Application of Phase 6 Watershed Model for Climate Change Assessment

CHAMP Annual Joint Meeting – November 2018

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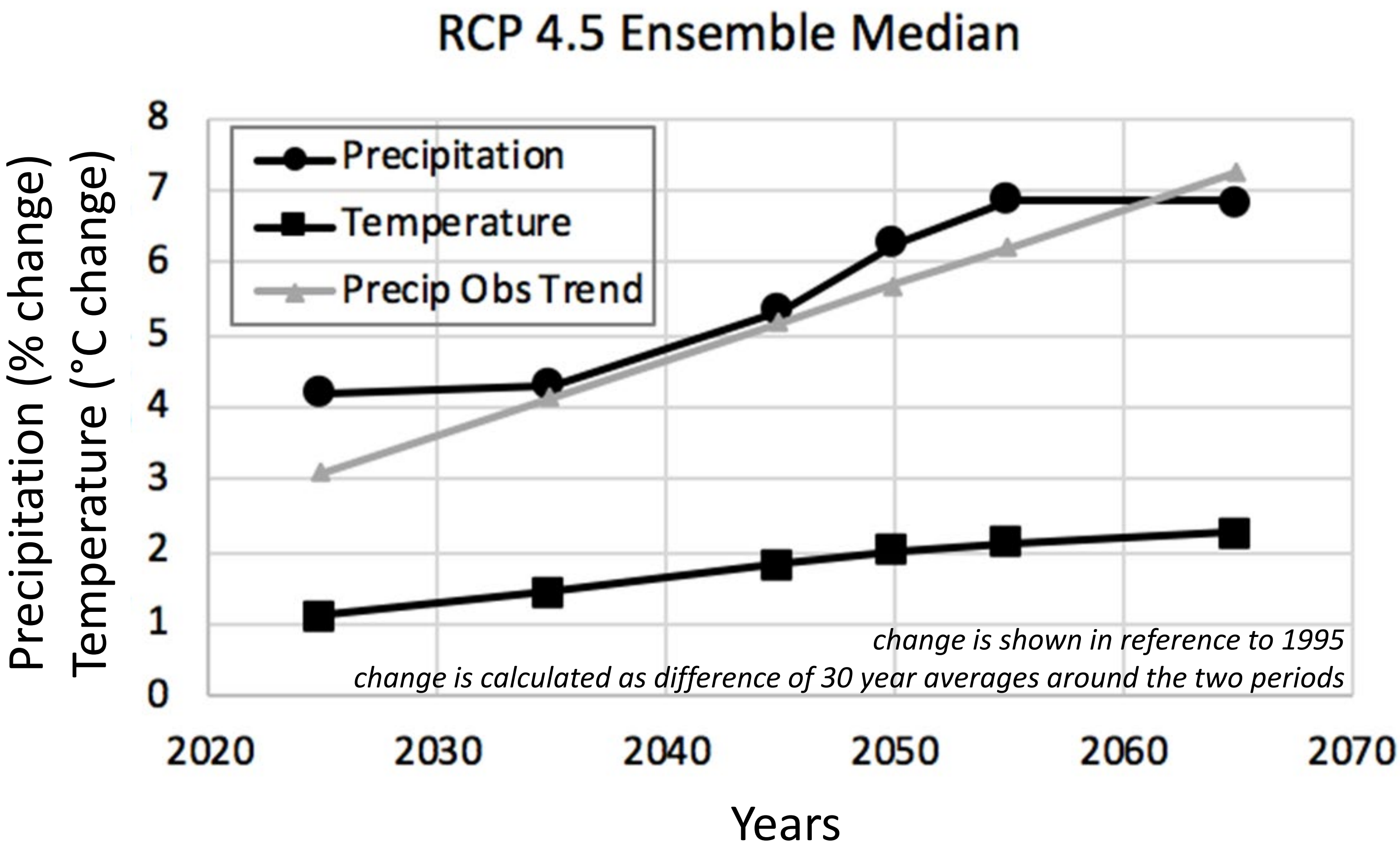
[1] Penn State, [2] US EPA, [3] USGS

Presentation outline

- Estimated impacts of 2025 and 2050 climate change on the watershed delivery of nutrients and sediment
- Evaluation of downscaling techniques (BCSD & MACA)
- CHAMP climate change scenarios and results

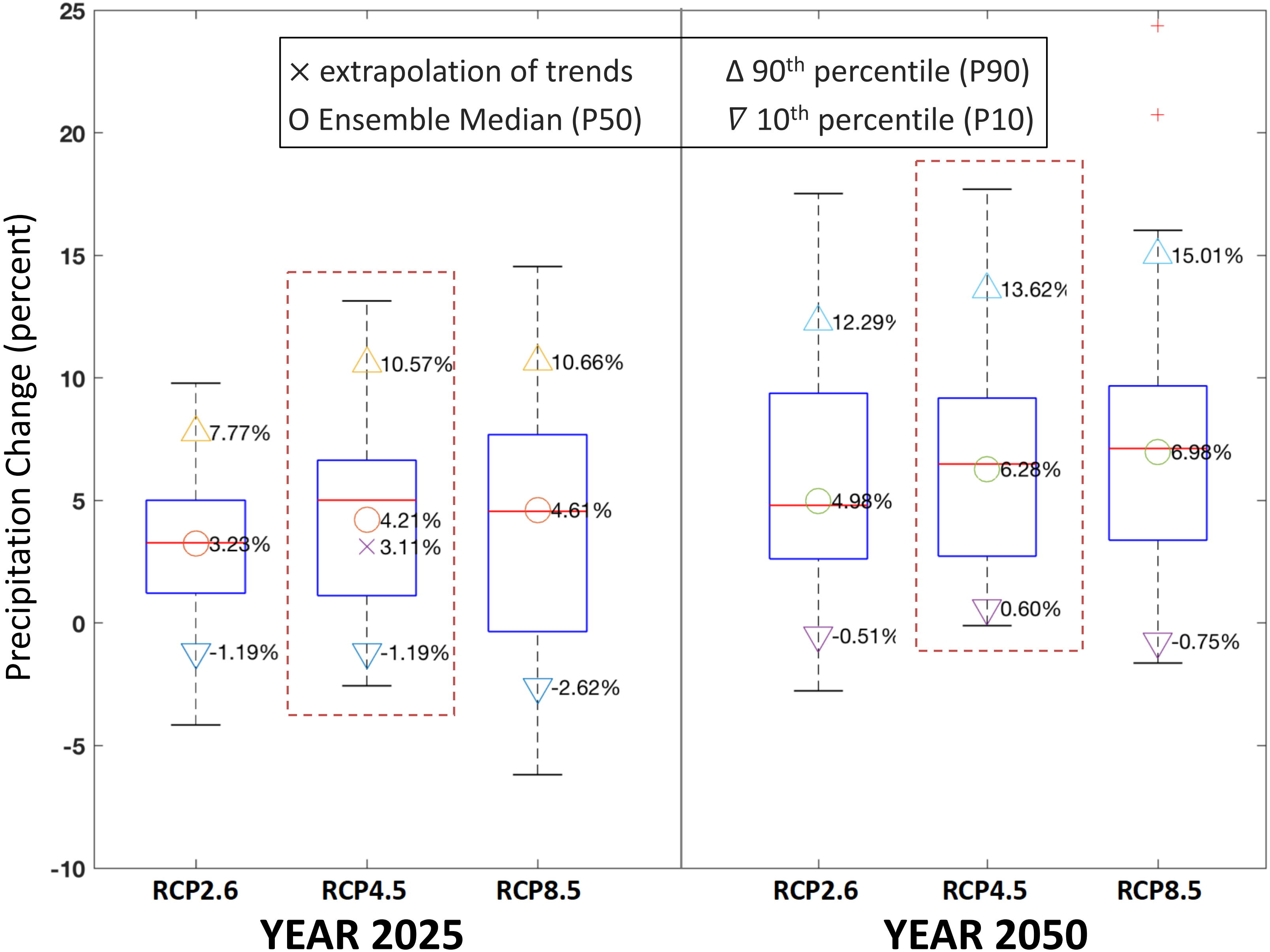
Summary of precipitation and temperature

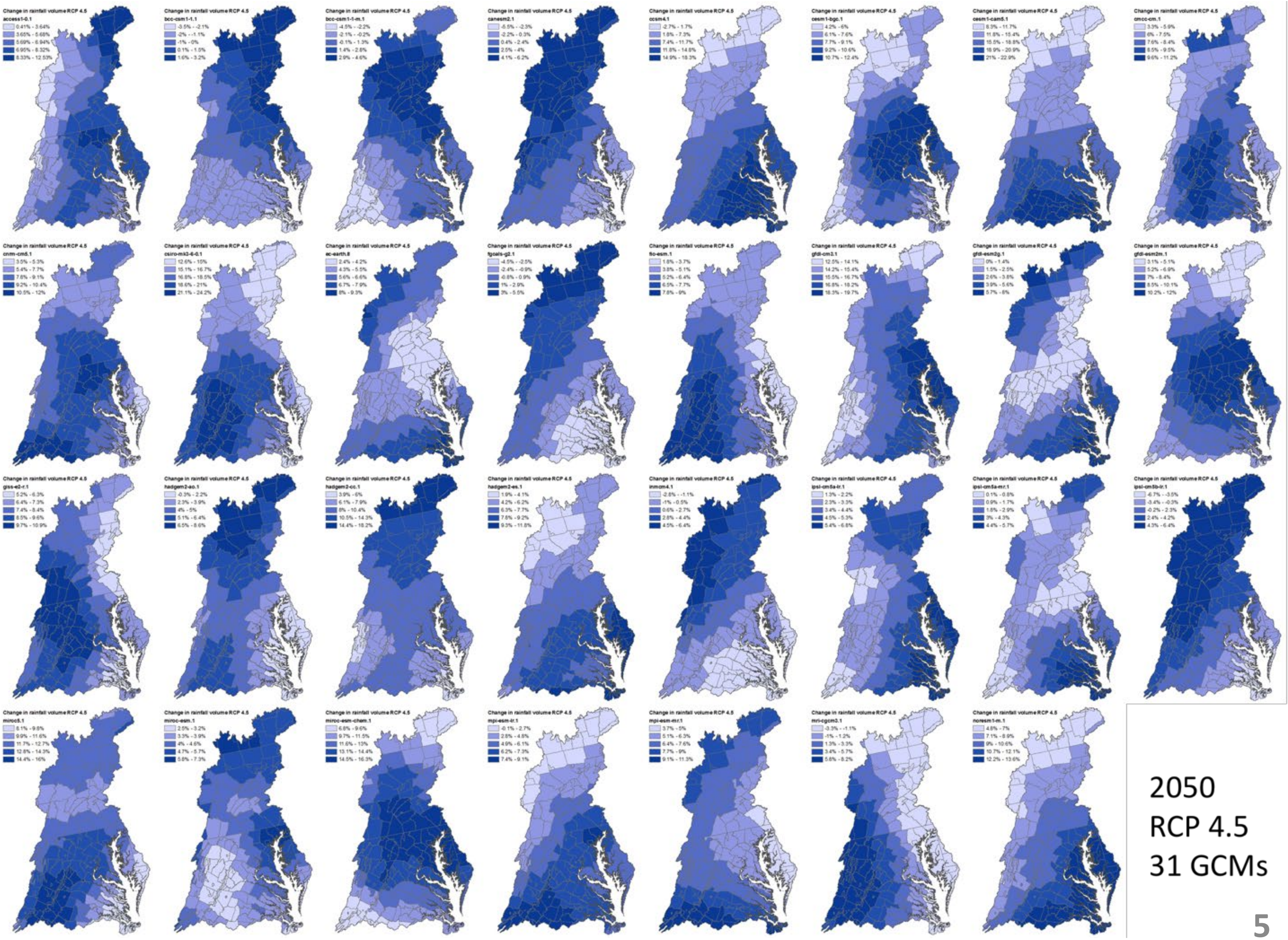


***Trend**: extrapolation of long-term (88-year) linear trends*

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

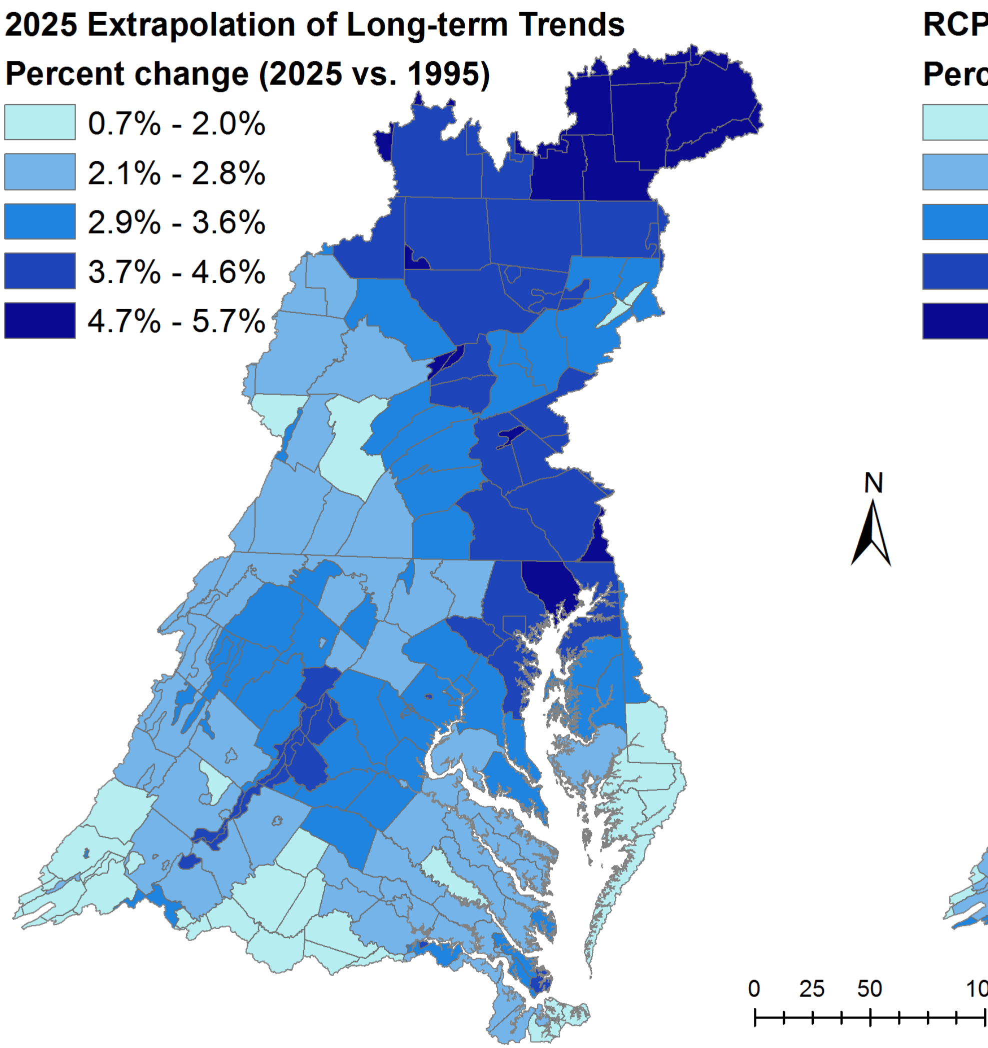
Summary of precipitation change





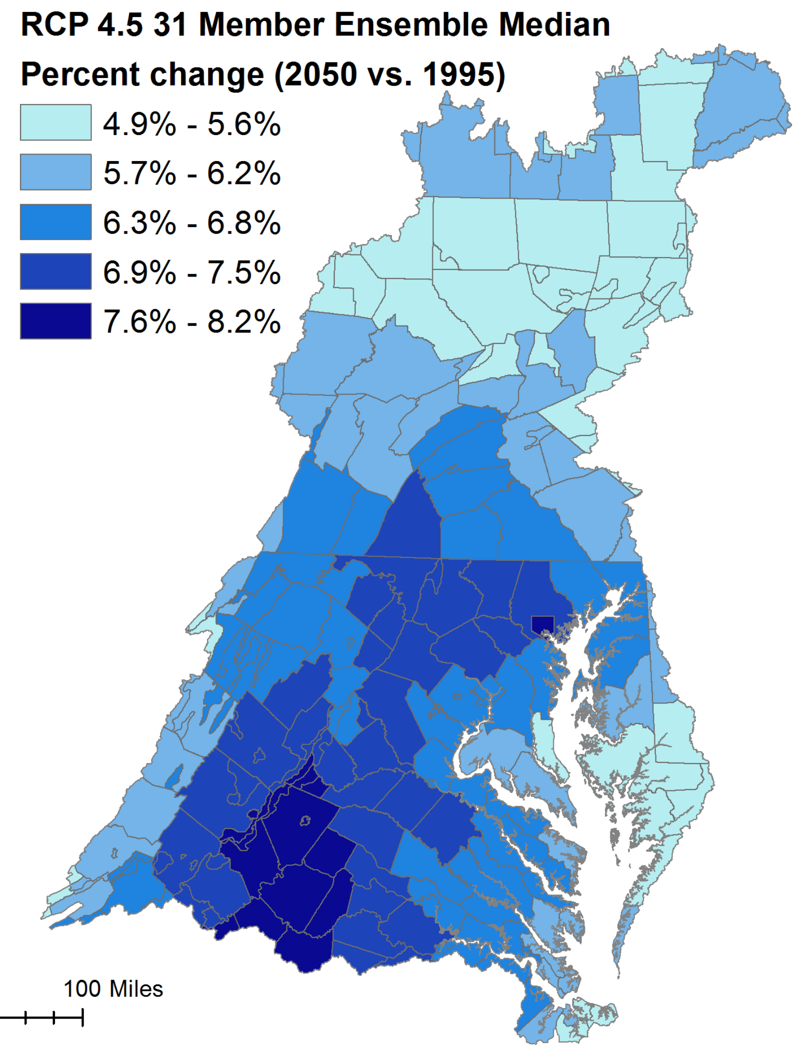
2050
RCP 4.5
31 GCMs

YEAR 2025



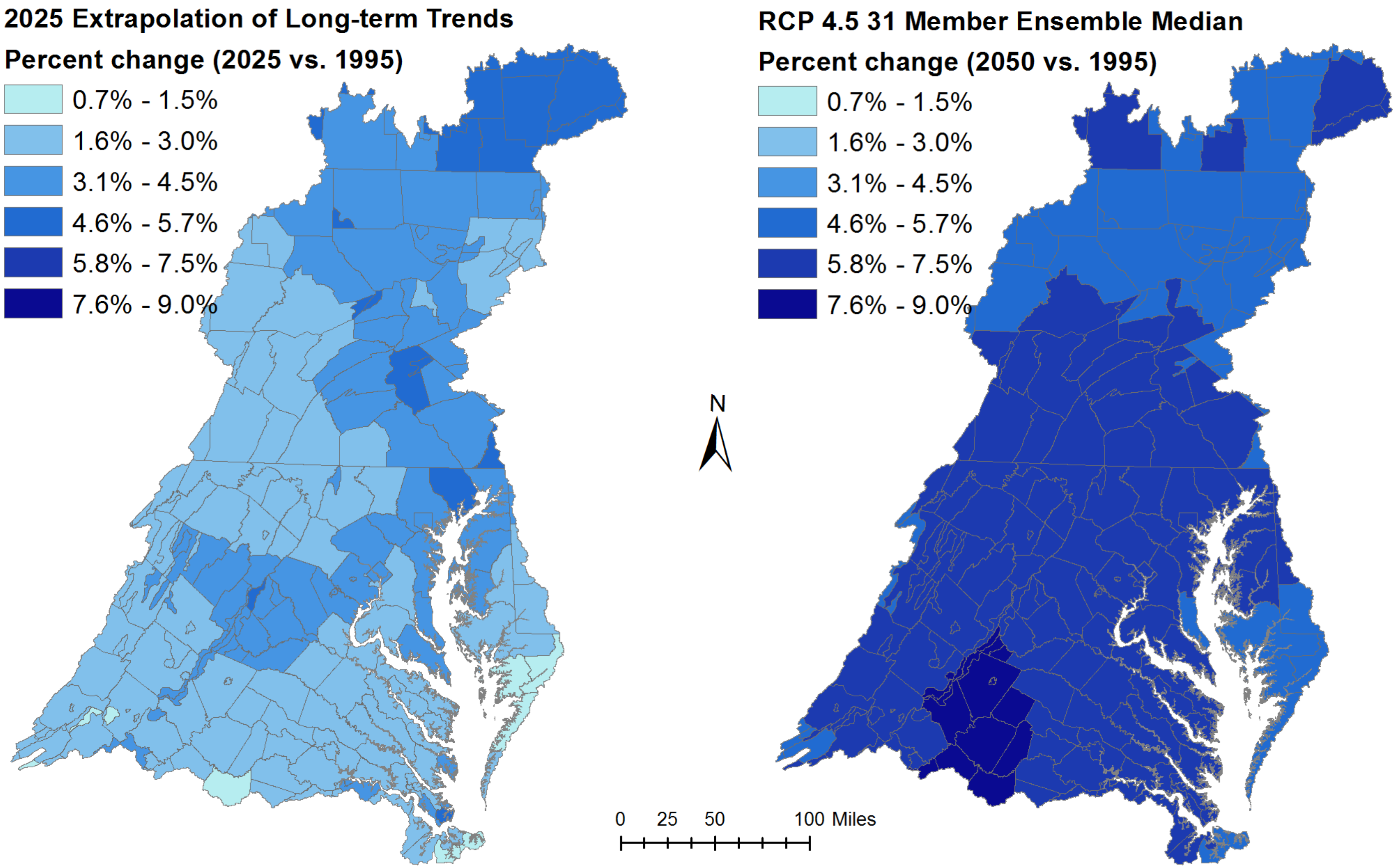
3.11% increase in average annual rainfall volume

YEAR 2050



6.28% increase in average annual rainfall volume

YEAR 2025 | YEAR 2050

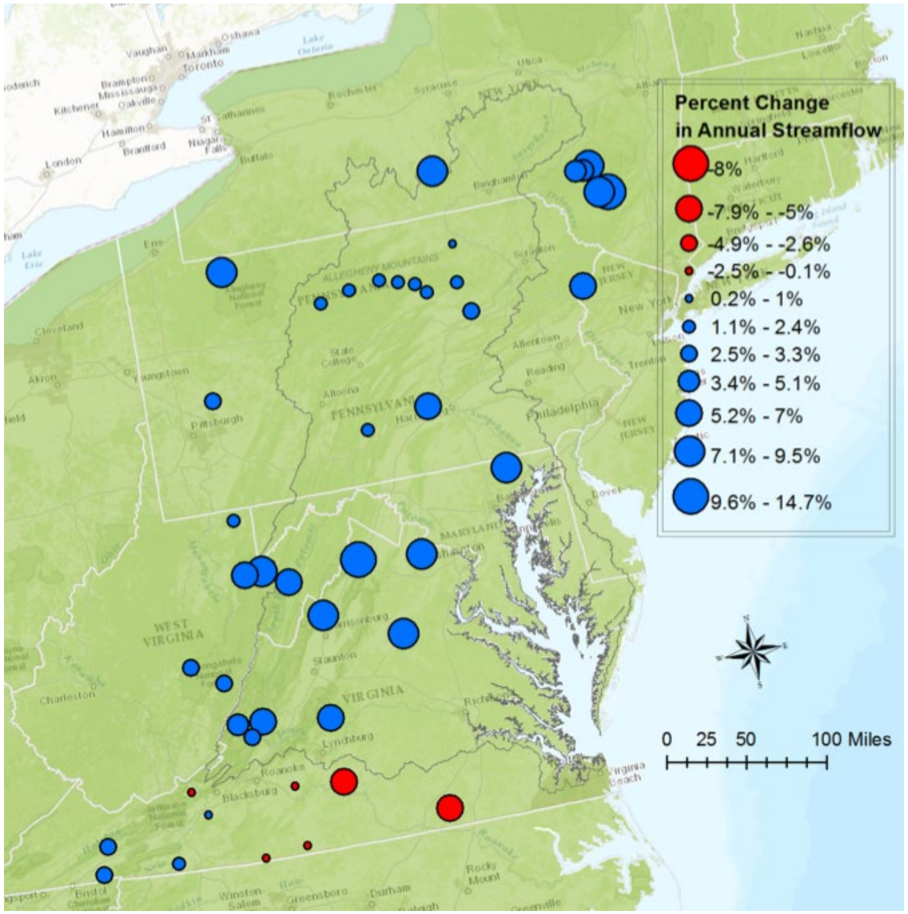


3.11% increase in average annual rainfall volume

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].



