%)**	2070	20.6	11%
	High	10-50 years	**100-yr (1%)**	2050	19.3	2%
	Medium	10-50 years	**50-yr (2%)**	2050	18.9	5%
	Low	10-50 years	**25-yr (4%)**	2050	18.4	11%
	High	10 years or less	**50-yr (2%)**	2030	17.1	2%
	Medium	10 years or less	**25-yr (4%)**	2030	16.7	5%
	Low	10 years or less	**10-yr (10%)**	2030	16.2	10%

[1] PEx output is not a standard MC-FRM output and would need to be obtained from the MC-FRM.

1.The target planning horizons, base flood elevations, and median cumulative probability are examples site-specific to Joe Moakley Park in Boston, MA Only. The projected flood elevations are from the PEx shown in Table 3.5. The median cumulative probability was estimated using the planning horizons and projected flood elevations. The only column shown to users in the Tool is the output column with the recommended Return Period (% AEP).

Table 3.5. Draft Example of Site-Specific Probability of Exceedance (PEx) Output[1]

Annual Exceedance Probability	*Present*	*2030*	*2050*	*2070*
	Base Flood Elevation (ft-BCB)	Base Flood Elevation (ft-BCB)	Base Flood Elevation (ft-BCB)	Base Flood Elevation (ft-BCB)
0.1	17.4	18.5	20.4	22.1
0.2	17.0	18.1	20.0	21.7
0.5	16.5	17.5	19.3	21.0
1	16.0	17.1	18.9	20.6
2	15.6	16.7	18.4	20.1
5	15.1	16.2	17.8	19.0
10	14.6	15.8	17.3	18.5
20	14.2	15.3	16.7	18.3
25	14.0	15.2	16.5	18.2

1. The base flood elevations are site-specific to Joe Moakley park in Boston, MA only. This type of output is not provided through the RMAT Standards, but it can be requested from the MC-FRM to estimate cumulative probabilities, such as is shown in Table 3.4. Users would receive the base flood elevation for the recommended return period (or Annual Exceedance Probability) and planning horizon from the MC-FRM.

3.2.6 DESIGN CRITERIA

Design criteria are design parameters generated by the Climate Resilience Design Standards as an output, which vary by climate parameter. Design criteria values are numerical values calculated by the user, based on recommended Tiered Methodology output from the Climate Resilience Design Standards Tool. The design criteria available as output from the Tool for sea level rise/ storm surge is shown in Table 3.6, below.

Table 3.6. Design Criteria Outputs from the Tool for the Sea Level Rise & Storm Surge Climate Parameter

	DESIGN CRITERIA
Sea Level Rise/Storm Surge	Tidal Benchmarks
	Base Flood Elevation (BFE)
	Design Flood Elevation (DFE)
	Wave Heights

	Duration of Flooding
	Design Flood Velocity
	Wave Forces
	Scour or Erosion

The assets designed for the sea level rise/ storm surge climate parameter will not all need to consider every design criterion presented in Table 3.6. These design criteria are only recommended for projects of a specific asset type and location. These variations are presented in Table 3.7, below.

Table 3.7. Relationships for how Design Criteria Outputs are recommended for Sea Level Rise/ Storm Surge Climate Parameter

	Design Criteria	Design Criteria Recommended For[1]	
		Asset Type	*Project Location*
Sea Level Rise/Storm Surge	**Tidal Benchmarks**	All assets	Located along the coast and/or within MC-FRM tidal benchmark shoreline for recommended planning horizon
	Base Flood Elevation (BFE)	All assets	Located within MC-FRM recommended return period for recommended planning horizon
	Design Flood Elevation (DFE)	All assets	Located within MC-FRM recommended return period for recommended planning horizon
	Wave Heights	Infrastructure assets, building assets, coastal ecosystem assets	Located along the waterfront or within MC-FRM active wave zone
	Duration of Flooding	Infrastructure assets, building assets, other natural resources ecosystems (other than coastal)	Located within MC-FRM recommended return period for recommended planning horizon
	Design Flood Velocity	Infrastructure assets, building assets, coastal ecosystem assets	Located within MC-FRM recommended return period for recommended planning horizon

	Wave Forces	Infrastructure assets, building assets, coastal ecosystem assets	Located along the waterfront or within MC-FRM active wave zone
	Scour or Erosion	Infrastructure assets and coastal ecosystem assets	Located within MC-FRM recommended return period for recommended planning horizon

1. Design criteria are recommended if both the asset type and project location are true.

3.2.7 TIERED METHODOLOGY

Tiered methodology is defined the recommended methodology to establish asset-specific design criteria values, by climate parameter. Tiered distinctions indicate the level of effort in calculation method approach. For the sea level rise/storm surge climate parameter, the data sources and methodologies recommended by the Standards for each design criteria are shown in Table 3.6, below. Since the MC-FRM provided Tier 3 data, there is no difference for methodologies based on criticality and useful life (refer to Figure 3.2). The design criteria values will be requested from the MC-FRM through the Tool as shown in Figure 3.3. See Table 3.9 and Figure 3.4 for an example of the output provided from MC-FRM.

Table 3.8. Data Sources & Methodologies Recommended from the Tool for the Sea Level Rise & Storm Surge Climate Parameter Design Criteria

	Design Criteria	**Data Sources & Methodologies**		
		Tier 3 - High Level of Effort	**Tier 2 - Average Level of Effort**	**Tier 1 - Low Level of Effort**
Sea Level Rise/Storm Surge	**Tidal Benchmarks**	Requested from MC-FRM		
	Base Flood Elevation (BFE)			
	Design Flood Elevation (DFE)			
	Wave Heights			
	Duration of Flooding			
	Design Flood Velocity			
	Wave Forces[1]	Calculated based on Design Criteria from MC-FRM		Not required
	Scour or Erosion[1]			

1. The design criteria for Wave Forces and Scour/Erosion are not outputs from the MC-FRM and need to be calculated using existing standard practices and MC-FRM outputs (as shown in Figure 3.3.).

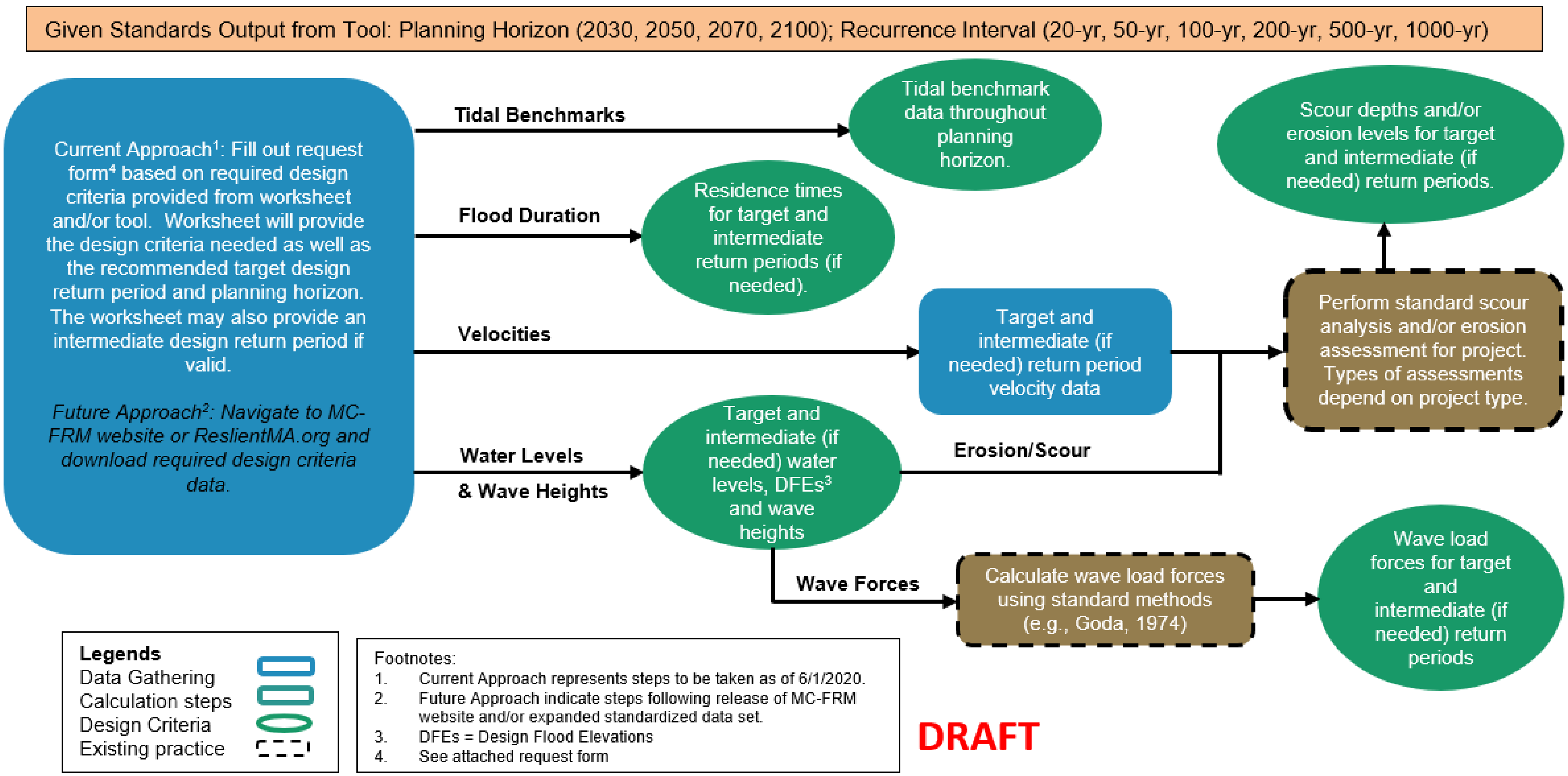

Figure 3.3. *Draft Tiered Methodology to Assess Sea Level Risk & Storm Surge Design Criteria Values as Recommended by the Climate Resilience Design Standards output from the Climate Design Standards Tool*

Table 3.9. Draft Example of Calculated Design Criteria Values for Sea Level Rise/ Storm Surge from MC-FRM based on recommended Standard Output provided by the Tool.

STANDARD OUTPUT	OUTPUT & MC-FRM EXAMPLE
Target Planning Horizon	**2070**
Intermediate Planning Horizon	**2050**
Return Period (% AEP)	**500-yr (0.2%)**
Base Flood Elevation	14.4 ft. NAVD88 – Intermediate 16.3 ft. NAVD88 – Target
Design Flood Elevation[1]	16.2 ft. NAVD88 – Intermediate 18.1 ft. NAVD88 – Target

1. Design Flood Elevation include freeboard and wave height.

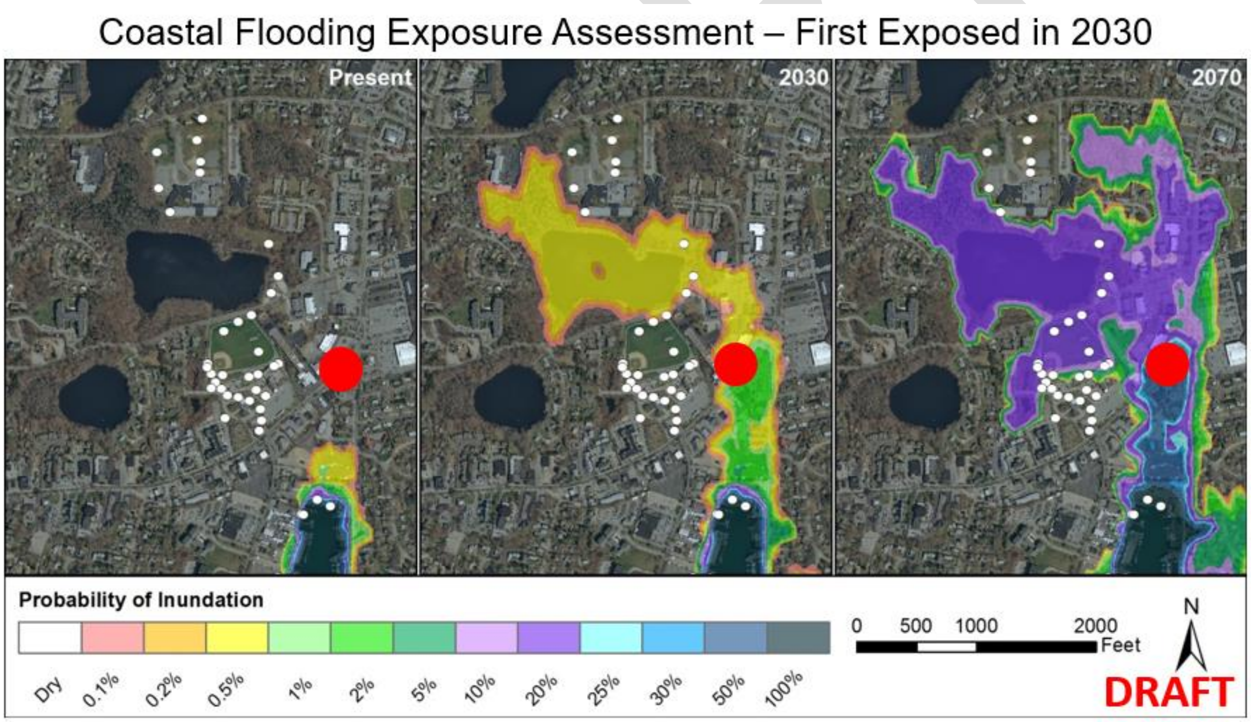

Figure 3.4. *Draft Example map provided from the MC-FRM request. Future versions of the Tool intend to have the maps built into the GIS feature.*

3.3 EXTREME PRECIPITATION STANDARDS OUTPUTS AND RELATIONSHIPS

3.3.1 OUTPUTS OVERVIEW

Upon submission of Project Inputs and review of preliminary Climate Risk Screening outputs, users will receive Standards for each climate parameter from the Tool. The Standards provided for the extreme precipitation climate parameter include the following: recommended planning horizon, return period, design criteria, and tiered methodology to calculate design criteria values. These outputs are discussed in further detail in Sections 3.3.2 through 3.3.5, below.

3.3.2 PLANNING HORIZONS

A planning horizon is defined as a future time period to which a project is recommended to be designed for, which allows the project to incorporate anticipated climate change projections. The Tool will provide a recommended planning horizon for incorporating climate resilience in the design of the asset. Recommended planning horizons provided by the Tool do not vary based on climate parameter but may vary by asset.

The recommended planning horizons are informed by the useful life of each asset, as indicated in Project Inputs. The relationships used to provide the recommended Planning Horizon are based on asset useful life, as indicated in Table 3.10.

Table 3.10. Recommended Planning Horizons Provided by the Tool, based on Asset Useful Life

ASSET USEFUL LIFE	RECOMMENDED PLANNING HORIZON[1] OUTPUT
0 to 10 years	**2030[2]**
11 years to 20 years	**2050[3]**
21 years to 30 years	**2050[3]**
31 years to 40 years	**2070[4]**
41 years to 50 years	**2070[4]**
51 years to 60 years	**2070[4]**
61 years to 75 years	**2090[5]**
Greater than 75 years	**2090[5]**

1. The bounding years for the planning horizons are consistent with the SHMCAP and ResilientMA.org.
2. The bounding years for the 2030 planning horizon are 2020 through 2049.
3. The bounding years for the 2050 planning horizon are 2040 through 2069.
4. The bounding years for the 2070 planning horizon are 2060 through 2089.
5. The bounding years for the 2090 planning horizon are 2080 through 2099.

3.3.3 RETURN PERIOD

A return period is defined as the annual probability of occurrence of an event (also known as a recurrence interval). The Tool will provide a recommended return period for each asset in a project. The recommended return period will also be provided in terms of percent annual exceedance probability (AEP or "annual probability"). This distinction is based on industry practice and is described in further detail in the Glossary of Terminology, Section 1. Different State Agencies and municipalities may have their own standards for return periods. The recommended return periods provided by the Tool are advisory and do not replace regulatory requirements. These recommended return periods for each climate parameter are based on industry standards and professional judgment, asset criticality, and useful life. For extreme precipitation, exposure service life is equal to the asset's useful life. The recommended return periods for each Asset Category are shown in Table 3.11, below.

Table 3.11. Recommended Return Periods Provided by the Tool for the Extreme Precipitation Climate Parameter

	Criticality	Useful Life	BUILDINGS/ FACILITIES	FOR INFRASTRUCTURE				FOR NATURAL RESOURCES	
				Transportation	*Flood Control*	*Utilities*	*Solid/Haz. Waste*	*Coastal Ecosystem*	*Other*
			Return Period (Annual Probability)	**Return Period (Annual Probability)**	**Return Period (Annual Probability)**	**Return Period (Annual Probability)**	**Return Period (Annual Probability)**	**Return Period (Annual Probability)**	**Return Period (Annual Probability)**
EXTREME PRECIPITATION	High	50-100 years	**100-yr (1%)**	**100-yr (1%)**	**500-yr (0.2%)**	**100-yr (1%)**	**100-yr (1%)**	**N/A**	**200-yr (0.5%)**
	Medium	50-100 years	**50-yr (2%)**	**50-yr (2%)**	**100-yr (1%)**	**50-yr (2%)**	**50-yr (2%)**	**N/A**	**100-yr (1%)**
	Low	50-100 years	**25-yr (4%)**	**25-yr (4%)**	**50-yr (2%)**	**25-yr (4%)**	**25-yr (4%)**	**N/A**	**100-yr (1%)**
	High	10-50 years	**50-yr (2%)**	**50-yr (2%)**	**100-yr (1%)**	**50-yr (2%)**	**50-yr (2%)**	**N/A**	**100-yr (1%)**
	Medium	10-50 years	**25-yr (4%)**	**25-yr (4%)**	**50-yr (2%)**	**25-yr (4%)**	**25-yr (4%)**	**N/A**	**50-yr (2%)**
	Low	10-50 years	**10-yr (10%)**	**10-yr (10%)**	**25-yr (4%)**	**10-yr (10%)**	**10-yr (10%)**	**N/A**	**50-yr (2%)**
	High	10 years or less	**25-yr (4%)**	**25-yr (4%)**	**50-yr (2%)**	**25-yr (4%)**	**25-yr (4%)**	**N/A**	**100-yr (1%)**
	Medium	10 years or less	**10-yr (10%)**	**10-yr (10%)**	**25-yr (4%)**	**10-yr (10%)**	**10-yr (10%)**	**N/A**	**50-yr (2%)**
	Low	10 years or less	**5-yr (20%)**	**5-yr (20%)**	**10-yr (10%)**	**5-yr (20%)**	**5-yr (20%)**	**N/A**	**20-yr (5%)**

3.3.4 CUMULATIVE PROBABILITY

> Cumulative probability is defined as the measure of the total probability that a certain event will happen during a given period of time. Cumulative probability is calculated based on the equation:
>
> $$p_n = 1 - (1 - p)^n$$
>
> where 'p_n' equals the cumulative probability over 'n' number of years and 'p' equals annual probability, which is not constant due to climate change.

The recommended return periods for assets by climate parameter are based on industry standards and professional judgment, asset criticality, and useful life. However, the recommended return period output from the Tool is also informed by an asset's cumulative probability of being exposed to a climate event. The median cumulative probability from extreme precipitation for an asset can be calculated based on the asset's recommended planning horizon and site-specific projected design storm depths. The projected design storm depths corresponding to different annual probabilities by planning horizon can be estimated using the Tiered Methodology (discussed in Section 3.3.6).

An example of how the recommended return periods relate to cumulative probabilities for a site for extreme precipitation over the intended useful life of a Flood Control Asset Type is shown in Table 3.12. The median cumulative probability (based on the project planning horizon, projected rainfall depth, and approximation to current return period) informs the return period output provided by the Tool. An example of those calculation relationships is shown in Table 3.12, below.

Table 3.12. Draft Example of Cumulative Probability Calculation Informing the Recommended Return Periods for the Extreme Precipitation Climate Parameter Output from the Tool

			INFRASTRUCTURE				
			Flood Control				
				Example Site – South Boston, MA			
	Criticality	**Useful Life**	**Return Period (Annual Probability)**	***Planning Horizon[1]***	***Projected Rainfall Depth (in.)[1]***	***Approximation to Current Return Period[1]***	***Median Cumulative Probability[1]***
EXTREME PRECIPITATION	High	50-100 years	**500-yr (0.2%)**	*2070*	*16.8*	*0.05%*	*2%*
	Medium	50-100 years	**100-yr (1%)**	*2070*	*11.2*	*0.2%*	*10%*
	Low	50-100 years	**50-yr (2%)**	*2070*	*9.7*	*0.5%*	*22%*
	High	10-50 years	**100-yr (1%)**	*2050*	*10.1*	*0.2%*	*6%*
	Medium	10-50 years	**50-yr (2%)**	*2050*	*8.8*	*0.5%*	*14%*
	Low	10-50 years	**25-yr (4%)**	*2050*	*7.5*	*2%*	*45%*
	High	10 years or less	**50-yr (2%)**	*2030*	*7.6*	*1.5%*	*14%*
	Medium	10 years or less	**25-yr (4%)**	*2030*	*6.7*	*3%*	*26%*
	Low	10 years or less	**10-yr (10%)**	*2030*	*5.5*	*5%*	*40%*

1. The planning horizons, projected rainfall depths, and approximation to current return period all inform the median cumulative probability calculation presented, and are examples site-specific to Joe Moakley Park in Boston, MA Only. These four draft example columns inform the recommended return period calculated output provided by the Tool, but are NOT shown to users.

3.3.5 DESIGN CRITERIA

Design criteria are design parameters generated by the Climate Resilience Design Standards as an output, which vary by climate parameter. Design criteria values are numerical values calculated by the user, based on recommended Tiered Methodology output from the Climate Resilience Design Standards Tool. The design criteria available as output from the Tool for extreme precipitation is shown in Table 3.13, below.

Table 3.13. Design Criteria Outputs from the Tool for the Extreme Precipitation Climate Parameter

	Design Criteria
Extreme Precipitation	Total Precipitation Depth for 24-hour Design Storms
	Peak intensity for 24-hour design storms
	Riverine peak discharge
	Riverine peak flood elevation
	Duration of flooding for design storm
	Flood Pathways

The assets designed for the extreme precipitation climate parameter will not always receive every output design criterion presented in Table 3.14. These design criteria are only recommended for projects of a specific asset type and location. These variations are presented in Table 3.15, below.

Table 3.14. Project Type and Location When Design Criteria Output is Recommended from the Tool for the Extreme Precipitation Climate Parameter

	Design Criteria	Design Criteria Recommended For	
		Asset Type	*Project Location*
EXTREME PRECIPITATION	Total Precipitation Depth for 24-hour Design Storms	All infrastructure, building and natural resource assets except coastal ecosystems	All locations
	Peak intensity for 24-hour design storms	All infrastructure, building and natural resource assets except coastal ecosystems	All locations
	Riverine peak discharge	All infrastructure, building and natural resource assets except coastal ecosystems	Located within riverine environment, 0.1 mile from a waterbody, and/or FEMA 500 year

	Riverine peak flood elevation	All infrastructure, building and natural resource assets except coastal ecosystems	Located within riverine environment, 0.1 mile from a waterbody, and/or FEMA 500 year
	Duration of flooding for design storm	All infrastructure and building assets	All locations
	Flood Pathways	All infrastructure and building assets	Located within riverine environment, 0.1 mile from a waterbody, and/or FEMA 500 year

3.3.6 TIERED METHODOLOGY

Tiered methodology is defined the recommended methodology to establish asset-specific design criteria values, by climate parameter. Tiered distinctions indicate the level of effort in calculation method approach. For the extreme precipitation climate parameter, the data sources and methodologies recommended by the Standards for each design criteria are shown in Table 3.15, below. Further detailed methodology for calculating design criteria values are shown in Figures below. Example calculations using tiered methodology for determining design criteria values are included as Attachments at the end of Section 3.

Table 3.15. Data Sources & Methodologies Recommended from the Tool for the Extreme Precipitation Design Criteria

	Design Criteria	**Data Sources & Methodologies**		
		Tier 3 - High Level of Effort	**Tier 2 - Average Level of Effort**	**Tier 1 - Low Level of Effort**
EXTREME PRECIPITATION	**Total Precipitation Depth for 24-hour Design Storms**	Downscaled GCMs (from ResilientMA.org or LOCA dataset) and extreme value distribution analysis	NCA4 CSSR values and increase the NOAA Atlas 14 values by the change percentage as indicated	Atlas-14 90% of the upper 90% C.I (DEP proposed approach)
	Peak intensity for 24-hour design storms[1]	Type III distribution to future design storms estimated from downscaled GCMs and extreme value distribution analysis	Type III distribution to future design storms estimated using NCA4 CSSR method	Type III distribution to future design storms estimated using Atlas-14 90% of the upper 90% C.I
	Riverine peak discharge[1]	Hydrologic/hydraulic modeling at watershed/sub-watershed scale using future design storms		StreamStats using Zariello's Equation

	Riverine peak flood elevation[1]	Hydrologic/hydraulic modeling at watershed/sub-watershed scale using future design storms	Use Stage Discharge Curve from corresponding gage location used in StreamStats
	Duration of flooding for design storm[1]	Hydrologic/hydraulic modeling at watershed/sub-watershed scale using future design storms	Not needed.
	Flood Pathways[1]		Not needed.

1. These criteria are calculated based on precipitation depths affected by climate change. The methods to calculate these criteria are consistent with existing industry practices, but they should use the future precipitation depths.

