Application of Phase 6 Watershed Model to Climate Change Assessment

Modeling Workgroup Quarterly Meeting – October 2018

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Presentation outline

- Estimated impacts of 2025 and 2050 climate change on the watershed delivery of nutrients and sediment.

- Decadal series of climate change assessment for the years 2025, 2035, and 2045.

- Evaluation of MACA downscaling

2017 climate change assessment

2025

2050

2019 climate change assessment

2025

2035

2045
Summary of precipitation and temperature

**Trend**: extrapolation of long-term (88-year) trends

**Ensemble**: 31-member ensemble of RCP4.5 GCMs
Summary of precipitation change

YEAR 2025

YEAR 2050

× extrapolation of trends
O Ensemble Median (P50)
∇ 10th percentile (P10)

Precipitation Change (percent)

-10
-5
0
5
10
15
20
25

RCP2.6
RCP4.5
RCP8.5

-1.19%
3.23%
7.77%

-1.19%
4.21%
10.57%

-2.62%
4.61%
10.66%

-0.51%
4.98%
12.29%

-0.75%
0.60%
13.62%

-10
-5
0
5
10
15
20
25

RCP2.6
RCP4.5
RCP8.5

-1.19%
3.11%

4.61%

4.98%

0.60%

-0.51%

-0.75%

15.01%

6.98%

6.28%
3.11% increase in average annual rainfall volume

6.28% increase in average annual rainfall volume
3.11% increase in average annual rainfall volume

6.28% increase in average annual rainfall volume
1940-2014 observed streamflow trends

The study analyzed USGS GAGES-II data for a subset of Hydro-Climatic Data Network 2009 (HCDN-2009)\(^1\).

The map shows percent changes in the annual average streamflow for rivers and streams. U.S. Environmental Protection Agency. 2016. Climate change indicators in the United States, 2016. Fourth edition. EPA 430-R-16-004 \(^2\)


Summary of temperature change

YEAR 2025
- RCP2.6: 0.98°C
- RCP4.5: 1.12°C
- RCP8.5: 1.58°C

YEAR 2050
- RCP2.6: 1.53°C
- RCP4.5: 2.03°C
- RCP8.5: 2.70°C

× extrapolation of trends
O Ensemble Median (P50)
△ 90th percentile (P90)
▽ 10th percentile (P10)
1.12°C increase in average annual temperature

2.03°C increase in average annual temperature
1.12°C increase in average annual temperature

2.03°C increase in average annual temperature
The difference in PET using the Hamon and Hargreaves-Samani methods are shown. For 2025, the Hamon method estimated an increase in PET that was 3.36% greater than that from Hargreaves-Samani method. The change was even more pronounced for 2050, where PET estimated by Hamon method 6.26 percent greater than that from Hargreaves-Samani. Estimated change in PET using Penman Monteith (short reference) show better agreement with Hargreaves-Samani.
Summary of changes in delivery

Hydrologic response:
- rainfall volume & intensity
- snow and melt due to temperature
- evapotranspiration

Sediment response:
- rainfall intensity
- surface runoff
- riverine scour and deposition

Trend: projection of extrapolation of long-term trends
Ensemble: 31-member ensemble of RCP4.5 GCMs
Summary of changes in delivery

Nitrogen response:
- sensitivity to flow
- stream bank erosion
- denitrification, organic scour

Phosphorus response:
- sensitivities to flow and sediment (APLE)
- stream bank erosion
- scour/deposition of inorganic and organic (HSPF)

**Trend:** projection of extrapolation of long-term trends

**Ensemble:** 31-member ensemble of RCP4.5 GCMs

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**Nitrogen**

- Year 2025: 2.4%
- Year 2050: 8.3%

**Phosphorus**

- Year 2025: 3.1%
- Year 2050: 15.3%
Simulated changes in nitrogen delivery

- Year 2025:
  - Trend rainfall and Ensemble median temperature
  - Nitrogen delivery:
    - Ammonia: 0.55
    - Nitrate: 1.78
    - Organic N: 3.66

- Year 2050:
  - Ensemble median rainfall & temperature
  - Nitrogen delivery:
    - Ammonia: 0.67
    - Nitrate: 1.86
    - Organic N: 4.31

Arrows show relatively more increase in organic nitrogen as compared to inorganic.