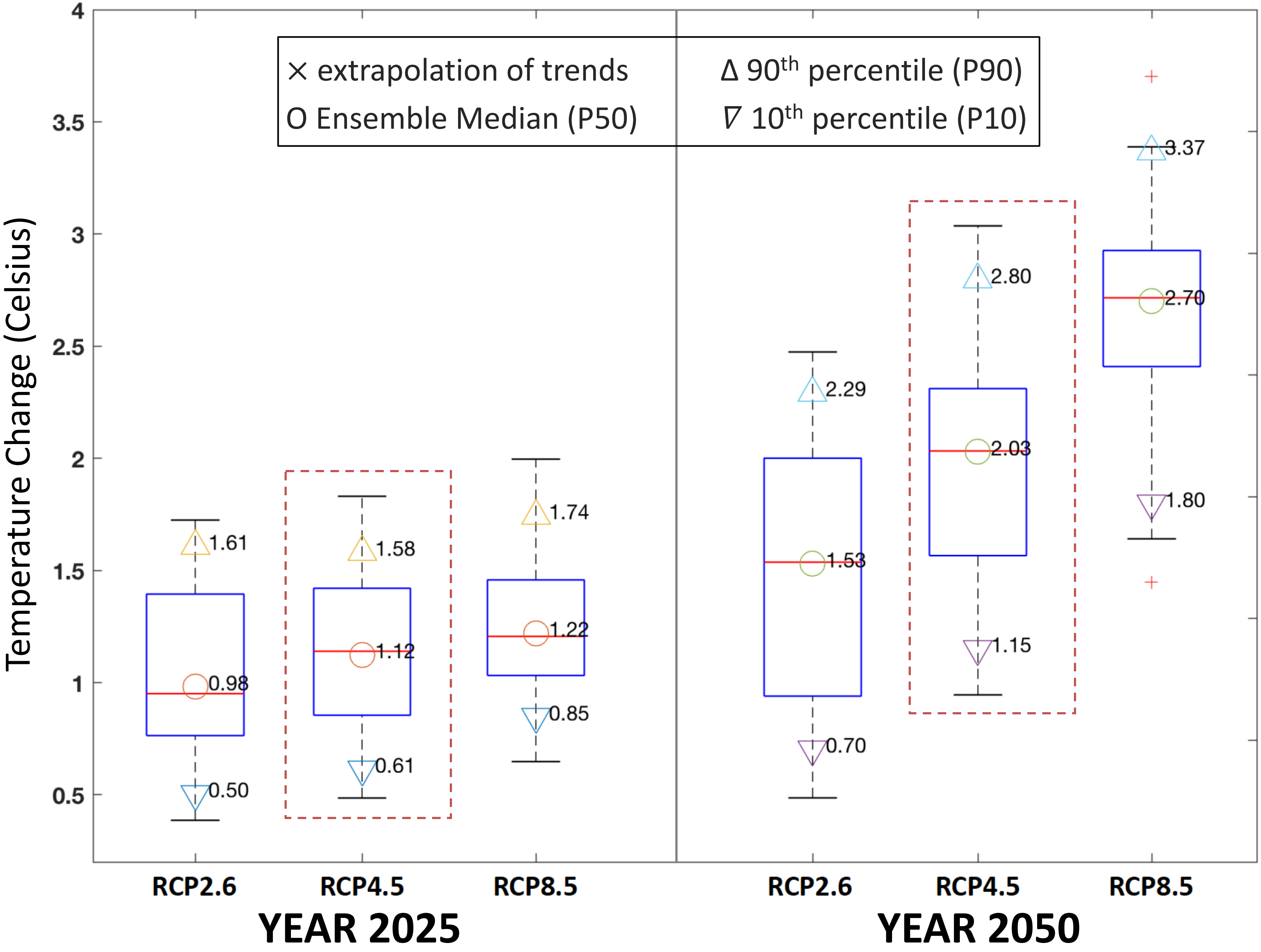
The map shows percent changes in the 30-year annual average streamflow for rivers and streams. U.S. Environmental Protection Agency. 2016. Climate change indicators in the United States, 2016. Fourth edition. EPA 430-R-16-004 [2]

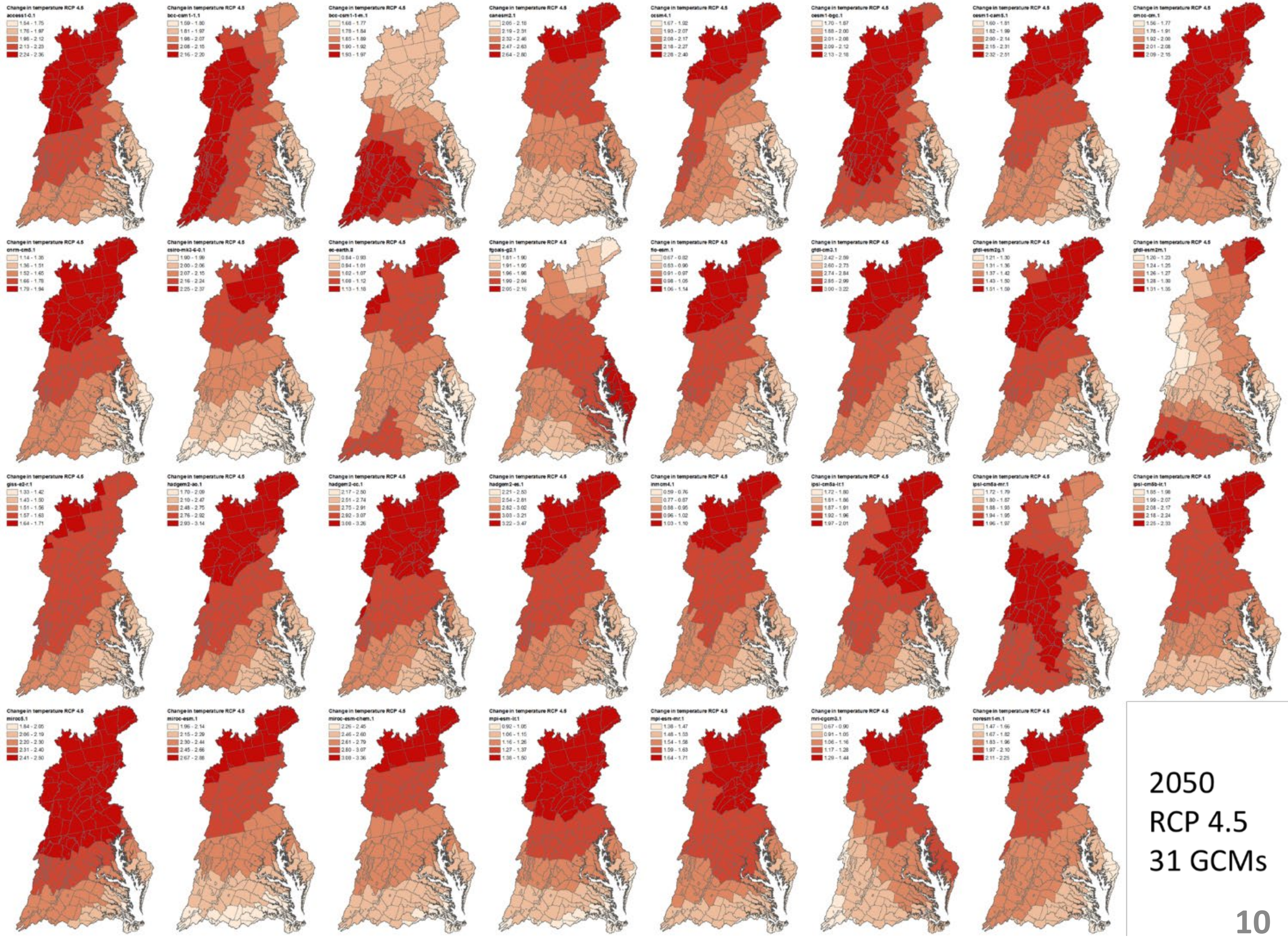
USGS station ID	Precipitation		Discharge	
	Slope	p-value	Slope	p-value
04252500	0.0007	**0.0011**	0.0021	<**0.0001**
01512500	0.0008	**0.0007**	0.0016	**0.0028**
01503000	0.0007	**0.0022**	0.0013	**0.0181**
01531000	0.0006	**0.0219**	0.0018	**0.0030**
01531500	0.0007	**0.0044**	0.0016	**0.0029**
01532000	0.0006	**0.0374**	0.0015	**0.0330**
01534000	0.0005	**0.0497**	0.0015	**0.0120**
01550000	0.0005	**0.0493**	0.0019	**0.0015**
01543000	0.0004	0.1000	0.0018	**0.0058**
01545500	0.0004	0.0953	0.0017	**0.0026**
01536500	0.0006	**0.0078**	0.0016	**0.0027**
01551500	0.0005	0.0612	0.0017	**0.0017**
01439500	0.0005	0.0972	0.0007	0.1661
01541500	0.0003	0.2357	0.0017	**0.0017**
01540500	0.0006	**0.0111**	0.0016	**0.0023**
01541000	0.0004	0.0985	0.0016	**0.0021**
01567000	0.0004	0.1577	0.0011	**0.0250**
01570500	0.0005	**0.0260**	0.0013	**0.0088**
North-South Split				
01562000	0.0004	0.1693	0.0007	0.2082
01638500	0.0004	0.1150	0.0008	0.1026
01608500	0.0004	0.1725	0.0010	0.0833
01636500	0.0005	0.1245	0.0008	0.0624
01606500	0.0003	0.1958	0.0009	0.1108
01668000	0.0006	0.0794	0.0004	0.4727
02035000	0.0003	0.2653	−0.0001	0.8243
02019500	0.0002	0.4333	0.0003	0.4836
03488000	0.0003	0.2480	0.0006	0.2841

Karen C. Rice, Douglas L. Moyer, and Aaron L. Mills, 2017. Riverine discharges to Chesapeake Bay: Analysis of long-term (1927 - 2014) records and implications for future flows in the Chesapeake Bay basin *JEM* 204 (2017) 246-254

[1] Lins, H.F. 2012. USGS Hydro-Climatic Data Network 2009 (HCDN-2009). U.S. Geological Survey Fact Sheet 2012-3047. https://pubs.usgs.gov/fs/2012/3047.
[2] U.S. EPA. 2016. Climate change indicators in the United States. www.epa.gov/climate-indicators; https://www.epa.gov/sites/production/files/2016-08/documents/climate_indicators_2016.pdf

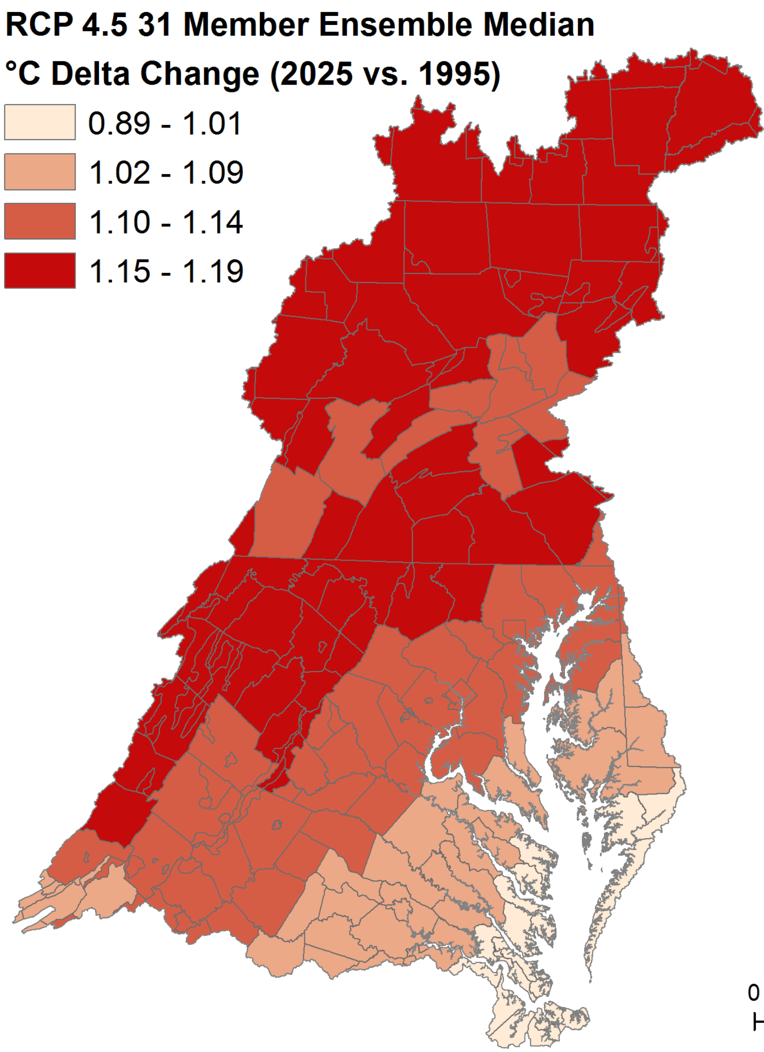
Summary of temperature change



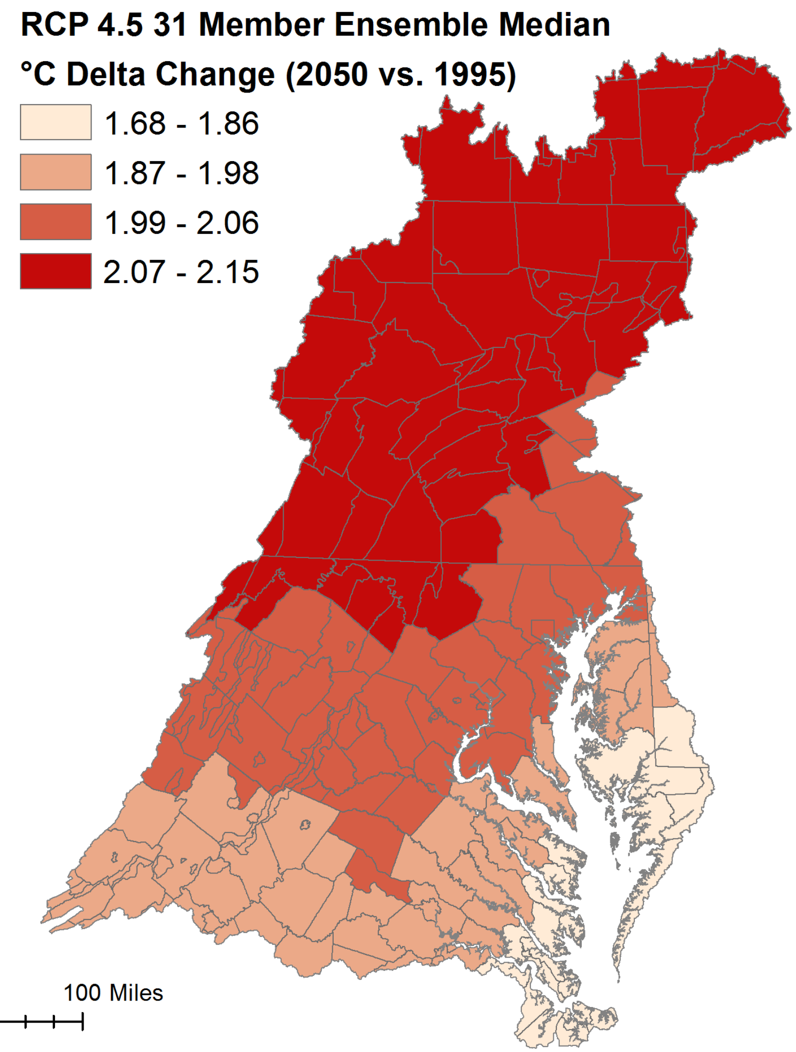


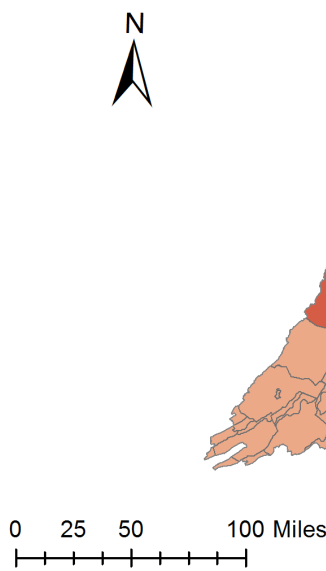
2050
RCP 4.5
31 GCMs

YEAR 2025



YEAR 2050

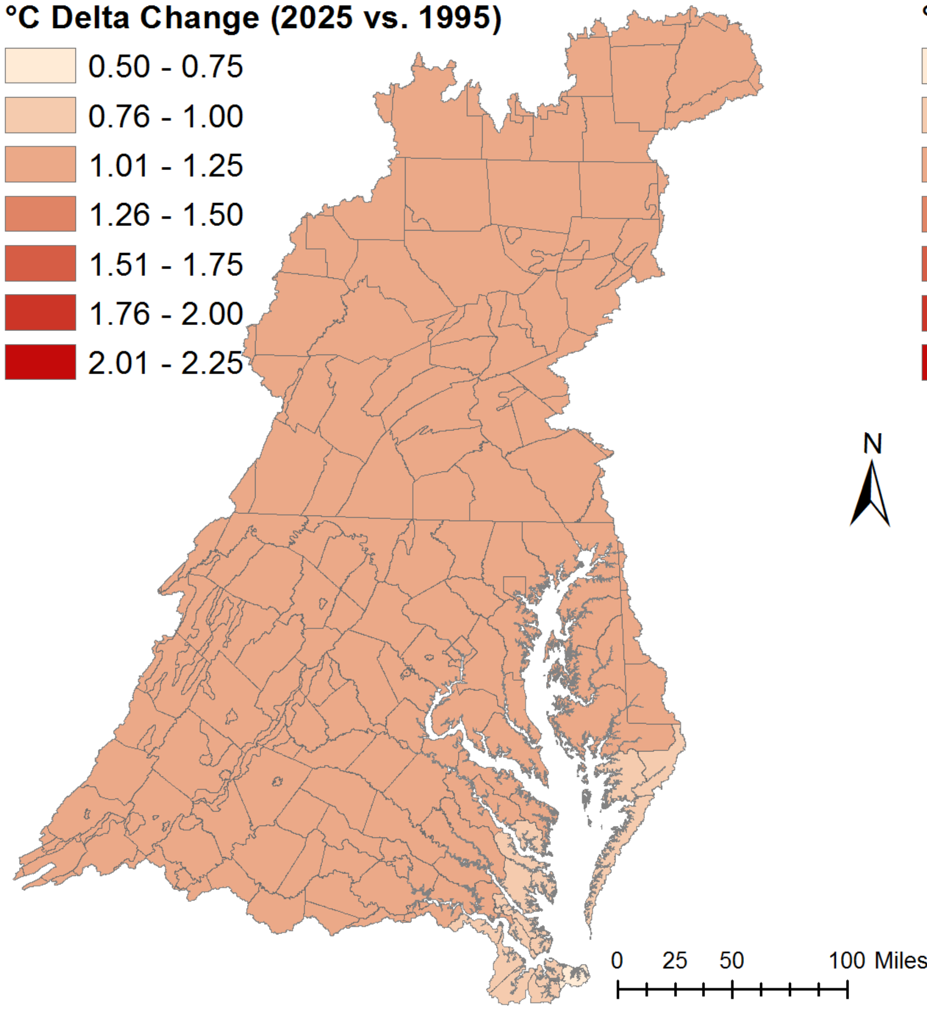




1.12°C increase in average annual temperature

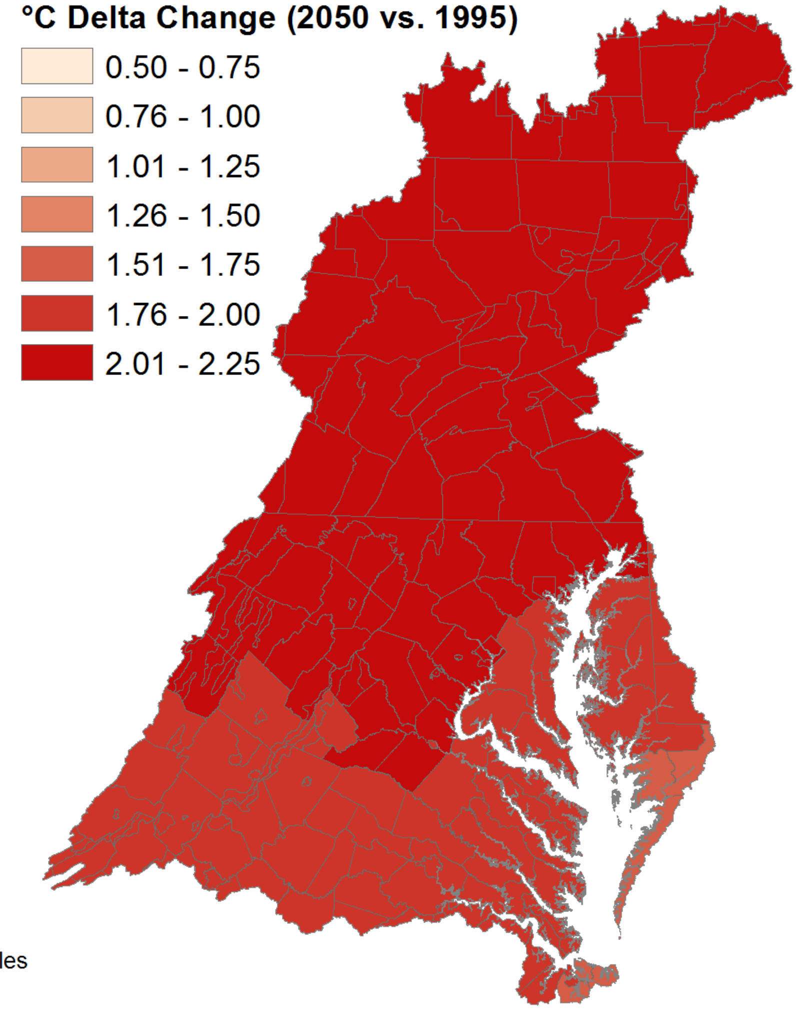
2.03°C increase in average annual temperature