3.3.6.1 Data Source Download for Extreme Precipitation -- LOCA Dataset

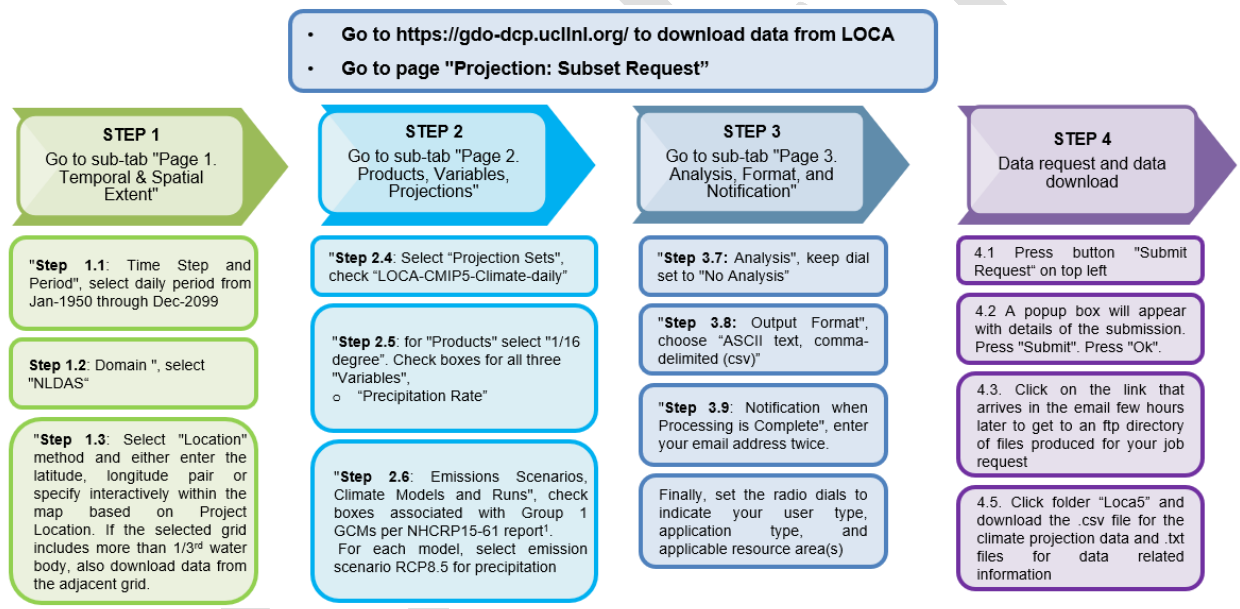

Figure 3.5. *Draft Methodology to Download Precipitation Climate Data and Projected as Recommended by the Climate Resilience Design Standards Tool*

Refer to Attachment 3.3A for an example of data download from the LOCA dataset.

3.3.6.2 Draft Tiered Methodology for Extreme Precipitation Depth and Intensity – Tier 3

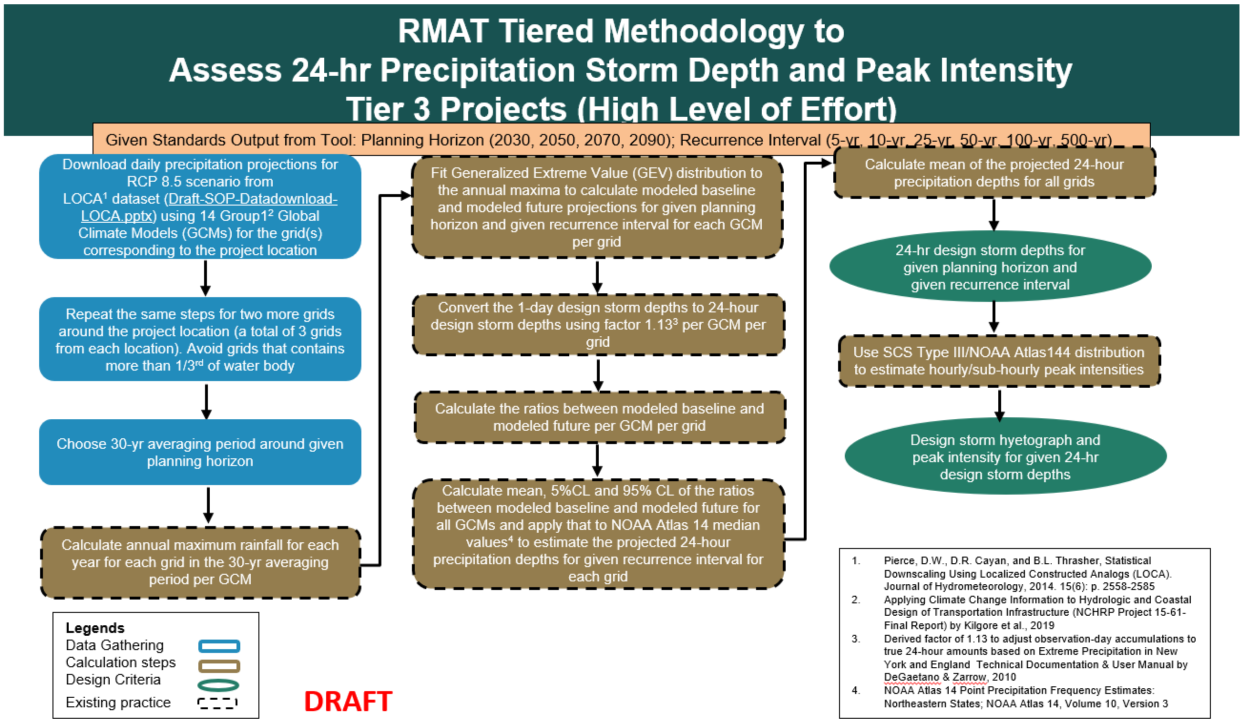

***Figure 3.6.** Draft Tier 3 Methodology to Assess Extreme Precipitation Design Criteria Values as Recommended by the Climate Resilience Design Standards Tool*

Refer to Attachment 3.3B for an example of draft methodology to assess extreme precipitation intensity and depth for Tier 3.

3.3.6.3 Draft Proposed Scope for Tiered Methodology for Extreme Precipitation – Tier 2

Overall Goals/Objectives of Proposed Scope

Based on feedback received from various State entities, such as the Executive Office of Energy and Environmental Affair (EOEEA), Massachusetts Department of Environmental Protection (MA-DEP) and Massachusetts Department of Conservation and Recreation (MA-DCR) on the Draft Climate Resilience Design Standards (the Standards) related to extreme precipitation, the project team has identified the need to develop locally regionalized data to estimate future precipitation depths for Annual Exceedance Probability (AEP) design storms of 24-hr duration. Initially, in the Standards the "Tier 2 Method" (recommended tiered methodology) for generating design criteria values (e.g. rainfall depths, peak intensity) for the 24-hour AEP design storms was based on using readily available future projections data. Therefore, the "Tier 2 Method" was based on using the 13% and 22% increase to the present NOAA Atlas 14 values to estimate the future 24-hour design storm depths for the 2030/2050 and 2070 planning horizons, respectively. These percent increases were based on using guidance from the report developed by the U.S. Global Change Research Program (USGCRP) in 2017 called the Climate Science Special Report (CSSR) as part of the Fourth National Climate Assessment (NAC4). However, these percent increases provided in the 2017 CSSR were specific to the 5% AEP (20-year) storm, were based on using the geographic area for all of Northeast, and did not include separate percent increase estimates for the four planning horizons of 2030, 2050, 2070 and 2090 that are consistent with the Commonwealth's State Hazard Mitigation and Climate Adaptation Plan (SHMCAP)[2].

Therefore, the primary objectives of this proposed scope of work are the following:

- Develop Statewide percent increase estimates for different Annual Exceedance Probability (AEP) design storms for each planning horizon for the Eastern and Western parts of the Commonwealth using industry-accepted standard methodology
- Receive consensus from the different State entities, academic and scientific experts on the percent increase estimates developed from this methodology
- Incorporate this tiered methodology as "Tier 2" methodology for the Draft Climate Resilience Design Standards Tool (the Tool)

Proposed Methodology

Since one of the objectives of this effort is to use industry-accepted standard methodology to develop the regionalized percent increase estimates, the methodology is based on using the report developed as part of the National Cooperative Highway Research Program (NCHRP) Project 15-61 with the final report published in 2019 titled "Applying Climate Change Information to Hydrologic and Coastal Design of Transportation Infrastructure" (referred to as "NCHRP 15-61 Report")[3]. The proposed methodology described in this scope has been presented, reviewed, and approved by EOEEA, DEP, DCR and leading academic and scientific experts from different universities in the Northeast, including Dr. Jennifer Jacobs (University of New Hampshire), Dr. Ellen Douglas (University of Massachusetts, Boston), Dr. Scott Steinschneider (Tufts University) and Dr. Jonathan Lamontagne (Tufts University). Also, Dr. Jacobs and Dr. Douglas are co-authors of the NCHRP 15-61 Report and have been able to vet that this proposed methodology follows NCHRP 15-61 guidelines.

The proposed methodology consists of the following steps:

- Step 1: Select locations corresponding to six (6) long-term weather station locations in Massachusetts. These stations will be selected such that there are three (3) locations in each of the two (2) NOAA Climate Regions (Coastal and Interior) as delineated in NOAA Atlas 14 Volume 10, shown in the figure below. These two climate regions for MA correspond approximately to the Eastern and Western parts of the State, so representative long-term weather stations will be selected from each Region for this analysis (e.g. weather stations in Eastern MA, such as Boston, Newburyport, East Wareham or Kingston-Plymouth and weather stations in Western MA, such as Pittsfield, Westfield and Worcester)

[2] Massachusetts Integrated State Hazard Mitigation and Climate Adaptation Plan, 2018 https://www.mass.gov/service-details/massachusetts-integrated-state-hazard-mitigation-and-climate-adaptation-plan

[3] http://onlinepubs.trb.org/onlinepubs/nchrp/docs/NCHRP1561FinalReport.pdf

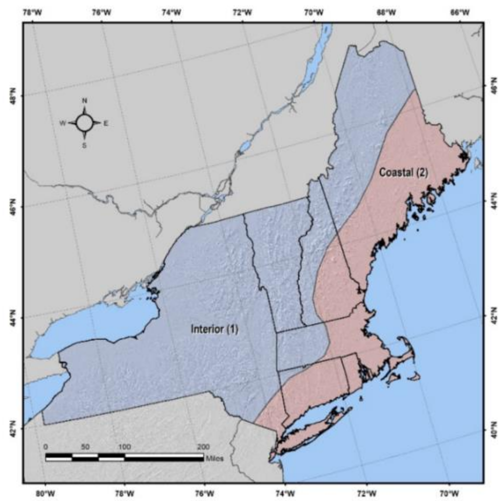

Figure 3.7. *Climate regions delineated for NOAA Atlas 14 Volume 10. Source:* [*https://www.nws.noaa.gov/oh/hdsc/PF_documents/Atlas14_Volume10.pdf*](https://www.nws.noaa.gov/oh/hdsc/PF_documents/Atlas14_Volume10.pdf)

- Step 2: Download daily precipitation projections for each location for each of the 14 Group 1 global climate models (GCMs) in the Localized Constructed Analogs (LOCA)[4] (Pierce et dataset. The LOCA dataset has also been used as part of the SHMCAP and the projections shown on ResilientMA.org. For this task, Group 1 GCMs are proposed to be used since these models are referred in the NCHRP 15-61 Report as the "most reliable" models that represent the most recent versions of reliable, very well-documented, long-established GCMs from modeling groups that have been working in this area for decades. Download the projections for three (3) grids for each location per NCHRP15-61 guidance.
- Step 3: Calculate modeled baseline and modeled future design storm projections for each AEP storm for each location for each grid for each of the four planning horizons (2030s, 2050s, 2070s, 2090s) by fitting a Generalized Extreme Value Distribution (GEV) to annual maximum daily projections for each GCM.
- Step 4: Calculate ratios between modeled baseline and modeled future design storm projections for each location for each grid for each planning horizon for each GCM.
- Step 5: Calculate mean and 90 percent confidence interval for the ratios across the 14 GCMs between modeled baseline and modeled future design storm projections for each location for each grid for each planning horizon.
- Step 6: Estimate the projected design storm depths and 90 percent confidence interval design storm depths for each AEP storm for each location for each grid. Take the mean of the three grids for each location to estimate the projected design storm depths and 90 percent confidence interval design storm depths for each AEP storm.

[4] Pierce, D.W., D.R. Cayan, and B.L. Thrasher. 2014. "Statistical Downscaling Using Localized Constructed Analogs (LOCA)." Journal of Hydrometeorology, Vol. 15, pp. 2558–2585

- Step 7: Compare the projected precipitation quantiles with NOAA Atlas 14 historical estimates for each future period for each location for all AEP storms, which would serve as a comparison between historical uncertainty and projected uncertainty from climate change.
- Step 8: Estimate the projected design storm depths and 90 percent confidence interval design storm depths for each AEP storm for each location for each planning horizon.
- Step 9: Calculate the regionalized percent increase between the projected 24-hour projected precipitation depths and NOAA historical estimates (using both mean and 90 percent confidence interval values), respectively for the three interior locations and the three coastal locations (corresponding to the NOAA climate regions) for more frequent AEP storms (2-yr, 5-yr, 10-yr) by near to mid-century (2030/2050) and late century (2070/2090)
- Step 10: Calculate the regionalized percent increase between the projected 24-hour projected precipitation depths and NOAA historical estimates (using both mean and 90 percent confidence interval values), respectively for the three interior locations and the three coastal locations (corresponding to the NOAA climate regions) for the less frequent AEP storms (25-yr, 50-yr, 100-yr) by near to mid-century (2030/2050) and late century (2070/2090).

Proposed Output

The final output from Steps 8 and 9 above will be reported as a table that will list the regionalized percent increase estimates for each region for 2030/2050 and 2070/2090 for the more frequent and the less frequent storms as illustrated in Table 3.16 below. The values reported in this table will be referenced in the Tier 2 Method of the Standards and the Tool to estimate the 24-hour design storm depths. These percent increases can then be applied for any location in Massachusetts and the future design storm depths for any AEP storm can be estimated by applying the relevant percent increase to the corresponding NOAA Atlas 14 24-hour design storm values for that location.

Table 3.16. Proposed Tier 2 percent increase to NOAA Atlas 14 values based on given planning horizon for each given 24-hr AEP design storm depth

Location	Design Storms	Mid-Century (2030/2050)	Late-century (2070/2100)
Coastal Region	More Frequent*	+ X%	+ X%
	Less Frequent**	+ X%	+ X%
Inland Region	More Frequent*	+ X%	+ X%
	Less Frequent**	+ X%	+ X%

* More frequent includes 2-yr, 5-yr, 10-yr design storms
** Less frequent includes 25-yr, 50-yr, 100-yr, 200-yr, 500-yr

Limitations and Future Updates

The proposed approach is one of the first attempts in the Commonwealth to come up with regionalized percent increase estimates of rainfall design storm depths across the entire State. However, in addition to testing the approach to the six locations used in this analysis, this approach needs to be tested and verified at other locations in the State, which is expected to occur in the future. As new and updated climate projections data are available for the

Commonwealth, this approach may need to be updated. Also, as part of the Massachusetts Climate and Hydrologic Risk Project that is currently underway, the EOEEA along with leading experts from USGS, Tufts University and Cornell University will be developing climate projections for all of Massachusetts, which will include future design storm projections. The regionalized percent increase estimates developed as part of the Standards and the Tool may need to be updated when the Statewide Climate and Hydrologic Risk Project is complete.

3.3.6.4 Draft Tiered Methodology for Extreme Precipitation Depth and Intensity – Tier 1

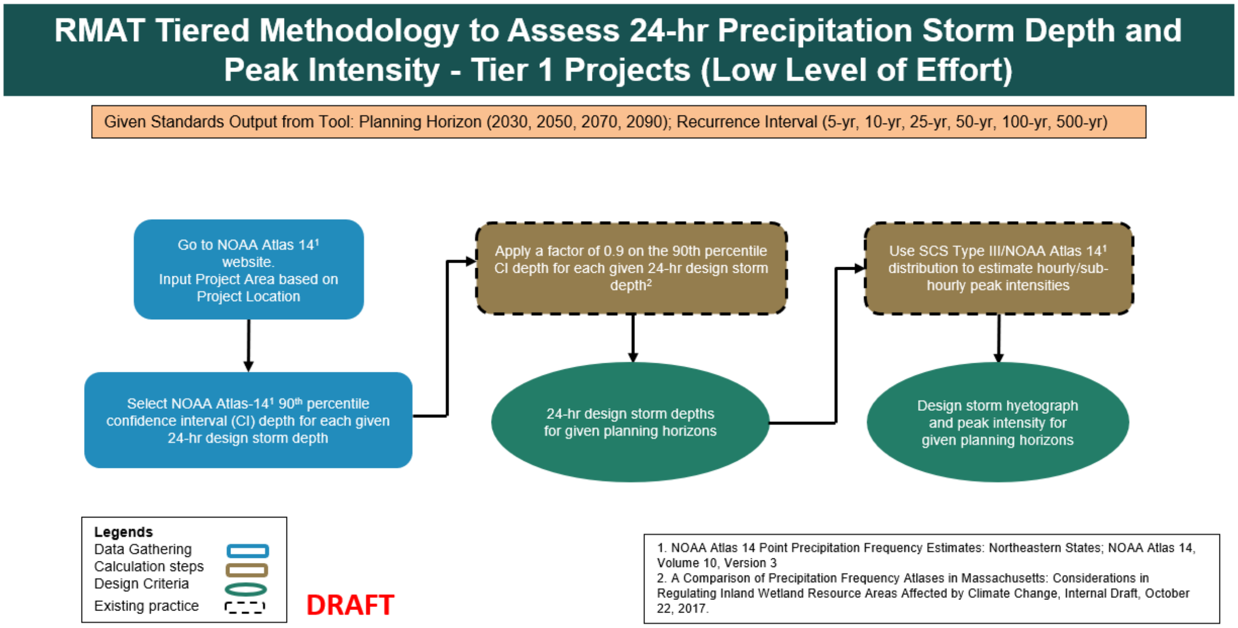

Figure 3.8. *Draft Tier 1 Methodology to Assess Extreme Precipitation Design Criteria Values as Recommended by the Climate Resilience Design Standards Tool*

Refer to Attachment 3.3B for an example of draft methodology to assess extreme precipitation intensity and depth for Tier 1.

3.3.6.5 Draft Tiered Methodology for Riverine Peak Discharge – Tiers 3 and 2

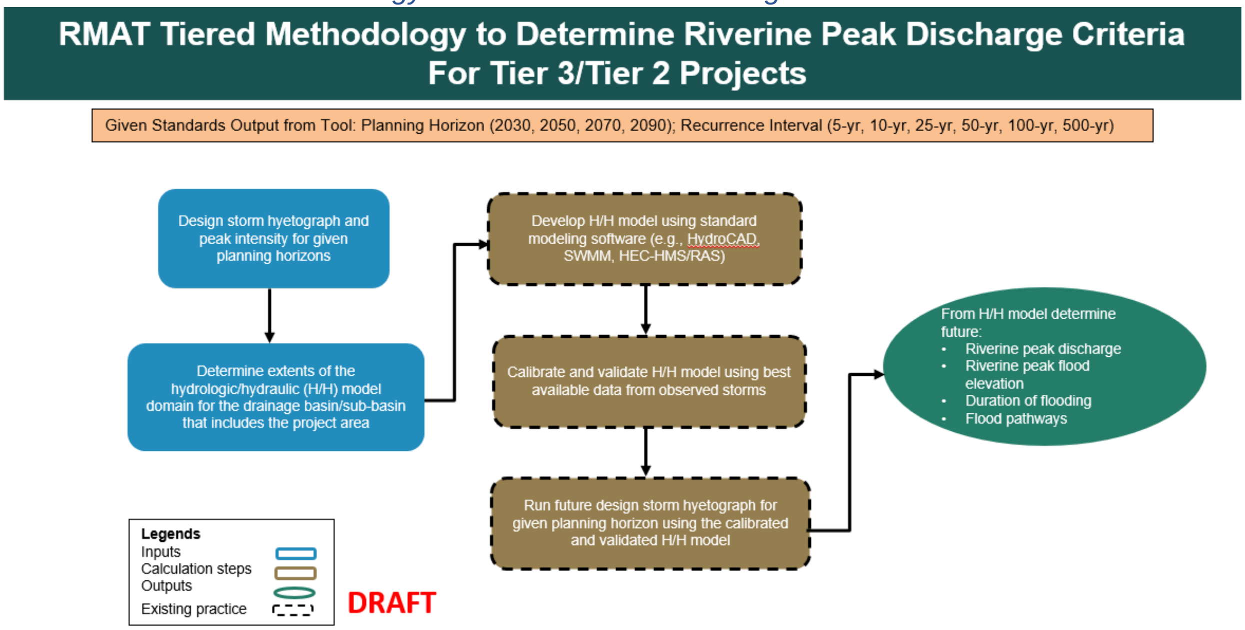

Figure 3.9. *Draft Tier 3/2 Methodology to Assess Extreme Precipitation Riverine Peak Discharge Design Criteria Values as Recommended by the Climate Resilience Design Standards Tool*

3.3.6.6 Draft Tiered Methodology for Riverine Peak Discharge – Tier 1

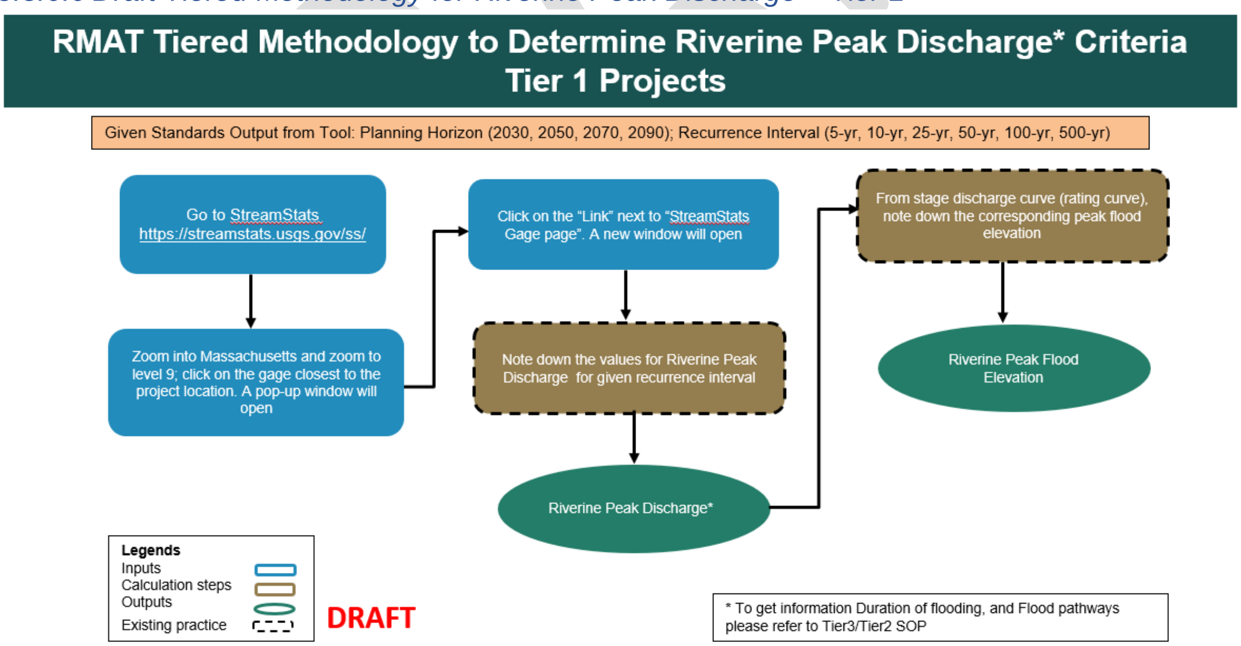

Figure 3.10. *Draft Tier 1 Methodology to Assess Extreme Precipitation Riverine Peak Discharge Design Criteria Values as Recommended by the Climate Resilience Design Standards Tool*

3.4 EXTREME HEAT STANDARDS OUTPUTS AND RELATIONSHIPS

3.4.1 OUTPUTS OVERVIEW

Upon submission of Project Inputs and review of preliminary Climate Risk Screening outputs, users will receive Standards for each climate parameter from the Tool. The Standards provided for the extreme heat climate parameter include the following: recommended planning horizon, return period, design criteria, and tiered methodology to calculate design criteria values. These outputs are discussed in further detail in Sections 3.3.2 through 3.3.5, below.

3.4.2 PLANNING HORIZONS

A planning horizon is defined as a future time period to which a project is recommended to be designed for, which allows the project to incorporate anticipated climate change projections. The Tool will provide a recommended planning horizon for incorporating climate resilience in the design of the asset. Recommended planning horizons provided by the Tool do not vary based on climate parameter but may vary by asset.

The recommended planning horizons are informed by the useful life of each asset, as indicated in Project Inputs. The relationships used to provide the recommended Planning Horizon are based on asset useful life, and are indicated in Table 3.17, below.

Table 3.17. Recommended Planning Horizons Provided by the Tool, based on Asset Useful Life

ASSET USEFUL LIFE	RECOMMENDED PLANNING HORIZON[1] OUTPUT
0 to 10 years	**2030**[2]
11 years to 20 years	**2050**[3]
21 years to 30 years	**2050**[3]
31 years to 40 years	**2070**[4]
41 years to 50 years	**2070**[4]
51 years to 60 years	**2070**[4]
61 years to 75 years	**2090**[5]
Greater than 75 years	**2090**[5]

1. The bounding years for the planning horizons are consistent with the SHMCAP and ResilientMA.org.
2. The bounding years for the 2030 planning horizon are 2020 through 2049.
3. The bounding years for the 2050 planning horizon are 2040 through 2069.
4. The bounding years for the 2070 planning horizon are 2060 through 2089.
5. The bounding years for the 2090 planning horizon are 2080 through 2099.

3.4.3 CONFIDENCE INTERVAL

A confidence interval is defined for this project as a range of values within which a design criterion falls, considering uncertainty in climate change projections. The confidence intervals usually correspond to the 10th, 50th and 90th percentile values based on climate change projections.

For the extreme heat climate parameter, the Tool will provide a recommended confidence interval for each asset, as opposed to a recommended return period. While asset useful life does inform the recommended return period output for the sea level rise/ storm surge and extreme precipitation climate parameters, it does not inform the recommended confidence interval output for the extreme heat climate parameter. This difference is because extreme heat design criteria do not depend on the asset's cumulative probability.