Simulated changes in phosphorus delivery

- Year 2025:
  - Trend rainfall and Ensemble median temperature
  - Phosphorus delivery:
    - Dissolved inorganic: 0.97
    - Particulate inorganic: 0.52
    - Organic P: 0.52

- Year 2050:
  - Ensemble median rainfall & temperature
  - Phosphorus delivery:
    - Dissolved inorganic: 0.67
    - Particulate inorganic: 1.86
    - Organic P: 4.74

Arrows show relatively more increase in particulate phosphorus as compared to dissolved inorganic phosphorus.

Trend: projection of extrapolation of long-term trends
Ensemble: 31-member ensemble of RCP4.5 GCMs
Uncertainty due to climatic inputs

Flow

- Year 2025: Trend rainfall, Ensemble 10%, temperature, Ensemble median
- Year 2050: Trend rainfall, Ensemble 90%

Phosphorus

- Year 2025: Trend rainfall, Ensemble 10%, temperature, Ensemble median
- Year 2050: Trend rainfall, Ensemble 90%

Nitrogen

- Year 2025: Trend rainfall, Ensemble 10%, temperature, Ensemble median
- Year 2050: Trend rainfall, Ensemble 90%

Sediment

- Year 2025: Trend rainfall, Ensemble 10%, temperature, Ensemble median
- Year 2050: Trend rainfall, Ensemble 90%
Presentation outline

- Estimated impacts of 2025 and 2050 climate change on the watershed delivery of nutrients and sediment.

- Decadal series of climate change assessment for the years 2025, 2035, and 2045.

- Evaluation of MACA downscaling

Timeframe:

- 2017 climate change assessment
- 2019 climate change assessment 2.0
- 2025
- 2035
- 2045
- 2050
<table>
<thead>
<tr>
<th>Year</th>
<th>Precipitation</th>
<th>Temperature</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Trend</td>
<td>Ensemble</td>
</tr>
<tr>
<td>2025</td>
<td>x</td>
<td>–</td>
</tr>
<tr>
<td>2035</td>
<td>?</td>
<td>?</td>
</tr>
<tr>
<td>2045</td>
<td>?</td>
<td>?</td>
</tr>
<tr>
<td>2050</td>
<td>–</td>
<td>x</td>
</tr>
</tbody>
</table>

- Selections highlighted in yellow are the STAC and CBP climate resiliency workgroup recommendations and CBP approved approaches for the 2017 Climate Change assessment.
- For 2035 and 2045 the Modeling Workgroup (September 2018) recommended (a) combining the two sources using weighted means for rainfall, (b) using the ensemble for temperature. Both approaches are consistent with the STAC 2016 Climate Change Workshop recommendations of observed precipitation trends for 2025 and ensemble precipitation estimates for 2050.
Hybrid: Trend – Ensemble Median

Separately for each land segment
showing data for one of the land segment
## Flow response

### Simulated Changes in Flow Delivery

<table>
<thead>
<tr>
<th>Percent change in delivery</th>
<th>Trend rainfall, Ensemble median temperature</th>
<th>Ensemble median rainfall &amp; temperature</th>
<th>Trend rainfall, Ensemble median temperature</th>
<th>Hybrid rainfall, Ensemble median temperature</th>
<th>Ensemble median rainfall &amp; temperature</th>
<th>Trend rainfall, Ensemble median temperature</th>
<th>Hybrid rainfall, Ensemble median temperature</th>
<th>Ensemble median rainfall &amp; temperature</th>
</tr>
</thead>
<tbody>
<tr>
<td>2025</td>
<td>2.33</td>
<td>3.62</td>
<td>3.27</td>
<td>3.63</td>
<td>3.98</td>
<td>4.21</td>
<td>4.41</td>
<td>4.39</td>
</tr>
<tr>
<td>2035</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2045</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