YEAR 2025



1.12°C increase in average annual temperature

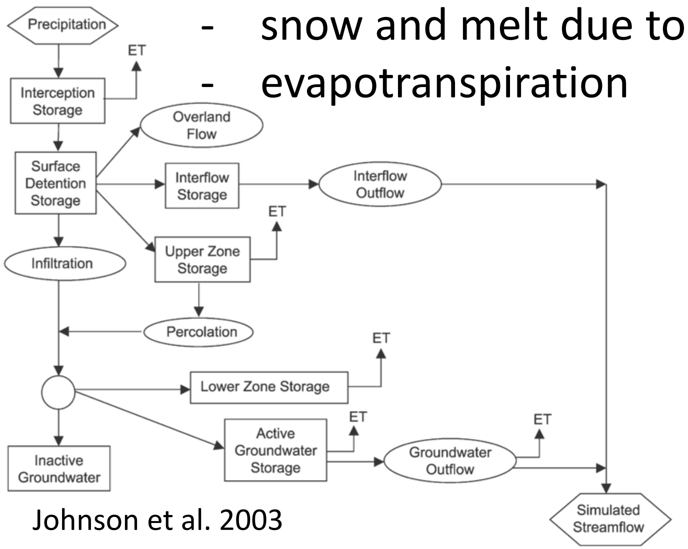
YEAR 2050



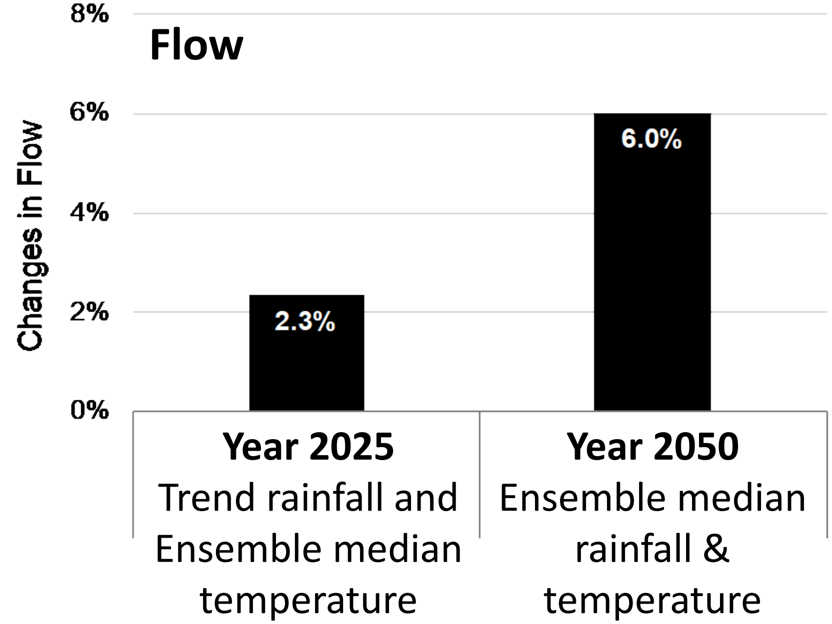
2.03°C increase in average annual temperature

Summary of changes in delivery

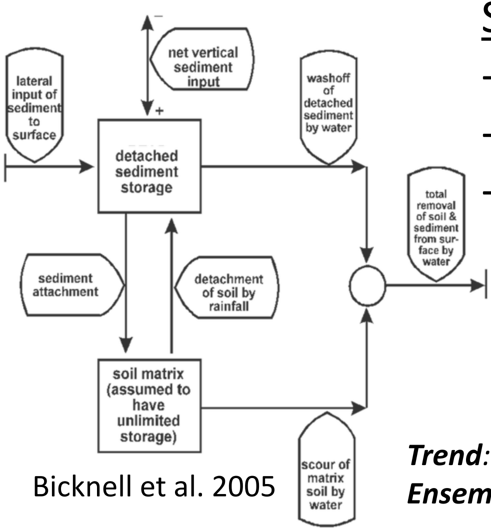
<u>Hydrologic response</u>:
- rainfall volume & intensity
- snow and melt due to temperature
- evapotranspiration



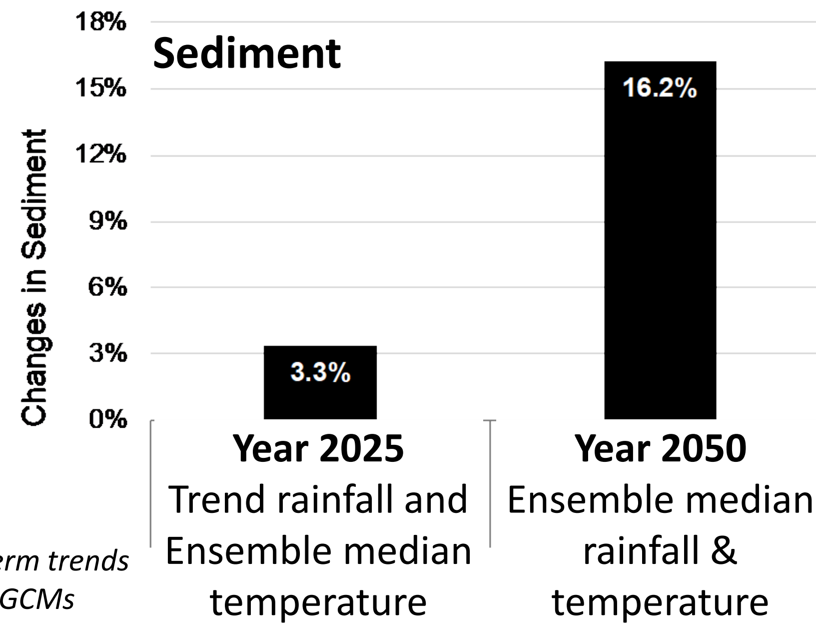
Johnson et al. 2003



<u>Sediment response</u>:
- rainfall intensity
- surface runoff
- riverine scour and deposition



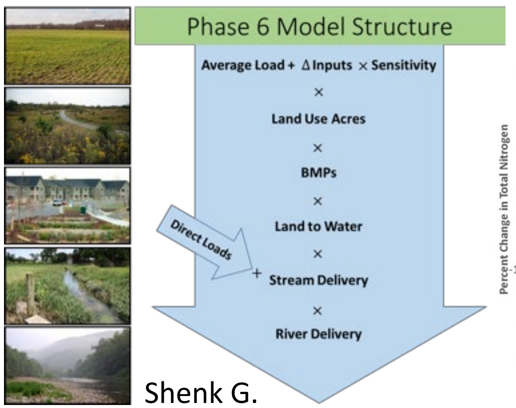
Bicknell et al. 2005



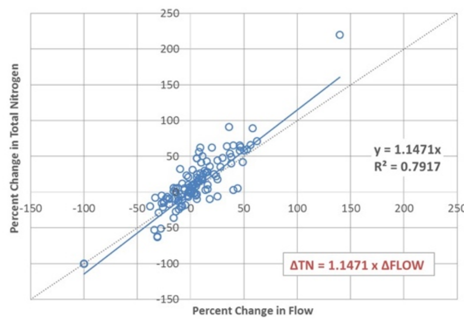
Trend: *projection of extrapolation of long-term trends*
Ensemble: *31-member ensemble of RCP4.5 GCMs*

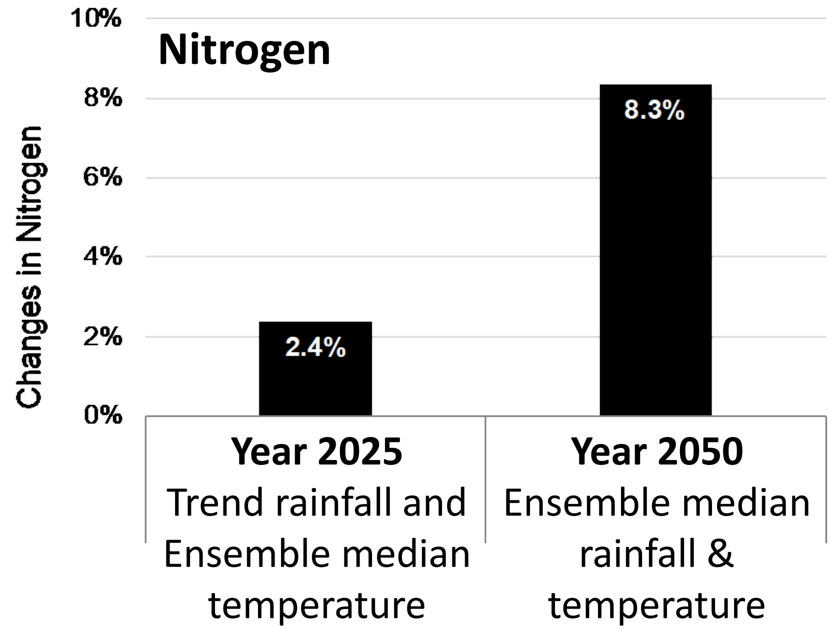
Summary of changes in delivery

<u>Nitrogen response</u>:
- sensitivity to flow
- stream bank erosion
- denitrification, organic scour

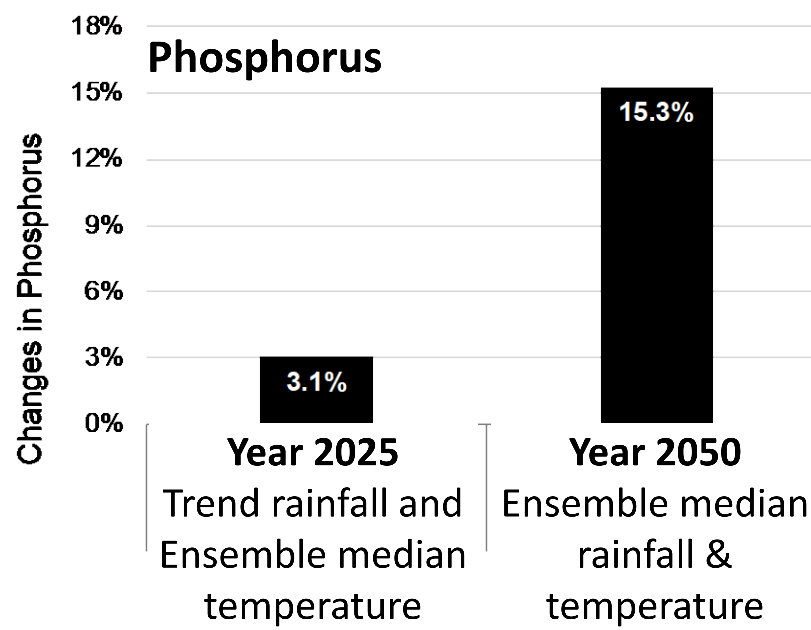


Shenk G.





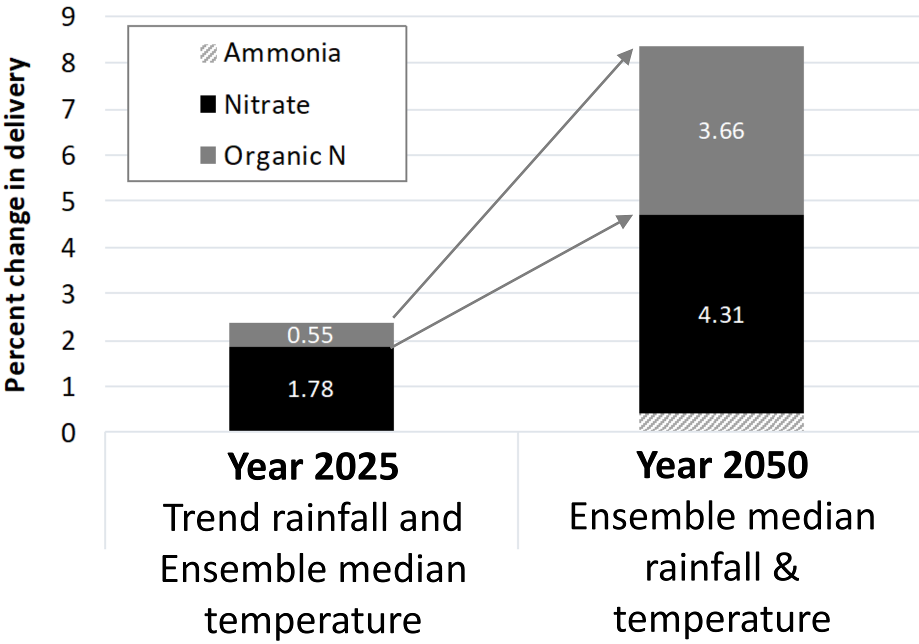
<u>Phosphorus response</u>:
- sensitivities to flow and sediment (APLE)
- stream bank erosion
- scour/deposition of inorganic and organic (HSPF)



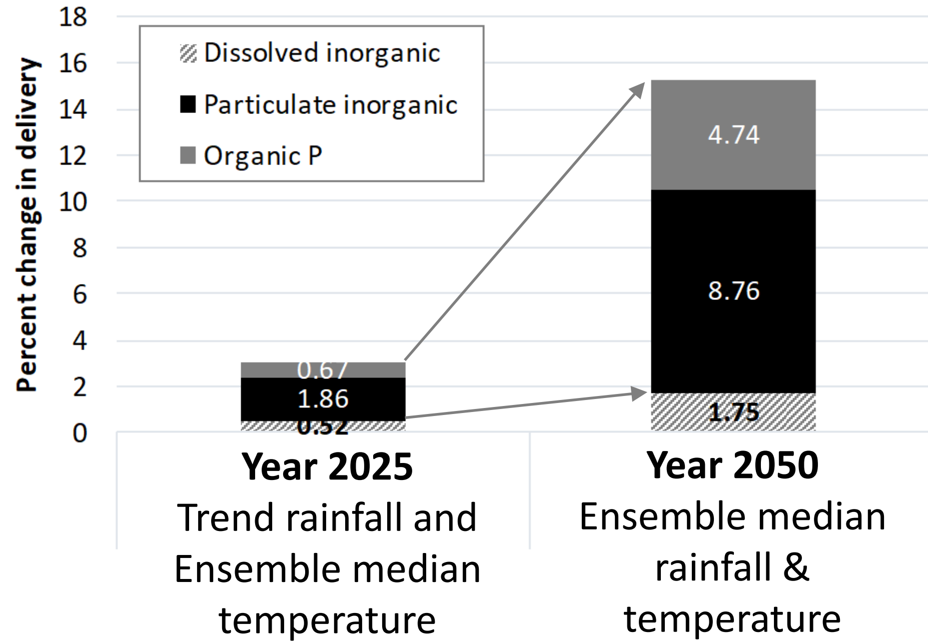
***Trend**: projection of extrapolation of long-term trends*
***Ensemble**: 31-member ensemble of RCP4.5 GCMs*

Nitrogen and phosphorus species

Simulated changes in nitrogen delivery



Simulated changes in phosphorus delivery

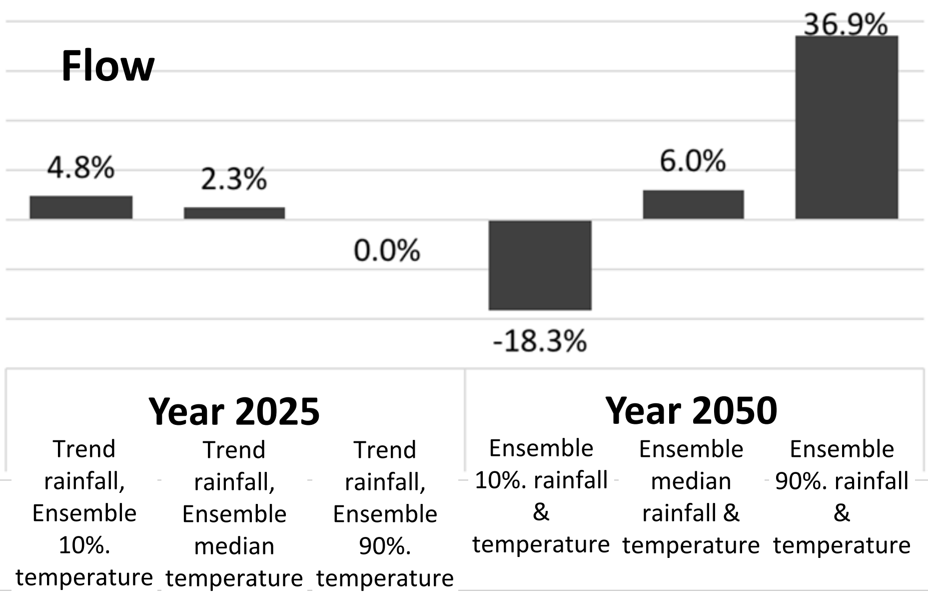


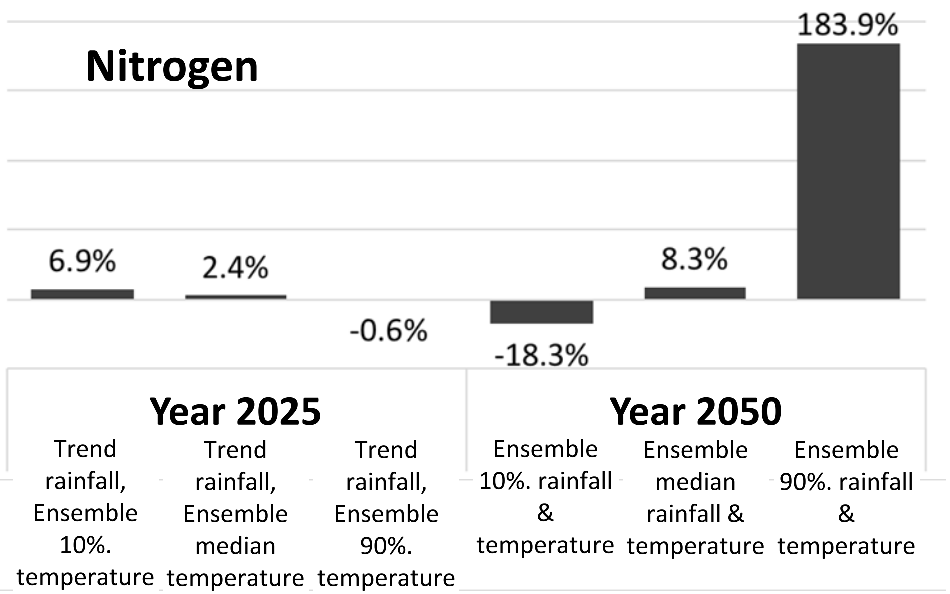
Arrows show relatively more increase in organic nitrogen as compared to inorganic.

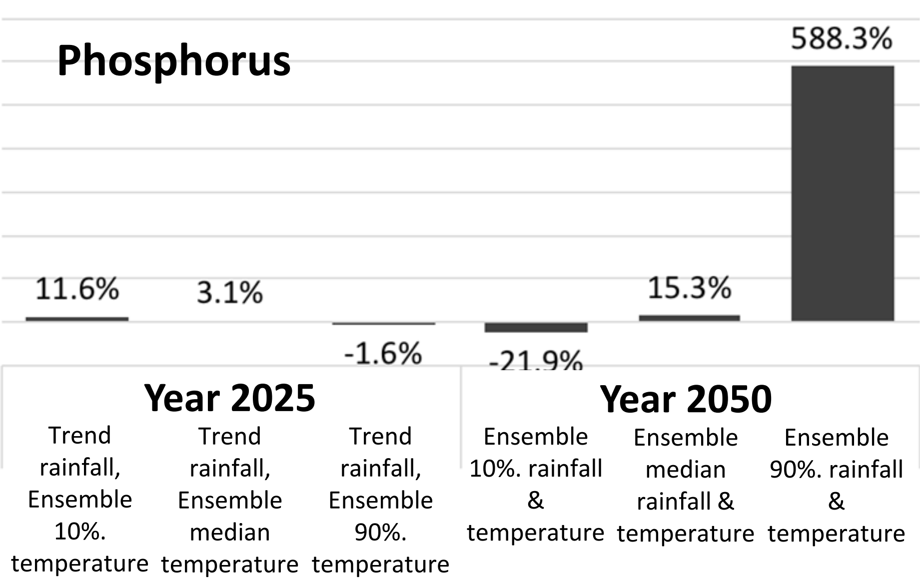
Arrows show relatively more increase in particulate phosphorus as compared to dissolved inorganic phosphorus.

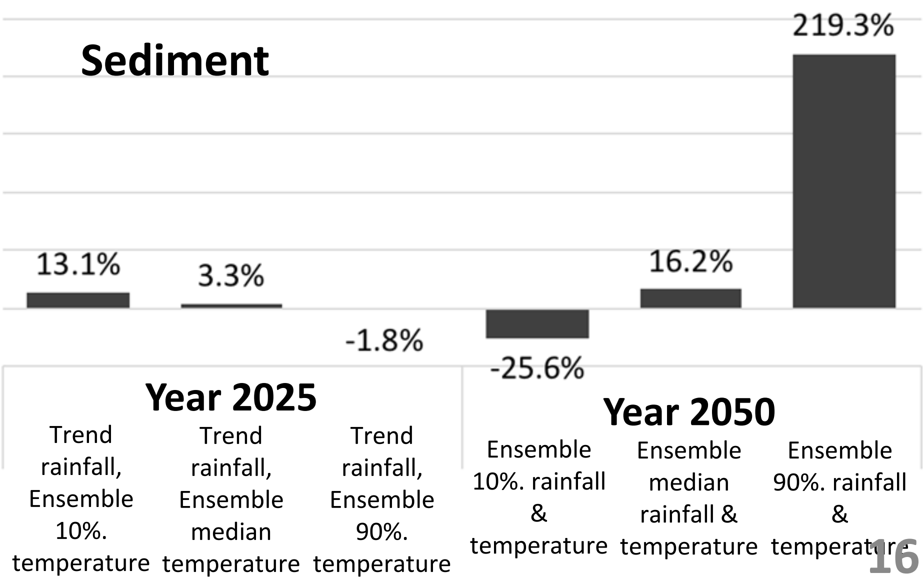
Trend*: projection of extrapolation of long-term trends*
Ensemble*: 31-member ensemble of RCP4.5 GCMs*

Uncertainty due to climatic inputs





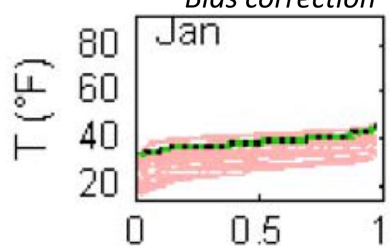




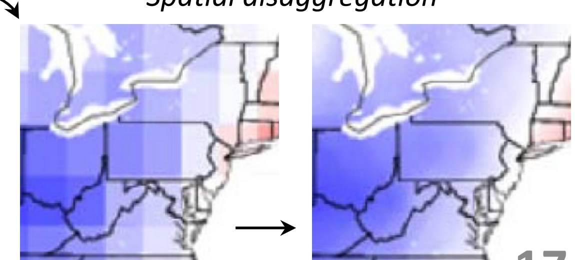
Evaluation of downscaling

- 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]

Bias correction



Spatial disaggregation



[1] Used in Chesapeake Bay 2017 Climate Change Assessment
[2] https://www.chesapeakebay.net/channel_files/25919/najjar_combined.pdf

Evaluation of downscaling

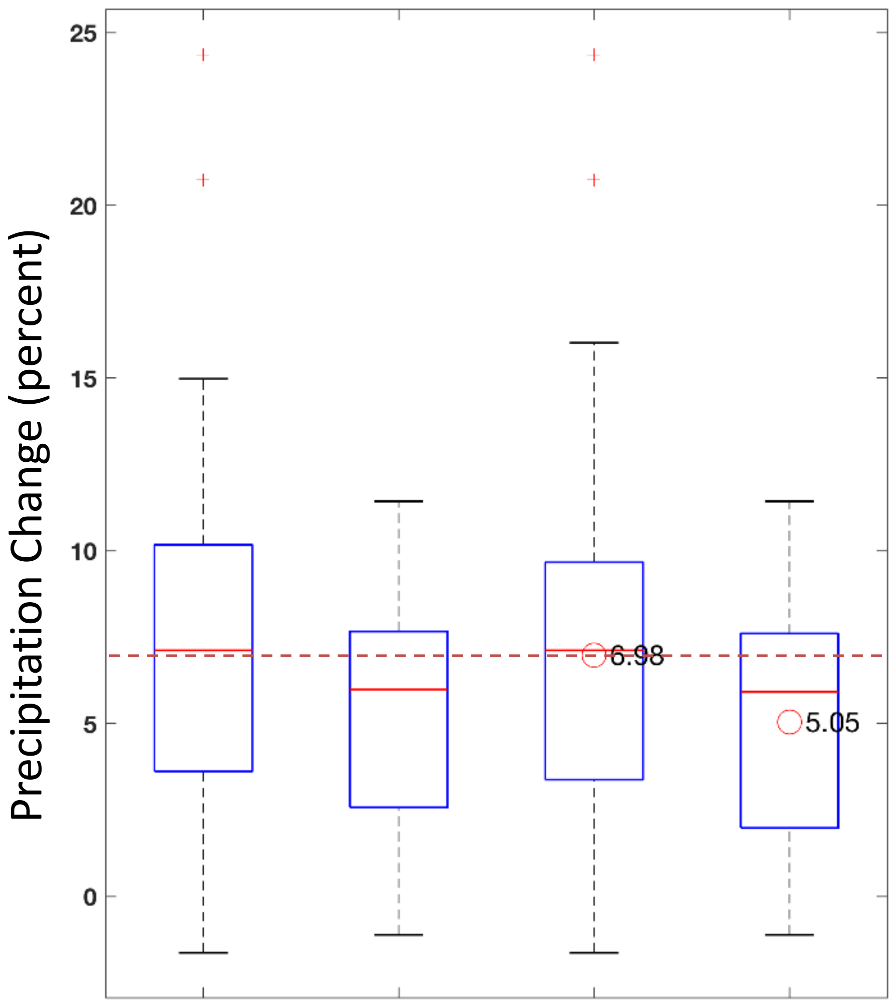
Table: MACA and BCSD data inventory details

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

[1] Abatzoglou, J.T., Brown, T.J., 2012. A comparison of statistical downscaling methods suited for wildfire applications. Int. J. Climatol. 32: 772–780
[2] Reclamation, 2013. 'Downscaled CMIP3 and CMIP5 Climate and Hydrology Projections', prepared by the U.S. Department of the Interior, Bureau of Reclamation, Technical Services Center. 47pp.