The confidence intervals recommended by the Tool are also dependent on asset construction type, as opposed to asset type for the sea level rise/ storm surge and extreme precipitation climate parameters. This difference is due to the difficulty in accommodating for extreme heat resilience in existing construction design. The output is therefore based on asset construction type in order to improve the standard of design criteria for new and existing construction projects, specific to the type of construction materials used each asset category.

The recommended confidence intervals for each asset category and construction type are shown in Table 3.18 and 3.19, below.

Table 3.18. Recommended Confidence Intervals by Construction Type (Infrastructure and Buildings/Facilities) Provided by the Tool for the Extreme Heat Climate Parameter

EXTREME HEAT	Criticality	CONFIDENCE INTERVALS FOR BUILDINGS/FACILITIES & INFRASTRUCTURE			
		New Construction	**Major Repair/ Retrofit**	**Renovation**	**Maintenance (critical repair or environmental)**
	High	**90th Percentile**	**90th Percentile**	**50th Percentile**	**50th Percentile**
	Medium	**90th Percentile**	**50th Percentile**	**50th Percentile**	**50th Percentile**
	Low	**50th Percentile**	**50th Percentile**	**10th Percentile**	**10th Percentile**

Table 3.19. Recommended Confidence Intervals by Construction Type (Natural Resources) Provided by the Tool for the Extreme Heat Climate Parameter

EXTREME HEAT	Criticality	CONFIDENCE INTERVALS FOR NATURAL RESOURCES			
		New Construction	**Maintenance (environmental)**	**Restoration or Enhancement**	**Dam Removal**
	High	**50th Percentile**	**50th Percentile**	**50th Percentile**	**50th Percentile**
	Medium	**50th Percentile**	**50th Percentile**	**50th Percentile**	**50th Percentile**
	Low	**10th Percentile**	**10th Percentile**	**10th Percentile**	**10th Percentile**

3.4.4 DESIGN CRITERIA

Design criteria are design parameters generated by the Climate Resilience Design Standards as an output, which vary by climate parameter. Design criteria values are numerical values calculated by the user, based on recommended Tiered Methodology output from the Climate Resilience Design Standards Tool. The design criteria available as output from the Tool for extreme heat is shown in Table 3.20, below.

Table 3.20. Design Criteria Outputs from the Tool for the Extreme Heat Climate Parameter

	Design Criteria
Extreme Heat	Annual/summer/winter average temperature
	Heat Index
	Days per year with max temperature > 95°F
	Days per year with max temperature > 90°F
	Days per year with minimum temperature < 32°F
	Number of heat waves per year
	Average heat wave duration (days)
	Cooling degree days (base = 65°F)
	Heating degree days (base = 65°F)
	Growing degree days

The assets designed for the extreme heat climate parameter will not always receive every output design criterion presented in Table 3.21. These design criteria are only recommended for projects of a specific asset type and location. These variations are presented in Table 3.22, below.

Table 3.21. Project Type and Location When Design Criteria Output is Recommended from the Tool for the Extreme Heat Climate Parameter

	Design Criteria	Design Criteria Recommended For	
		Asset Type	Project Location
EXTREME HEAT	Annual/summer/winter average temperature	All assets	All locations
	Heat Index	All buildings and infrastructure assets, open space assets	
	Days per year with max temperature > 95°F	All assets excluding coastal ecosystems and open space assets	
	Days per year with max temperature > 90°F	All buildings and infrastructure assets	
	Days per year with minimum temperature < 32°F	All buildings and infrastructure assets	
	Number of heat waves per year	All buildings and infrastructure assets, open space assets	
	Average heat wave duration (days)	All buildings and infrastructure assets, open space assets	
	Cooling degree days (base = 65°F)	All buildings assets	
	Heating degree days (base = 65°F)	All buildings assets	
	Growing degree days	All natural resources assets excluding coastal ecosystems	

3.4.5 TIERED METHODOLOGY

Tiered methodology is defined the recommended methodology to establish asset-specific design criteria values, by climate parameter. Tiered distinctions indicate the level of effort in calculation method approach. For the extreme heat climate parameter, the data sources and methodologies recommended by the Standards for each design criteria are shown in Table 3.22, below. Further detailed methodology for calculating design criteria values are shown in Figures below. Example calculations using tiered methodology for determining design criteria values will be presented as Attachments in future draft versions of this Section 3 document.

Table 3.22. Data Sources & Methodologies Recommended from the Tool for the Extreme Heat Design Criteria

	Design Criteria	Data Sources & Methodologies		
		Tier 3 - High Level of Effort	**Tier 2 - Average Level of Effort**	**Tier 1 - Low Level of Effort**
EXTREME HEAT	**Annual/summer/winter average temperature**	Downscaled GCMs (from MACA dataset)	ResilientMA.org	
	Heat Index		Percent increase to historic maximums based on City of Cambridge Climate Change Projections Report	
	Days per year with max temperature > 95°F		ResilientMA.org	
	Days per year with max temperature > 90°F			
	Days per year with minimum temperature < 32°F			
	Number of heat waves per year[1]		Number of historic heat waves from nearest weather station data[2]	
	Average heat wave duration (days) [1]			
	Cooling degree days (base = 65°F)		ResilientMA.org	
	Heating degree days (base = 65°F)			
	Growing degree days			

1. These items are design criteria that are calculated based on historic data. The methods to develop these criteria do not change.
2. Based on lack of existing published relationships for current and future number and duration of heat waves, historical information is recommended for the Tier 2 method. Users may select the Tier 3 method to calculate future heat wave design criteria as needed.

3.4.5.1 Data Source Download for Extreme Heat -- MACA Dataset

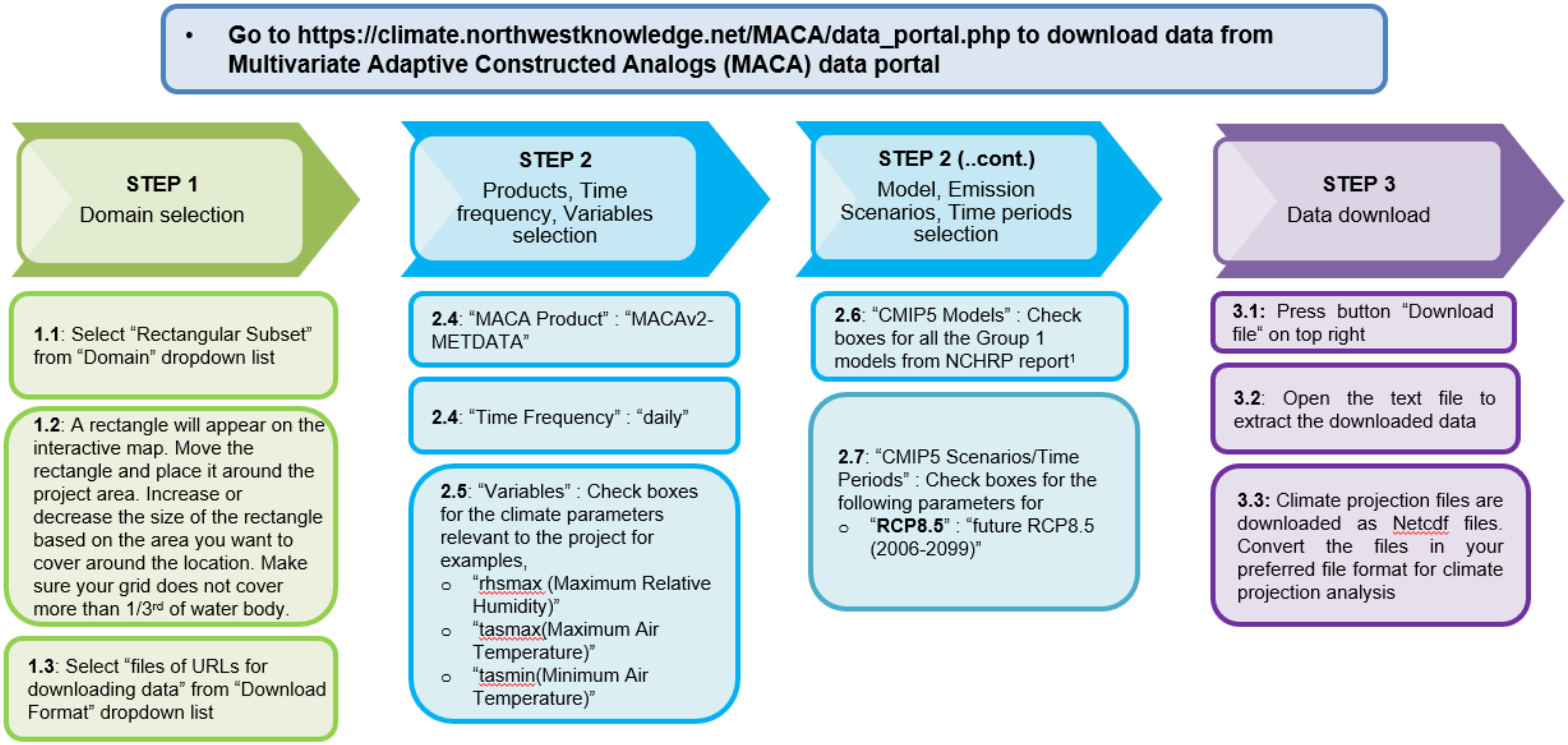

Figure 3.11. *Draft Methodology to Download Heat Climate Data and Projected as Recommended by the Climate Resilience Design Standards Tool*

Refer to Attachment 3.4A for an example of data download from the MACA dataset.

3.4.5.2 Draft Tiered Methodology for Extreme Heat – Average Temperature

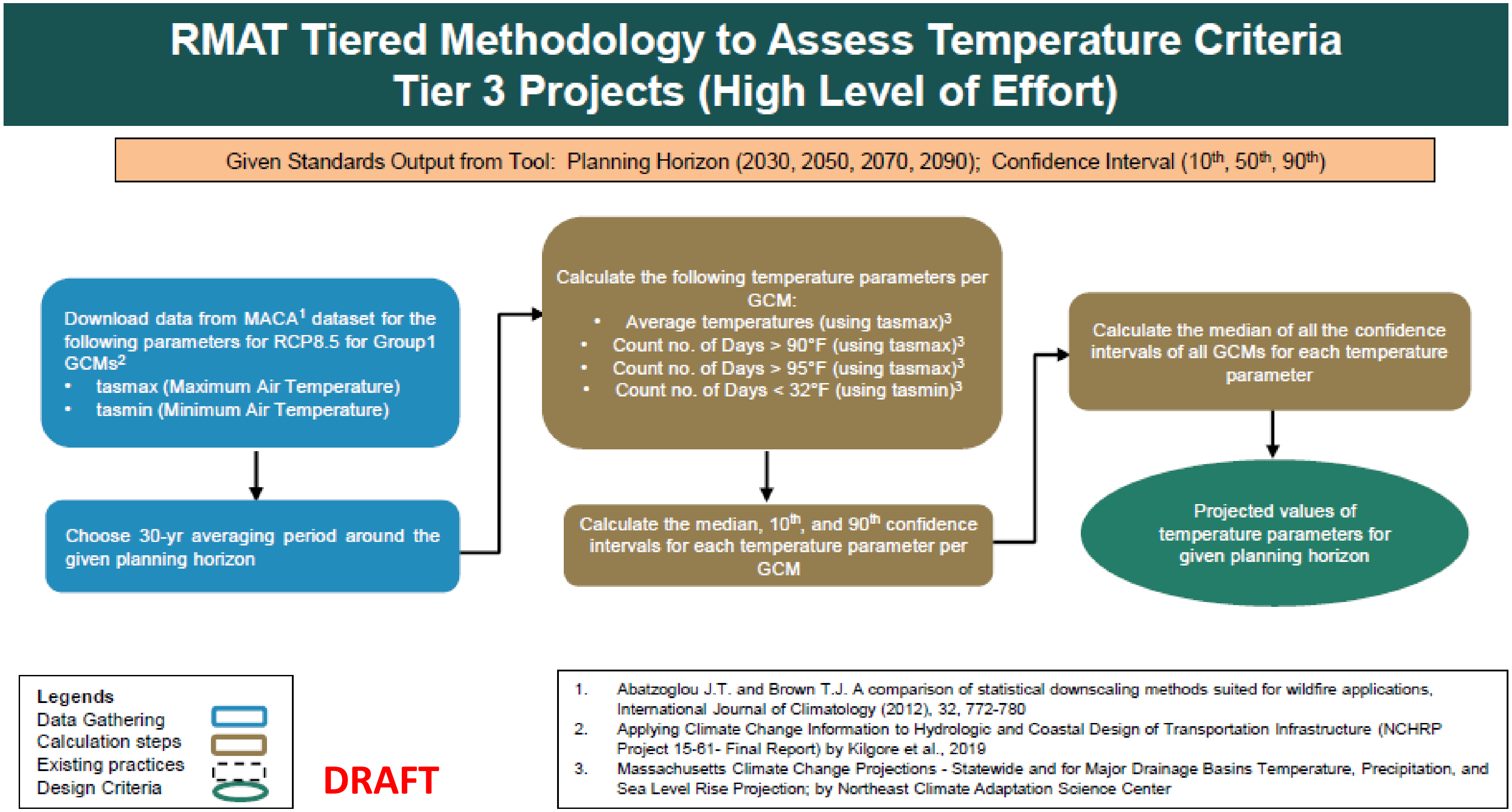

***Figure 3.12.** Draft Tier 3 Methodology to Assess Average Temperature Design Criteria Values as Recommended by the Extreme Heat Climate Parameter Climate Resilience Design Standards Output*

Refer to Attachment 3.4B for an example of draft methodology to assess extreme heat average temperature design criteria values for Tier 3 methodology.

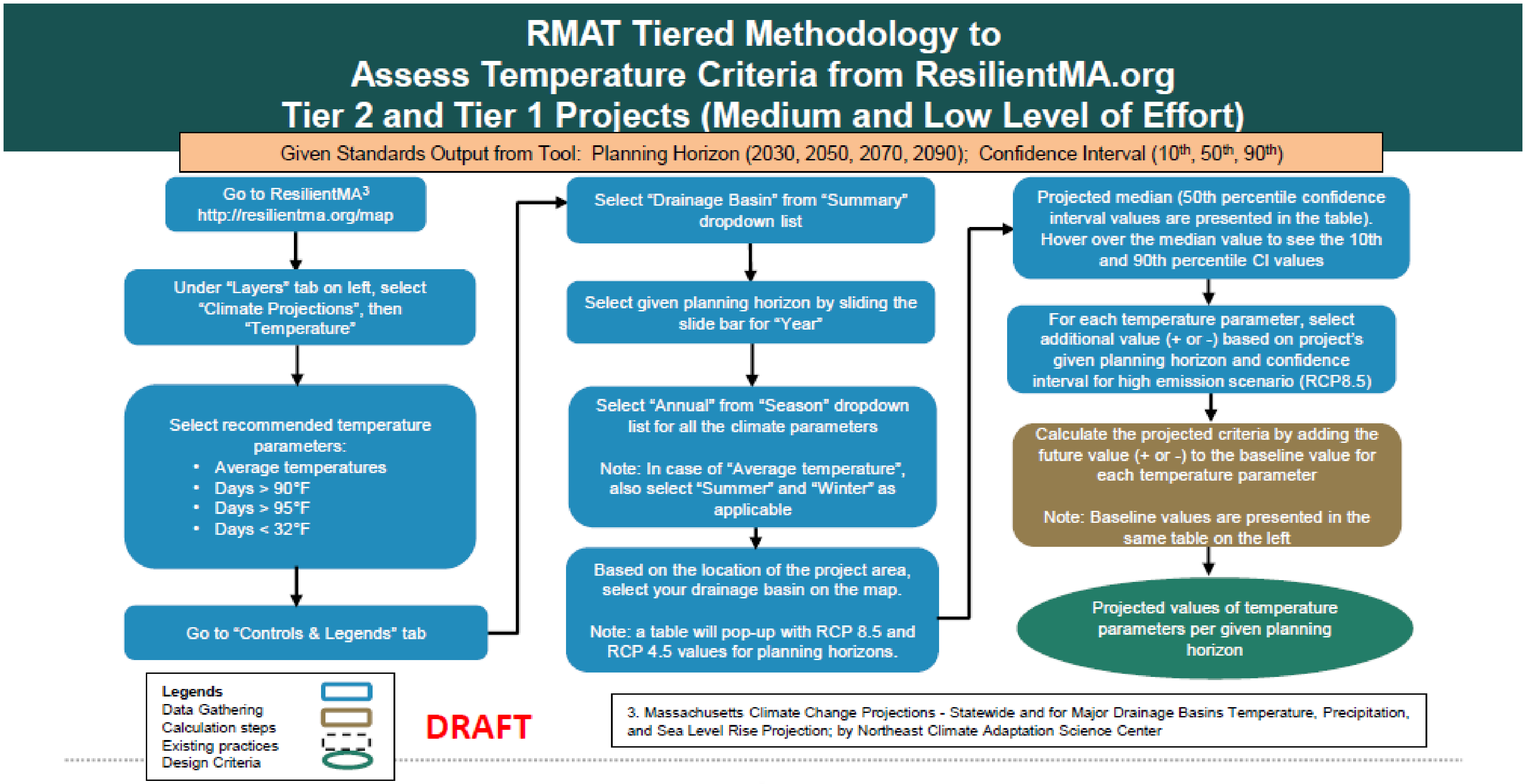

Figure 3.13. *Draft Tier 1 and 2 Methodology to Assess Average Temperature Criteria Values as Recommended by the Extreme Heat Climate Parameter Climate Resilience Design Standards Output*

Refer to Attachment 3.4B for an example of draft methodology to assess extreme heat average temperature design criteria values for Tier 2/1 methodology.

3.4.5.3 Draft Tiered Methodology for Extreme Heat – Degree Days

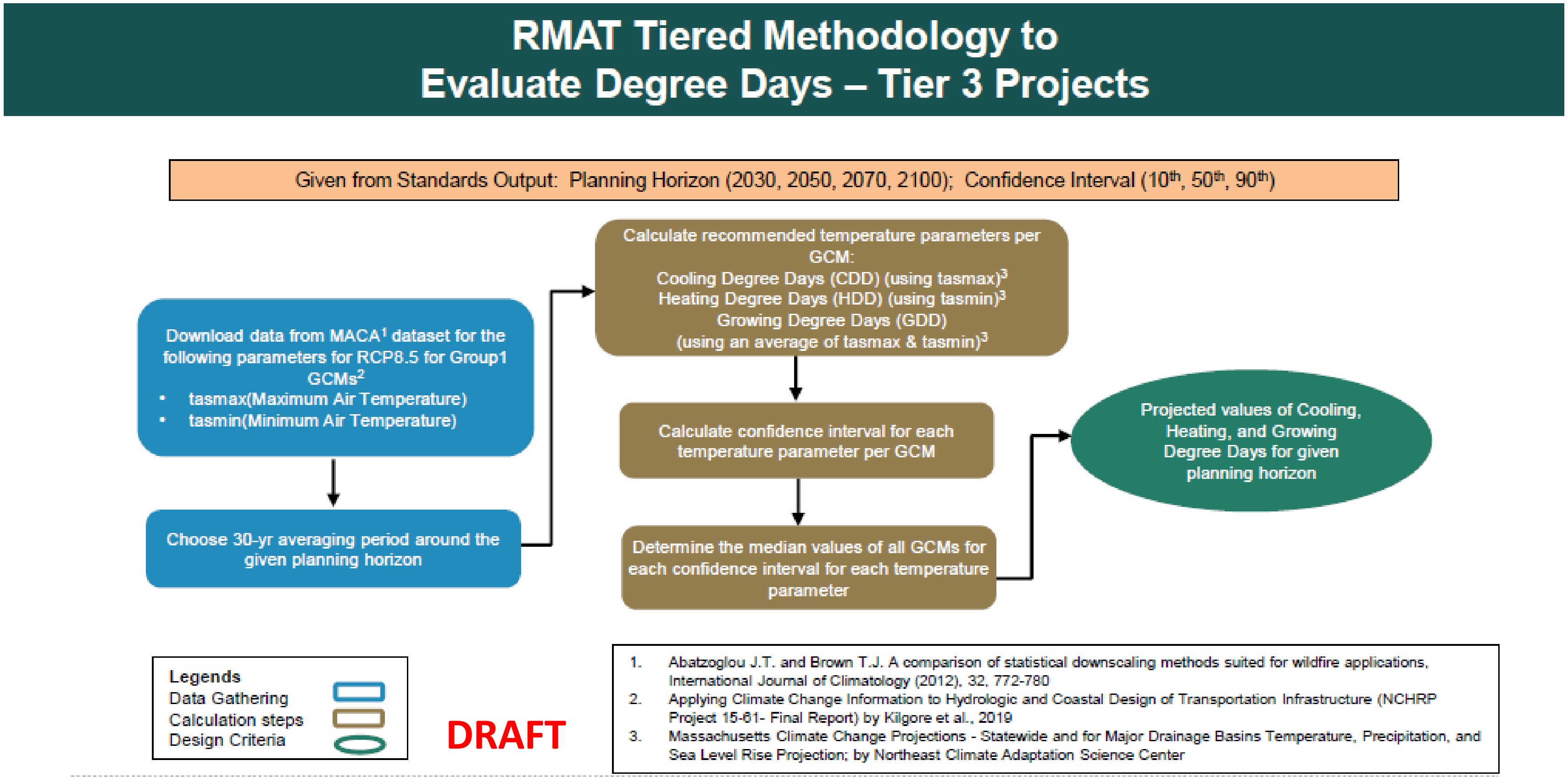

Figure 3.14. *Draft Tier 3 Methodology to Assess Degree Days Design Criteria Values as Recommended by the Extreme Heat Climate Parameter Climate Resilience Design Standards Output*

Refer to Attachment 3.4C for an example of draft methodology to evaluate extreme heat degree days design criteria values for Tier 3 methodology.

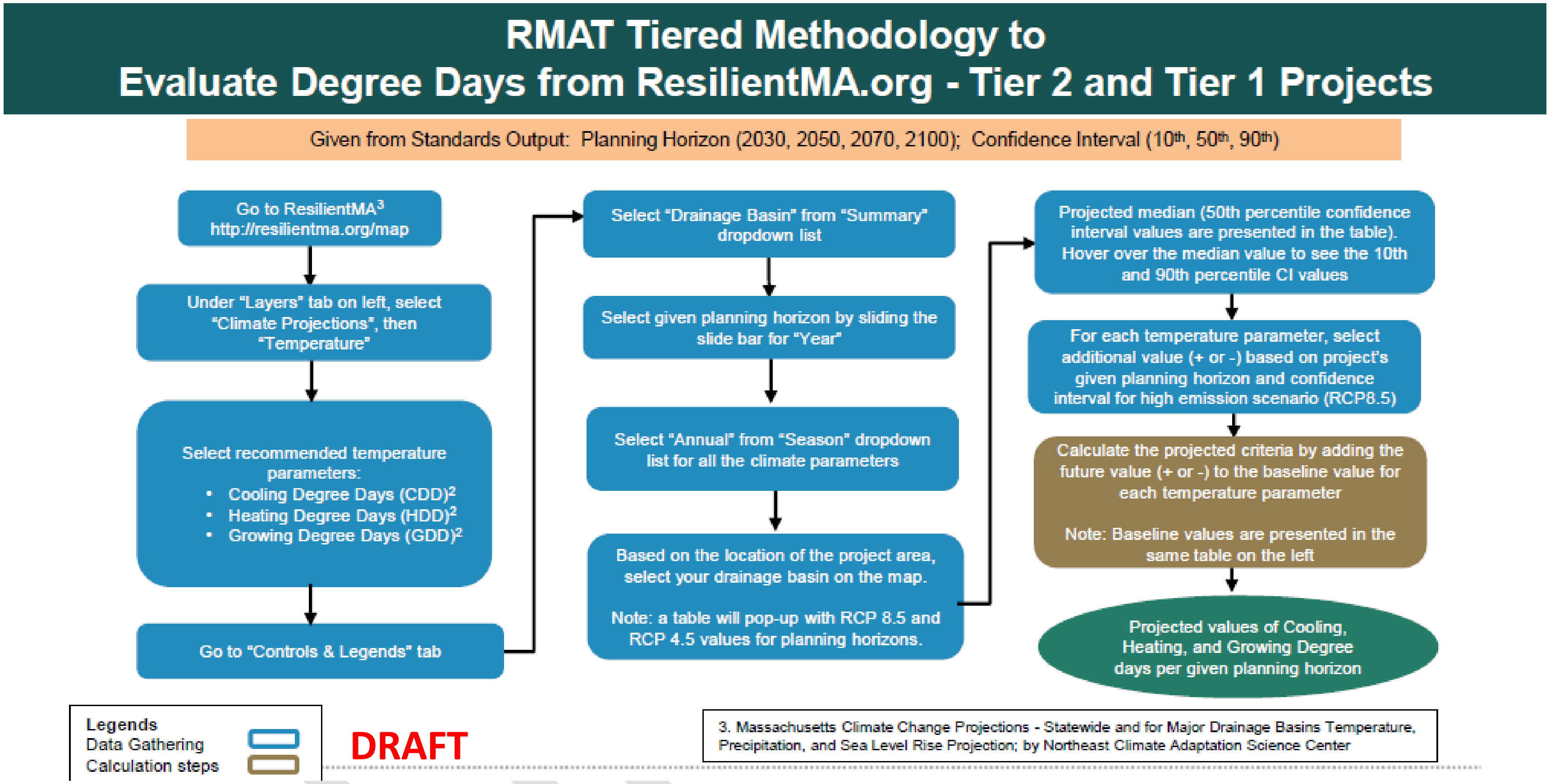

Figure 3.15. *Draft Tier 2/1 Methodology to Assess Degree Days Design Criteria Values as Recommended by the Extreme Heat Climate Parameter Climate Resilience Design Standards Output*

Refer to Attachment 3.4C for an example of draft methodology to evaluate extreme heat degree days design criteria values for Tier 2/1 methodology.