_Trend_: projection of extrapolation of long-term trends  
_Ensemble_: 31-member ensemble of RCP4.5 GCMs  
_Hybrid_: weighted average of trend and ensemble
**Sediment response**

**Simulated Changes in Sediment Delivery**

<table>
<thead>
<tr>
<th>Year</th>
<th>Trend rainfall, Ensemble median temperature</th>
<th>Ensemble median rainfall &amp; temperature</th>
<th>Trend rainfall, Ensemble median temperature</th>
<th>Hybrid rainfall, Ensemble median temperature</th>
<th>Ensemble median rainfall &amp; temperature</th>
</tr>
</thead>
<tbody>
<tr>
<td>2025</td>
<td>3.31</td>
<td>4.62</td>
<td>3.44</td>
<td>5.31</td>
<td>5.96</td>
</tr>
<tr>
<td>2035</td>
<td>3.44</td>
<td>5.31</td>
<td>5.69</td>
<td>7.91</td>
<td>8.02</td>
</tr>
<tr>
<td>2045</td>
<td>5.69</td>
<td>7.91</td>
<td>8.02</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Trend:** projection of extrapolation of long-term trends  
**Ensemble:** 31-member ensemble of RCP4.5 GCMs  
**Hybrid:** weighted average of trend and ensemble
Nitrogen response

Simulated Changes in Nitrogen Delivery

<table>
<thead>
<tr>
<th>Percent change in delivery</th>
<th>2025</th>
<th>2035</th>
<th>2045</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Trend</strong> rainfall, <strong>Ensemble</strong> median temperature</td>
<td>0.65</td>
<td>1.29</td>
<td>1.27</td>
</tr>
<tr>
<td>Ensemble median rainfall &amp; temperature</td>
<td>1.60</td>
<td>2.18</td>
<td>2.69</td>
</tr>
</tbody>
</table>

**Trend**: projection of extrapolation of long-term trends

**Ensemble**: 31-member ensemble of RCP4.5 GCMs

**Hybrid**: weighted average of trend and ensemble
\[ y = 0.2098x + 2 \times 10^6 \]
\[ R^2 = 0.9517 \]

\[ y = 4 \times 10^{-9}x^2 - 4.6616x + 1 \times 10^9 \]
\[ R^2 = 0.969 \]

\[ y = 5 \times 10^{-10}x^2 - 0.6518x + 2 \times 10^8 \]
\[ R^2 = 0.9585 \]

\[ y = 6.1018x + 7 \times 10^6 \]
\[ R^2 = 0.982 \]
### Phosphorus response

#### Simulated Changes in Phosphorus Delivery

<table>
<thead>
<tr>
<th>Percent change in delivery</th>
<th>2025</th>
<th>2035</th>
<th>2045</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Trend</strong> rainfall, Ensemble median</td>
<td>0.67 1.85</td>
<td>0.63 2.23</td>
<td>0.92 1.23</td>
</tr>
<tr>
<td><strong>Ensemble median rainfall &amp; temperature</strong></td>
<td>1.22 2.54</td>
<td>1.07 3.13</td>
<td>1.16 3.50</td>
</tr>
<tr>
<td><strong>Hybrid</strong> rainfall, Ensemble median</td>
<td>0.52 0.83</td>
<td>0.80 0.80</td>
<td>1.40 3.47</td>
</tr>
<tr>
<td><strong>Ensemble median rainfall &amp; temperature</strong></td>
<td>1.22 2.54</td>
<td>1.07 3.13</td>
<td>1.16 3.50</td>
</tr>
</tbody>
</table>

- **Trend**: projection of extrapolation of long-term trends
- **Ensemble**: 31-member ensemble of RCP4.5 GCMs
- **Hybrid**: weighted average of trend and ensemble
**Flow vs. Particulate Inorg. Phosphorus**