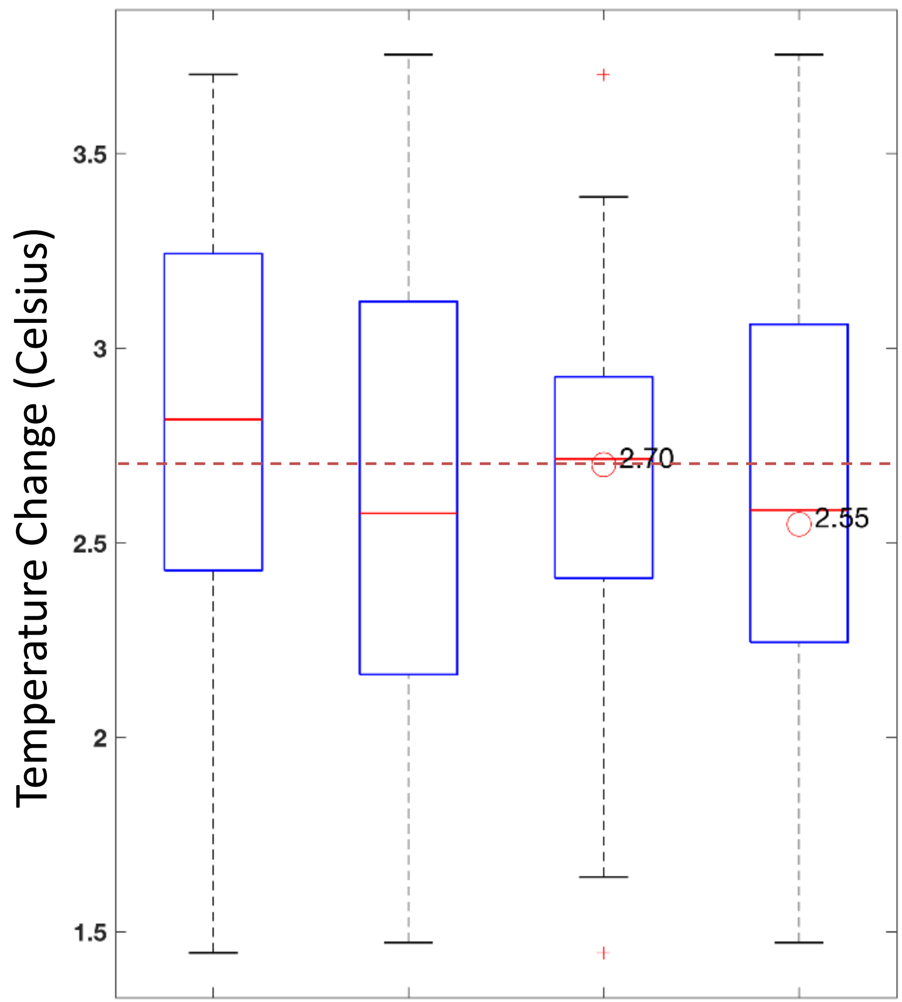
Summary of BCSD & MACA delta change

RCP 8.5
2050 vs. 1995



BCSD 19 GCMs | MACA 19 GCMs | BCSD 31 GCMs | MACA 20 GCMs

Identical set of GCMs



BCSD 19 GCMs | MACA 19 GCMs | BCSD 31 GCMs | MACA 20 GCMs

Identical set of GCMs

Evaluation of BCSD & MACA delta change

- Delta change for rainfall volume and temperature were evaluated.
- 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.

RCP 8.5

2025 vs. 1995

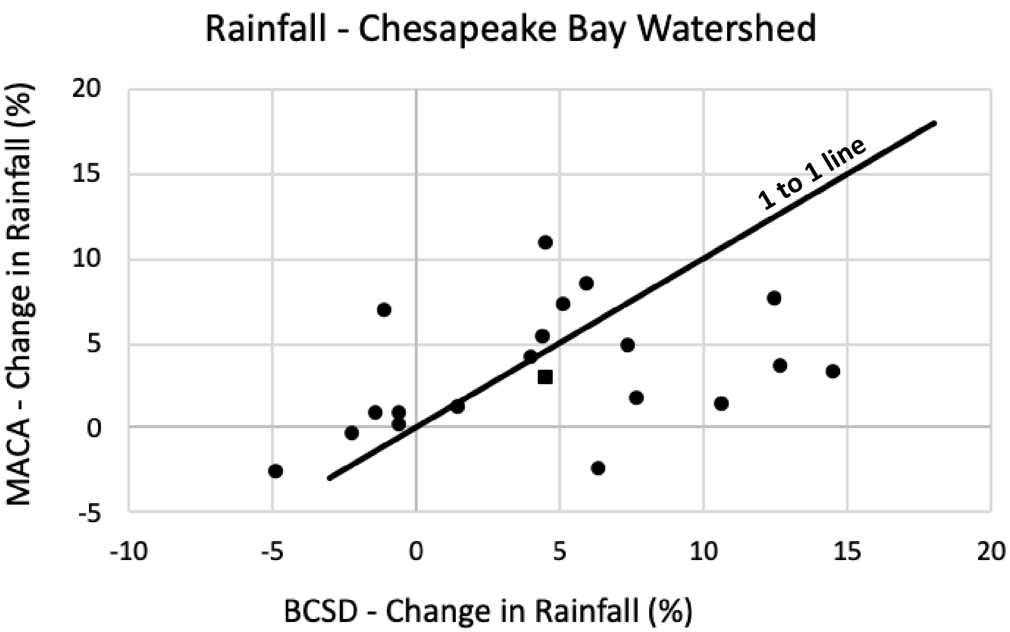


Figure shows delta % change in annual rainfall volume from 19 matching GCMs after downscaling.

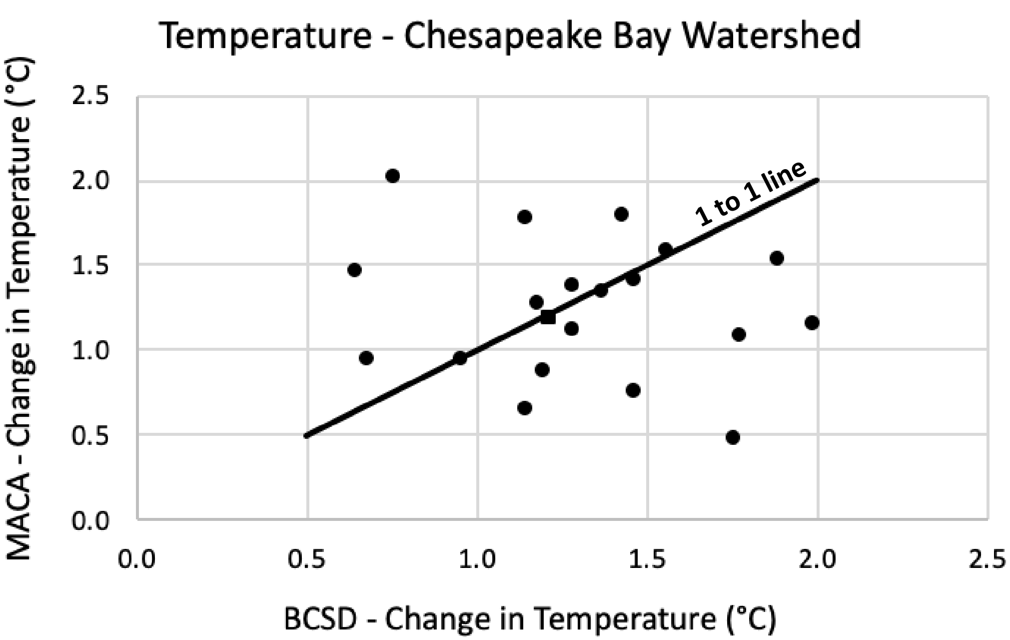


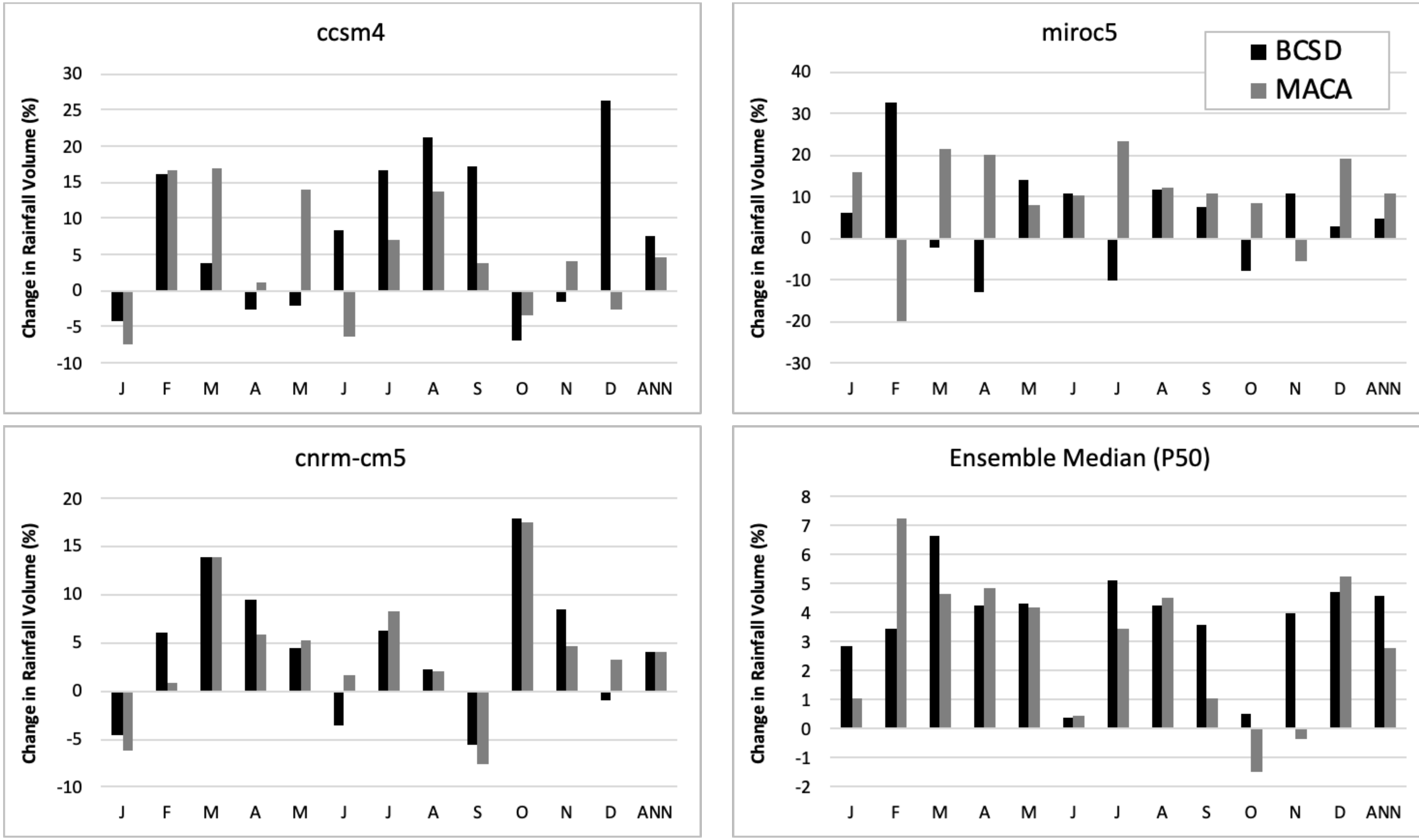
Figure shows delta degree Celsius change for temperature from 19 matching GCMs after downscaling.

Chesapeake Bay Watershed – Rainfall

CHAMP Assessment
2019 Assessment

RCP 8.5

2025 vs. 1995

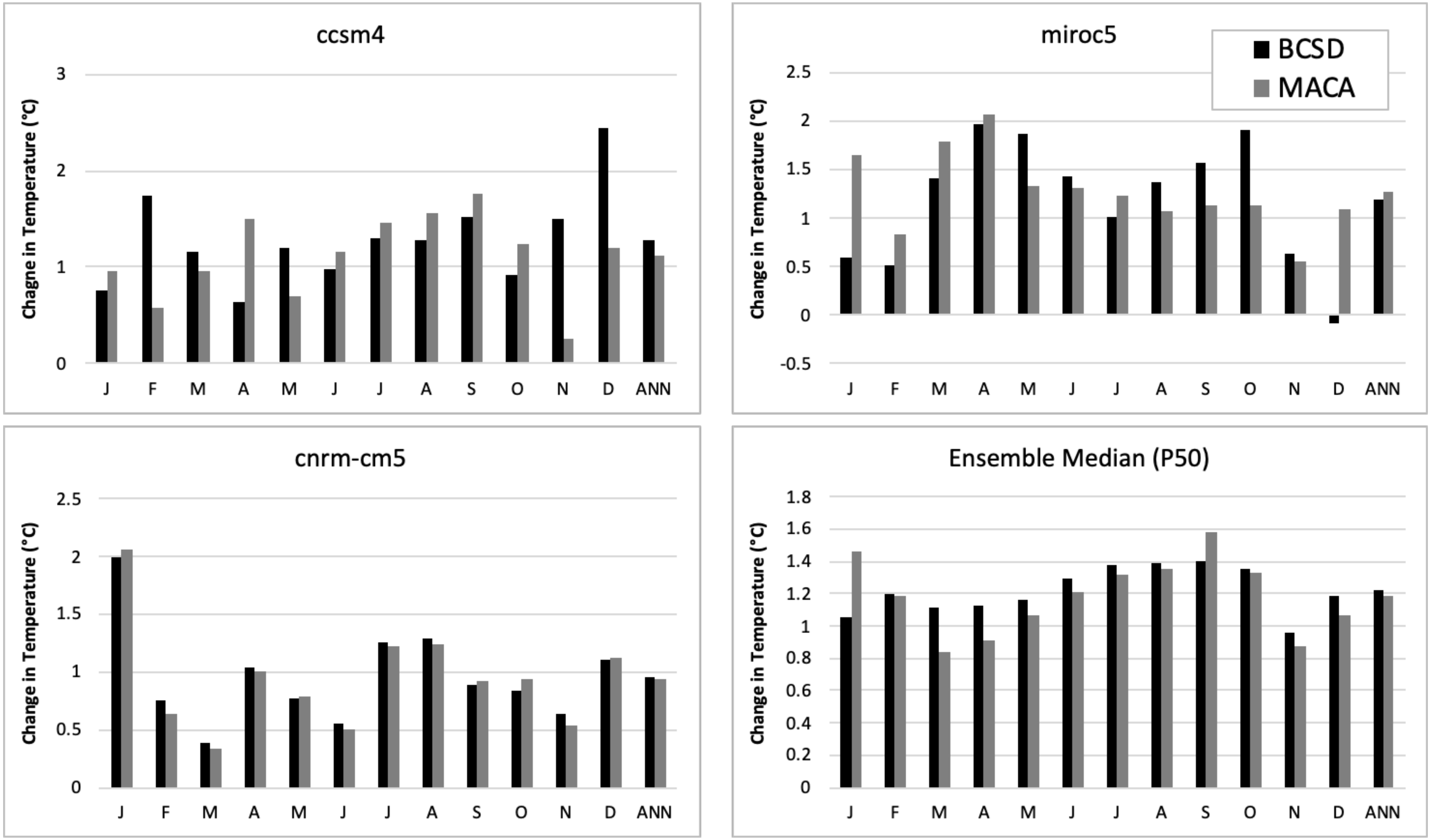


Chesapeake Bay Watershed – Temperature

CHAMP Assessment
2019 Assessment

RCP 8.5

2025 vs. 1995



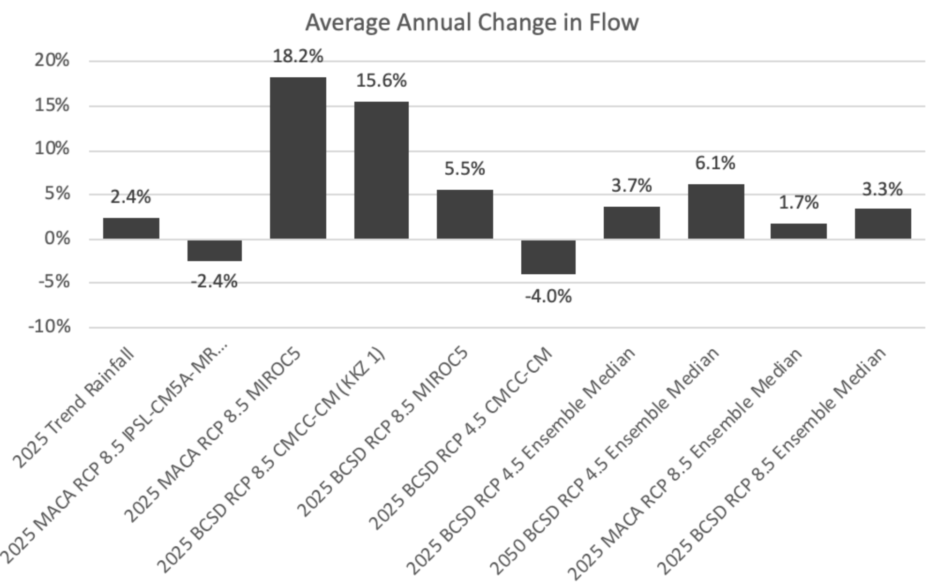
CHAMP Climate Change Scenarios

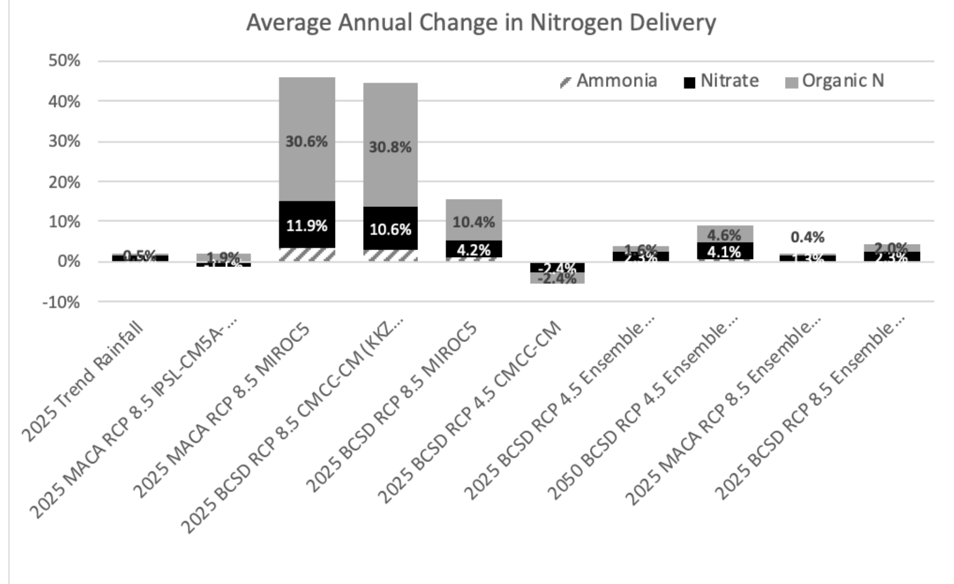
List of scenarios for CHAMP 2025 climate change assessment to investigate the impact of downscaling, and watershed model responses