3.4.5.4 Draft Tiered Methodology for Extreme Heat – Heat Waves

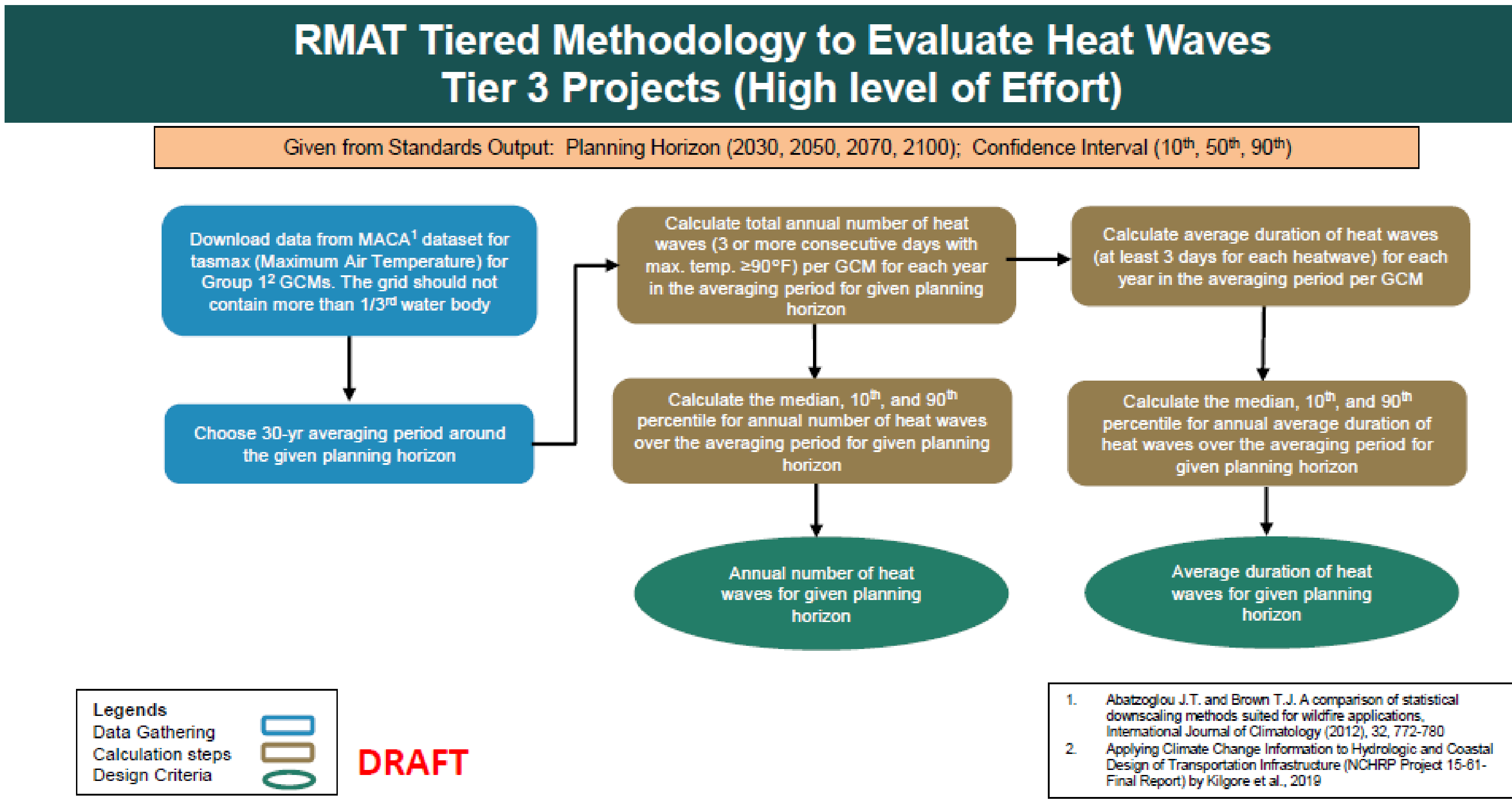

Figure 3.16. *Draft Tier 3 Methodology to Evaluate Heat Waves Design Criteria Values as Recommended by the Extreme Heat Climate Parameter Climate Resilience Design Standards Output*

Refer to Attachment 3.4D for an example of draft methodology to evaluate extreme heat waves design criteria values for Tier 3 methodology.

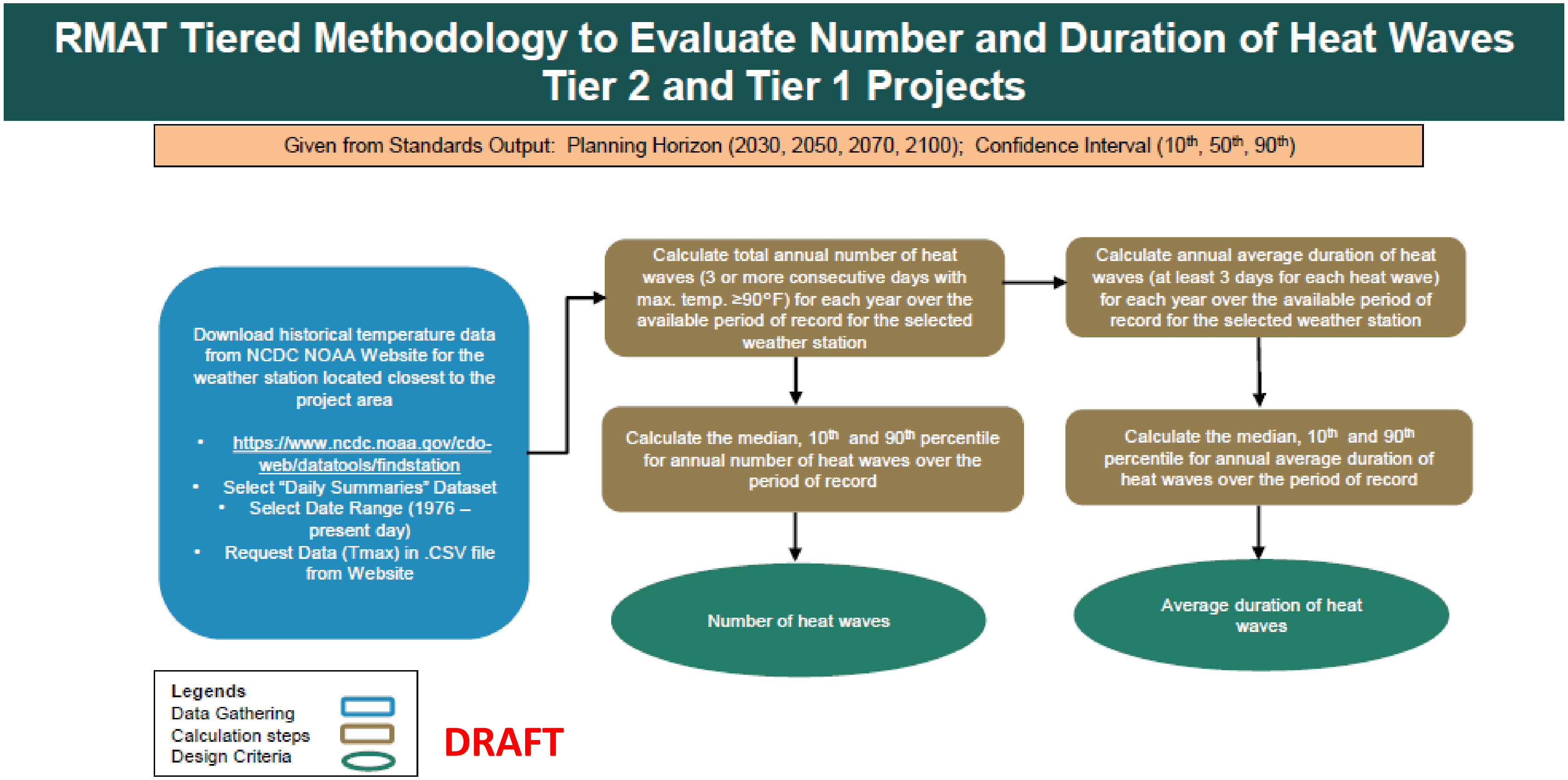

Figure 3.17. *Draft Tier 1 and 2 Methodology to Assess the Number and Duration of Heat Waves Design Criteria Values as Recommended by the Extreme Heat Climate Parameter Climate Resilience Design Standards Output*

Refer to Attachment 3.4D for an example of draft methodology to evaluate extreme heat waves design criteria values for Tier 2/1 methodology.

3.4.5.5 Draft Proposed Scope for Tiered Methodology for Extreme Heat – Heat Index

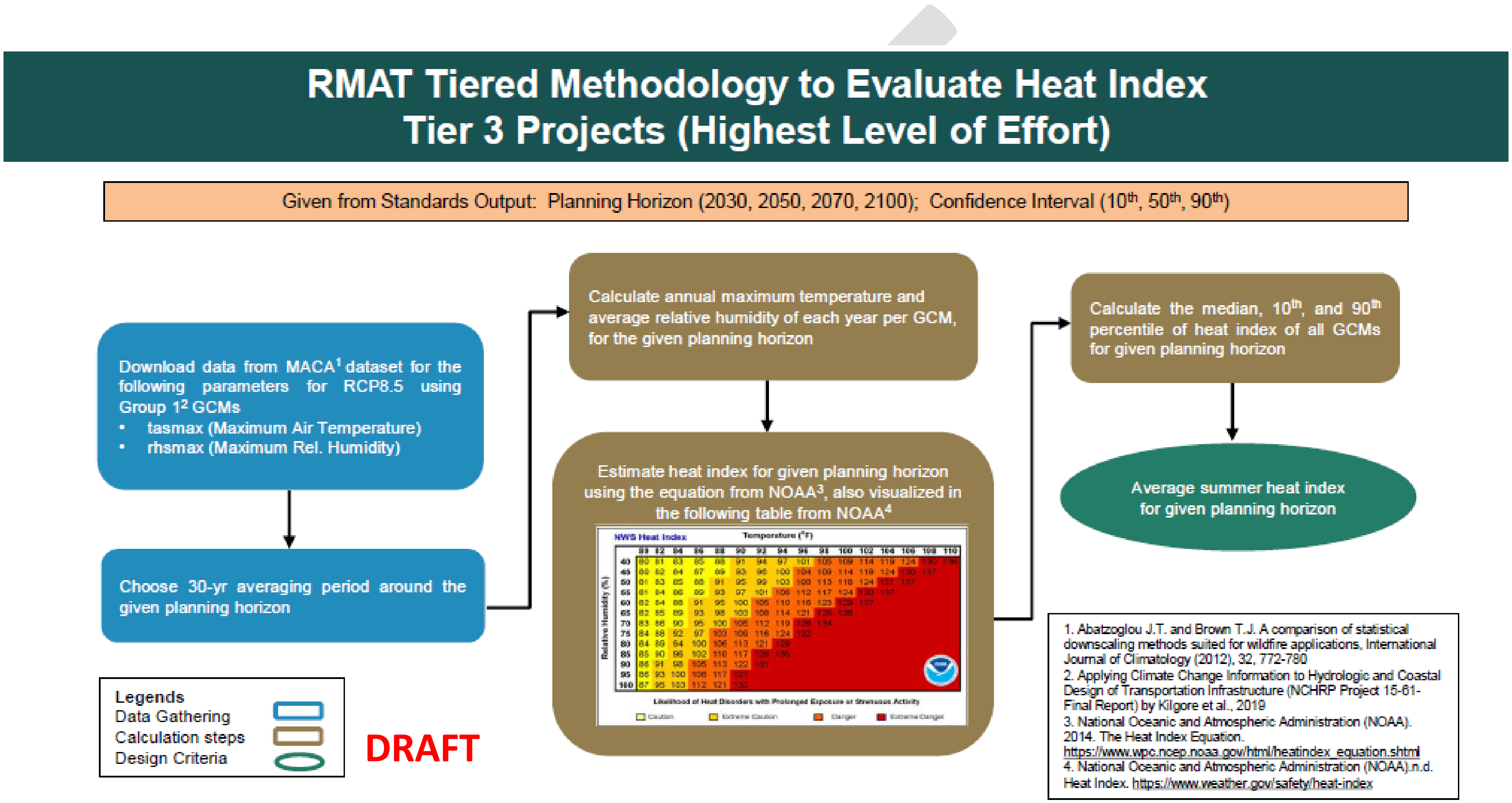

Figure 3.18. *Draft Tier 3 Methodology to Evaluate Heat Index Design Criteria Values as Recommended by the Extreme Heat Climate Parameter Climate Resilience Design Standards Output*

Refer to Attachment 3.4E for an example of draft methodology to evaluate extreme heat index design criteria values for Tier 3 methodology.

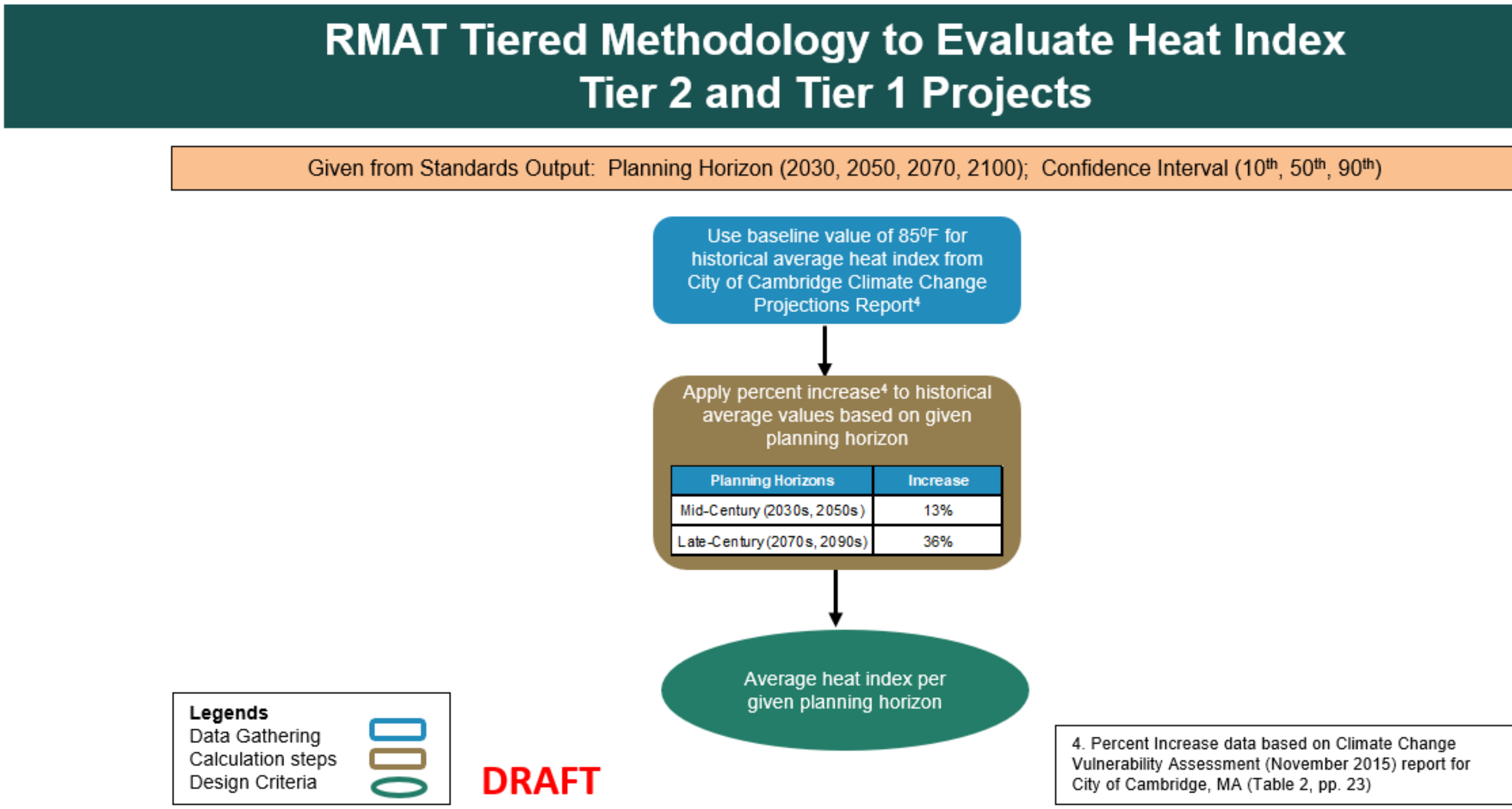

Figure 3.19. *Draft Tier 1 and 2 Methodology to Evaluate Heat Index Design Criteria Values as Recommended by the Extreme Heat Climate Parameter Climate Resilience Design Standards Output*

Refer to Attachment 3.4E for an example of draft methodology to evaluate extreme heat index design criteria values for Tier 2/1 methodology.

Section 3 Attachments

Attachment 3.3A – Example Data Source Download for Extreme Precipitation -- LOCA Dataset

Attachment 3.3B - Draft Tiered Methodology Example for Extreme Precipitation Depth and Intensity, All Tiers

Attachment 3.4A - Data Source Download Example for Extreme Heat -- MACA Dataset

Attachment 3.4B - Draft Tiered Methodology Example for Extreme Heat – Avg. Temp., All Tiers

Attachment 3.4C - Draft Tiered Methodology Example for Extreme Heat – Degree Days, All Tiers

Attachment 3.4D - Draft Tiered Methodology Example for Extreme Heat – Heat Waves, All Tiers

Attachment 3.4E - Draft Tiered Methodology Example for Extreme Heat – Heat Index, All Tiers

Attachment 3.3A – Example Data Source Download for Extreme Precipitation -- LOCA Dataset

RMAT Methodology to Download Data from LOCA Website

- **Go to https://gdo-dcp.ucllnl.org/ to download data from LOCA**
- **Go to page "Projection: Subset Request"**

STEP 1
Go to sub-tab "Page 1. Temporal & Spatial Extent"

"**Step 1.1**: Time Step and Period", select daily period from Jan-1950 through Dec-2099

Step 1.2: Domain ", select "NLDAS"

"**Step 1.3**: Select "Location" method and either enter the latitude, longitude pair or specify interactively within the map based on Project Location. If the selected grid includes more than 1/3rd water body, also download data from the adjacent grid.

STEP 2
Go to sub-tab "Page 2. Products, Variables, Projections"

"**Step 2.4**: Select "Projection Sets", check "LOCA-CMIP5-Climate-daily"

"**Step 2.5**: for "Products" select "1/16 degree". Check boxes for all three "Variables",
- "Precipitation Rate"

"**Step 2.6**: Emissions Scenarios, Climate Models and Runs", check boxes associated with Group 1 GCMs per NHCRP15-61 report[1].
For each model, select emission scenario RCP8.5 for precipitation

STEP 3
Go to sub-tab "Page 3. Analysis, Format, and Notification"

"**Step 3.7:** Analysis", keep dial set to "No Analysis"

"**Step 3.8:** Output Format", choose "ASCII text, comma-delimited (csv)"

"**Step 3.9**: Notification when Processing is Complete", enter your email address twice.

Finally, set the radio dials to indicate your user type, application type, and applicable resource area(s)

STEP 4
Data request and data download

4.1 Press button "Submit Request" on top left

4.2 A popup box will appear with details of the submission. Press "Submit". Press "Ok".

4.3. Click on the link that arrives in the email few hours later to get to an ftp directory of files produced for your job request

4.5. Click folder "Loca5" and download the .csv file for the climate projection data and .txt files for data related information

1. Applying Climate Change Information to Hydrologic and Coastal Design of Transportation Infrastructure (NCHRP Project 15-61- Final Report) by Kilgore et al., 2019

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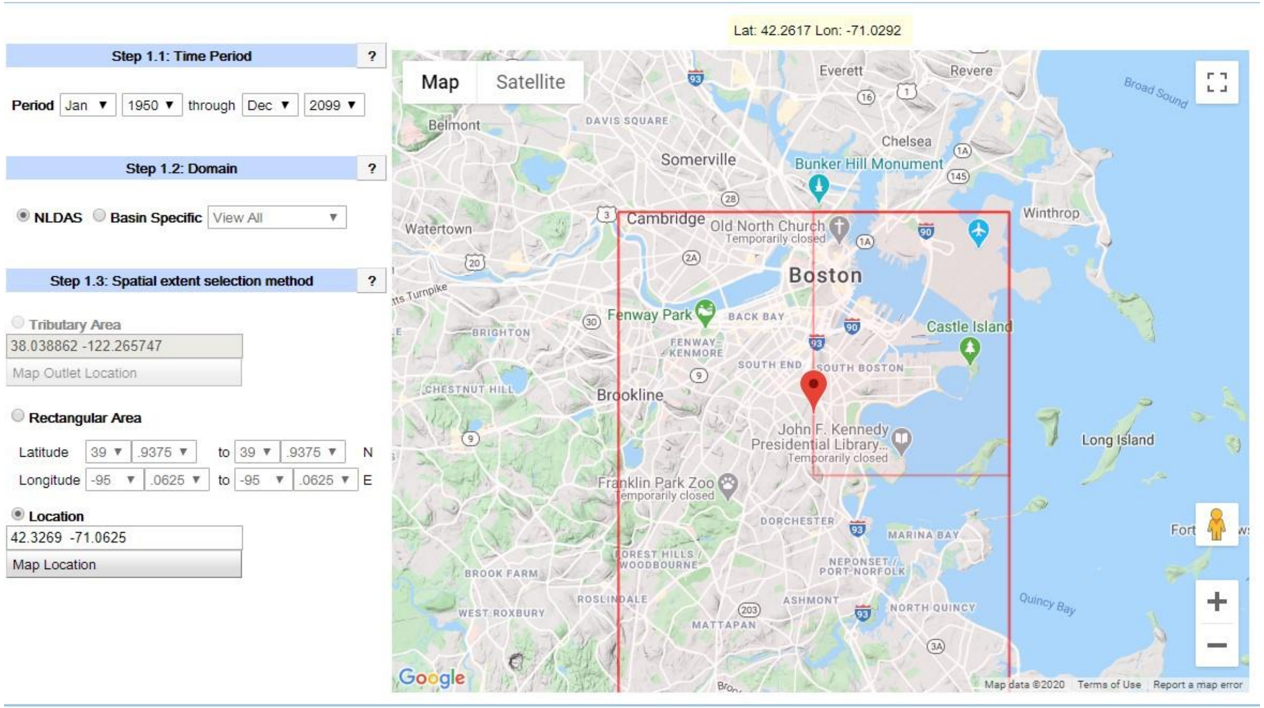
LOCA Dataset: Project Area and Time Selection



LOCA Dataset: Projection Set and Variables Selection

Enter specifications on three page form below. Then press 'Submit Request'. ?

Submit Request

Form Status (completed == green)

1.1 | 1.2 | 1.3 | 2.4 | 2.5 | 2.6 | 3.7 | 3.8 | 3.9 | 3.10

Size (%, 100 max): 6

Page 1: Temporal & Spatial Extent | **Page 2: Products, Variables, Projections** | **Page 3: Analysis, Format, & Notification**

Step 2.4: Select Projection Set (Green text indicates projection set form completed) ?

- BCSD-CMIP3-Climate-monthly
- BCCAv2-CMIP3-Climate-daily
- BCSD-CMIP3-Hydrology-monthly
- BCSD-CMIP5-Climate-monthly
- BCCAv2-CMIP5-Climate-daily
- BCSD-CMIP5-Hydrology-monthly
- LOCA-CMIP5-Climate-daily (selected)

BCSD-CMIP3-Climate-monthly | BCCAv2-CMIP3-Climate-daily | BCSD-CMIP3-Hydrology-monthly | BCSD-CMIP5-Climate-monthly | BCCAv2-CMIP5-Climate-daily | BCSD-CMIP5-Hydrology-monthly | **LOCA-CMIP5-Climate-daily**

Step 2.5: Products & Variables -- daily projections ?

Products
- [x] 1/16 degree LOCA projections
- [x] 1/16 degree Observed data (1950-2005)
- [ ] 1 degree LOCA projections

Variables
- [x] Precipitation Rate (mm/day)
- [ ] Min Surface Air Temperature (deg C)
- [ ] Max Surface Air Temperature (deg C)

LOCA Dataset: Group1* GCM Selections for Emission Scenario RCP8.5

De-select all runs	None											
Select all runs	All											
Climate Models:	Emissions Path: RCP8.5											
access1-0	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
access1-3	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
bcc-csm1-1	☑	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
bcc-csm1-1-m	☑	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
canesm2	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
ccsm4	☐	☐	☐	☐	☐	☑	☐	☐	☐	☐	☐	☐
cesm1-bgc	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
cesm1-cam5	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
cmcc-cm	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
cmcc-cms	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
cnrm-cm5	☑	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
csiro-mk3-6-0	☑	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
ec-earth	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
fgoals-g2	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
gfdl-cm3	☑	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
gfdl-esm2g	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
gfdl-esm2m	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
giss-e2-h	☐	☑	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
giss-e2-r	☐	☑	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
hadgem2-ao	☑	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
hadgem2-cc	☑	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
hadgem2-es	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
inmcm4	☑	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
ipsl-cm5a-lr	☑	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
ipsl-cm5a-mr	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
miroc-esm	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
miroc-esm-chem	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
miroc5	☑	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
mpi-esm-lr	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
mpi-esm-mr	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
mri-cgcm3	☑	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
noresm1-m	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐

* Applying Climate Change Information to Hydrologic and Coastal Design of Transportation Infrastructure (NCHRP Project 15-61- Final Report) by Kilgore et al., 2019

LOCA Dataset: Type of Analysis, Output Format, and Others

Enter specifications on three page form below. Then press 'Submit Request'. ?

Submit Request

Form Status (completed == green)

1.1 1.2 1.3 2.4 2.5 2.6 3.7 3.8 3.9 3.10

Size (%, 100 max): 181

Page 1: Temporal & Spatial Extent | Page 2: Products, Variables, Projections | Page 3: Analysis, Format, & Notification

Step 3.7: Analysis ?

- (●) No Analysis (Extracting Time Series only)
- ( ) Statistics
- [ ] Period Mean
- [ ] Period Standard Deviation
- [ ] Spatial Mean
- [ ] Spatial Standard Deviation

Step 3.8: Output Format ?