Flow (ac-ft/yr) Millions

Particulate Inorg. P (lb/yr) x 100000

\[ y = 5E-10x^2 - 0.6205x + 2E+08 \]

\[ R^2 = 0.9619 \]

**Flow vs. Organic Phosphorus**

Flow (ac-ft/yr) Millions

Organic P (lb/yr) x 100000

\[ y = 3E-10x^2 - 0.4202x + 1E+08 \]

\[ R^2 = 0.9483 \]

**Sediment vs. Particulate Inorg. Phosphorus**

Sediment (tons/yr) x 100000

Particulate Inorg. P (lb/yr) x 100000

\[ y = 0.951x - 4E+06 \]

\[ R^2 = 0.9948 \]

**Sediment vs. Organic Phosphorus**

Sediment (tons/yr) x 100000

Organic P (lb/yr) x 100000

\[ y = 0.464x + 2E+06 \]

\[ R^2 = 0.9738 \]
Presentation outline

- Estimated impacts of 2025 and 2050 climate change on the watershed delivery of nutrients and sediment.

- Decadal series of climate change assessment for the years 2025, 2035, and 2045.

- Evaluation of MACA downscaling
Evaluation of MACA downscaling

- Statistical downscaling is intended for overcoming model biases and spatial resolution of GCMs.
- There are a number of widely used statistical downscaling techniques:
  - **BCSD**[^1] – Bias Correction Spatial Disaggregation
  - BCCA – Bias Correction with Constructed Analogs
  - **MACA** – Multivariable Adaptive Constructed Analogs
  - LOCA – Localized Constructed Analogs
- Najjar & Harrmann presented a detailed overview of MACA to Modeling Workgroup in April 2018[^2]

[^1]: Used in Chesapeake Bay 2017 Climate Change Assessment
[^2]: https://www.chesapeakebay.net/channel_files/25919/najjar_combined.pdf
### Evaluation of MACA downscaling

#### Table: MACA and BCSD data inventory details

<table>
<thead>
<tr>
<th></th>
<th>MACA</th>
<th>BCSD</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Source</strong></td>
<td>Processed by PSU (Herrmann and Najjar); University of Idaho Abatzoglou and Brown, 2012&lt;sup&gt;[1]&lt;/sup&gt;</td>
<td>Processed at CBPO Bureau of Reclamation, Technical Services Center, Denver&lt;sup&gt;[2]&lt;/sup&gt;</td>
</tr>
<tr>
<td><strong>GCMs</strong></td>
<td>20 models</td>
<td>31 models</td>
</tr>
<tr>
<td><strong>RCPs</strong></td>
<td>RCP 4.5, RCP 8.5</td>
<td>RCP 2.6, 4.5 and 8.5</td>
</tr>
<tr>
<td><strong>Period</strong></td>
<td>1981-2065 (1950-2099)</td>
<td>1950-2099</td>
</tr>
<tr>
<td><strong>Spatial</strong></td>
<td>1/24 degree (~4 km)</td>
<td>1/8 degree (~12 km)</td>
</tr>
<tr>
<td><strong>Temporal</strong></td>
<td>Monthly</td>
<td>Monthly</td>
</tr>
<tr>
<td><strong>Variables</strong></td>
<td>Precipitation, Temperature (min, max, average), Vapor pressure, Atmospheric pressure, Shortwave and Longwave radiations, Specific humidity, Eastward and Northward velocities, Wind speed</td>
<td>Precipitation, Air Temperature (min, max, average)</td>
</tr>
</tbody>
</table>


Summary of BCSD & MACA delta change

Temperature Change (Celsius)

RCP 8.5
2050 vs. 1995

Identical set of GCMs

Precipitation Change (percent)

Identical set of GCMs
Evaluation of BCSD & MACA delta change

- Delta change for rainfall volume and temperature were evaluated for two geographies
  - Land segment N51610 Falls Church, VA. It is the smallest land segment in the watershed (~1280 acres).
  - Entire watershed

- Subsequent slides show that choice for downscaling result in different delta change for both rainfall volume and temperature.