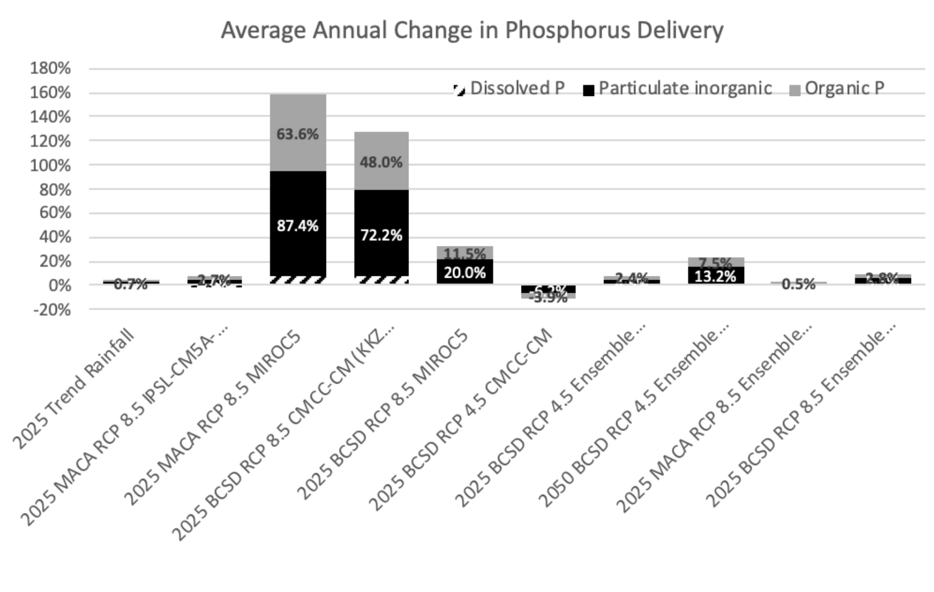
SNo.	SCENARIO NAME	SCENARIO DESCRIPTION
01	MFBASE1808CXXNONERXXMXX	**Baseline representing calibration 1991-2000 condition**
02	MFBASE1808C25T88YR45P50	**2025 Trend Rainfall, BCSD RCP 4.5 Ensemble Median temperature**
03	MFBASE1808C25MACAR85M27	**2025 MACA RCP 8.5 IPSL-CM5A-MR (KKZ Rank = 1)**
04	MFBASE1808C25MACAR85M31	**2025 MACA RCP 8.5 MIROC5**
05	MFBASE1808C25BCSDR85M09	**2025 BCSD RCP 8.5 CMCC-CM (KKZ Rank = 1)**
06	MFBASE1808C25BCSDR85M31	**2025 BCSD RCP 8.5 MIROC5**
07	MFBASE1808C25BCSDR45M09	**2025 BCSD RCP 4.5 CMCC-CM**
08	MFBASE1808C25BCSDR45P50	**2025 BCSD RCP 4.5 Ensemble Median**
09	MFBASE1808C50BCSDR45P50	***2050* BCSD RCP 4.5 Ensemble Median**
10	MFBASE1808C25MACAR85P50	**2025 MACA RCP 8.5 Ensemble Median**
11	MFBASE1808C25BCSDR85P50	**2025 BCSD RCP 8.5 Ensemble Median**

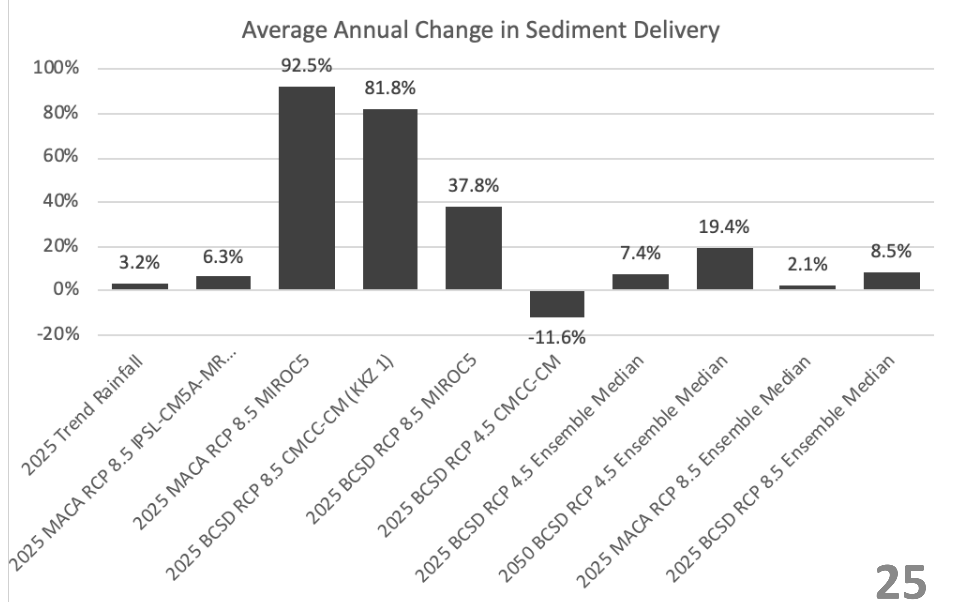
Marjy Friedrichs
Kyle Hinson

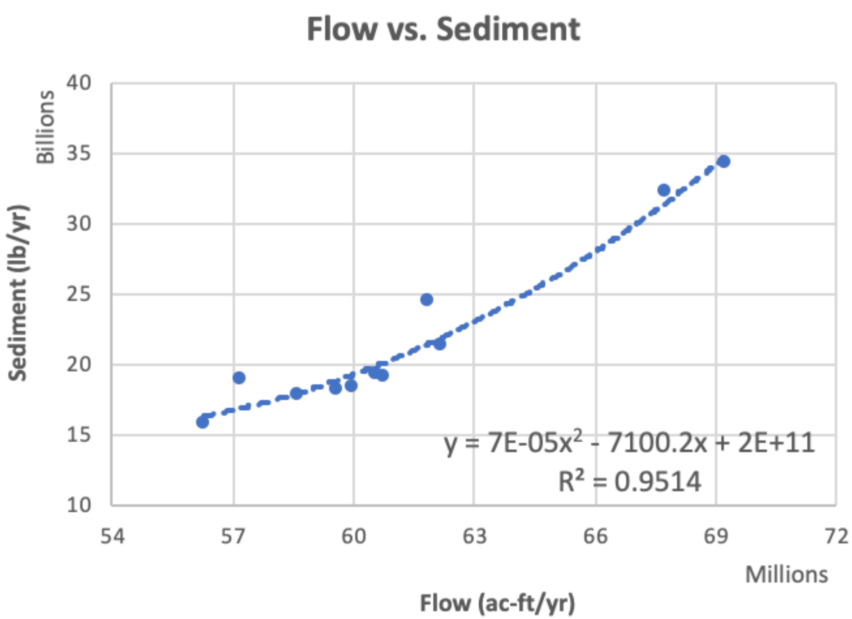
CBP Watershed Model results – Average Annual

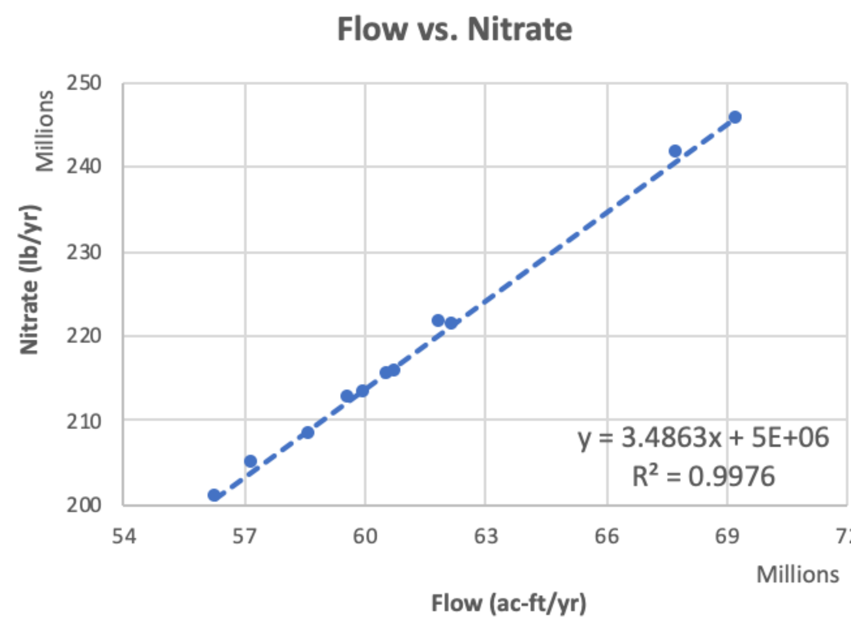


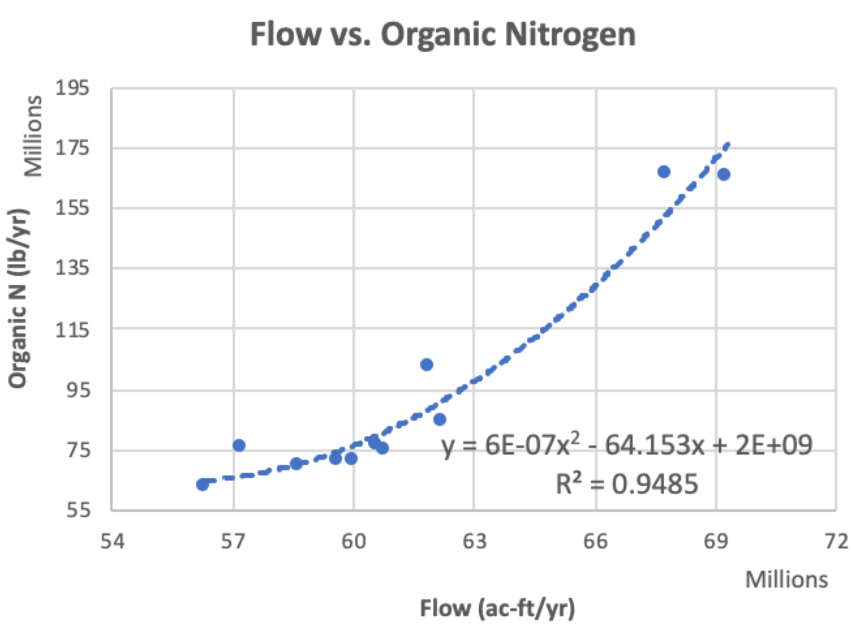


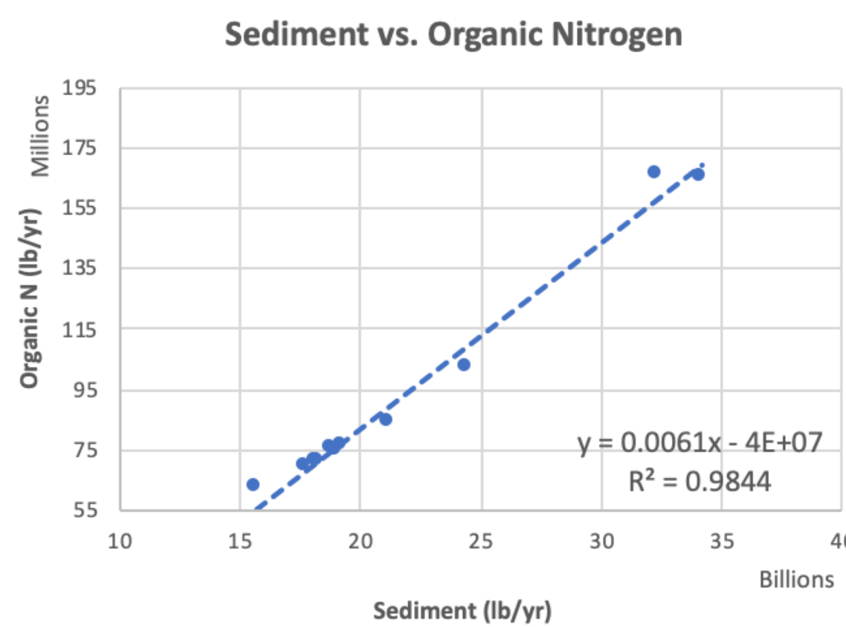


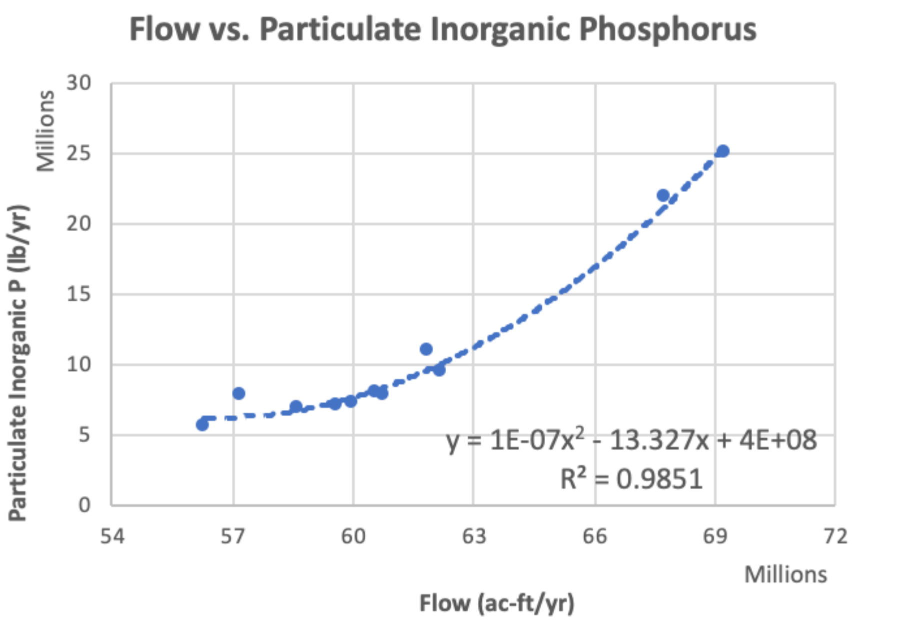


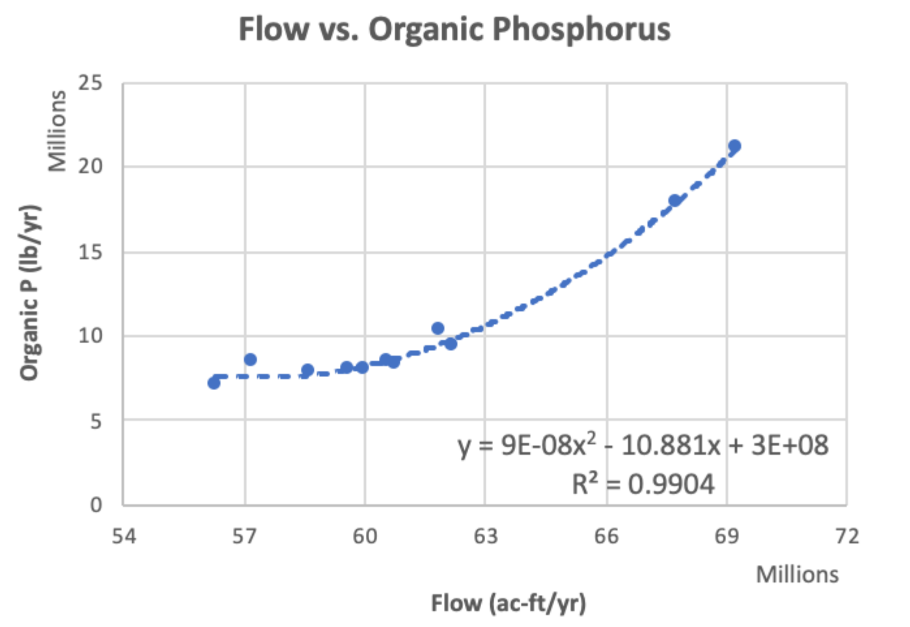

Flow vs. Sediment
Sediment (lb/yr)
Billions
40
35
30
25
20
15
10
54
57
60
63
66
69
72
Millions
Flow (ac-ft/yr)
y = 7E-05x² - 7100.2x + 2E+11
R² = 0.9514

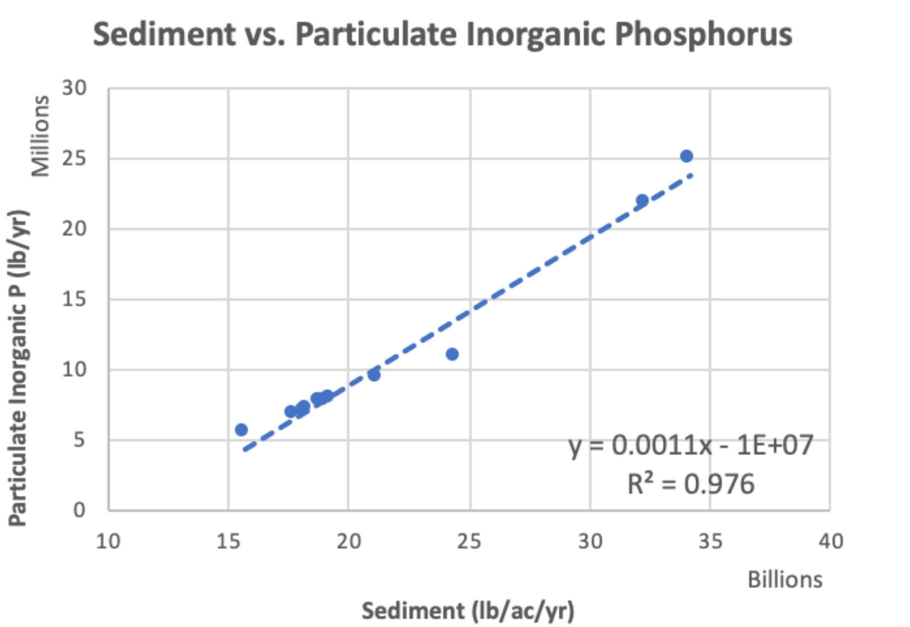

Flow vs. Nitrate
Nitrate (lb/yr)
Millions
250
240
230
220
210
200
54
57
60
63
66
69
72
Millions
Flow (ac-ft/yr)
y = 3.4863x + 5E+06
R² = 0.9976

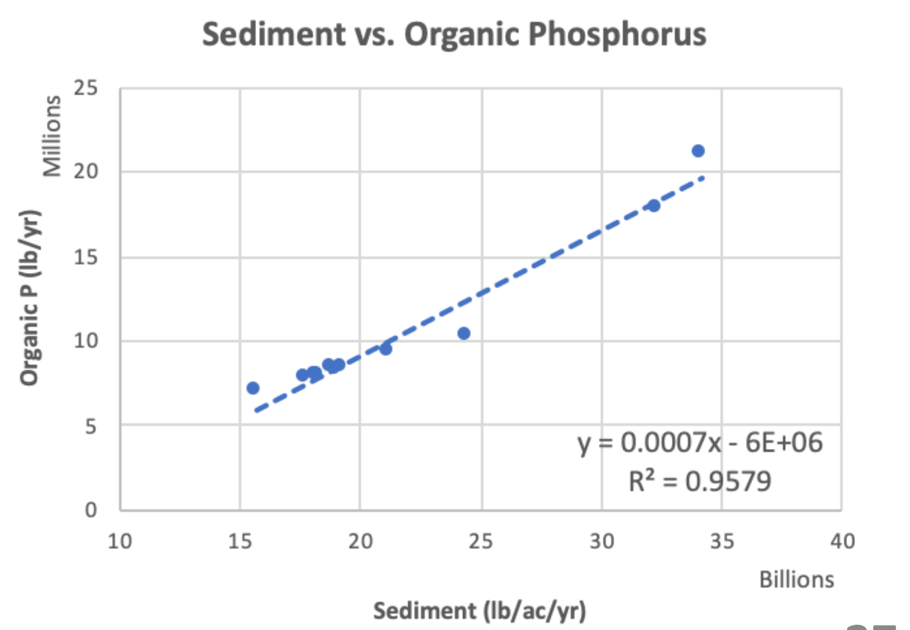

Flow vs. Organic Nitrogen
Organic N (lb/yr)
Millions
195
175
155
135
115
95
75
55
54
57
60
63
66
69
72
Millions
Flow (ac-ft/yr)
y = 6E-07x² - 64.153x + 2E+09
R² = 0.9485


Sediment vs. Organic Nitrogen
Organic N (lb/yr)
Millions
195
175
155
135
115
95
75
55
10
15
20
25
30
35
40
Billions
Sediment (lb/yr)
y = 0.0061x - 4E+07
R² = 0.9844

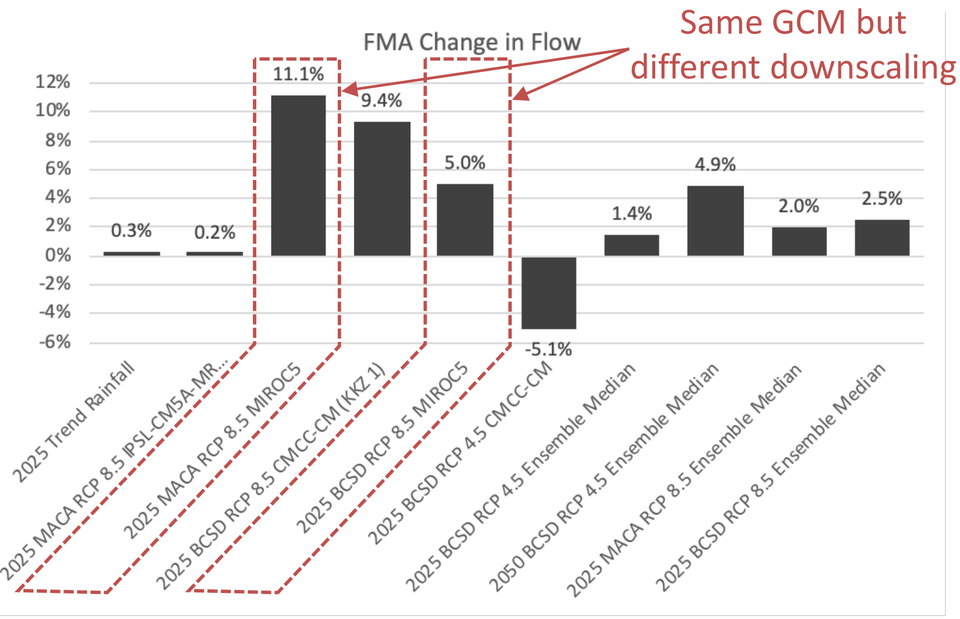

Flow vs. Particulate Inorganic Phosphorus
Particulate Inorganic P (lb/yr)
Millions
30
25
20
15
10
5
0
54
57
60
63
66
69
72
Millions
Flow (ac-ft/yr)
y = 1E-07x² - 13.327x + 4E+08
R² = 0.9851

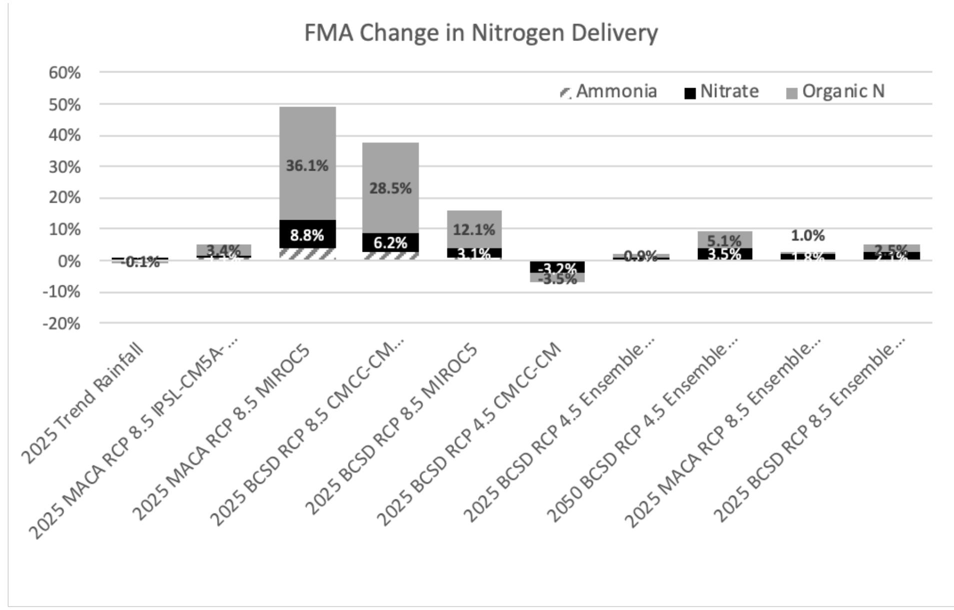

Flow vs. Organic Phosphorus
Organic P (lb/yr)
Millions
25
20
15
10
5
0
54
57
60
63
66
69
72
Millions
Flow (ac-ft/yr)
y = 9E-08x² - 10.881x + 3E+08
R² = 0.9904