- ( ) NetCDF
- (●) ASCII text, comma-delimited (csv)

Step 3.9: Notification when Processing is Complete ?

roy.rupsa@wseinc.com Email Address

roy.rupsa@wseinc.com Email Address Confirm

LynnPrecip Tag/Label for request (Optional, characters may be letters, numbers, or '_')

Step 3.10: Usage Information

Please specify usage information below. This information will help LLNL and Reclamation track how this archive is serving various sectors and entities in the user community. For entity and application lists, please make one selection. For sector, please make one or multiple selections.

Entity	Application	Sector(s)
( ) Govt. - Federal	( ) Research	[ ] Water Quantity
( ) Govt. - State	( ) Environmental Documentation	[ ] Water Quality
( ) Govt. - Regional/Local	( ) Endangered Species consultation	[x] Flood Management
( ) Research Institution	(●) Vulnerability Assessment	[ ] Energy
( ) Academic Institution	( ) Adaptation Planning	[ ] Air Quality
(●) Private Sector	( ) Other	[ ] Ecosystem - Land
( ) Non-Govt. Organization		[ ] Ecosystem - Aquatic
( ) Other		[ ] Social Systems
		[ ] Other

Attachment 3.3B - Draft Tiered Methodology Example for Extreme Precipitation Depth and Intensity, All Tiers

RMAT Tiered Methodology to Assess 24-hr Precipitation Storm Depth and Peak Intensity
Tier 3 Projects (High Level of Effort)

Given Standards Output from Tool: Planning Horizon (2030, 2050, 2070, 2090); Recurrence Interval (5-yr, 10-yr, 25-yr, 50-yr, 100-yr, 500-yr)

Download daily precipitation projections for RCP 8.5 scenario from LOCA[1] dataset (Draft-SOP-Datadownload-LOCA.pptx) using 14 Group1[2] Global Climate Models (GCMs) for the grid(s) corresponding to the project location

Repeat the same steps for two more grids around the project location (a total of 3 grids from each location). Avoid grids that contains more than 1/3rd of water body

Choose 30-yr averaging period around given planning horizon

Calculate annual maximum rainfall for each year for each grid in the 30-yr averaging period per GCM

Fit Generalized Extreme Value (GEV) distribution to the annual maxima to calculate modeled baseline and modeled future projections for given planning horizon and given recurrence interval for each GCM per grid

Convert the 1-day design storm depths to 24-hour design storm depths using factor 1.13[3] per GCM per grid

Calculate the ratios between modeled baseline and modeled future per GCM per grid

Calculate mean, 5%CL and 95% CL of the ratios between modeled baseline and modeled future for all GCMs and apply that to NOAA Atlas 14 median values[4] to estimate the projected 24-hour precipitation depths for given recurrence interval for each grid

Calculate mean of the projected 24-hour precipitation depths for all grids

24-hr design storm depths for given planning horizon and given recurrence interval

Use SCS Type III/NOAA Atlas144 distribution to estimate hourly/sub-hourly peak intensities

Design storm hyetograph and peak intensity for given 24-hr design storm depths

1. Pierce, D.W., D.R. Cayan, and B.L. Thrasher, Statistical Downscaling Using Localized Constructed Analogs (LOCA). Journal of Hydrometeorology, 2014. 15(6): p. 2558-2585
2. Applying Climate Change Information to Hydrologic and Coastal Design of Transportation Infrastructure (NCHRP Project 15-61- Final Report) by Kilgore et al., 2019
3. Derived factor of 1.13 to adjust observation-day accumulations to true 24-hour amounts based on Extreme Precipitation in New York and England Technical Documentation & User Manual by DeGaetano & Zarrow, 2010
4. NOAA Atlas 14 Point Precipitation Frequency Estimates: Northeastern States; NOAA Atlas 14, Volume 10, Version 3

Legends
Data Gathering
Calculation steps
Design Criteria
Existing practice

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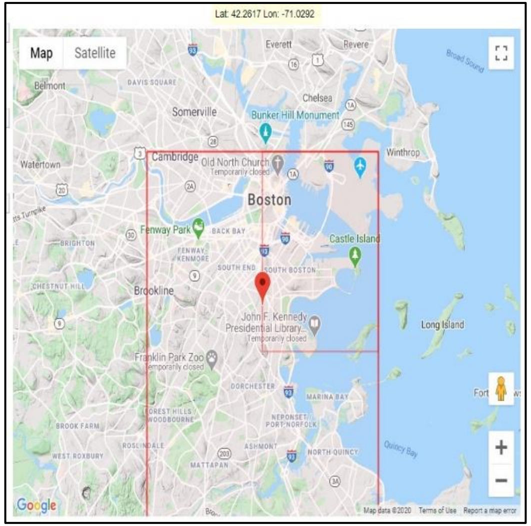
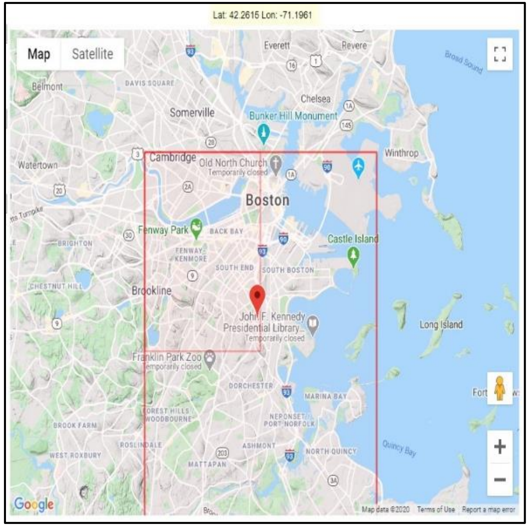
RMAT Tiered Methodology to Assess 24-hr Precipitation Storm Depth

Tier 3 Example: Moakley Park, South Boston, MA (Step1: Selecting project area, the inset LOCA grid was considered for analysis)





snip of the third grid.

DRAFT

Weston & Sampson

RMAT Tiered Methodology to Assess 24-hr Precipitation Storm Depth

Tier 3 Example: Moakley Park, South Boston, MA (Step2: Calculating Annual Maximum for each GCM each Grid for RCP 8.5)

YEAR	Max of bcc-csm1-1.1	Max of bcc-csm1-1-m.1	Max of ccsm4.6	Max of cnrm-cm5.1	Max of csiro-mk3-6-0.1	Max of gfdl-cm3.1	Max of giss-e2-h.6	Max of giss-e2-r.6	Max of hadgem2-ao.1	Max of hadgem2-cc.1	Max of inmcm4.1	Max of ipsl-cm5a-lr.1	Max of miroc5.1	Max of mri-cgcm3.1
2060	208.7	170.6	221.6	189.3	317.2	139.8	194.6	171.1	173.6	183.2	154.5	175.5	146.2	128.9
2061	173.0	163.2	157.1	182.5	152.1	125.6	146.5	156.9	160.6	171.5	125.3	169.7	144.3	119.9
2062	111.9	152.9	145.4	151.6	125.8	124.8	127.3	133.6	150.4	122.3	116.4	143.6	140.2	117.3
2063	109.7	135.1	129.2	130.0	119.0	116.1	124.7	114.6	142.2	117.6	112.9	124.2	135.5	107.4
2064	104.9	134.4	120.3	92.5	92.7	109.5	123.4	111.6	118.1	116.2	112.2	97.9	125.4	104.3
2065	92.4	132.1	109.3	92.2	91.3	107.8	110.4	105.9	117.4	109.8	101.8	90.3	117.1	103.8
2066	92.0	124.4	108.8	87.5	90.3	104.0	100.6	99.2	107.9	93.9	100.7	90.1	113.3	91.3
2067	85.6	118.6	99.6	87.1	90.2	96.6	88.5	98.7	102.0	89.9	91.2	89.9	107.9	91.0
2068	85.0	112.8	90.8	86.8	87.3	95.9	88.2	98.3	100.3	87.5	85.8	85.5	103.3	89.9
2069	82.1	111.1	76.8	85.1	83.9	93.1	82.5	87.6	99.3	86.5	75.9	80.9	100.0	88.5
2070	81.8	105.2	74.7	78.6	82.0	91.9	81.7	86.1	98.8	84.6	73.8	80.4	93.7	87.0
2071	73.3	98.7	72.1	78.0	81.9	87.6	80.8	76.5	98.2	79.3	72.4	78.4	88.9	84.5
2072	72.5	91.1	69.9	77.9	79.5	85.9	78.6	69.1	90.0	77.9	71.0	76.3	88.9	78.0
2073	72.2	90.5	68.1	77.6	76.3	80.3	75.6	68.3	87.9	77.1	71.0	72.7	86.8	74.9
2074	69.1	86.3	68.0	71.0	76.2	78.0	74.9	65.4	84.1	75.1	70.6	71.2	81.9	73.2
2075	67.6	82.4	66.3	68.6	75.9	75.1	72.6	64.5	81.8	74.7	70.2	70.8	74.6	73.0
2076	66.9	79.1	66.2	68.1	75.2	74.2	70.5	64.1	76.3	73.6	68.1	69.9	73.7	72.1
2077	66.8	75.4	65.4	67.3	70.7	74.0	66.5	63.8	74.9	73.4	63.1	69.7	70.7	71.3
2078	65.6	74.0	62.6	65.0	70.3	73.2	64.7	62.2	74.4	72.4	61.1	68.8	68.5	66.4
2079	65.1	68.0	61.2	64.3	69.1	73.2	64.6	61.2	74.4	72.3	59.8	68.2	68.2	66.4
2080	64.7	67.7	61.1	60.6	66.9	70.9	61.6	59.5	73.8	67.9	59.3	64.9	66.9	65.3
2081	62.6	67.0	59.0	59.1	66.0	68.9	61.4	59.2	71.8	63.8	58.0	62.9	65.7	65.0
2082	61.3	65.8	57.1	56.6	65.0	68.0	56.0	58.7	62.5	59.0	51.3	62.6	61.4	59.1
2083	60.5	65.1	53.8	54.5	62.1	60.8	55.7	56.5	62.4	58.9	49.0	60.0	60.1	52.3
2084	54.7	64.4	53.6	49.9	61.7	60.2	52.2	56.4	60.3	58.9	47.0	59.1	59.7	51.3
2085	54.7	61.1	51.2	49.4	58.0	56.5	51.2	52.2	56.0	58.5	45.9	54.1	57.8	50.2
2086	50.1	51.4	45.6	47.0	57.4	55.0	50.1	48.3	55.3	56.3	45.5	53.9	54.5	48.9
2087	43.8	49.8	43.4	46.8	53.5	52.5	48.0	47.7	55.1	54.6	45.3	50.4	54.4	46.5
2088	40.9	45.6	40.8	43.8	50.8	50.5	46.4	45.8	51.5	53.6	43.7	44.9	54.1	40.6
2089	28.1	40.4	36.5	41.2	47.8	42.4	44.9	37.5	50.5	46.6	43.0	44.0	50.2	40.1

RMAT Tiered Methodology to Assess 24-hr Precipitation Storm Depth

Tier 3 Example: Moakley Park, South Boston, MA (Step3: Fitting GEV Distribution on annual maxima of each grid for each GCM)

	Year	Rank	Max of bcc-csm1-1.1	b1	b2	Max of bcc-csm1-1-m.1	b1	b2	Max of ccsm4.6	b1	b2	Max of cnrm-cm5.1	b1	b2	Max of csiro-mk3-6-0.1	b1	b2
	2060	1	208.71	6.96	6.96	170.61	5.69	5.69	221.58	7.39	7.39	189.26	6.31	6.31	317.22	10.57	10.57
	2061	2	173.04	5.57	5.37	163.16	5.25	5.06	157.13	5.06	4.88	182.48	5.87	5.66	152.11	4.90	4.72
	2062	3	111.94	3.47	3.23	152.89	4.74	4.41	145.41	4.51	4.19	151.57	4.70	4.37	125.79	3.90	3.62
	2063	4	109.66	3.28	2.93	135.07	4.04	3.60	129.24	3.86	3.45	129.98	3.88	3.47	119.04	3.56	3.18
	2064	5	104.93	3.02	2.58	134.39	3.86	3.31	120.34	3.46	2.96	92.48	2.66	2.28	92.67	2.66	2.28
	2065	6	92.40	2.55	2.09	132.09	3.64	2.99	109.28	3.01	2.48	92.16	2.54	2.09	91.25	2.52	2.07
	2066	7	91.96	2.43	1.91	124.36	3.29	2.58	108.83	2.88	2.26	87.52	2.31	1.82	90.31	2.39	1.88
	2067	8	85.59	2.16	1.62	118.61	3.00	2.25	99.63	2.52	1.89	87.07	2.20	1.65	90.21	2.28	1.71
	2068	9	84.98	2.05	1.47	112.78	2.72	1.94	90.79	2.19	1.57	86.78	2.09	1.50	87.27	2.11	1.50
	2069	10	82.12	1.89	1.28	111.11	2.55	1.73	76.80	1.77	1.20	85.12	1.96	1.33	83.86	1.93	1.31
	2070	11	81.81	1.79	1.15	105.16	2.30	1.48	74.71	1.63	1.05	78.59	1.72	1.10	82.04	1.79	1.15
	2071	12	73.29	1.52	0.92	98.71	2.04	1.24	72.07	1.49	0.91	78.01	1.61	0.98	81.90	1.69	1.03
	2072	13	72.54	1.42	0.81	91.09	1.78	1.02	69.88	1.37	0.78	77.91	1.52	0.87	79.51	1.55	0.89
	2073	14	72.18	1.33	0.71	90.53	1.66	0.89	68.11	1.25	0.67	77.59	1.43	0.76	76.28	1.40	0.75
	2074	15	69.13	1.19	0.60	86.34	1.49	0.74	67.96	1.17	0.59	71.05	1.22	0.61	76.24	1.31	0.66
	2075	16	67.65	1.09	0.51	82.42	1.33	0.62	66.32	1.07	0.50	68.58	1.10	0.51	75.89	1.22	0.57
	2076	17	66.87	1.00	0.43	79.15	1.18	0.51	66.19	0.99	0.42	68.07	1.02	0.44	75.20	1.12	0.48
	2077	18	66.78	0.92	0.36	75.39	1.04	0.41	65.41	0.90	0.35	67.33	0.93	0.36	70.74	0.98	0.38
	2078	19	65.60	0.83	0.30	73.99	0.94	0.33	62.64	0.79	0.28	65.00	0.82	0.29	70.27	0.89	0.32
	2079	20	65.08	0.75	0.24	67.99	0.78	0.25	61.16	0.70	0.23	64.27	0.74	0.24	69.15	0.79	0.26
	2080	21	64.67	0.67	0.19	67.69	0.70	0.20	61.11	0.63	0.18	60.55	0.63	0.18	66.86	0.69	0.20
	2081	22	62.56	0.58	0.14	66.98	0.62	0.15	59.04	0.54	0.14	59.12	0.54	0.14	66.01	0.61	0.15
	2082	23	61.25	0.49	0.11	65.79	0.53	0.11	57.07	0.46	0.10	56.61	0.46	0.10	65.03	0.52	0.11
	2083	24	60.52	0.42	0.07	65.08	0.45	0.08	53.76	0.37	0.07	54.54	0.38	0.07	62.13	0.43	0.08
	2084	25	54.71	0.31	0.04	64.38	0.37	0.05	53.64	0.31	0.04	49.87	0.29	0.04	61.66	0.35	0.05
	2085	26	54.67	0.25	0.03	61.13	0.28	0.03	51.20	0.24	0.03	49.41	0.23	0.02	57.98	0.27	0.03
	2086	27	50.08	0.17	0.01	51.35	0.18	0.01	45.65	0.16	0.01	47.01	0.16	0.01	57.42	0.20	0.01
	2087	28	43.76	0.10	0.00	49.85	0.11	0.00	43.45	0.10	0.00	46.79	0.11	0.00	53.47	0.12	0.00
	2088	29	40.95	0.05	0.00	45.56	0.05	0.00	40.79	0.05	0.00	43.82	0.05	0.00	50.76	0.06	0.00
	2089	30	28.13	0.00	0.00	40.44	0.00	0.00	36.53	0.00	0.00	41.18	0.00	0.00	47.77	0.00	0.00
# of years	**30**																
	L-Moments			48	36		57	42		51	39		49	37		53	40
GEV w/ Lmom	lambda1		78.92			92.80			81.19			80.32			86.53		
	lambda2		17.57			20.43			20.54			18.65			19.12		
	lambda3		5.81			3.35			7.58			6.62			9.36		
	skew		0.33			0.16			0.37			0.35			0.49		

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RMAT Tiered Methodology to Assess 24-hr Precipitation Storm Depth

Tier 3 Example: Moakley Park, South Boston, MA (Step4: Calculate ratios between baseline and future for each GCM for each grid)

2070s (2060-2089) RCP8.5 Grid1														
T-yr Event	Max of bcc-csm1-1.1	Max of bcc-csm1-1-m.1	Max of ccsm4.6	Max of cnrm-cm5.1	Max of csiro-mk3-6-0.1	Max of gfdl-cm3.1	Max of giss-e2-h.6	Max of giss-e2-r.6	Max of hadgem2-ao.1	Max of hadgem2-cc.1	Max of inmcm4.1	Max of ipsl-cm5a-lr.1	Max of miroc5.1	Max of mri-cgcm3.1
	Ratios to modeled baseline													
2-yr, 24-hr	1.14	1.47	1.15	1.10	1.16	1.10	1.13	1.09	1.31	1.30	1.12	1.18	1.19	1.24
5-yr, 24-hr	1.15	1.51	1.30	1.16	1.20	1.05	1.24	1.10	1.32	1.27	1.18	1.29	1.22	1.25
10-yr, 24-hr	1.16	1.50	1.41	1.21	1.29	1.02	1.31	1.11	1.32	1.28	1.19	1.40	1.25	1.21
25-yr, 24-hr	1.17	1.45	1.55	1.30	1.49	0.99	1.39	1.13	1.32	1.32	1.18	1.61	1.30	1.15
50-yr, 24-hr	1.19	1.40	1.66	1.39	1.71	0.96	1.45	1.15	1.31	1.37	1.16	1.80	1.33	1.09
100-yr, 24-hr	1.20	1.34	1.78	1.48	1.99	0.94	1.51	1.17	1.30	1.43	1.13	2.03	1.36	1.03
200-yr, 24-hr	1.22	1.28	1.90	1.58	2.36	0.92	1.56	1.19	1.29	1.50	1.09	2.31	1.40	0.97
500-yr, 24-hr	1.25	1.19	2.08	1.74	3.01	0.89	1.63	1.22	1.27	1.61	1.04	2.75	1.45	0.89

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RMAT Tiered Methodology to Assess 24-hr Precipitation Storm Depth

Tier 3 Example: Moakley Park, South Boston, MA (Step5: calculating mean of the ratios for all GCMs and adding ratios to NOAA Atlas 14 Values)

2070s (2060-2089) RCP8.5 Grid1											
Recurrence intervals	**NOAA 14 Precip. (in.)**	**NOAA 14 Precip. 5% CI (in.)**	**NOAA 14 Precip. 95% CI (in.)**	**No. of Models**	**Mean of ratios**	**Std Dev. of ratios**	**5% CL of ratios**	**95% CL of ratios**	**Projected Precip. (in.)**	**Projected Precip. 5% CI (in.)**	**Projected Precip. 95% CI (in.)**
2-yr	3.3	2.8	3.8	14	1.19	0.11	1.15	1.24	3.9	3.7	4.0
5-yr	4.3	3.6	5.1	14	1.23	0.11	1.18	1.28	5.3	5.1	5.5
10-yr	5.1	4.3	6.1	14	1.26	0.13	1.21	1.32	6.5	6.2	6.7
25-yr	6.3	5.1	8.0	14	1.31	0.18	1.23	1.39	8.2	7.8	8.7
50-yr	7.2	5.6	9.3	14	1.35	0.24	1.25	1.46	9.7	8.9	10.4
100-yr	8.1	6.1	11.0	14	1.41	0.33	1.26	1.55	11.4	10.2	12.6
200-yr	9.3	6.4	12.8	14	1.47	0.45	1.27	1.67	13.6	11.8	15.4
500-yr	11.1	7.3	15.9	14	1.57	0.65	1.29	1.86	17.5	14.3	20.6

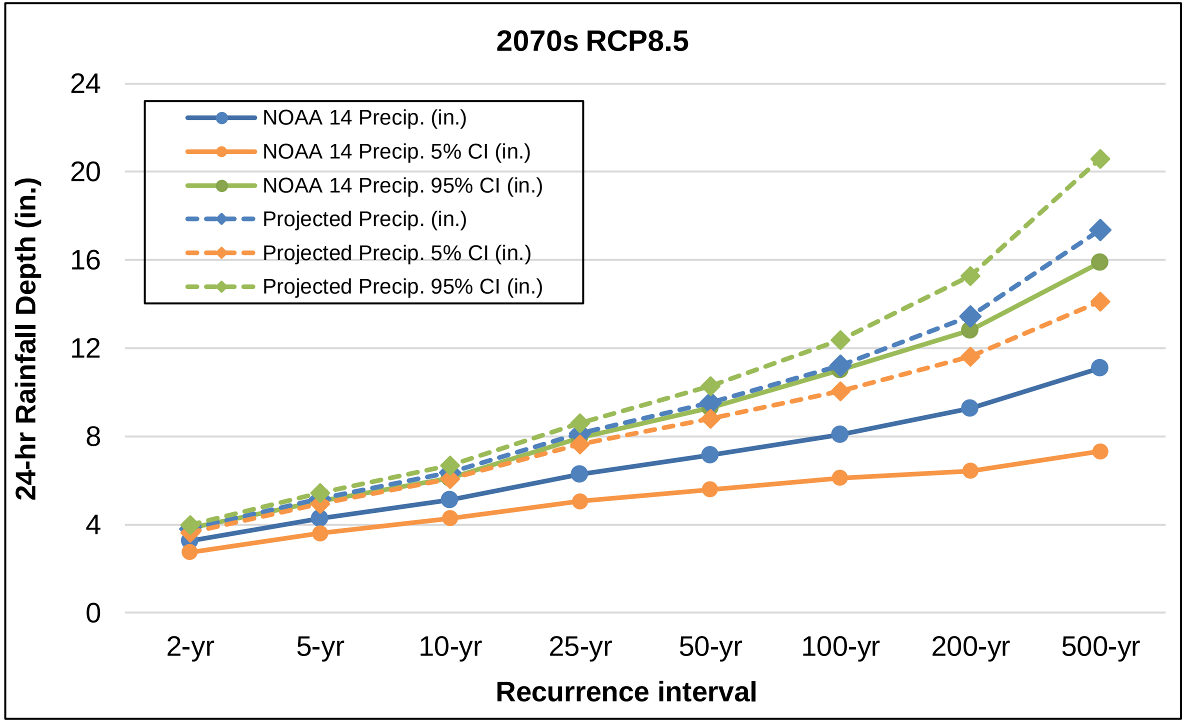
RMAT Tiered Methodology to Assess 24-hr Precipitation Storm Depth

Tier 3 Example: Moakley Park, South Boston, MA (Step5: calculating mean of the projected 24-hour precipitation depths for all grids)

2070s (2060-2089) RCP8.5 Average of the Grids			
Recurrence intervals	**Projected Precip. (in.)**	**Projected Precip. 5% CI (in.)**	**Projected Precip. 95% CI (in.)**
2-yr	3.8	3.6	4.0
5-yr	5.2	4.9	5.4
10-yr	6.4	6.1	6.7
25-yr	8.1	7.6	8.6
50-yr	9.5	8.8	10.3
100-yr	11.2	10.1	12.4
200-yr	13.5	11.6	15.3
500-yr	17.4	14.1	20.6

RMAT Tiered Methodology to Assess 24-hr Precipitation Storm Depth

Tier 3 Example: Moakley Park, South Boston, MA (Step6: comparing the projected precipitation quantiles with NOAA Atlas 14 historical estimates)



RMAT Tiered Methodology to Assess 24-hr Precipitation Storm Depth and Peak Intensity

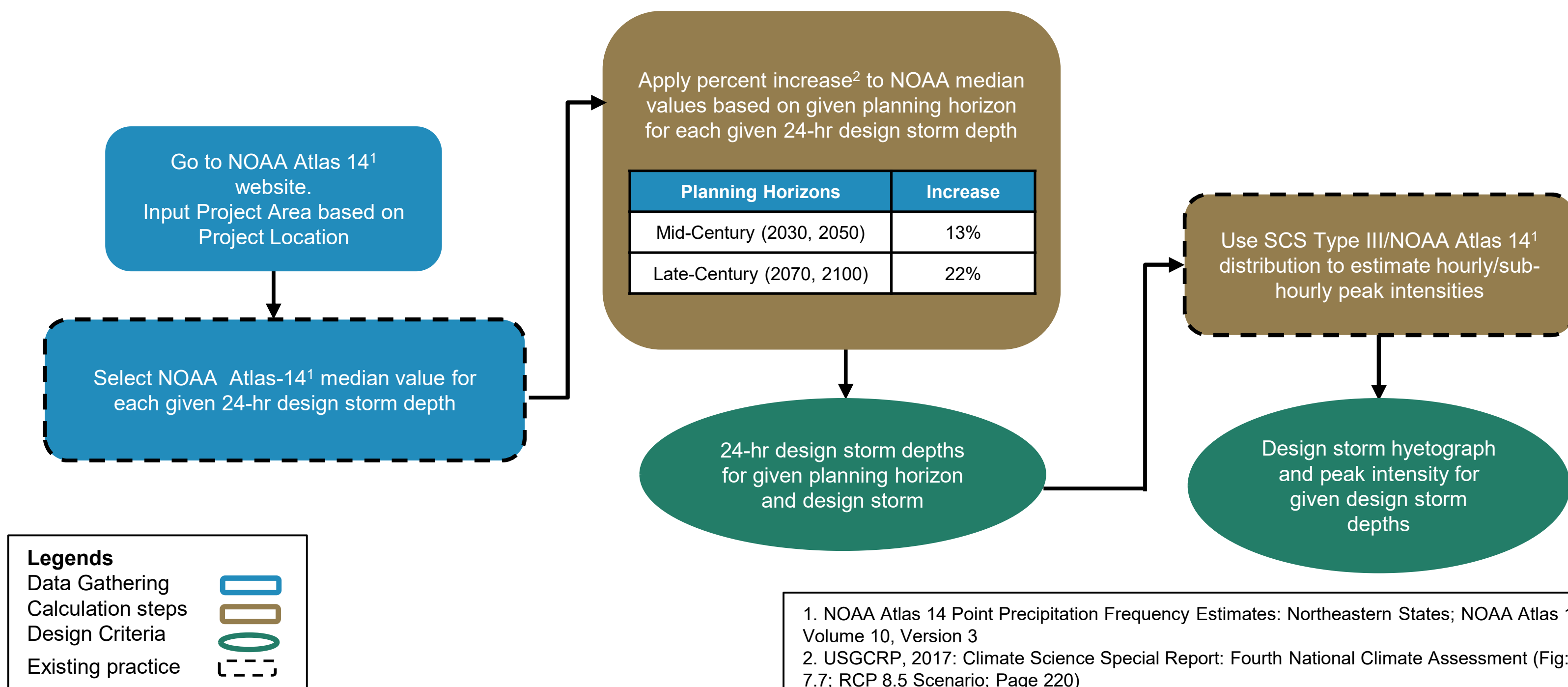
Tier 3 Example: Moakley Park, South Boston, MA (Step7: 24-hr design storm hyetographs for peak intensity for given planning horizon and design storm)

Recurrence Interval (Years)	NOAA Atlas 14 Present Baseline -24hr (in)	Tier3 2070 Values -24hr (in)
2-yr	3.3	3.8
5-yr	4.3	5.2
10-yr	5.1	6.4
25-yr	6.3	8.1
50-yr	7.2	9.5
100-yr	8.1	11.2
200-yr	9.3	13.5
500-yr	11.1	17.4

10yr -24 hr 2070s		6.4 in	
Duration (hr)	Ratio	Cumulative depth (in.)	Hourly peak intensity (in./hr)
0	0	0	0
1	0.01	0.06	0.06
2	0.02	0.13	0.06
3	0.03	0.19	0.07
4	0.04	0.27	0.08
5	0.06	0.36	0.09
6	0.07	0.45	0.10
7	0.09	0.57	0.12
8	0.11	0.72	0.15
9	0.15	0.92	0.20
10	0.19	1.19	0.27
11	0.25	1.58	0.38
12	0.50	3.15	1.58
13	0.75	4.73	1.58
14	0.81	5.11	0.38
15	0.85	5.38	0.27
16	0.89	5.58	0.20
17	0.91	5.73	0.15
18	0.93	5.85	0.12
19	0.94	5.94	0.10
20	0.96	6.03	0.09
21	0.97	6.11	0.08
22	0.98	6.18	0.07
23	0.99	6.24	0.06
24	1	6.30	0.06

RMAT Tiered Methodology to Assess 24-hr Precipitation Storm Depth and Peak Intensity - Tier 2 Projects (Medium Level of Effort)

Given Standards Output from Tool: Planning Horizon (2030, 2050, 2070, 2090); Recurrence Interval (5-yr, 10-yr, 25-yr, 50-yr, 100-yr, 500-yr)



Planning Horizons	Increase
Mid-Century (2030, 2050)	13%
Late-Century (2070, 2100)	22%

1. NOAA Atlas 14 Point Precipitation Frequency Estimates: Northeastern States; NOAA Atlas 14, Volume 10, Version 3
2. USGCRP, 2017: Climate Science Special Report: Fourth National Climate Assessment (Fig: 7.7; RCP 8.5 Scenario; Page 220)

Note: Refer to Section 3.3.6.3 for proposed scope to update percent increase for Tier 2.