- Rainfall data showed higher seasonal differences.

- However, ensemble median tend to overcome those differences and improve consistency between downscaled datasets.
Figure shows delta % change in annual rainfall volume from 19 matching GCMs after downscaling.

Figure shows delta degree Celsius change for temperature from 19 matching GCMs after downscaling.
Falls Church, VA – Rainfall

RCP 8.5
2050 vs. 1995

Change in Rainfall Volume (%)

ccsm4

miroc5

cnrm-cm5

Ensemble Median (P50)
Falls Church, VA – Temperature

Ensemble Median (P50)

RCP 8.5
2050 vs. 1995
Figure shows delta % change in annual rainfall volume from 19 matching GCMs after downscaling.

Figure shows delta degree Celsius change for temperature from 19 matching GCMs after downscaling.
Chesapeake Bay Watershed – Rainfall

RCP 8.5
2050 vs. 1995

Change in Rainfall Volume (%)
ccsm4

-10 -5 0 5 10 15 20 25 30
J F M A M J J A S O N D ANN

Change in Rainfall Volume (%)
micro5

-20 -10 0 10 20 30 40 50
J F M A M J J A S O N D ANN

Change in Rainfall Volume (%)
cnrm-cm5

-15 -10 -5 0 5 10 15 20 25 30
J F M A M J J A S O N D ANN

Change in Rainfall Volume (%)
Ensemble Median (P50)

-2 -1 0 1 2 3 4 5 6 7 8 9 10 11 12 13 14
J F M A M J J A S O N D ANN

Change in Rainfall Volume (%)
Ensemble Median (P50)

-10 -5 0 5 10 15
J F M A M J J A S O N D ANN
Summary and Conclusions

▪ Estimated impacts of 2025 and 2050 climate change on the delivery of nutrients and sediment were shown for the Chesapeake Bay watershed.

▪ Estimated changes in delivery of flow, nutrients, and sediment were shown for decadal assessments of the years 2025, 2035, and 2045, where hybrid approach for rainfall delta change was implemented.

▪ Synthesis of inputs and model results provided insights into the overall behavior of the model response.

▪ Comparison of downscaling methods showed differences in estimated delta change for individual GCMs. But ensemble median had better agreement.

▪ Analysis did not include changes in land-use, crop yields, atmospheric deposition, and best management practices (BMPs).

▪ Trend-based rainfall projection (estimated from annual rainfall data) did not have any monthly/seasonal component.
Simulated change in hydrology (HSPF)

Simulated change in sediment washoff (HSPF)

Simulated change in export from land (Phase 6 sensitivities)

Small streams response (imperviousness + stream bed/bank)

Sparling | Simulation of nutrient species (nitrate vs. nitrogen)

Riverine response (scour/deposition + biogeochemical)
Presentation outline

- Estimated impacts of 2025 and 2050 climate change on the watershed delivery of nutrients and sediment.

2017 Assessment of climate change

- Decadal series of climate change assessment for the years 2025, 2035, and 2045.

2019 Assessment of climate change
The workshop culminated with the following specific recommendations related to the selection, use, and application of climate projections and forecasts for the 2017 Midpoint Assessment.

1. The Partnership should seek agreement on the use of consistent climate scenarios for regional projections of Chesapeake Bay condition and the benefits of an integrated source of climate change projection simulation data that all seven jurisdictions could draw from.

2. For the 2017 Midpoint Assessment, use historical (~100 years) trends to project precipitation to 2025 as opposed to utilizing an ensemble of future projections from GCMs. Shorter term climate change projections using GCMs have large uncertainties because climate models are structured to look further out and at much larger scales.

3. The Partnership should carefully consider the representation of evapotranspiration in Watershed Model calibration and scenarios because the calculation method for evapotranspiration has a strong influence on the strength and direction of future water balance change.