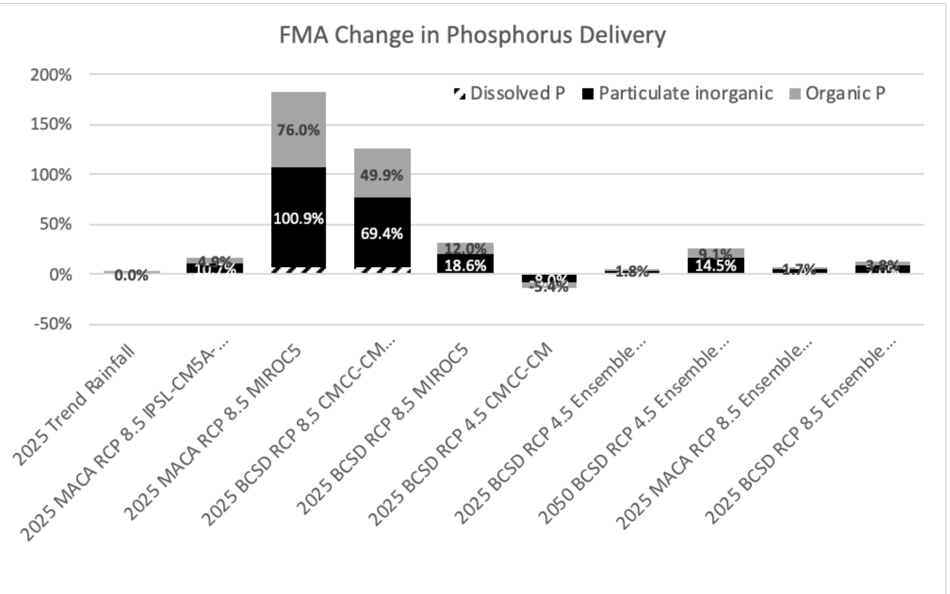

Sediment vs. Particulate Inorganic Phosphorus
Particulate Inorganic P (lb/yr)
Millions
30
25
20
15
10
5
0
10
15
20
25
30
35
40
Billions
Sediment (lb/ac/yr)
y = 0.0011x - 1E+07
R² = 0.976

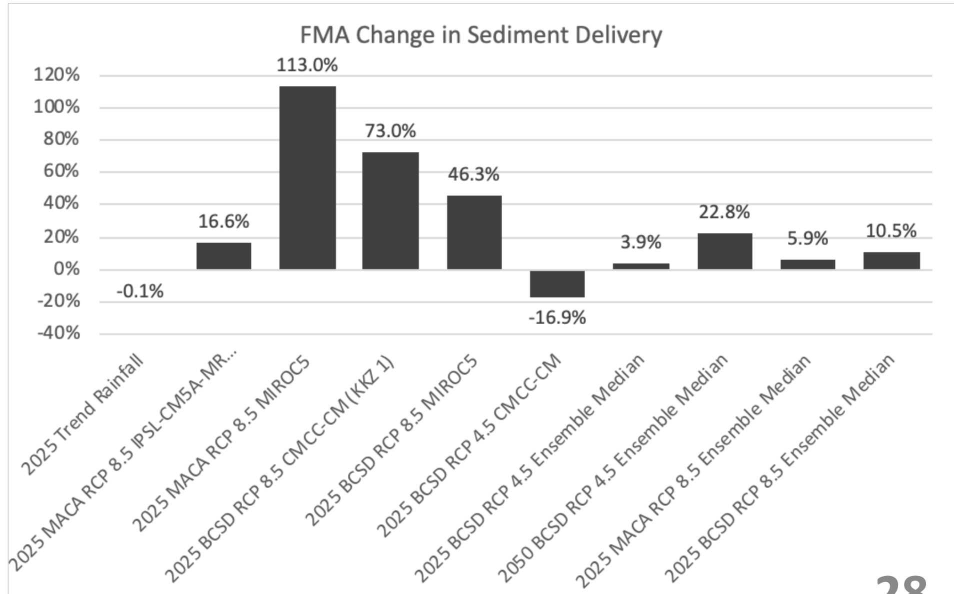

Sediment vs. Organic Phosphorus
Organic P (lb/yr)
Millions
25
20
15
10
5
0
10
15
20
25
30
35
40
Billions
Sediment (lb/ac/yr)
y = 0.0007x - 6E+06
R² = 0.9579

CBP Watershed Model results – Feb+Mar+Apr

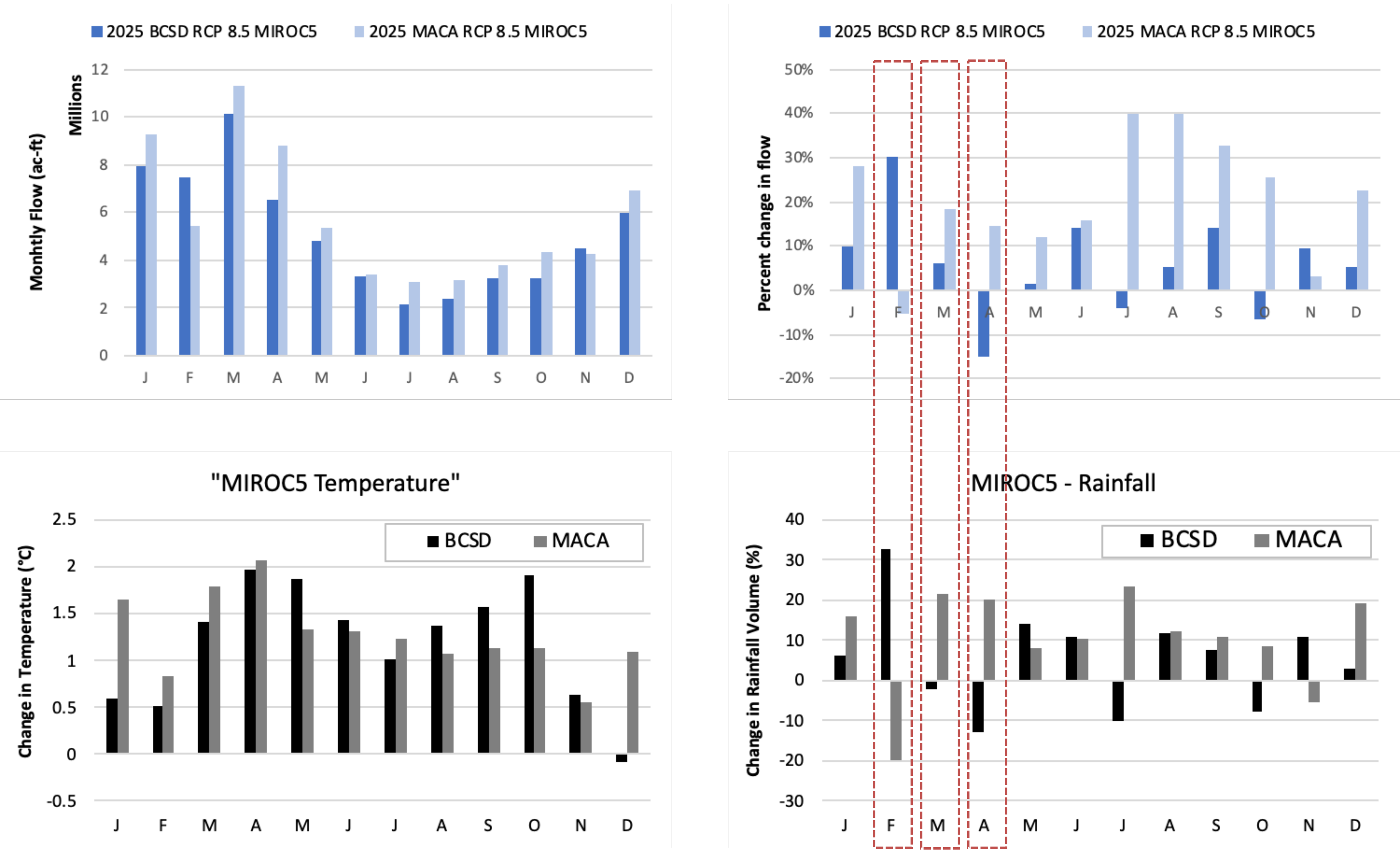






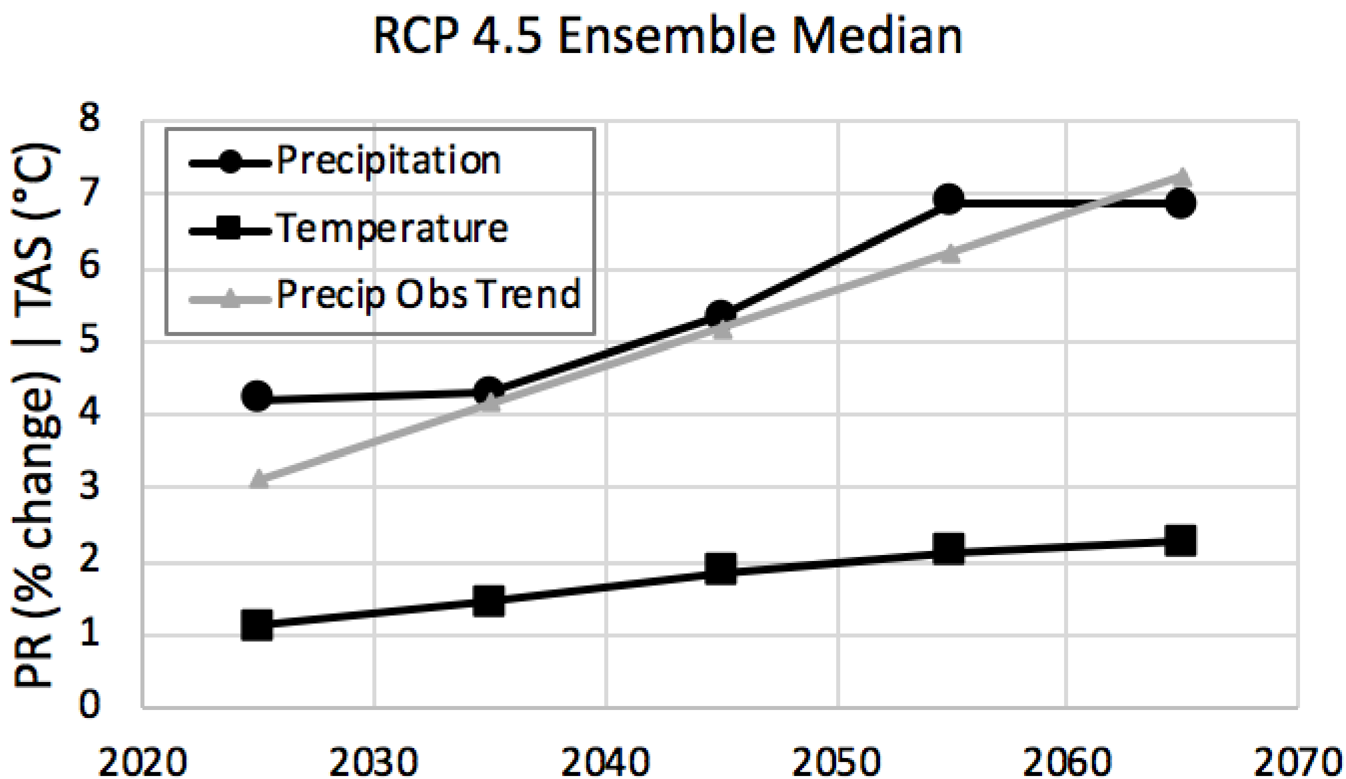


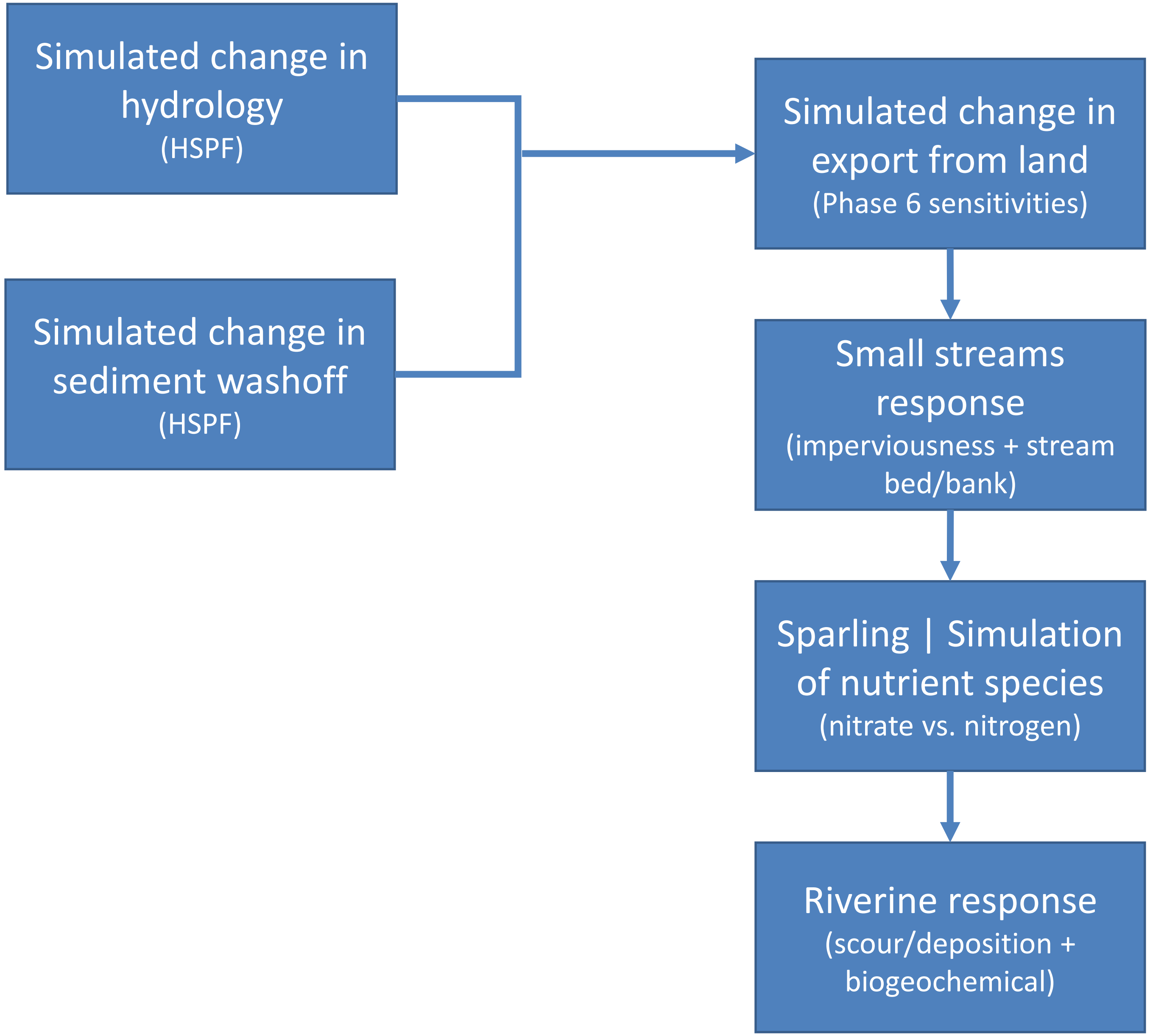
Input change vs. simulated flow response



Summary and Conclusions

- Estimated impacts of 2025 and 2050 climate change on the watershed delivery of nutrients and sediment were shown.
- 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.
- The direction of CBP decision makers, the guidance of STAC, and the collaboration with CHAMP will be collectively applied in the 2019 Climate Change Assessment.


RCP 4.5 Ensemble Median
PR (% change) | TAS (°C)
Precipitation
Temperature
Precip Obs Trend
0
1
2
3
4
5
6
7
8
2020
2030
2040
2050
2060
2070


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

STAC recommendations [1]


The Development of Climate Projections for Use in Chesapeake Bay Program Assessments

STAC Workshop Report
March 7-8, 2016
Annapolis, MD

stac

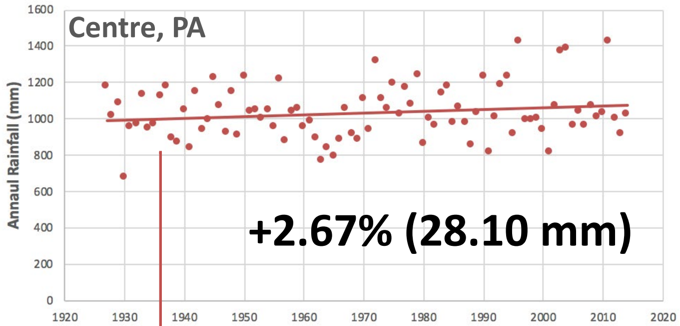
STAC Publication 16-006

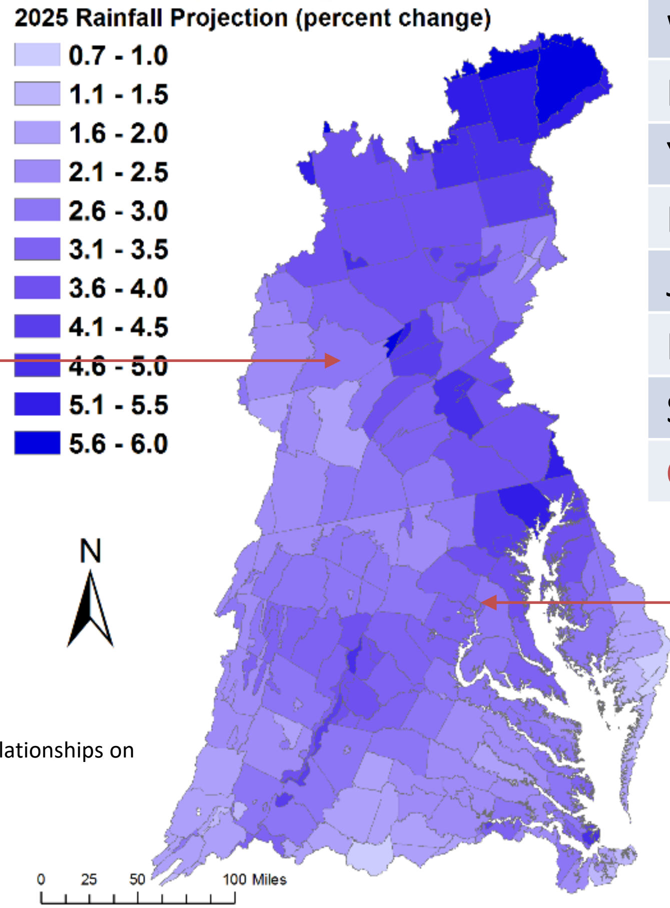
The workshop culminated with the following specific recommendations related to the selection, use, and application of climate projections and forecasts for the 2017 Midpoint Assessment.

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

[1] Page 8 http://www.chesapeake.org/pubs/360_Johnson2016.pdf

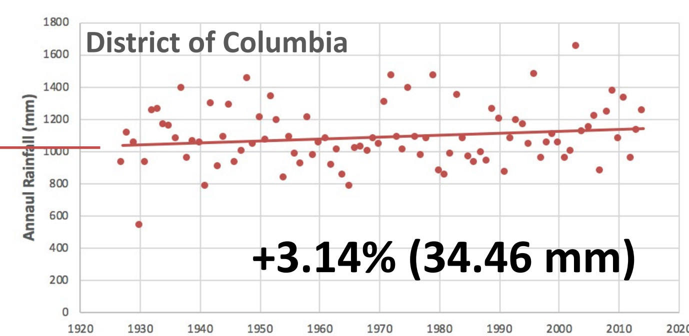
Rainfall projections using 88-years of annual PRISM[1] data trends





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

Major Basins	PRISM Trend
Youghiogheny River	2.1%
Patuxent River Basin	3.3%
Western Shore	4.1%
Rappahannock River Basin	3.2%
York River Basin	2.6%
Eastern Shore	2.5%
James River Basin	2.2%
Potomac River Basin	2.8%
Susquehanna River Basin	3.7%
Chesapeake Bay Watershed	**3.1%**



[1] Parameter-elevation Relationships on Independent Slopes Model

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.