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RMAT Tiered Methodology to
Assess 24-hr Precipitation Storm Depth and Peak Intensity
Tier 2 Example: Moakley Park, South Boston, MA
(24-hr design storm depths for given planning horizon and design storm)

Recurrence Interval (Years)	NOAA Atlas 14 Present Baseline - 24hr (in)	Tier2 - 2030 Values 13% increase on NOAA baseline (in)	Tier2 - 2070 Values 22% increase on NOAA baseline (in)
2-yr	3.3	3.7	4.0
5-yr	4.3	4.8	5.2
10-yr	5.1	5.8	6.2
25-yr	6.3	7.1	7.7
50-yr	7.2	8.1	8.7
100-yr	8.1	9.1	9.9
200-yr	9.3	10.5	11.3
500-yr	11.1	12.5	13.5

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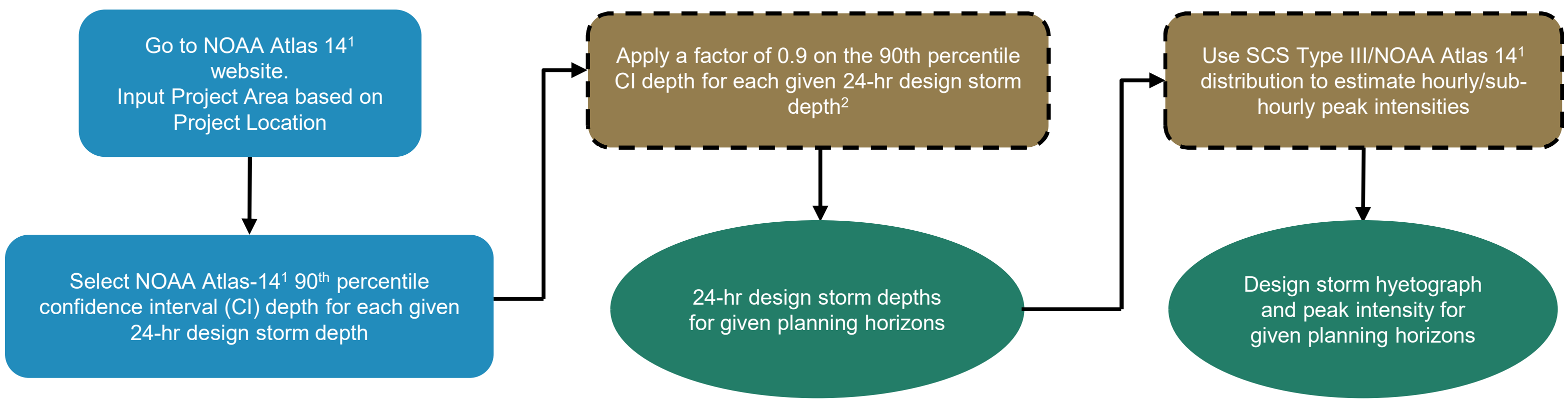
RMAT Tiered Methodology to Assess 24-hr Precipitation Storm Depth and Peak Intensity - Tier 1 Projects (Low Level of Effort)

Given Standards Output from Tool: Planning Horizon (2030, 2050, 2070, 2090); Recurrence Interval (5-yr, 10-yr, 25-yr, 50-yr, 100-yr, 500-yr)



Legends
Data Gathering
Calculation steps
Design Criteria
Existing practice

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1. NOAA Atlas 14 Point Precipitation Frequency Estimates: Northeastern States; NOAA Atlas 14, Volume 10, Version 3
2. A Comparison of Precipitation Frequency Atlases in Massachusetts: Considerations in Regulating Inland Wetland Resource Areas Affected by Climate Change, Internal Draft, October 22, 2017.

RMAT Tiered Methodology to Assess
24-hr Precipitation Storm Depth and Peak Intensity

Tier 1 Example: Moakley Park, South Boston, MA (24-hr design storm depths for given recurrence intervals)

Recurrence Interval (Years)	NOAA Atlas 14 Present Baseline - 24hr (in)	NOAA Atlas 14 Present Baseline - 24hr (90th percentile) (in)	Tier3 90% of 90th percentile of NOAA baseline (in)
2-yr	3.3	3.8	3.4
5-yr	4.3	5.1	4.6
10-yr	5.1	6.1	5.5
25-yr	6.3	8.0	7.2
50-yr	7.2	9.3	8.4
100-yr	8.1	11.0	9.9
200-yr	9.3	12.8	11.5
500-yr	11.1	15.9	14.3

RMAT Tiered Methodology to Assess 24-hr Precipitation Storm Depth and Peak Intensity

Comparison Across Tiers for Moakley Park, South Boston, MA

Recurrence Interval (Years)	NOAA Atlas 14 Present Baseline (in)	Tier 3 2070 Values (in)	Tier 2 2070 Values (in)	Tier 1 values (in)
2-yr	3.3	3.8	4.0	3.4
5-yr	4.3	5.2	5.2	4.6
10-yr	5.1	6.4	6.2	5.5
25-yr	6.3	8.1	7.7	7.2
50-yr	7.2	9.5	8.7	8.4
100-yr	8.1	11.2	9.9	9.9
200-yr	9.3	13.5	11.3	11.5
500-yr	11.1	17.4	13.5	14.3

Attachment 3.4A - Data Source Download Example for Extreme Heat -- MACA Dataset

RMAT Methodology to Download Data from MACA Website

- Go to https://climate.northwestknowledge.net/MACA/data_portal.php to download data from Multivariate Adaptive Constructed Analogs (MACA) data portal

STEP 1
Domain selection

1.1: Select "Rectangular Subset" from "Domain" dropdown list

1.2: A rectangle will appear on the interactive map. Move the rectangle and place it around the project area. Increase or decrease the size of the rectangle based on the area you want to cover around the location. Make sure your grid does not cover more than 1/3rd of water body.

1.3: Select "files of URLs for downloading data" from "Download Format" dropdown list

STEP 2
Products, Time frequency, Variables selection

2.4: "MACA Product" : "MACAv2-METDATA"

2.4: "Time Frequency" : "daily"

2.5: "Variables" : Check boxes for the climate parameters relevant to the project for examples,
- "rhsmax (Maximum Relative Humidity)"
- "tasmax(Maximum Air Temperature)"
- "tasmin(Minimum Air Temperature)"

STEP 2 (..cont.)
Model, Emission Scenarios, Time periods selection

2.6: "CMIP5 Models" : Check boxes for all the Group 1 models from NCHRP report[1]

2.7: "CMIP5 Scenarios/Time Periods" : Check boxes for the following parameters for
- "**RCP8.5**" : "future RCP8.5 (2006-2099)"

STEP 3
Data download

3.1: Press button "Download file" on top right

3.2: Open the text file to extract the downloaded data

3.3: Climate projection files are downloaded as Netcdf files. Convert the files in your preferred file format for climate projection analysis

1. Applying Climate Change Information to Hydrologic and Coastal Design of Transportation Infrastructure (NCHRP Project 15-61- Final Report) by Kilgore et al., 2019

Weston & Sampson

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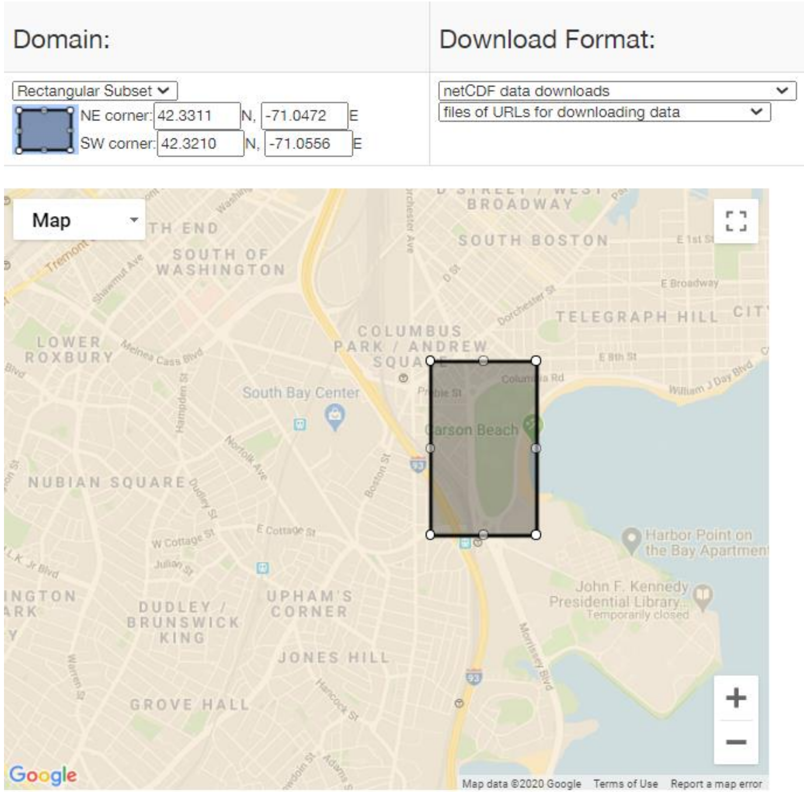
MACA Dataset: Project Area, and Download Format Selection



MACA Dataset: Product, Time Frequency, and Variables Selection

MACA PRODUCT

- MACAv2-LIVNEH
- MACAv1-METDATA
- MACAv2-METDATA (selected)

TIME FREQUENCY

- daily (selected)
- monthly
- Annual
- DJF(Dec-Feb)
- MAM (March-May)
- JJA (June-Aug)
- SON (Sept-Nov)

VARIABLES

Select All | DeSelect All

- [ ] huss (Specific Humidity)
- [ ] pr (Precipitation)
- [x] rhsmax (Maximum Relative Humidity)
- [ ] rhsmin (Minimum Relative Humidity)
- [ ] rsds (Downwelling Solar Radiation)
- [x] tasmin(Minimum Air Temperature)
- [x] tasmax(Maximum Air Temperature)
- [ ] vpd (Vapor Pressure Deficit)
- [ ] uas (Eastward Wind Component)
- [ ] vas (Northward Wind Component)

MACA Dataset: Group1* GCM Selections

CMIP5 MODELS

Select All | DeSelect All

- [x] bcc-csm1-1 (China)
- [x] bcc-csm1-1-m (China)
- [ ] BNU-ESM (China)
- [ ] CanESM2 (Canada)
- [x] CCSM4 (USA)
- [x] CNRM-CM5 (France)
- [x] CSIRO-Mk3-6-0 (Australia)
- [x] GFDL-ESM2G (USA)
- [ ] GFDL-ESM2M (USA)
- [x] HadGEM2-CC365 (United Kingdom)
- [ ] HadGEM2-ES365 (United Kingdom)
- [x] inmcm4 (Russia)
- [x] IPSL-CM5A-LR (France)
- [ ] IPSL-CM5A-MR (France)
- [x] IPSL-CM5B-LR (France)
- [x] MIROC5 (Japan)
- [ ] MIROC-ESM (Japan)
- [ ] MIROC-ESM-CHEM (Japan)
- [x] MRI-CGCM3 (Japan)
- [ ] NorESM1-M (Norway)

*Applying Climate Change Information to Hydrologic and Coastal Design of Transportation Infrastructure (NCHRP Project 15-61- Final Report) by Kilgore et al., 2019

MACA Dataset: Emission Scenario (RCP8.5) and Time Selection

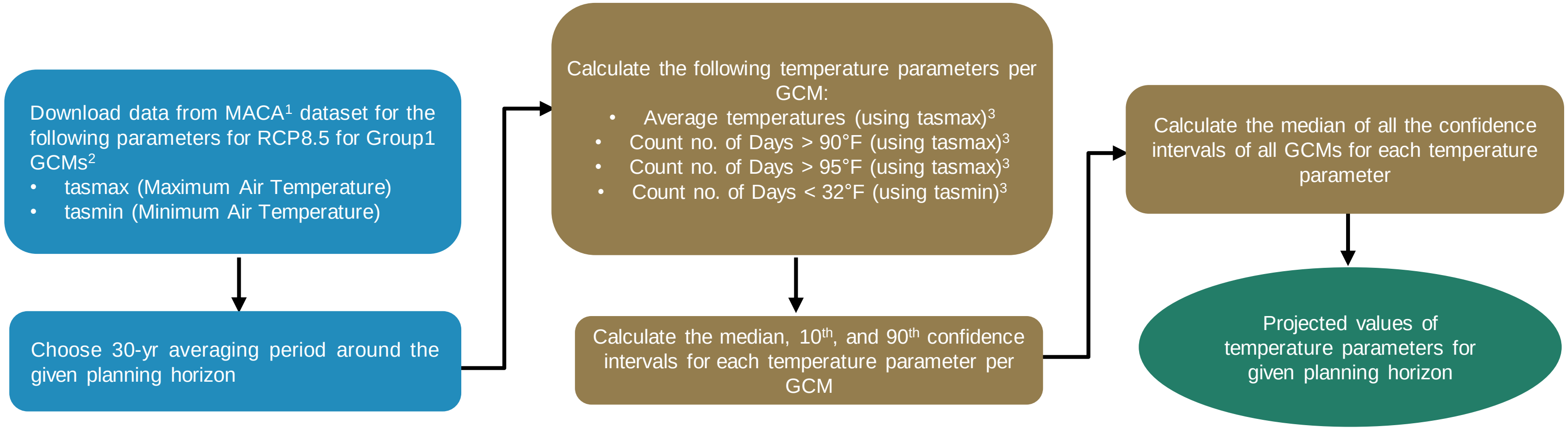
RCP 8.5

- [ ] rcp85 (2006-2010)
- [ ] rcp85 (2011-2015)
- [ ] rcp85 (2016-2020)
- [ ] rcp85 (2021-2025)
- [ ] rcp85 (2026-2030)
- [ ] rcp85 (2031-2035)
- [ ] rcp85 (2036-2040)
- [ ] rcp85 (2041-2045)
- [ ] rcp85 (2046-2050)
- [ ] rcp85 (2051-2055)
- [ ] rcp85 (2056-2060)
- [ ] rcp85 (2061-2065)
- [ ] rcp85 (2066-2070)
- [ ] rcp85 (2071-2075)
- [ ] rcp85 (2076-2080)
- [ ] rcp85 (2081-2085)
- [ ] rcp85 (2086-2090)
- [ ] rcp85 (2091-2095)
- [ ] rcp85 (2096-2099)
- [x] future RCP8.5 (2006-2099)
- [ ] future RCP8.5 (2006 - 2099)

Attachment 3.4B - Draft Tiered Methodology Example for Extreme Heat – Avg. Temperature, All Tiers

RMAT Tiered Methodology to Assess Temperature Criteria
Tier 3 Projects (High Level of Effort)

Given Standards Output from Tool: Planning Horizon (2030, 2050, 2070, 2090); Confidence Interval (10th, 50th, 90th)



Legends
- Data Gathering
- Calculation steps
- Existing practices
- Design Criteria

1. Abatzoglou J.T. and Brown T.J. A comparison of statistical downscaling methods suited for wildfire applications, International Journal of Climatology (2012), 32, 772-780
2. Applying Climate Change Information to Hydrologic and Coastal Design of Transportation Infrastructure (NCHRP Project 15-61- Final Report) by Kilgore et al., 2019
3. Massachusetts Climate Change Projections - Statewide and for Major Drainage Basins Temperature, Precipitation, and Sea Level Rise Projection; by Northeast Climate Adaptation Science Center

RMAT Tiered Methodology to Assess Temperature Criteria

(Step1: Calculate days above 90ºF for each GCM)

Tier 3 Example: Moakley Park, Boston

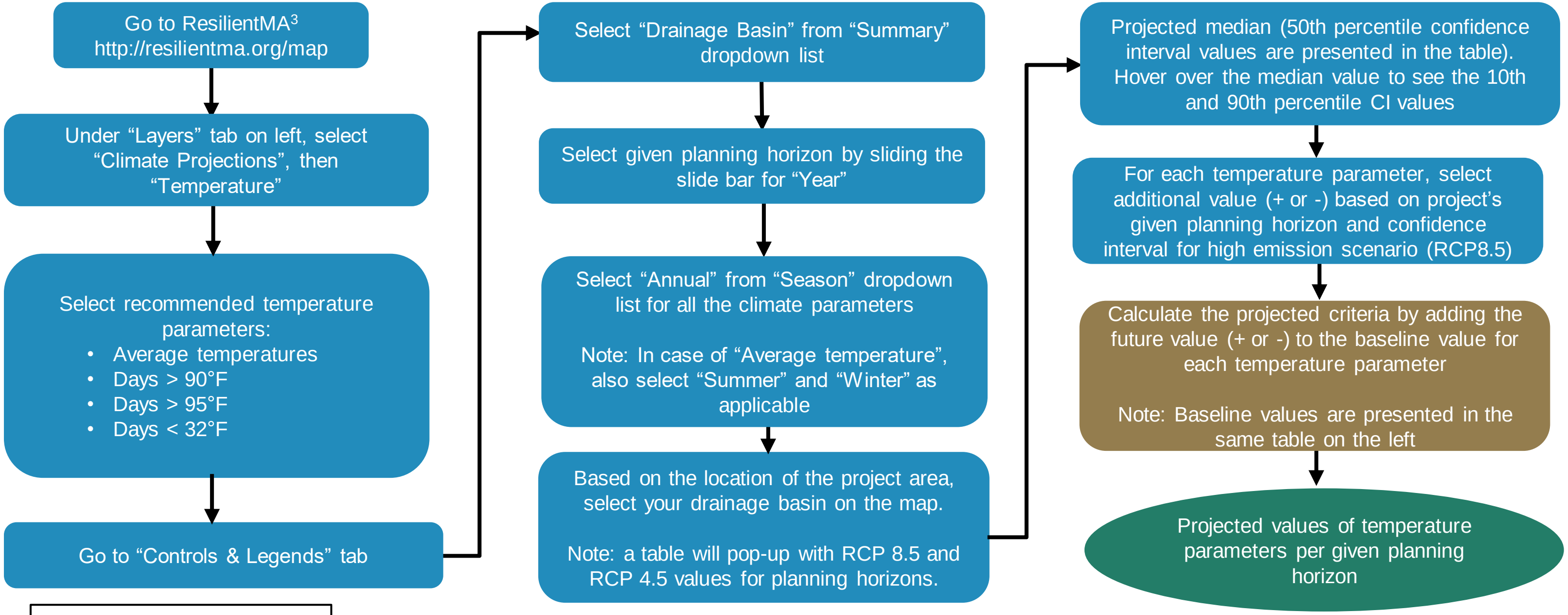
YEAR	bcc-csm1-1	bcc-csm1-1-m	CCSM4	CNRM-CM5	CSIRO-Mk3-6-0	HadGEM2-CC365	inmcm4	IPSL-CM5A-LR	IPSL-CM5B-LR	MIROC5	MRI-CGCM3
2060	28	24	34	14	28	69	23	38	68	42	16
2061	16	54	46	18	27	47	26	18	21	52	37
2062	4	31	51	39	17	68	19	16	56	32	16
2063	25	23	23	48	40	66	17	42	37	28	25
2064	55	66	36	36	51	41	20	51	15	52	34
2065	35	66	30	18	46	63	1	58	60	53	17
2066	27	37	32	9	33	64	27	30	42	36	17
2067	42	39	41	19	49	52	9	21	34	53	20
2068	34	32	44	28	54	78	24	40	32	33	34
2069	59	44	21	37	30	49	8	58	48	52	22
2070	46	55	40	41	39	54	6	64	60	27	29
2071	39	40	33	54	19	61	18	59	41	48	26
2072	13	57	40	33	34	31	5	49	65	34	22
2073	54	43	50	58	48	59	11	51	29	56	30
2074	40	21	44	21	66	47	26	59	73	52	36
2075	59	46	37	20	50	72	5	42	34	57	35
2076	30	56	42	50	34	39	4	30	58	67	23
2077	47	23	31	33	48	65	7	51	61	41	21
2078	49	33	35	67	53	65	10	60	55	44	16
2079	50	24	38	33	21	51	25	47	64	43	26
2080	70	34	45	40	42	68	25	64	58	66	38
2081	76	39	47	35	55	72	23	66	49	36	29
2082	68	43	54	42	50	93	18	47	47	47	20
2083	33	30	53	30	32	81	26	70	46	45	19
2084	47	54	52	35	53	41	26	57	46	48	21
2085	40	46	54	26	49	85	7	57	24	73	39
2086	61	64	42	15	47	85	16	40	46	55	26
2087	22	40	33	19	53	61	16	39	55	45	29
2088	44	47	52	53	64	45	27	56	57	41	24
2089	71	52	61	42	53	63	8	50	88	64	35
10th percentile	17	23	30	15	22	41	5	22	25	32	16
50th percentile	43	42	42	34	48	63	18	51	49	48	26
90th percentile	70	63	54	54	55	85	26	64	68	66	37

RMAT Tiered Methodology to Assess Temperature Criteria
(Step 2: Calculate Median, 10th and 90th percentiles for all GCMs)
Tier 3 Example: Moakley Park, Boston

2070s	Avg temp (°F)	# days > 90°F	# days > 95°F	# days < 32°F
10th percentile	64.9	22	5	65
Median	66.7	43	16	45
90th percentile	69.5	63	28	24

RMAT Tiered Methodology to Assess Temperature Criteria from ResilientMA.org Tier 2 and Tier 1 Projects (Medium and Low Level of Effort)

Given Standards Output from Tool: Planning Horizon (2030, 2050, 2070, 2090); Confidence Interval (10^{th}, 50^{th}, 90^{th})