4. Looking forward, the 2050 timeframe is more appropriate for selecting and incorporating a suite of global climate scenarios and simulations to provide long-term projections for the management community, and an ongoing adaptive process to incorporate climate change into decision-making as implementation moves forward.

5. Beyond the 2017 Midpoint Assessment, it is recommended that the CBP use 2050 projections for best management practice (BMP) design, efficiencies, effectiveness, selection, and performance – given that many of the BMPs implemented now could be in use beyond 2050.

6. For any 2050 assessment, use an ensemble or multiple global climate model approach, selecting model outputs that bound the range of key climate variables (e.g., temperature, precipitation) for the Chesapeake Bay region. Use multiple scenarios covering a range of
Rainfall projections using 88-years of annual PRISM\(^1\) data trends

### Change in Rainfall Volume 2021-2030 vs. 1991-2000

<table>
<thead>
<tr>
<th>Major Basins</th>
<th>PRISM Trend</th>
</tr>
</thead>
<tbody>
<tr>
<td>Youghiogheny River</td>
<td>2.1%</td>
</tr>
<tr>
<td>Patuxent River Basin</td>
<td>3.3%</td>
</tr>
<tr>
<td>Western Shore</td>
<td>4.1%</td>
</tr>
<tr>
<td>Rappahannock River Basin</td>
<td>3.2%</td>
</tr>
<tr>
<td>York River Basin</td>
<td>2.6%</td>
</tr>
<tr>
<td>Eastern Shore</td>
<td>2.5%</td>
</tr>
<tr>
<td>James River Basin</td>
<td>2.2%</td>
</tr>
<tr>
<td>Potomac River Basin</td>
<td>2.8%</td>
</tr>
<tr>
<td>Susquehanna River Basin</td>
<td>3.7%</td>
</tr>
<tr>
<td><strong>Chesapeake Bay Watershed</strong></td>
<td><strong>3.1%</strong></td>
</tr>
</tbody>
</table>

\(^1\) Parameter-elevation Relationships on Independent Slopes Model

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**Figure:**

- **Map:** Chesapeake Bay Watershed with rainfall projections.
- **Graph:** Change in rainfall volume for 2021-2030 vs. 1991-2000.
- **Legend:** 2025 Rainfall Projection (percent change)
- **Note:** Change in rainfall volume for Centre, PA and District of Columbia.
Ensemble analysis of GCM projections – RCP 4.5

- An ensemble analysis of statistically downscaled projections were used from BCSD CMIP5\(^1\) dataset.
- Change were calculated as differences in 30-year averages.

<table>
<thead>
<tr>
<th>ACCESS1-0</th>
<th>FGOALS-g2</th>
<th>IPSL-CM5A-LR</th>
</tr>
</thead>
<tbody>
<tr>
<td>BCC-CSM1-1</td>
<td>FIO-ESM</td>
<td>IPSL-CM5A-MR</td>
</tr>
<tr>
<td>BCC-CSM1-1-M</td>
<td>GFDL-CM3</td>
<td>IPSL-CM5B-LR</td>
</tr>
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<td>GFDL-ESM2G</td>
<td>MIROC-ESM</td>
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<td>GISS-E2-H-CC</td>
<td>MIROC5</td>
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<td>GISS-E2-R</td>
<td>MPI-ESM-LR</td>
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<td>CESM1-CAM5</td>
<td>GISS-E2-R-CC</td>
<td>MPI-ESM-MR</td>
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<td>HadGEM2-AO</td>
<td>MRI-CGCM3</td>
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<td>CNRM-CM5</td>
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<tr>
<td>EC-EARTH</td>
<td>INMCM4</td>
<td></td>
</tr>
</tbody>
</table>

31 member ensemble


[1] BCSD – Bias Correction Spatial Disaggregation; [1] CMIP5 – Coupled Model Intercomparison Project 5
Average annual precipitation and temperature from the 31 bias-corrected downscaled global circulation models are shown for a land segment (N11001). Shown in blue line is the ensemble median. Data used in model calibration from NLDAS-2 are shown in black.