ACCESS1-0	FGOALS-g2	IPSL-CM5A-LR
BCC-CSM1-1	FIO-ESM	IPSL-CM5A-MR
BCC-CSM1-1-M	GFDL-CM3	IPSL-CM5B-LR
BNU-ESM	GFDL-ESM2G	MIROC-ESM
CanESM2	GFDL-ESM2M	MIROC-ESM-CHEM
CCSM4	GISS-E2-H-CC	MIROC5
CESM1-BGC	GISS-E2-R	MPI-ESM-LR
CESM1-CAM5	GISS-E2-R-CC	**MPI-ESM-MR**
CMCC-CM	HadGEM2-AO	MRI-CGCM3
CNRM-CM5	HadGEM2-CC	NorESM1-M
CSIRO-MK3-6-0	HadGEM2-ES	
EC-EARTH	INMCM4	

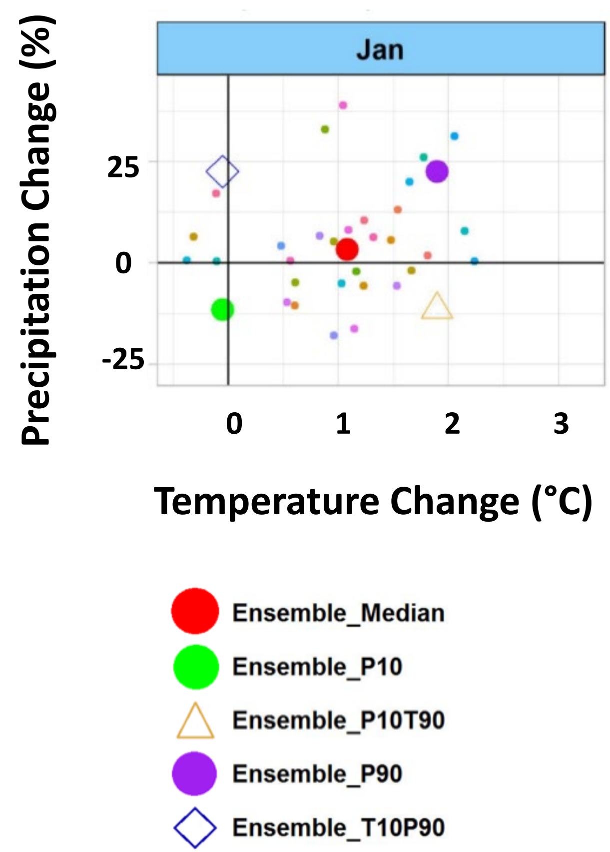
31 member ensemble

Data unavailable

GCM Used

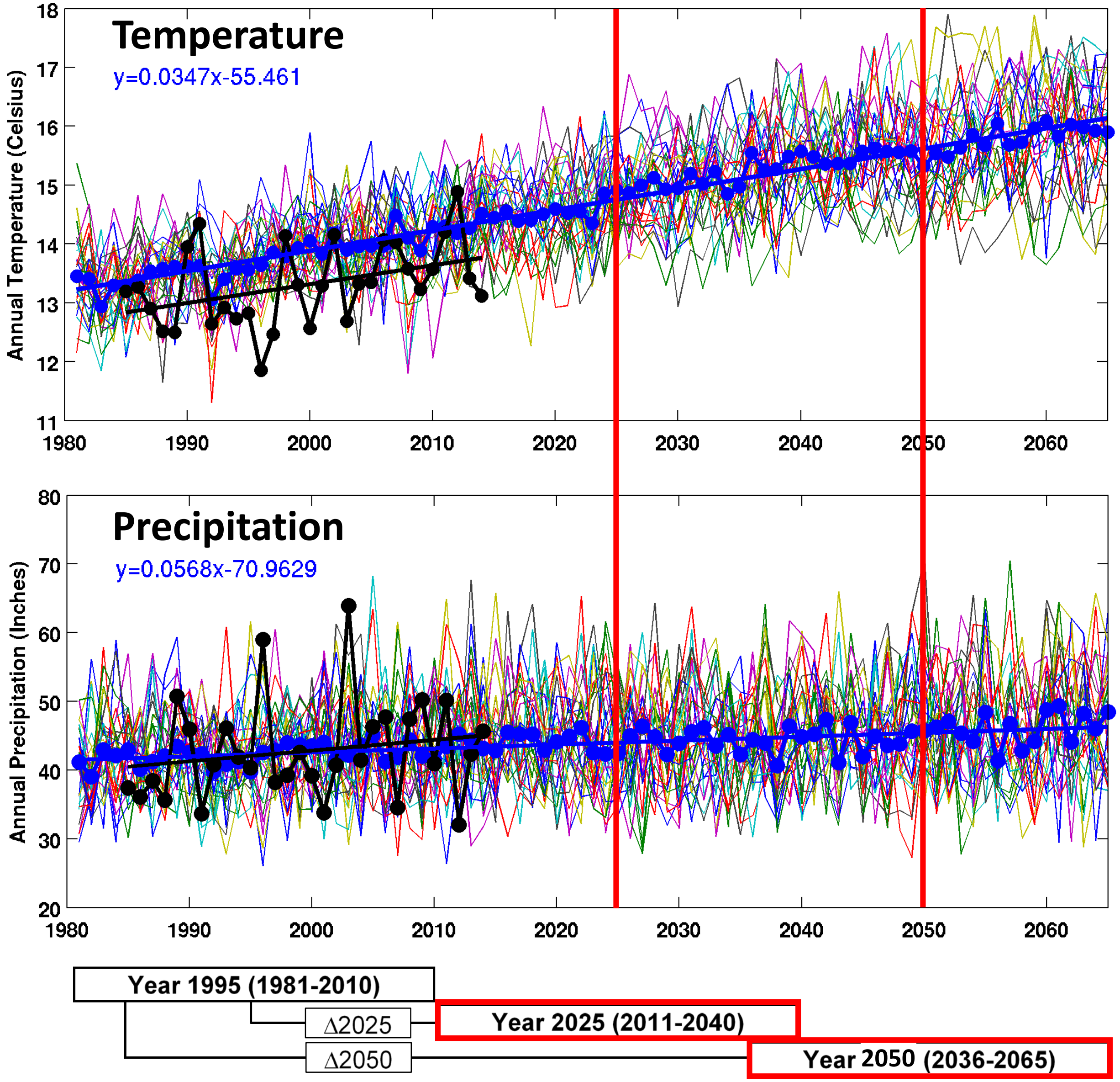
Selection updated

P90 – 90th percentile
P50 – median ensemble
P10 – 10th percentile



[1] Reclamation, 2013. 'Downscaled CMIP3 and CMIP5 Climate and Hydrology Projections: Release of Downscaled CMIP5 Climate Projections, Comparison with preceding Information, and Summary of User Needs', prepared by the U.S. Department of the Interior, Bureau of Reclamation, Technical Services Center, Denver, Colorado. 47pp.

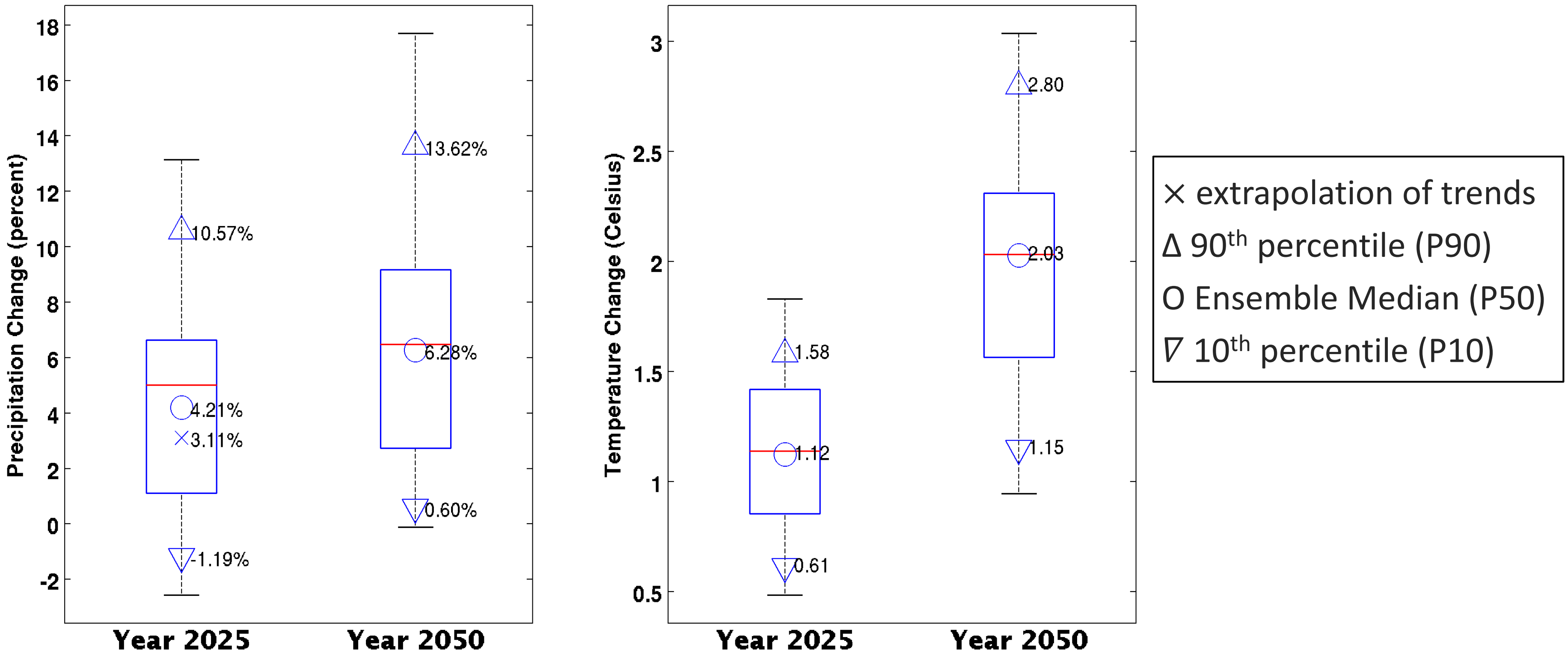
[1] BCSD – Bias Correction Spatial Disaggregation;
[1] CMIP5 – Coupled Model Intercomparison Project 5



Data shown for the District of Columbia for illustration.

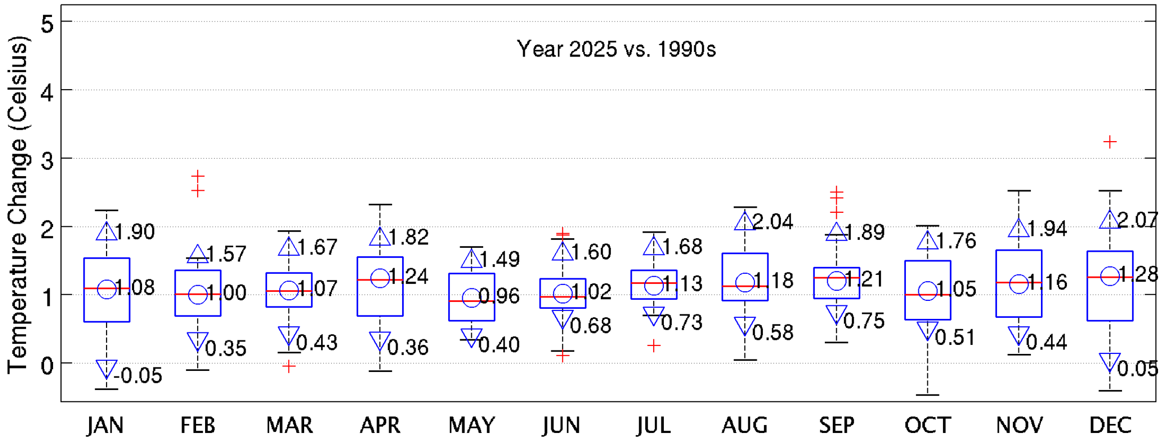
Average annual precipitation and temperature from the 31 bias-corrected downscaled global circulation models are shown for a land segment (N11001). Shown in blue line is the ensemble median. Data used in model calibration from NLDAS-2 are shown in black

Projected changes in precipitation and temperature (RCP 4.5) – *Average Annual*

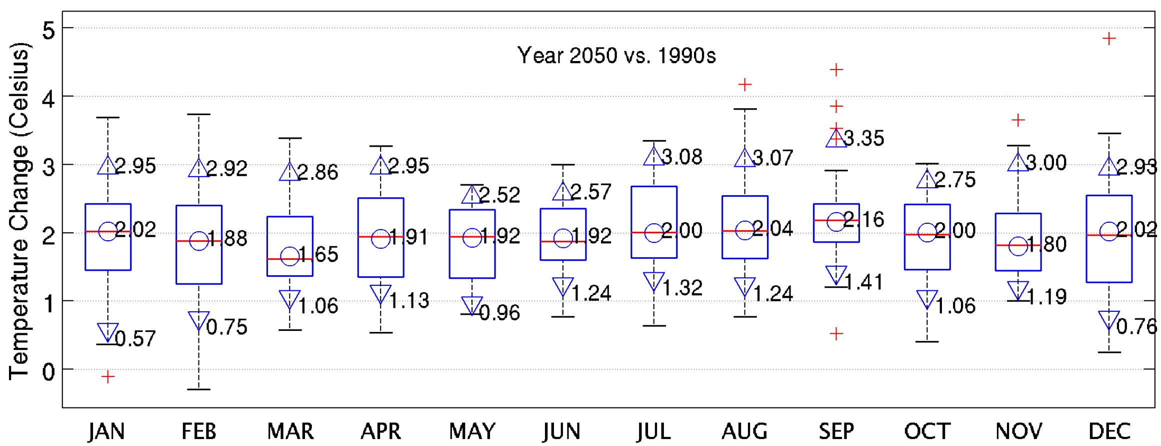


Summary of RCP4.5 average annual rainfall and temperature change for the Chesapeake Bay watershed are shown. Then range for 10th percentile (P10), ensemble median (P50), and 90th percentile (P90) are shown. The estimated change in rainfall volume based on the extrapolation of long-term trends are also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

Projected changes in temperature (RCP 4.5)



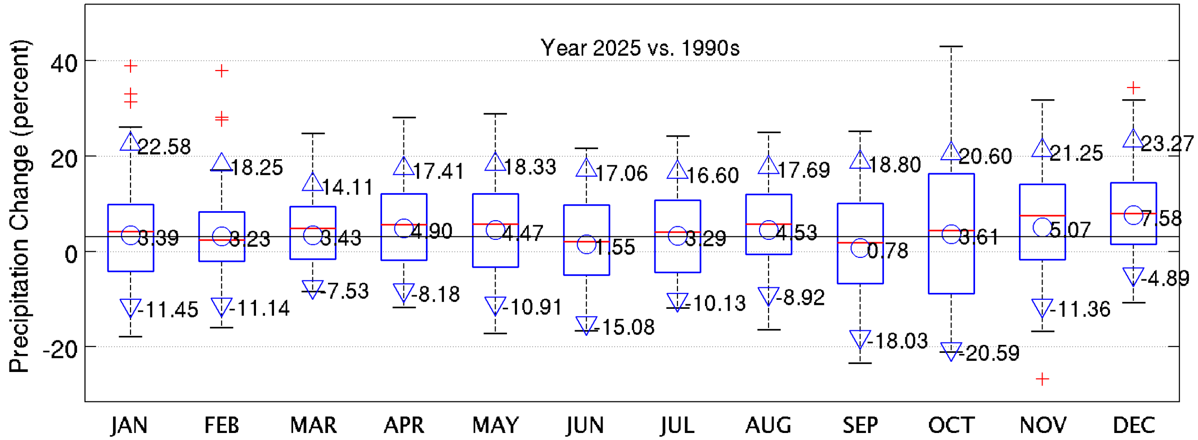
Watershed average of ensemble median is +1.12 ^{o}C



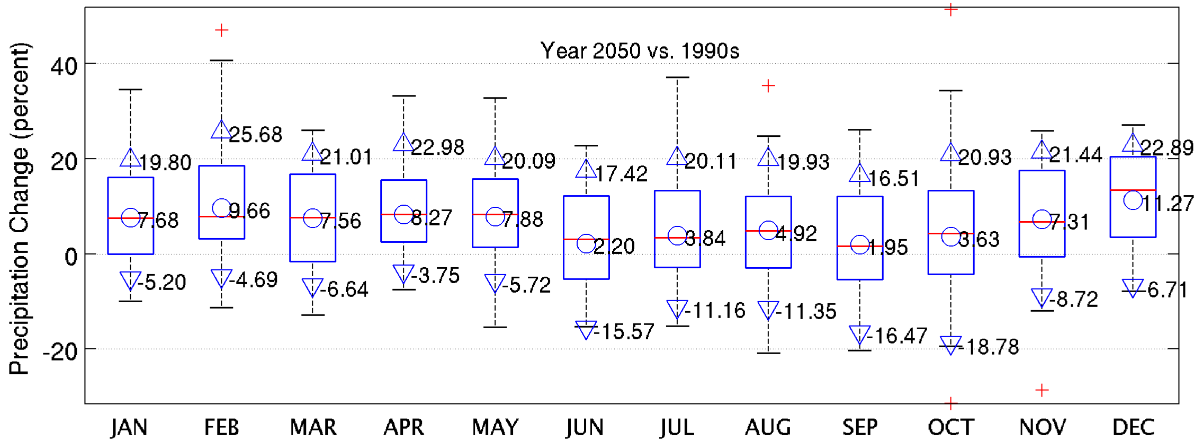
Watershed average of ensemble median is +2.02 ^{o}C

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.

Projected changes in precipitation (RCP 4.5)



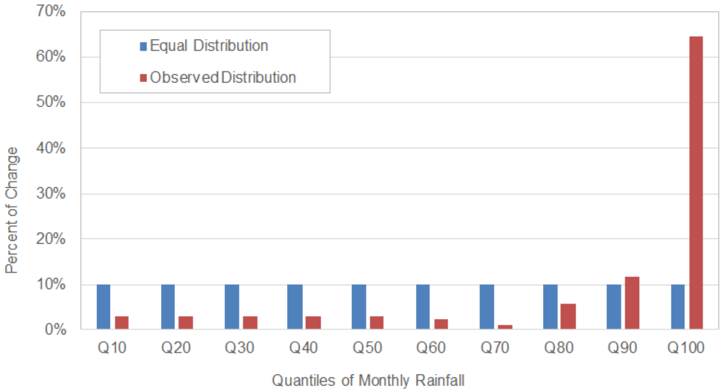
Watershed average of ensemble median is +4.21% *(+3.11% estimated using extrapolation of long term trend)*



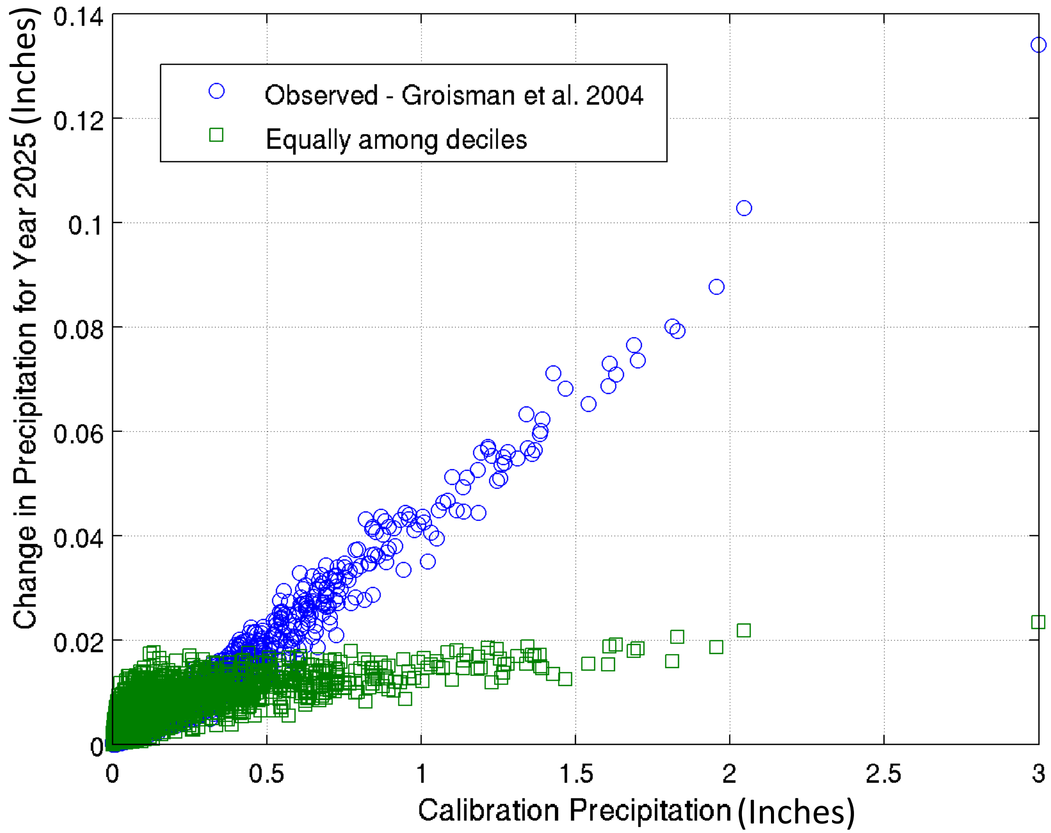
Watershed average of ensemble median is +6.28%

Monthly 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 10th percentile (P10), ensemble median (P50), and the 90th percentile (P90) bounds.

Monthly delta change to hourly events

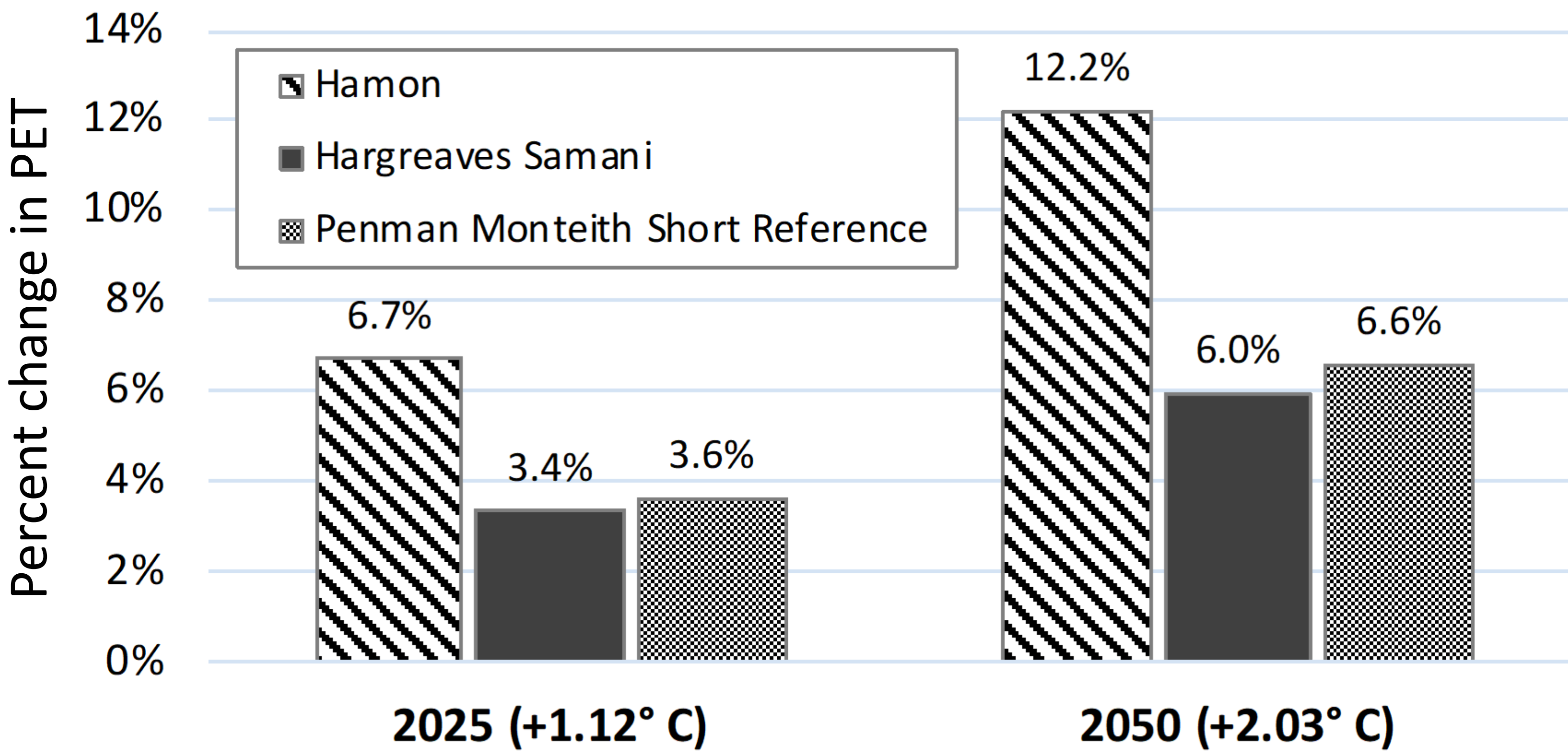


Observed changes in rainfall intensity over the last century (based on Figure 10 in Groisman et al. 2004). The equal allocation distribution (blue) is contrasted with the distribution obtained based on observed changes (red).