Legends
Data Gathering
Calculation steps
Existing practices
Design Criteria

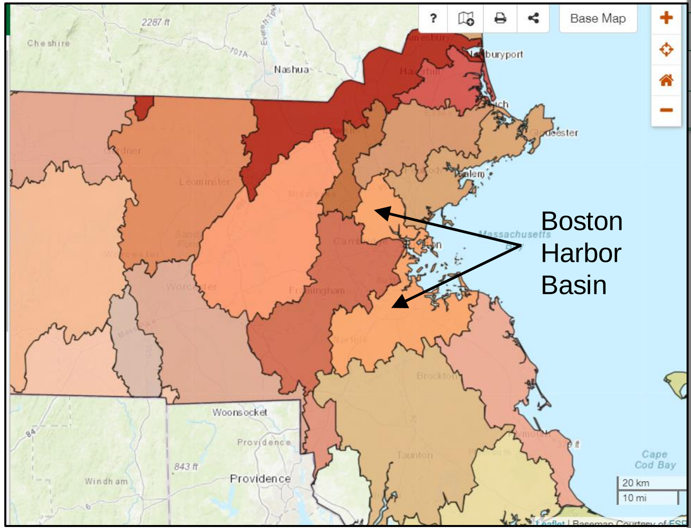
DRAFT

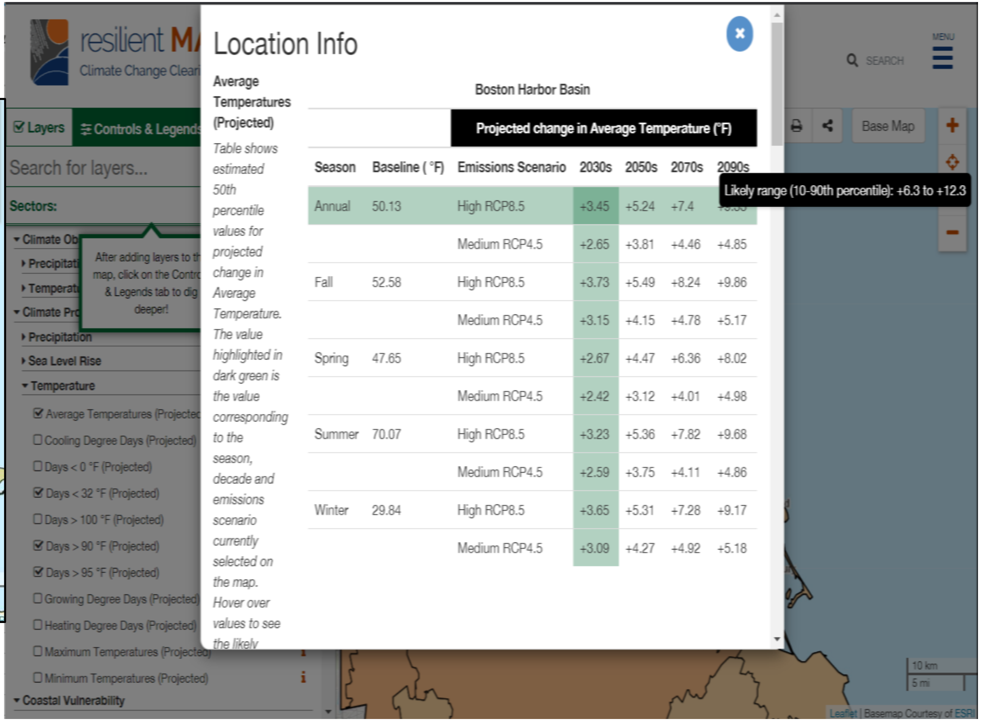
3. Massachusetts Climate Change Projections - Statewide and for Major Drainage Basins Temperature, Precipitation, and Sea Level Rise Projection; by Northeast Climate Adaptation Science Center

Weston & Sampson

RMAT Tiered Methodology to Assess Temperature Criteria from ResilientMA.org

Tier 2/1 Example: Moakley Park, Boston (Boston Harbor Basin)





Season	Baseline (°F)	Emissions Scenario	2030s	2050s	2070s	2090s
Annual	50.13	High RCP8.5	+3.45	+5.24	+7.4	[illegible]
		Medium RCP4.5	+2.65	+3.81	+4.46	+4.85
Fall	52.58	High RCP8.5	+3.73	+5.49	+8.24	+9.86
		Medium RCP4.5	+3.15	+4.15	+4.78	+5.17
Spring	47.65	High RCP8.5	+2.67	+4.47	+6.36	+8.02
		Medium RCP4.5	+2.42	+3.12	+4.01	+4.98
Summer	70.07	High RCP8.5	+3.23	+5.36	+7.82	+9.68
		Medium RCP4.5	+2.59	+3.75	+4.11	+4.86
Winter	29.84	High RCP8.5	+3.65	+5.31	+7.28	+9.17
		Medium RCP4.5	+3.09	+4.27	+4.92	+5.18

RMAT Tiered Methodology to Assess Temperature Criteria from ResilientMA.org

Tier 2/1 Example: Moakley Park, Boston (Boston Harbor Basin)

2070s	Avg temp (^oF)	# days > 90^oF	# days > 95^oF	# days < 32^oF
10th percentile	55.3	28	9	84
Median	57.5	48	20	72
90th percentile	60.4	63	35	52

RMAT Tiered Methodology to Assess Temperature Criteria
Comparison Across Tiers
Example: Moakley Park, Boston

2070s	Tier 3 Avg temp (°F)	Tier 2/1 Avg temp (°F)	Tier 3 # days > 90°F	Tier 2/1 # days > 90°F	Tier 3 # days > 95°F	Tier 2/1 # days > 95°F	Tier 3 # days < 32°F	Tier 2/1 # days < 32°F
10^{th} percentile	64.6	55.3	22	28	5	9	65	84
Median	66.3	57.5	43	48	16	20	45	72
90^{th} percentile	69.4	60.4	63	63	28	35	24	52

REFERENCES

1. Abatzoglou J.T. and Brown T.J. A comparison of statistical downscaling methods suited for wildfire applications, International Journal of Climatology (2012), 32, 772-780

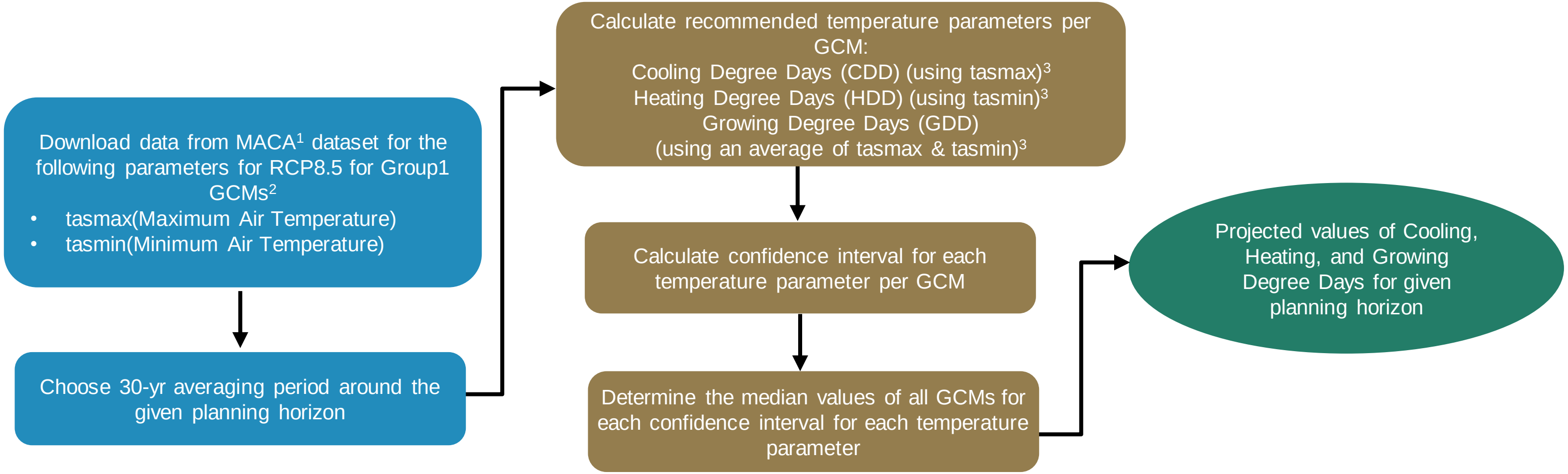
2. Applying Climate Change Information to Hydrologic and Coastal Design of Transportation Infrastructure (NCHRP Project 15-61- Final Report) by Kilgore et al., 2019

3. Massachusetts Climate Change Projections - Statewide and for Major Drainage Basins Temperature, Precipitation, and Sea Level Rise Projections; by Northeast Climate Adaptation Science Center and published by Massachusetts Executive Office of Energy and Environmental Affairs, 2018.

Attachment 3.4C - Draft Tiered Methodology Example for Extreme Heat – Degree Days, All Tiers

RMAT Tiered Methodology to Evaluate Degree Days – Tier 3 Projects

Given from Standards Output: Planning Horizon (2030, 2050, 2070, 2100); Confidence Interval (10^{th}, 50^{th}, 90^{th})



Legends
Data Gathering
Calculation steps
Design Criteria

1. Abatzoglou J.T. and Brown T.J. A comparison of statistical downscaling methods suited for wildfire applications, International Journal of Climatology (2012), 32, 772-780
2. Applying Climate Change Information to Hydrologic and Coastal Design of Transportation Infrastructure (NCHRP Project 15-61- Final Report) by Kilgore et al., 2019
3. Massachusetts Climate Change Projections - Statewide and for Major Drainage Basins Temperature, Precipitation, and Sea Level Rise Projection; by Northeast Climate Adaptation Science Center

RMAT Tiered Methodology to Evaluate Degree Days - Tier 3 Projects (Step 0: Complete MACA data download)

RMAT Methodology to Download Data from MACA Website

- Go to https://climate.northwestknowledge.net/MACA/data_portal.php to download data from Multivariate Adaptive Constructed Analogs (MACA) data portal

STEP 1
Domain selection

1.1: Select "Rectangular Subset" from "Domain" dropdown list

1.2: A rectangle will appear on the interactive map. Move the rectangle and place it around the project area. Increase or decrease the size of the rectangle based on the area you want to cover around the location. Make sure your grid does not cover more than 1/3rd of water body.

1.3: Select "files of URLs for downloading data" from "Download Format" dropdown list

STEP 2
Products, Time frequency, Variables selection

2.4: "MACA Product" : "MACAv2-METDATA"

2.4: "Time Frequency" : "daily"

2.5: "Variables" : Check boxes for the climate parameters relevant to the project for examples,
- "rhsmax (Maximum Relative Humidity)"
- "tasmax(Maximum Air Temperature)"
- "tasmin(Minimum Air Temperature)"

STEP 2 (..cont.)
Model, Emission Scenarios, Time periods selection

2.6: "CMIP5 Models" : Check boxes for all the Group 1 models from NCHRP report[1]

2.7: "CMIP5 Scenarios/Time Periods" : Check boxes for the following parameters for
- "**RCP8.5**" : "future RCP8.5 (2006-2099)"

STEP 3
Data download

3.1: Press button "Download file" on top right

3.2: Open the text file to extract the downloaded data

3.3: Climate projection files are downloaded as Netcdf files. Convert the files in your preferred file format for climate projection analysis

1. Applying Climate Change Information to Hydrologic and Coastal Design of Transportation Infrastructure (NCHRP Project 15-61- Final Report) by Kilgore et al., 2019

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RMAT Tiered Methodology to Evaluate Degree Days - Tier 3 Projects (Step 1: Calculate Average Daily Temp. from tasmax and tasmin) Example: 2070s CDDs for Moakley Park, Boston

			2060-2089											
yyyy-mm-dd	Year	Month	bcc-csm1-1	bcc-csm1-1-m	CCSM4	CNRM-CM5	CSIRO-Mk3-6-0	HadGEM2-CC365	inmcm4	IPSL-CM5A-LR	IPSL-CM5B-LR	MIROC5	MRI-CGCM3
1/1/2060	2060	1	41.8	48.6	42.1	45.7	41.5	33.2	24.9	51.5	39.6	39.8	49.0
1/2/2060	2060	1	53.1	28.5	41.1	46.0	35.2	40.4	30.5	51.8	37.5	33.4	53.1
1/3/2060	2060	1	54.2	23.9	42.4	36.6	36.1	39.9	28.7	42.6	34.2	38.5	41.2
1/4/2060	2060	1	50.8	33.1	37.5	37.0	36.7	43.3	33.0	33.2	39.6	38.4	31.3
1/5/2060	2060	1	65.7	39.8	30.3	36.7	37.5	45.8	35.2	30.3	41.1	38.9	39.7
1/6/2060	2060	1	54.6	41.2	29.5	33.1	37.3	39.5	46.5	41.1	37.4	40.3	43.5
1/7/2060	2060	1	50.0	34.9	26.8	31.7	40.1	40.0	38.4	43.5	40.0	40.2	50.3
1/8/2060	2060	1	51.4	27.4	27.7	38.0	36.3	40.6	31.9	43.7	45.1	40.8	52.6
1/9/2060	2060	1	53.8	42.2	33.1	43.2	30.5	39.1	42.5	35.5	42.8	40.4	58.3
1/10/2060	2060	1	48.0	40.0	25.8	38.5	25.8	34.7	53.5	32.2	39.3	37.4	41.2
1/11/2060	2060	1	36.2	33.1	29.1	43.8	29.6	33.6	64.4	36.7	40.1	35.7	29.3
1/12/2060	2060	1	36.7	37.3	38.0	44.0	35.4	38.0	48.0	26.1	37.3	36.9	32.2
1/13/2060	2060	1	45.9	35.0	50.9	47.3	35.8	45.3	43.2	26.1	32.7	37.8	46.7
1/14/2060	2060	1	35.5	24.5	43.5	42.6	36.5	43.7	33.7	39.4	33.2	33.7	41.5
1/15/2060	2060	1	33.9	21.1	28.0	43.7	39.4	36.5	14.3	41.5	36.2	27.7	28.4
1/16/2060	2060	1	40.0	20.5	23.0	43.1	40.7	33.9	17.4	39.7	35.2	36.2	18.4
1/17/2060	2060	1	43.3	37.7	30.3	50.8	44.9	38.8	32.7	36.5	36.8	37.6	21.1
1/18/2060	2060	1	39.8	37.6	39.6	50.4	47.1	46.4	36.2	39.2	45.3	29.2	37.8
1/19/2060	2060	1	32.4	39.7	37.8	42.1	48.5	44.5	21.0	44.4	33.2	30.2	34.2
1/20/2060	2060	1	40.9	25.5	43.8	35.6	45.9	45.2	15.1	46.3	23.6	36.1	20.8
1/21/2060	2060	1	46.5	22.2	35.2	36.7	38.8	34.3	24.2	38.0	31.4	32.3	31.2
1/22/2060	2060	1	40.7	13.5	23.2	39.0	25.8	39.5	29.9	29.2	36.6	21.9	44.2
1/23/2060	2060	1	30.0	9.5	45.9	31.5	38.7	41.3	36.4	43.4	40.6	22.3	44.5
1/24/2060	2060	1	27.6	15.6	31.9	33.9	38.9	37.7	43.7	36.3	33.0	22.5	32.1
1/25/2060	2060	1	35.6	29.6	27.8	32.6	38.5	29.4	37.7	32.6	30.4	27.3	27.5
1/26/2060	2060	1	37.7	40.4	36.1	29.5	37.5	32.1	33.9	37.3	37.5	38.4	19.8
1/27/2060	2060	1	35.9	43.9	34.1	25.2	41.6	31.1	37.8	27.4	36.1	44.1	23.9
1/28/2060	2060	1	40.2	47.9	44.2	29.7	42.9	32.7	36.7	25.3	43.9	43.9	27.4
1/29/2060	2060	1	42.9	49.3	35.7	35.4	41.7	30.7	38.4	19.4	47.0	41.7	33.8
1/30/2060	2060	1	39.6	47.0	39.9	38.5	41.9	23.0	43.2	20.4	42.2	48.4	45.3
1/31/2060	2060	1	34.7	41.6	25.4	43.9	42.8	21.2	40.2	23.6	32.3	48.3	42.3
2/1/2060	2060	2	29.4	33.8	23.4	45.4	43.9	16.8	42.6	21.8	33.7	44.1	50.3
2/2/2060	2060	2	30.7	32.9	23.9	48.9	49.3	18.9	38.0	33.6	36.0	41.2	44.1
2/3/2060	2060	2	35.2	35.7	39.9	54.7	51.9	25.2	32.1	21.1	43.3	39.4	32.2
2/4/2060	2060	2	32.2	36.9	38.4	42.8	44.7	32.9	39.7	26.7	42.1	42.1	30.6
2/5/2060	2060	2	30.0	38.3	30.5	33.8	34.7	35.1	26.1	25.8	47.2	36.8	33.3
2/6/2060	2060	2	34.3	29.8	41.5	35.8	23.5	35.4	23.7	12.7	51.4	29.1	46.4
12/24/2089	2089	12	47.2	47.2	31.7	47.0	46.8	42.3	47.9	49.9	43.4	29.8	46.2
12/25/2089	2089	12	42.7	38.9	27.8	46.1	44.3	44.2	53.1	53.8	33.0	31.6	47.0
12/26/2089	2089	12	42.0	37.0	28.0	41.0	50.4	53.7	45.3	49.2	23.9	24.9	38.8
12/27/2089	2089	12	35.4	33.4	29.9	39.4	57.5	47.9	39.7	41.2	25.3	21.6	44.7
12/28/2089	2089	12	34.8	36.7	32.1	41.1	57.1	48.5	40.7	45.8	38.8	16.6	56.9
12/29/2089	2089	12	42.8	34.7	36.7	31.7	41.5	60.0	32.0	49.6	62.4	17.4	59.8
12/30/2089	2089	12	44.4	33.7	36.8	32.9	37.3	56.1	31.4	41.7	65.5	29.7	51.3
12/31/2089	2089	12	49.9	30.8	49.0	41.9	37.3	43.4	26.0	31.7	59.5	38.3	34.9

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RMAT Tiered Methodology to Evaluate Degree Days - Tier 3 Projects (Step 2: Calculate the sum of degree days for all GCMs) Example: 2070s CDDs for Moakley Park, Boston

Row Labels	Sum of bcc-csm1-1	Sum of bcc-csm1-1-m	Sum of CCSM4	Sum of CNRM-CM5	Sum of CSIRO-Mk3-6-0	Sum of HadGEM2-CC365	Sum of inmcm4	Sum of IPSL-CM5A-LR	Sum of IPSL-CM5B-LR	Sum of MIROC5	Sum of MRI-CGCM3
2060	1387	1262	1281	1212	1304	2017	1223	1521	1811	1663	1127
2061	1115	1737	1510	1046	1373	1892	1263	1156	1271	1707	1473
2062	872	1627	1641	1611	1224	2077	1108	1129	1733	1399	1071
2063	1324	1276	1398	1635	1571	1966	1109	1569	1715	1423	1354
2064	1833	1780	1237	1475	1719	1725	1057	1915	1203	1745	1425
2065	1617	2139	1348	1417	1484	2040	1037	1899	1729	1679	1098
2066	1479	1468	1589	920	1424	2052	1306	1517	1428	1615	1143
2067	1566	1342	1565	1211	1726	1813	916	1343	1690	1767	1085
2068	1520	1460	1597	1250	1815	2397	1132	1677	1492	1385	1450
2069	1898	1580	1240	1575	1420	1641	987	1962	1566	1727	1262
2070	1556	1641	1553	1798	1509	1946	918	1908	1884	1365	1402
2071	1622	1540	1370	1873	1350	2047	1153	1883	1771	1662	1370
2072	1088	1670	1528	1435	1454	1672	915	1792	1851	1569	1307
2073	1697	1469	1508	1761	1663	2132	1042	1874	1342	1816	1498
2074	1415	1217	1793	1430	1972	1969	1382	2016	2161	1628	1586
2075	1813	1713	1555	1230	1826	2194	848	1707	1544	1828	1454
2076	1519	1745	1498	1775	1392	1797	892	1579	1704	1896	1158
2077	1769	1361	1269	1459	1746	2100	1082	1915	2034	1647	1174
2078	1528	1526	1565	2194	1828	2131	1001	2114	1796	1696	1207
2079	1788	1293	1491	1486	1346	2000	1135	1983	2060	1574	1388
2080	1979	1531	1622	1554	1526	2106	1224	2057	1886	2072	1626
2081	2071	1491	1549	1517	1806	2403	1276	1951	1801	1582	1476
2082	1851	1575	1695	1651	1792	2757	1184	1932	1618	1836	1219
2083	1483	1516	1740	1217	1479	2436	1336	2140	1777	1727	1182
2084	1549	1750	1800	1520	1713	1831	1270	1930	1708	1711	1324
2085	1678	1759	1765	1449	1854	2504	1081	1846	1504	2188	1668
2086	1825	2002	1711	1191	1611	2640	1113	1725	1858	1830	1301
2087	1339	1605	1355	1397	1958	2103	1081	1612	1825	1590	1377
2088	1613	1676	1697	1820	1840	1818	1467	2134	1786	1723	1379
2089	2168	1647	1781	1585	1848	2107	939	1964	2320	1939	1563

Min	872	1217	1237	920	1224	1641	848	1129	1203	1365	1071
Max	2168	2139	1800	2194	1972	2757	1467	2140	2320	2188	1668
Med	1590	1577	1554	1481	1637	2049	1109	1891	1752	1702	1362
Mean	1599	1580	1542	1490	1619	2077	1116	1792	1729	1700	1338
10th percentile	1136	1278	1270	1193	1347	1732	915	1360	1351	1401	1101
50th percentile	1590	1577	1554	1481	1637	2049	1109	1891	1752	1702	1362
90th percentile	1971	1778	1780	1818	1853	2498	1333	2108	2058	1935	1583

Growing Degree Days (GDD)	Heating Degree Days (HDD)	Cooling Degree Days (CDD)
All Months	Months of October to April	Months of May to September
Sum days of Avg. Daily Temp - 50 > 0	Sum days of 65 - avg. daily temp > 0	Sum days of avg. daily temp - 65 > 0

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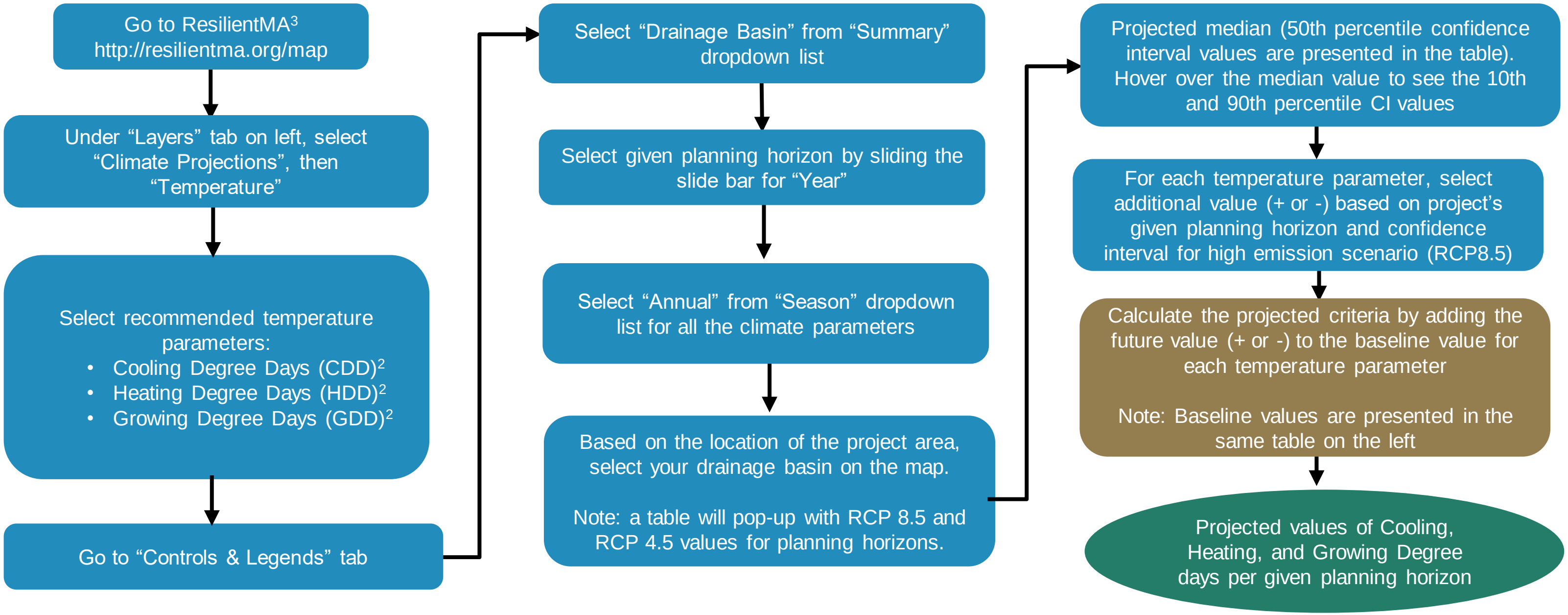
RMAT Tiered Methodology to Evaluate Degree Days - Tier 3 Projects (Step 2: Calculate Median, 10th, and 90th percentiles for all GCMs) Example: 2070s Degree Days for Moakley Park, Boston

2070s	CDD	HDD	GDD
10th percentile	1278	3344	4021
Median	1590	3785	4374
90th percentile	1853	4419	5051

RMAT Tiered Methodology to Evaluate Degree Days from ResilientMA.org - Tier 2 and Tier 1 Projects

Given from Standards Output: Planning Horizon (2030, 2050, 2070, 2100); Confidence Interval (10th, 50th, 90th)



Legends
Data Gathering
Calculation steps
Design Criteria

3. Massachusetts Climate Change Projections - Statewide and for Major Drainage Basins Temperature, Precipitation, and Sea Level Rise Projection; by Northeast Climate Adaptation Science Center

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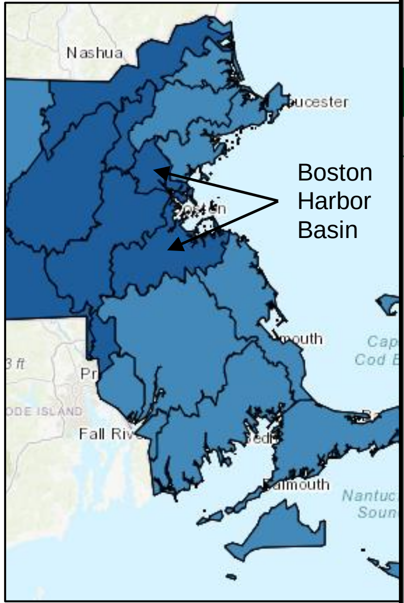
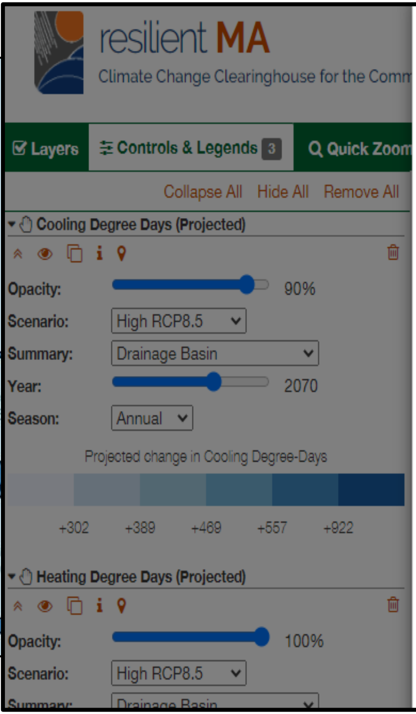
Weston & Sampson

RMAT Tiered Methodology to
Evaluate Degree Days from ResilientMA.org - Tier 2 and Tier 1 Projects
Example: 2070s CDDs for Moakley Park, Boston (Boston Harbor Basin)





Location Info

Cooling Degree Days (Projected)

Table shows estimated 50th percentile values for projected change in Cooling Degree Days. The value highlighted in dark green is the value corresponding to the season, decade and emissions scenario currently selected on the map. Hover over values to see the likely range (10th to 90th percentile) for any given value. Projected decreases are denoted by a minus (-) sign .