Data shown for the District of Columbia for illustration.
Projected changes in precipitation and temperature (RCP 4.5) – Average Annual

Summary of RCP4.5 average annual rainfall and temperature change for the Chesapeake Bay watershed are shown. Then range for 10th percentile (P10), ensemble median (P50), and 90th percentile (P90) are shown. The estimated change in rainfall volume based on the extrapolation of long-term trends are also shown (with marker symbol x).
Projected changes in temperature (RCP 4.5)

Monthly change in temperature for the Chesapeake Bay Watershed is shown. Box plot shows distribution of projected change based on 31-member ensemble of RCP 4.5 for the years 2025 and 2050. Additional three marker keys show 10th percentile (P10), ensemble median (P50), and 90th percentile (P90) bounds.

Watershed average of ensemble median is +1.12 °C

Watershed average of ensemble median is +2.02 °C
Projected changes in precipitation (RCP 4.5)

Monthly change in precipitation volume for the Chesapeake Bay Watershed is shown. Box plot shows distribution of projected change based on 31-member ensemble of RCP 4.5 for the years 2025 and 2050. For the year 2025 projected change based on long term trend is shown in black line. Additional three marker keys show 10\textsuperscript{th} percentile (P10), ensemble median (P50), and the 90\textsuperscript{th} percentile (P90) bounds.

Watershed average of ensemble median is +4.21\% (+3.11\% estimated using extrapolation of long term trend)

Watershed average of ensemble median is +6.28\%
Monthly delta change to hourly events

Observed changes in rainfall intensity over the last century (based on Figure 10 in Groisman et al. 2004). The equal allocation distribution (blue) is contrasted with the distribution obtained based on observed changes (red).

Additional rainfall added to the baseline daily rainfall over the 10-year period for a Phase 6 land segment (Potter, PA) is shown. In the method based on observed intensity trends, (Groisman et al. 2004) more volume is added to 10th decile resulting in higher intensity events become stronger.
Simulated changes in the delivery of flow, nutrients, and sediment to the Chesapeake Bay for year 2025 and 2050 climate change scenarios are shown.
## Uncertainty due to climatic inputs

<table>
<thead>
<tr>
<th>Period</th>
<th>Climate Change Scenario</th>
<th>Flow percent</th>
<th>Nitrogen percent</th>
<th>Phosphorus percent</th>
<th>Sediment percent</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Year</strong></td>
<td><strong>2025</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Trend rainfall, Ensemble 10%. temperature</td>
<td>4.8%</td>
<td>6.9%</td>
<td>11.6%</td>
<td>13.1%</td>
<td></td>
</tr>
<tr>
<td>Trend rainfall, Ensemble median Temperature</td>
<td>2.3%</td>
<td>2.4%</td>
<td>3.1%</td>
<td>3.3%</td>
<td></td>
</tr>
<tr>
<td>Trend rainfall, Ensemble 90%. temperature</td>
<td>0.0%</td>
<td>-0.6%</td>
<td>-1.6%</td>
<td>-1.8%</td>
<td></td>
</tr>
<tr>
<td><strong>Year</strong></td>
<td><strong>2050</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ensemble 10%. rainfall &amp; temperature</td>
<td>-18.3%</td>
<td>-18.3%</td>
<td>-21.9%</td>
<td>-25.6%</td>
<td></td>
</tr>
<tr>
<td>Ensemble median rainfall &amp; temperature</td>
<td>6.0%</td>
<td>8.3%</td>
<td>15.3%</td>
<td>16.2%</td>
<td></td>
</tr>
<tr>
<td>Ensemble 90%. rainfall &amp; temperature</td>
<td>36.9%</td>
<td>183.9%</td>
<td>588.3%</td>
<td>219.3%</td>
<td></td>
</tr>
</tbody>
</table>

**Trend:** projection of extrapolation of long-term trends

**Ensemble:** 31-member ensemble of RCP4.5 GCMs