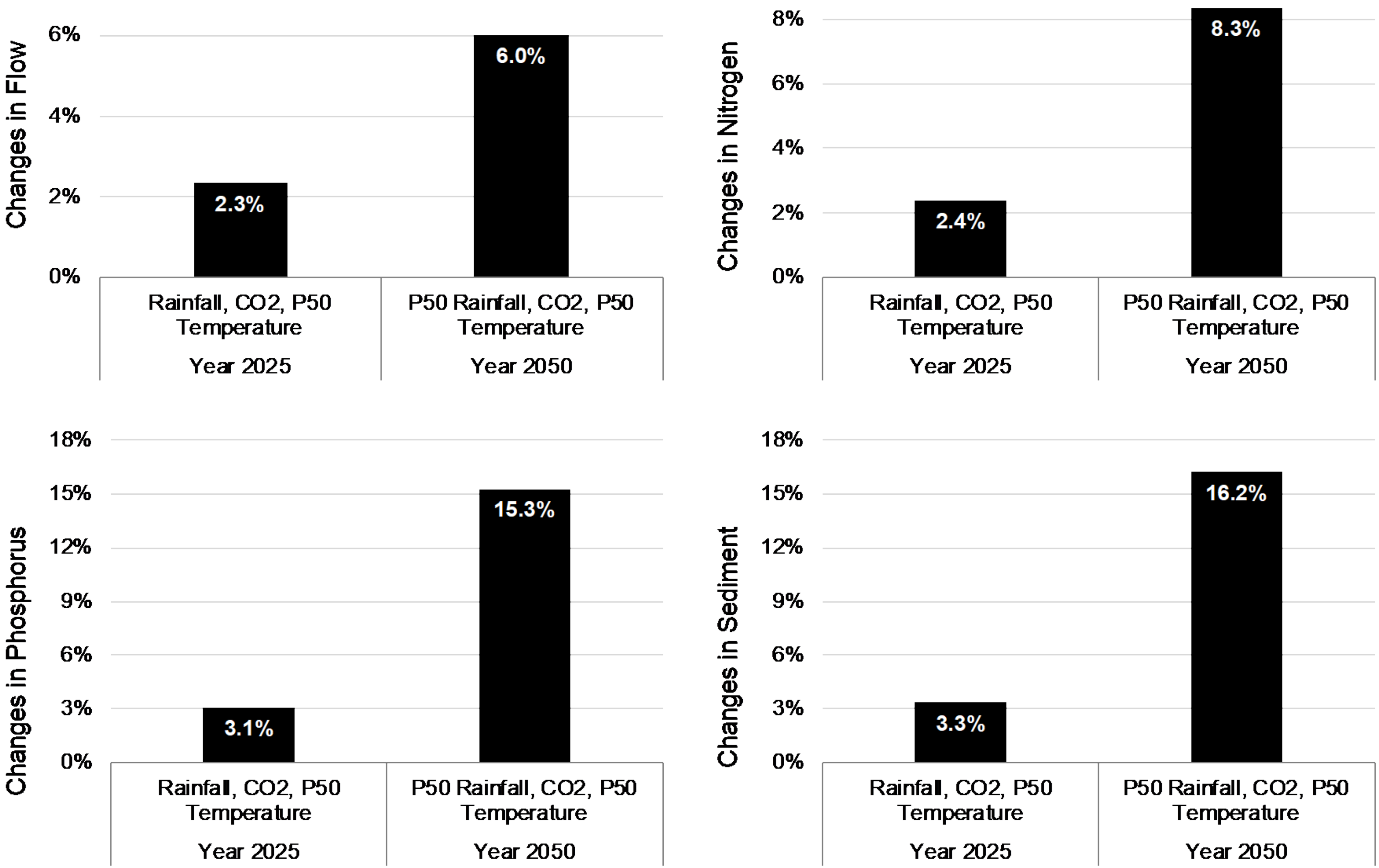
Additional rainfall added to the baseline daily rainfall over the 10-year period for a Phase 6 land segment (Potter, PA) is shown. In the method based on observed intensity trends, (Groisman et al. 2004) more volume is added to 10th decile resulting in higher intensity events become stronger.

Estimation of potential evapotranspiration (PET)



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



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

Period	Climate Change Scenario	Flow percent	Nitrogen percent	Phosphorus percent	Sediment percent
Year 2025	Trend rainfall, Ensemble 10%. temparature	4.8%	6.9%	11.6%	13.1%
	Trend rainfall, Ensemble median Temparature	2.3%	2.4%	3.1%	3.3%
	Trend rainfall, Ensemble 90%. temparature	0.0%	-0.6%	-1.6%	-1.8%
Year 2050	Ensemble 10%. rainfall & temparature	-18.3%	-18.3%	-21.9%	-25.6%
	Ensemble median rainfall & temparature	6.0%	8.3%	15.3%	16.2%
	Ensemble 90%. rainfall & temparature	36.9%	183.9%	588.3%	219.3%

Trend: *projection of extrapolation of long-term trends*
Ensemble: *31-member ensemble of RCP4.5 GCMs*

RCP 8.5
2025 vs. 1995

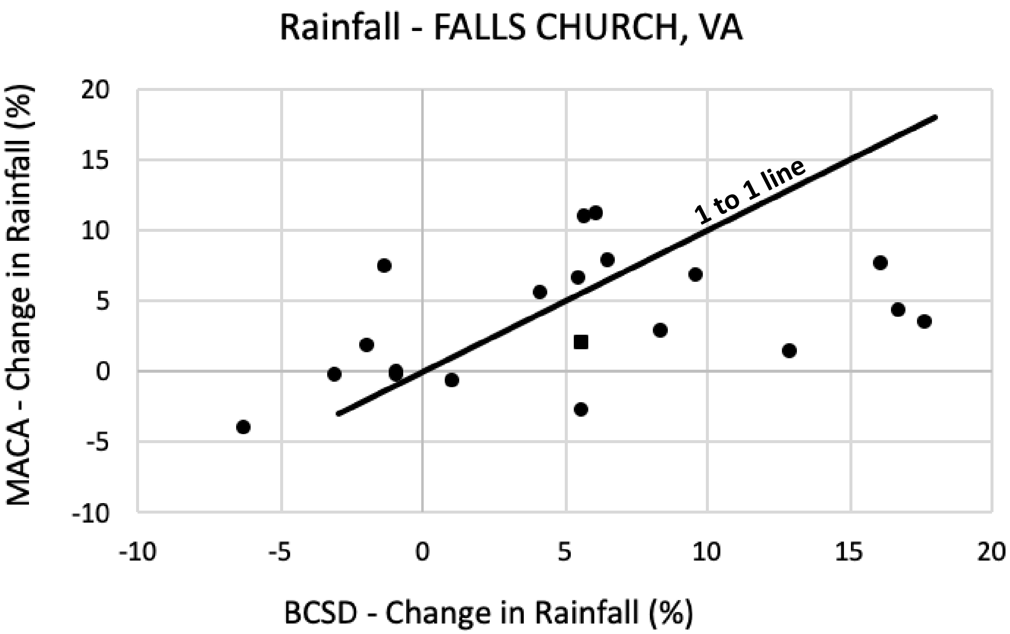


Figure shows delta % change in annual rainfall volume from 19 matching GCMs after downscaling.

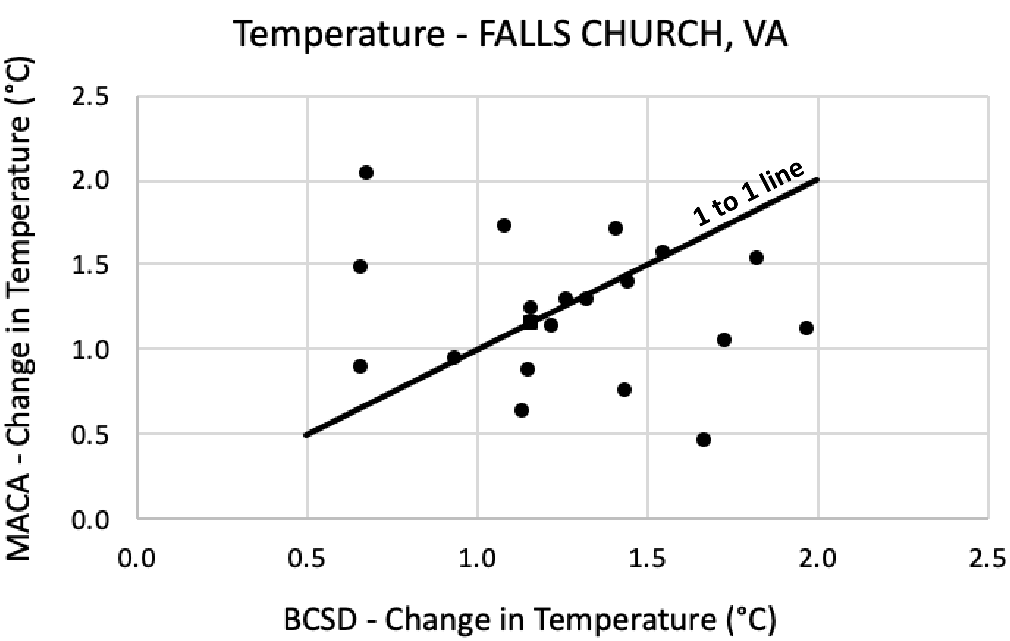


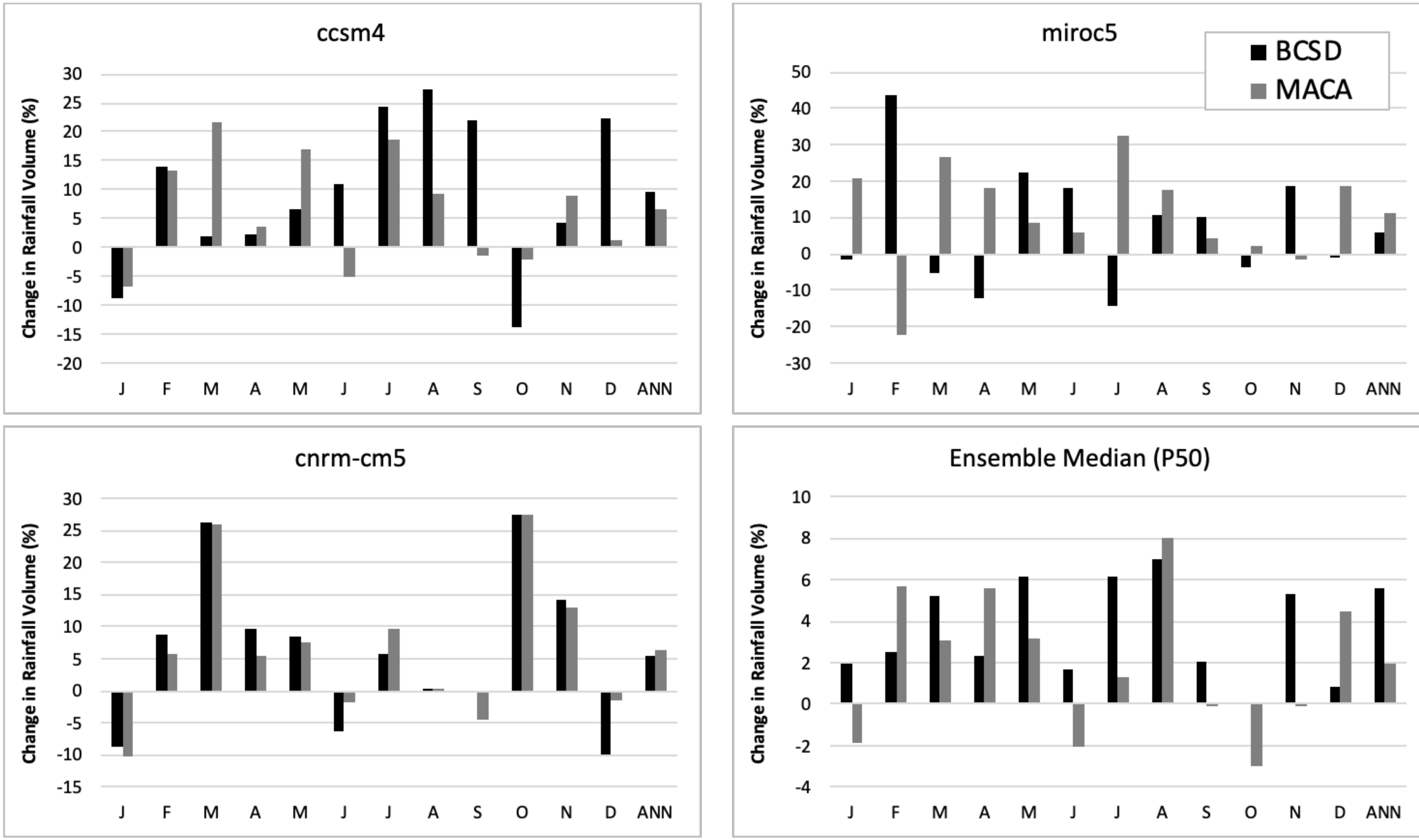
Figure shows delta degree Celsius change for temperature from 19 matching GCMs after downscaling.

Falls Church, VA – Rainfall

CHAMP Assessment
2019 Assessment

RCP 8.5

2025 vs. 1995

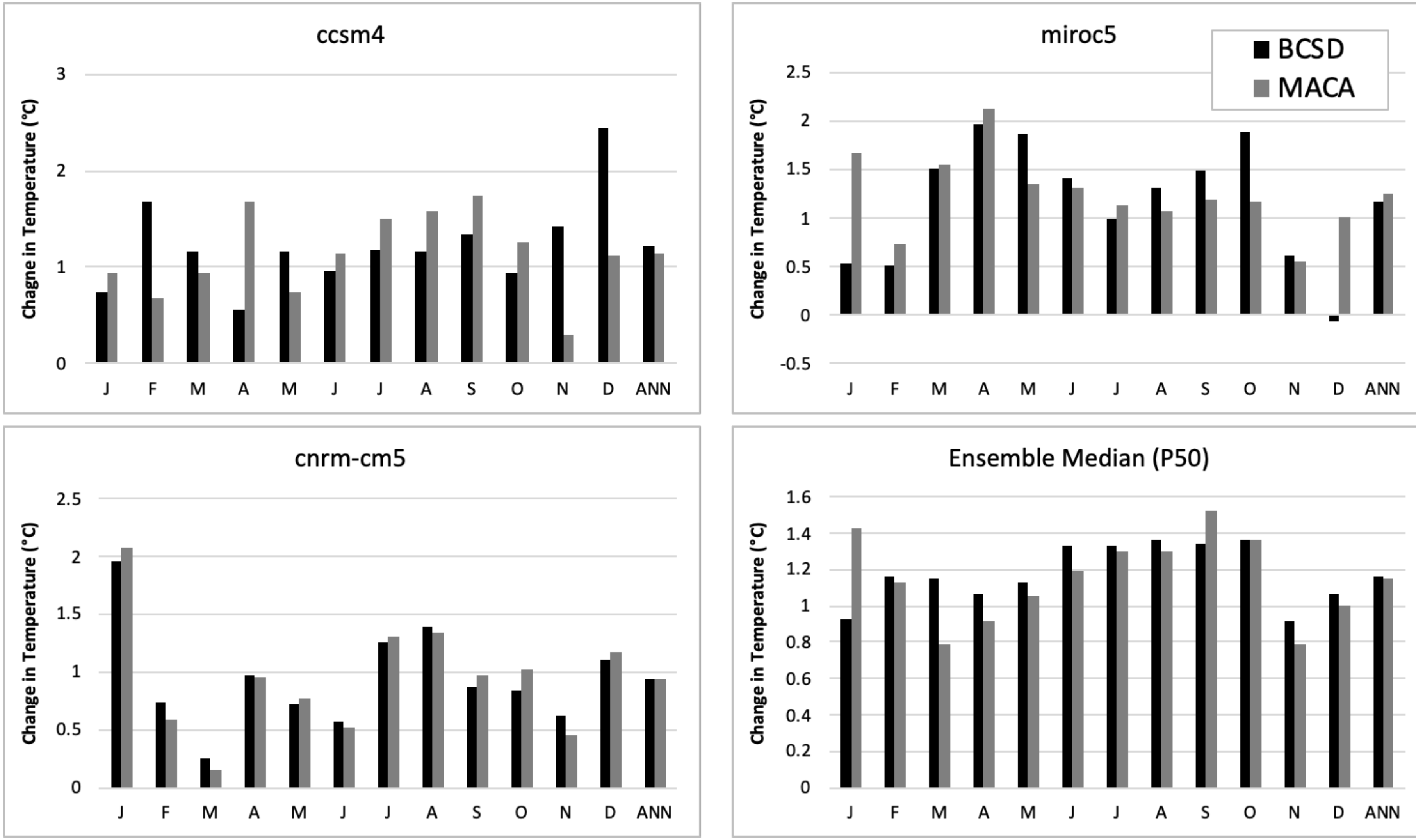


Falls Church, VA – Temperature

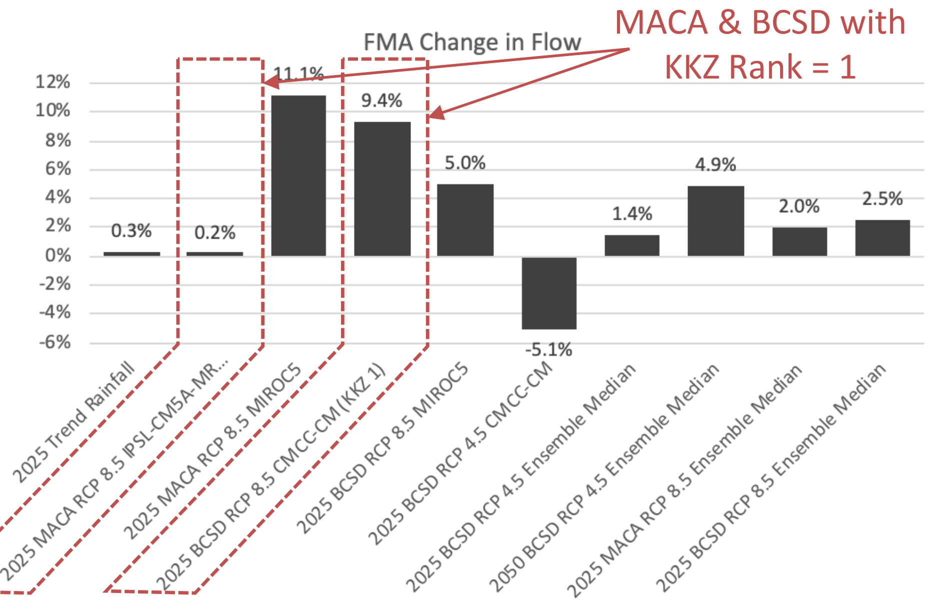
CHAMP Assessment
2019 Assessment

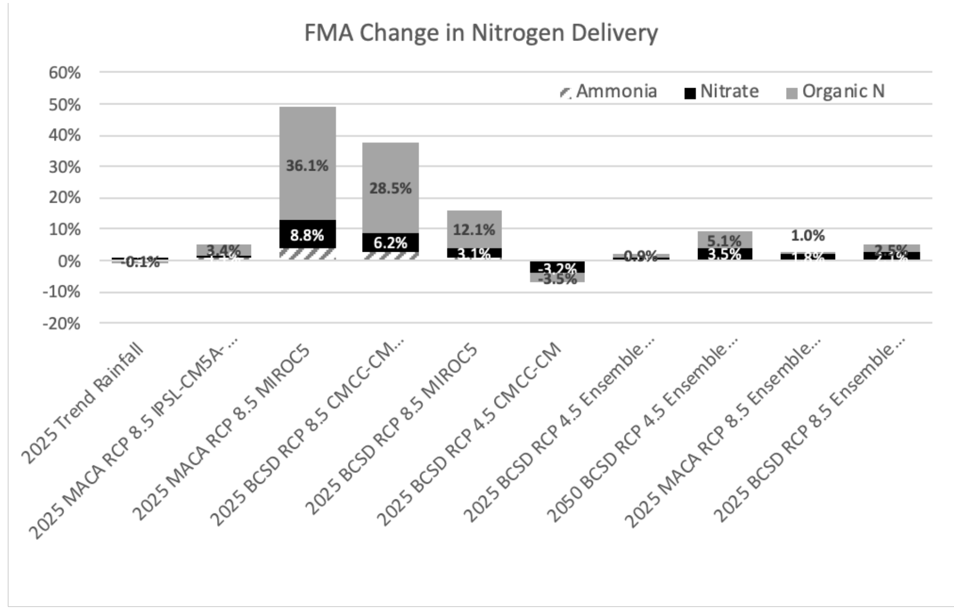
RCP 8.5

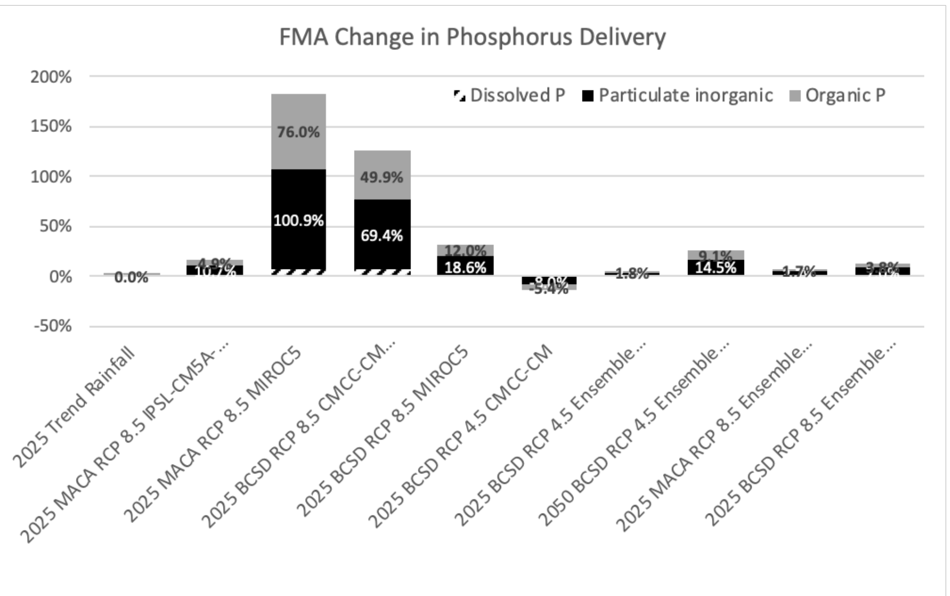
2025 vs. 1995

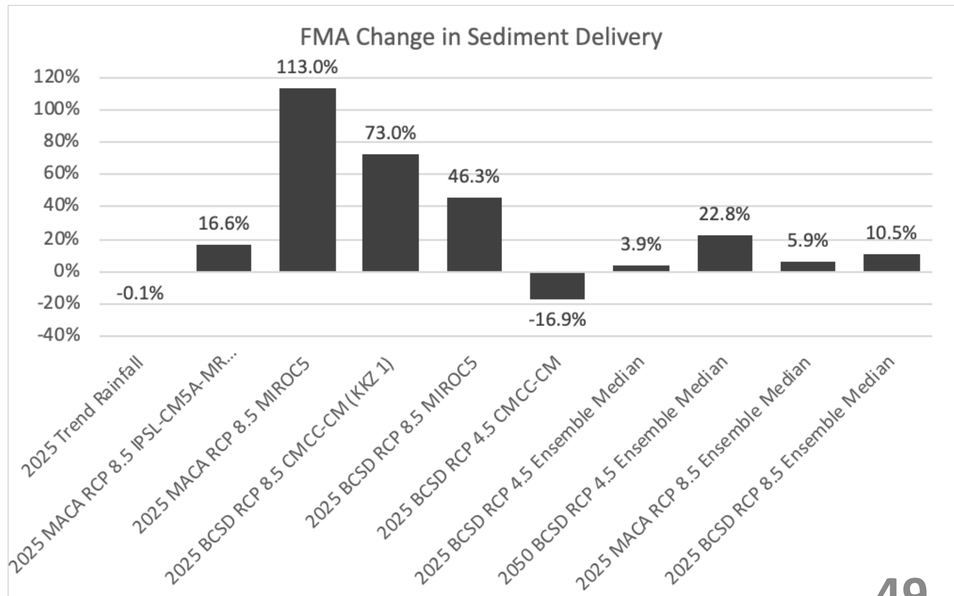


CBP Watershed Model results – Feb+Mar+Apr









Input change vs. simulated flow response