Boston Harbor Basin

			Projected change in Cooling Degree-Days		
Season	**Baseline (Degree-Days)**	**Emissions Scenario**	**2030s**	**2050s**	**2070s**
Annual	636.02	High RCP8.5	+354.4	+610.57	+945.7
		Medium RCP4.5	+287.17	+410.99	+480.55
Fall	60.45	High RCP8.5	+76.44	+134.55	+228.28
		Medium RCP4.5	+66.02	+93.43	+108.47
Spring	26.94	High RCP8.5	+25.97	+46.22	+79.5
		Medium RCP4.5	+19.11	+26.82	+34.14
Summer	544.48	High RCP8.5	+252.78	+436.2	+654.41
		Medium RCP4.5	+205.06	+300.54	+335.98
Winter	0.00	High RCP8.5	+1.62	+2.76	+1.98
		Medium RCP4.5	+1.17	+2.08	+0.65

Weston & Sampson

RMAT Tiered Methodology to Evaluate Degree Days from ResilientMA.org - Tier 2 and Tier 1 Projects Example: Moakley Park, Boston

Planning Horizon	Percentile	Cooling Degree Days
2070s	10th percentile	1198
	50th percentile	**1582**
	90th percentile	2040

RMAT Tiered Methodology
Cooling Degree Days – Comparison Across Tiers
Example: Moakley Park, Boston

Planning Horizon	Percentile	Tier 3 Cooling Degree Days	Tier 2/1 Cooling Degree Days
2070s	10th percentile	1278	1198
	50th percentile	**1590**	**1582**
	90th percentile	1853	2040

REFERENCES

1. Abatzoglou J.T. and Brown T.J. A comparison of statistical downscaling methods suited for wildfire applications, International Journal of Climatology (2012), 32, 772-780

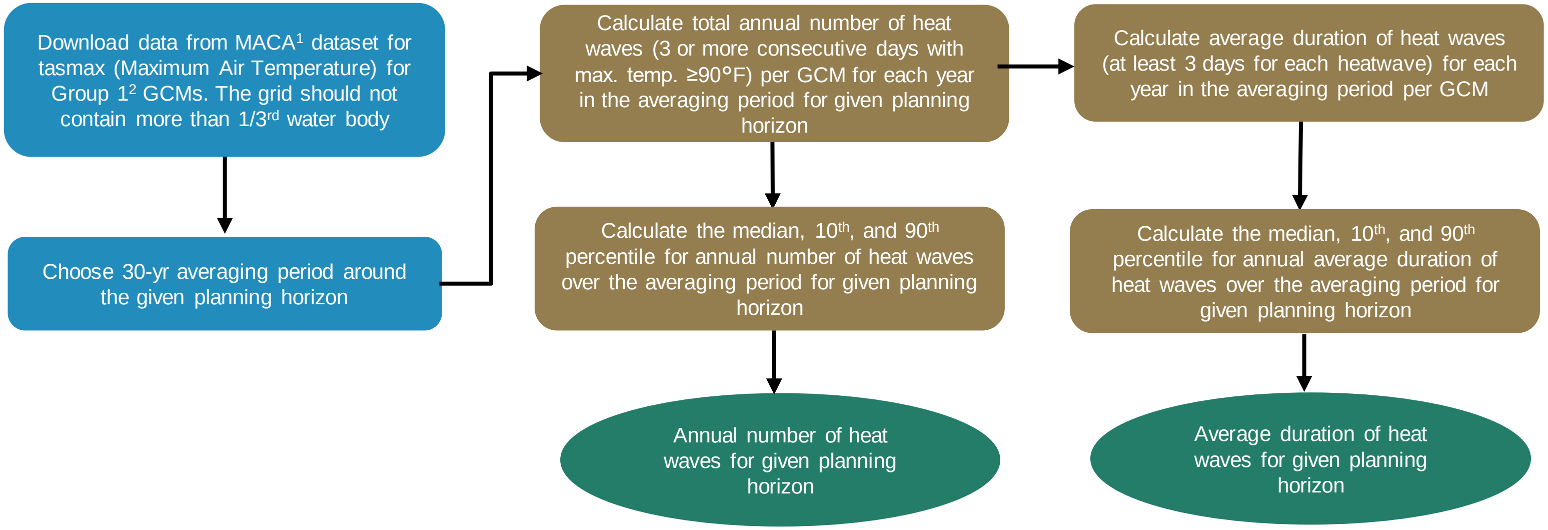
2. Applying Climate Change Information to Hydrologic and Coastal Design of Transportation Infrastructure (NCHRP Project 15-61- Final Report) by Kilgore et al., 2019

3. Massachusetts Climate Change Projections - Statewide and for Major Drainage Basins Temperature, Precipitation, and Sea Level Rise Projections; by Northeast Climate Adaptation Science Center and published by Massachusetts Executive Office of Energy and Environmental Affairs

Attachment 3.4D - Draft Tiered Methodology Example for Extreme Heat – Heat Waves, All Tiers

RMAT Tiered Methodology to Evaluate Heat Waves
Tier 3 Projects (High level of Effort)

Given from Standards Output: Planning Horizon (2030, 2050, 2070, 2100); Confidence Interval (10^{th}, 50^{th}, 90^{th})



Legends
Data Gathering
Calculation steps
Design Criteria

DRAFT

1. Abatzoglou J.T. and Brown T.J. A comparison of statistical downscaling methods suited for wildfire applications, International Journal of Climatology (2012), 32, 772-780
2. Applying Climate Change Information to Hydrologic and Coastal Design of Transportation Infrastructure (NCHRP Project 15-61-Final Report) by Kilgore et al., 2019

RMAT Tiered Methodology to Evaluate Heat Waves- Tier 3 Projects (Step 0: Complete MACA data download)

RMAT Methodology to Download Data from MACA Website

- **Go to https://climate.northwestknowledge.net/MACA/data_portal.php to download data from Multivariate Adaptive Constructed Analogs (MACA) data portal**

STEP 1
Domain selection

1.1: Select "Rectangular Subset" from "Domain" dropdown list

1.2: A rectangle will appear on the interactive map. Move the rectangle and place it around the project area. Increase or decrease the size of the rectangle based on the area you want to cover around the location. Make sure your grid does not cover more than 1/3rd of water body.

1.3: Select "files of URLs for downloading data" from "Download Format" dropdown list

STEP 2
Products, Time frequency, Variables selection

2.4: "MACA Product" : "MACAv2-METDATA"

2.4: "Time Frequency" : "daily"

2.5: "Variables" : Check boxes for the climate parameters relevant to the project for examples,
- "rhsmax (Maximum Relative Humidity)"
- "tasmax(Maximum Air Temperature)"
- "tasmin(Minimum Air Temperature)"

STEP 2 (..cont.)
Model, Emission Scenarios, Time periods selection

2.6: "CMIP5 Models" : Check boxes for all the Group 1 models from NCHRP report[1]

2.7: "CMIP5 Scenarios/Time Periods" : Check boxes for the following parameters for
- "**RCP8.5**" : "future RCP8.5 (2006-2099)"

STEP 3
Data download

3.1: Press button "Download file" on top right

3.2: Open the text file to extract the downloaded data

3.3: Climate projection files are downloaded as Netcdf files. Convert the files in your preferred file format for climate projection analysis

1. Applying Climate Change Information to Hydrologic and Coastal Design of Transportation Infrastructure (NCHRP Project 15-61- Final Report) by Kilgore et al., 2019

RMAT Tiered Methodology to Evaluate Heat Waves - Tier 3 Projects (Step 1: Calculate Days ≥90°F) Example: Moakley Park, Boston

Year	Sum of bcc-csm1-1	Sum of bcc-csm1-1-m	Sum of CCSM4	Sum of CNRM-CM5	Sum of CSIRO-Mk3-6-0	Sum of HadGEM2-CC365	Sum of inmcm4	Sum of IPSL-CM5A-LR	Sum of IPSL-CM5B-LR	Sum of MIROC5	Sum of MRI-CGCM3
2060	3	4	6	2	3	9	4	4	7	5	3
2061	2	8	7	2	3	5	2	2	2	8	5
2062	1	3	5	6	2	9	4	2	4	5	4
2063	2	3	3	5	7	5	4	4	5	4	4
2064	5	8	6	7	9	7	1	8	2	7	8
2065	6	6	4	3	6	7	0	5	9	8	1
2066	4	4	3	1	5	8	2	4	5	5	1
2067	8	8	6	2	7	7	1	4	4	7	4
2068	5	5	5	4	8	6	4	3	3	6	6
2069	8	3	2	4	4	7	0	8	6	10	2
2070	4	7	7	6	4	6	1	6	9	3	3
2071	5	6	5	7	2	9	2	7	5	5	4
2072	1	8	4	4	4	4	0	8	9	3	3
2073	3	8	5	9	7	8	1	8	6	6	4
2074	6	2	6	3	9	6	4	9	4	6	3
2075	7	6	5	3	7	8	1	3	5	9	6
2076	3	8	6	7	6	5	0	5	4	7	4
2077	6	3	3	4	7	6	2	9	8	4	3
2078	7	4	3	7	6	9	1	6	5	5	2
2079	6	2	5	5	3	8	4	6	9	6	3
2080	5	5	7	6	4	6	3	7	6	8	4
2081	8	6	7	4	7	8	3	7	7	4	6
2082	7	3	9	8	4	8	1	8	4	8	3
2083	4	5	9	2	3	5	3	8	6	5	2
2084	6	8	9	6	6	7	3	9	4	7	4
2085	4	6	7	3	7	6	2	5	3	10	5
2086	8	6	4	2	5	10	1	3	6	8	5
2087	3	3	5	2	4	8	1	6	9	4	4
2088	5	4	5	7	5	6	4	6	7	6	3
2089	4	9	11	7	4	6	0	4	6	10	5

Min	1	2	2	1	2	4	0	2	2	3	1
Max	8	9	11	9	9	10	4	9	9	10	8
Med	5	6	5	4	5	7	2	6	6	6	4
Mean	5	5	6	5	5	7	2	6	6	6	4
10th percentile	2	3	3	2	3	5	0	3	3	4	2
50th percentile	5	6	5	4	5	7	2	6	6	6	4
90th percentile	8	8	9	7	8	9	4	9	9	10	6

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RMAT Tiered Methodology to Evaluate Heat Waves - Tier 3 Projects (Step 2: Calculate Median, 10th, and 90th percentiles for all GCMs) Example: Moakley Park, Boston

2070	# of Heat Waves
10th percentile	3
Median	5
90th percentile	8

RMAT Tiered Methodology to Evaluate Number and Duration of Heat Waves Tier 2 and Tier 1 Projects

Given from Standards Output: Planning Horizon (2030, 2050, 2070, 2100); Confidence Interval (10^{th}, 50^{th}, 90^{th})

Download historical temperature data from NCDC NOAA Website for the weather station located closest to the project area

- https://www.ncdc.noaa.gov/cdo-web/datatools/findstation
- Select "Daily Summaries" Dataset
- Select Date Range (1976 – present day)
- Request Data (Tmax) in .CSV file from Website

Calculate total annual number of heat waves (3 or more consecutive days with max. temp. ≥90°F) for each year over the available period of record for the selected weather station

Calculate the median, 10^{th} and 90^{th} percentile for annual number of heat waves over the period of record

Number of heat waves

Calculate annual average duration of heat waves (at least 3 days for each heat wave) for each year over the available period of record for the selected weather station

Calculate the median, 10^{th} and 90^{th} percentile for annual average duration of heat waves over the period of record

Average duration of heat waves

Legends
Data Gathering
Calculation steps
Design Criteria

Weston & Sampson

DRAFT

REFERENCES

1. Abatzoglou J.T. and Brown T.J. A comparison of statistical downscaling methods suited for wildfire applications, International Journal of Climatology (2012), 32, 772-780

2. Applying Climate Change Information to Hydrologic and Coastal Design of Transportation Infrastructure (NCHRP Project 15-61- Final Report) by Kilgore et al., 2019

Attachment 3.4E - Draft Tiered Methodology Example for Extreme Heat – Heat Index, All Tiers

RMAT Tiered Methodology to Evaluate Heat Index
Tier 3 Projects (Highest Level of Effort)

Given from Standards Output: Planning Horizon (2030, 2050, 2070, 2100); Confidence Interval (10th, 50th, 90th)

Download data from MACA[1] dataset for the following parameters for RCP8.5 using Group 1[2] GCMs
- tasmax (Maximum Air Temperature)
- rhsmax (Maximum Rel. Humidity)

Choose 30-yr averaging period around the given planning horizon

Calculate annual maximum temperature and average relative humidity of each year per GCM, for the given planning horizon

Estimate heat index for given planning horizon using the equation from NOAA[3], also visualized in the following table from NOAA[4]

NWS Heat Index — Temperature (°F)

Relative Humidity (%)	80	82	84	86	88	90	92	94	96	98	100	102	104	106	108	110
40	80	81	83	85	88	91	94	97	101	105	109	114	119	124	130	136
45	80	82	84	87	89	93	96	100	104	109	114	119	124	130	137	
50	81	83	85	88	91	95	99	103	108	113	118	124	131	137		
55	81	84	86	89	93	97	101	106	112	117	124	130	137			
60	82	84	88	91	95	100	105	110	116	123	129	137				
65	82	85	89	93	98	103	108	114	121	128	136					
70	83	86	90	95	100	105	112	119	126	134						
75	84	88	92	97	103	109	116	124	132							
80	84	89	94	100	106	113	121	129								
85	85	90	96	102	110	117	126	135								
90	86	91	98	105	113	122	131									
95	86	93	100	108	117	127										
100	87	95	103	112	121	132										

Likelihood of Heat Disorders with Prolonged Exposure or Strenuous Activity

Caution | Extreme Caution | Danger | Extreme Danger

Calculate the median, 10th, and 90th percentile of heat index of all GCMs for given planning horizon

Average summer heat index for given planning horizon

Legends
- Data Gathering
- Calculation steps
- Design Criteria

1. Abatzoglou J.T. and Brown T.J. A comparison of statistical downscaling methods suited for wildfire applications, International Journal of Climatology (2012), 32, 772-780
2. Applying Climate Change Information to Hydrologic and Coastal Design of Transportation Infrastructure (NCHRP Project 15-61-Final Report) by Kilgore et al., 2019
3. National Oceanic and Atmospheric Administration (NOAA). 2014. The Heat Index Equation. https://www.wpc.ncep.noaa.gov/html/heatindex_equation.shtml
4. National Oceanic and Atmospheric Administration (NOAA).n.d. Heat Index. https://www.weather.gov/safety/heat-index

RMAT Tiered Methodology to Evaluate Heat Index - Tier 3 Projects (Step 0: Complete MACA data download)

RMAT Methodology to Download Data from MACA Website

- Go to https://climate.northwestknowledge.net/MACA/data_portal.php to download data from Multivariate Adaptive Constructed Analogs (MACA) data portal

STEP 1
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STEP 2
Products, Time frequency, Variables selection

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- "tasmax(Maximum Air Temperature)"
- "tasmin(Minimum Air Temperature)"

STEP 2 (..cont.)
Model, Emission Scenarios, Time periods selection

2.6: "CMIP5 Models" : Check boxes for all the Group 1 models from NCHRP report[1]

2.7: "CMIP5 Scenarios/Time Periods" : Check boxes for the following parameters for
- "**RCP8.5**" : "future RCP8.5 (2006-2099)"

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RMAT Tiered Methodology to Evaluate Heat Index - Tier 3 Projects (Step 1: Calculate the median max. temp. and median avg. rel. humidity) Example: Moakley Park, Boston

2070s Tasmax

Row Labels	Max of bcc-csm1-1	Max of bcc-csm1-1-m	Max of CCSM4	Max of CNRM-CM5	Max of CSIRO-Mk3-6-0	Max of HadGEM2-CC365	Max of inmcm4	Max of IPSL-CM5A-LR	Max of IPSL-CM5B-LR	Max of MIROC5	Max of MRI-CGCM3	Median Max of Max-Temp
2060	104.5	99.3	99.9	97.1	102.1	105.7	97.7	98.2	100.4	101.0	97.6	99.87
2061	96.4	102.4	102.0	99.1	102.0	105.0	99.3	101.0	101.6	101.3	105.2	101.64
2062	92.2	101.5	103.0	104.8	101.0	109.2	96.7	99.3	100.4	97.0	97.0	100.43
2063	101.4	103.2	100.8	105.8	101.8	105.3	97.7	100.7	99.1	99.4	102.0	101.41
2064	101.2	102.5	101.1	102.9	104.0	106.5	97.9	102.3	96.7	102.7	96.7	
2065	98.0	102.3	101.2	96.8	107.9	107.7	92.6	102.0	98.8	101.1	96.9	
2066	100.6	101.4	98.7	94.5	104.9	103.5	99.7	102.6	103.3	99.6	97.6	
2067	99.4	101.6	101.9	96.9	107.8	102.9	96.7	97.6	101.8	100.0	98.2	
2068	100.0	101.8	99.2	101.7	105.1	109.6	97.2	105.0	99.1	100.7	98.3	
2069	103.3	102.0	100.0	104.7	102.1	101.2	102.0	101.9	100.0	101.4	96.7	
2070	101.9	101.8	104.2	103.6	101.1	107.7	94.8	104.2	100.5	98.5	105.2	
2071	102.8	103.3	100.5	105.3	98.7	108.1	95.2	99.2	100.6	104.1	100.9	
2072	94.1	108.0	103.1	97.2	103.7	104.7	93.8	100.6	103.2	103.4	98.1	
2073	105.8	100.8	104.5	103.4	103.1	111.8	92.5	102.6	101.0	102.6	98.1	
2074	102.3	98.9	104.4	99.5	107.7	107.6	99.6	100.1	104.0	100.0	104.6	
2075	102.5	101.0	104.7	102.4	106.1	109.6	93.3	102.9	97.7	101.5	98.2	
2076	102.0	101.2	102.7	103.2	101.9	106.4	93.1	99.1	102.6	100.8	98.5	
2077	102.4	95.1	98.7	97.1	103.0	113.4	103.4	105.9	100.2	102.1	98.1	
2078	105.3	99.8	102.1	107.8	104.6	108.3	95.4	105.8	100.1	101.9	98.7	
2079	101.2	102.5	102.2	98.9	98.3	105.7	98.6	103.2	102.3	105.2	97.7	
2080	104.1	100.9	103.6	102.3	104.8	109.1	97.4	104.5	102.6	103.0	98.6	
2081	104.3	104.5	104.9	103.2	104.8	113.7	98.6	104.2	100.1	98.7	96.3	
2082	103.8	102.9	102.1	103.4	104.4	112.8	95.9	103.1	102.0	101.5	100.9	
2083	100.3	97.9	102.9	98.8	101.2	112.0	95.5	102.6	102.5	100.0	100.0	
2084	101.5	103.4	103.2	97.3	102.1	104.6	99.9	106.0	102.5	98.2	97.8	
2085	102.6	101.6	104.9	98.5	100.9	112.9	93.9	109.2	101.3	102.4	96.9	
2086	105.1	104.8	107.2	97.1	104.8	112.5	98.7	105.8	102.3	99.7	102.2	
2087	96.9	103.9	100.2	96.8	103.3	109.7	102.6	107.3	101.3	105.1	97.4	
2088	102.4	102.8	105.3	101.3	103.6	111.6	99.4	106.4	102.0	100.7	100.6	
2089	108.0	105.0	107.5	101.8	110.3	105.1	91.9	105.6	107.5	105.5	101.7	

YEAR	Average of bcc-csm1-1	Average of bcc-csm1-1-m	Average of CNRM-CM5	Average of CSIRO-Mk3-6-0	Average of HadGEM2-CC365	Average of inmcm4	Average of IPSL-CM5A-LR	Average of IPSL-CM5B-LR	Average of MIROC5	Average of MRI-CGCM3	RHavg MEDIAN OF ALL GCMS
2060	78.5	79.2	79.4	78.7	76.7	78.9	79.4	74.6	79.1	79.2	79.0
2061	79.5	78.6	79.2	81.2	75.9	80.3	76.7	77.7	76.9	77.8	78.2
2062	79.5	79.4	79.2	80.1	76.5	80.6	76.6	77.2	78.9	79.4	79.3
2063	79.6	80.1	76.8	79.6	75.1	78.2	77.2	77.2	77.8	79.6	78.0
2064	76.8	77.7	78.6	79.1	76.0	79.5	76.0	77.8	77.6	79.2	77.7
2065	79.4	78.0	78.7	77.6	74.1	79.4	76.2	77.7	75.9	78.9	77.8
2066	79.6	79.6	80.3	79.9	74.6	79.9	76.6	77.3	78.9	78.5	79.3
2067	79.5	78.3	79.3	78.3	76.5	80.2	75.6	78.6	78.0	78.6	78.4
2068	79.1	80.4	78.3	76.7	75.8	80.9	76.9	75.6	79.3	79.2	78.7
2069	78.3	77.7	80.2	77.6	76.4	79.7	75.7	76.1	77.1	77.8	77.6
2070	79.0	78.4	77.9	78.0	76.5	79.1	74.6	77.6	78.3	80.2	78.1
2071	78.6	79.3	76.9	82.2	74.6	79.1	77.1	75.5	77.1	79.7	77.8
2072	79.1	77.8	78.0	78.2	78.1	79.7	75.0	76.5	77.1	80.0	78.0
2073	77.4	78.2	77.6	78.9	76.6	79.5	74.7	75.9	77.3	76.4	77.3
2074	80.0	80.9	80.3	76.9	74.4	80.1	76.7	76.5	76.9	79.5	78.2
2075	78.8	80.2	79.3	78.8	74.7	78.7	77.1	75.8	77.9	78.3	78.5
2076	79.5	79.4	77.2	79.7	75.0	79.5	76.3	77.1	77.2	78.7	78.0
2077	77.5	79.7	78.0	79.1	75.5	80.3	75.9	75.4	79.8	78.9	78.5
2078	79.2	81.1	77.3	79.1	75.7	80.2	75.5	76.0	77.8	80.0	78.5
2079	78.9	77.8	79.4	81.2	76.4	80.1	77.7	76.1	77.1	78.0	77.9
2080	77.4	80.8	77.6	81.7	73.5	77.6	75.9	77.1	76.5	78.1	77.5
2081	77.9	78.8	78.3	78.6	74.2	79.6	73.9	74.8	76.5	79.4	78.1
2082	79.3	78.6	76.9	80.3	75.5	80.0	78.6	75.3	76.7	80.7	78.6
2083	78.7	79.5	79.0	79.9	74.3	79.2	74.4	76.0	79.1	79.0	79.0
2084	77.4	80.5	78.3	79.6	76.3	79.9	76.3	74.8	79.2	79.1	78.7
2085	79.8	79.1	77.2	81.9	75.8	79.1	73.9	78.0	76.2	80.1	78.5
2086	78.9	77.8	80.2	79.3	74.0	78.6	73.9	78.7	76.5	79.1	78.7
2087	80.7	80.1	78.4	80.5	75.2	81.5	76.2	78.6	78.5	78.5	78.6
2088	80.3	80.3	77.9	78.4	75.8	79.4	74.9	76.0	78.7	78.4	78.4
2089	77.4	79.5	77.7	78.9	75.1	79.2	75.1	78.8	77.1	78.1	77.9

DRAFT

RMAT Tiered Methodology to Evaluate Heat Index - Tier 3 Projects (Step 2: Calculate heat index per year based on the NOAA Heat Index Eqn.) Example: Moakley Park, Boston

HI = -42.379 + 2.04901523*T + 10.14333127*RH - .22475541*T*RH - .00683783*T*T - .05481717*RH*RH + .00122874*T*T*RH + .00085282*T*RH*RH - .00000199*T*T*RH*RH

where,

HI = Heat Index

T = Temperature (tasmax)

RI = Relative Humidity (average rhsmax)

2070s Data			
Year	RHavg Median of All GCMs	Median Max of Max-Temp	Heat Index (As Per NOAA Eqn.)
2060	79	100	156
2061	78	102	164
2062	79	100	159
2063	78	101	162
2064	78	102	166
2065	78	101	160
2066	79	101	160
2067	78	100	156
2068	79	101	160
2069	78	102	164
2070	78	102	165
10th percentile	78	100	158
50th percentile	78	102	166
90th percentile	79	104	177

DRAFT

RMAT Tiered Methodology to Evaluate Heat Index
Tier 2 and Tier 1 Projects

Given from Standards Output: Planning Horizon (2030, 2050, 2070, 2100); Confidence Interval (10^{th}, 50^{th}, 90^{th})

Use baseline value of the historical average heat index

↓

Apply percent increase[5] to historical average values based on given planning horizon

Planning Horizons	Increase
Mid-Century (2030s, 2050s)	13%
Late-Century (2070s, 2090s)	36%

↓

Average heat index per given planning horizon

Legends
- Data Gathering
- Calculation steps
- Design Criteria

5. Percent Increase data based on Climate Change Vulnerability Assessment (November 2015) report for City of Cambridge, MA (Table 2, pp. 23)

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