

Application of Phase 6 Watershed Model to Climate Change Assessment

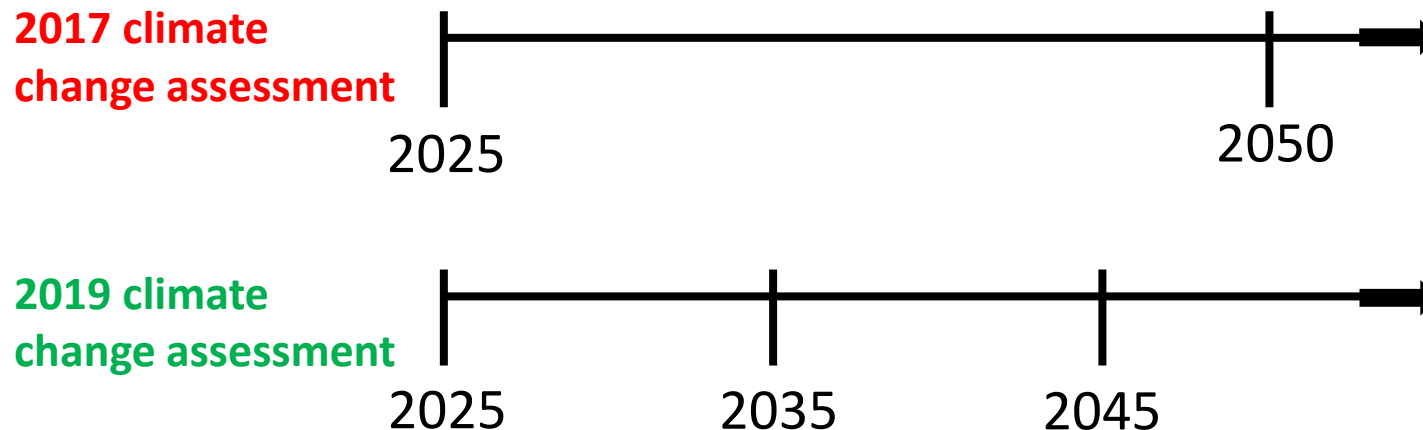
Modeling Workgroup Quarterly Meeting – October 2018

Gopal Bhatt¹ and Lewis Linker²

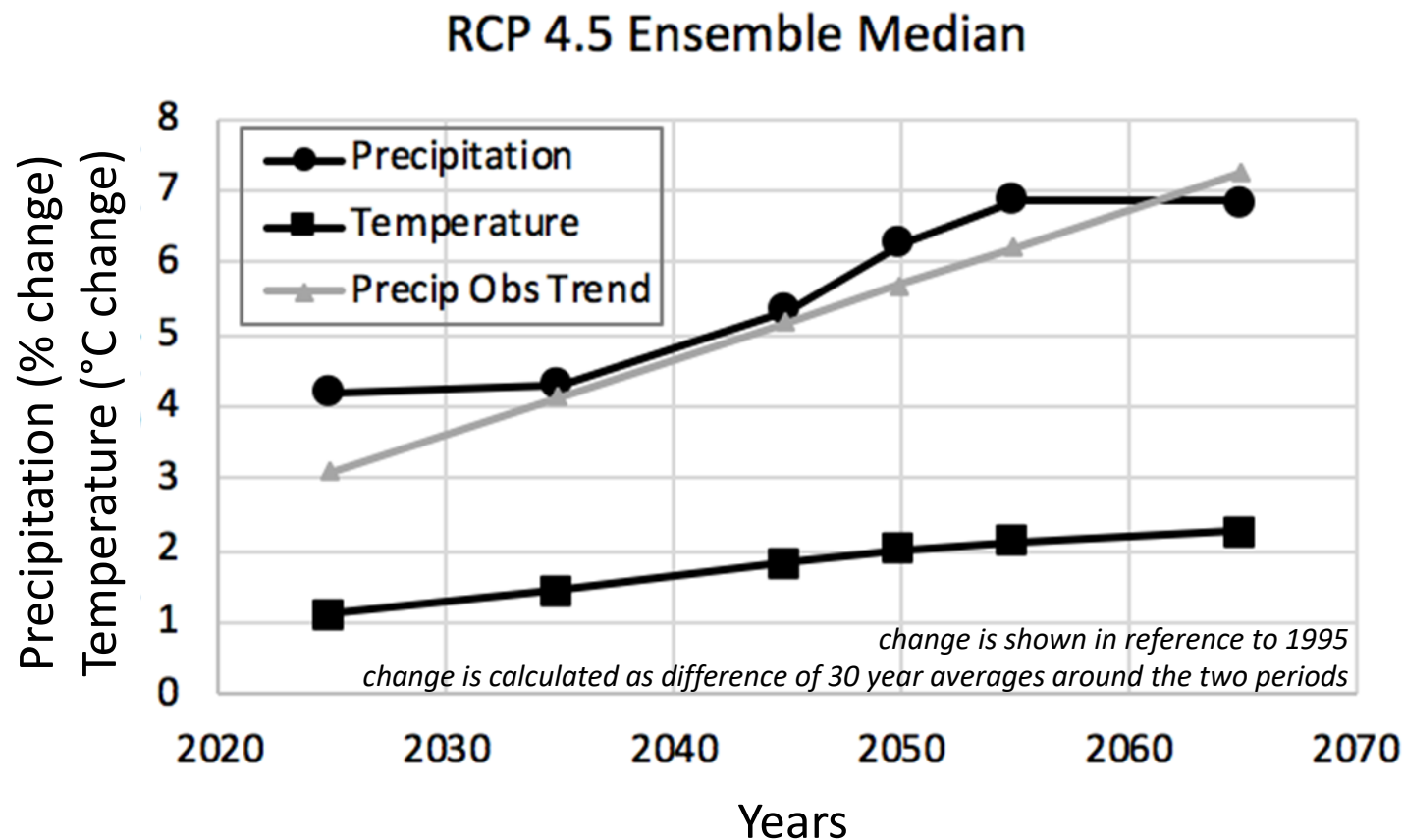
¹ Penn State, ² US EPA

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



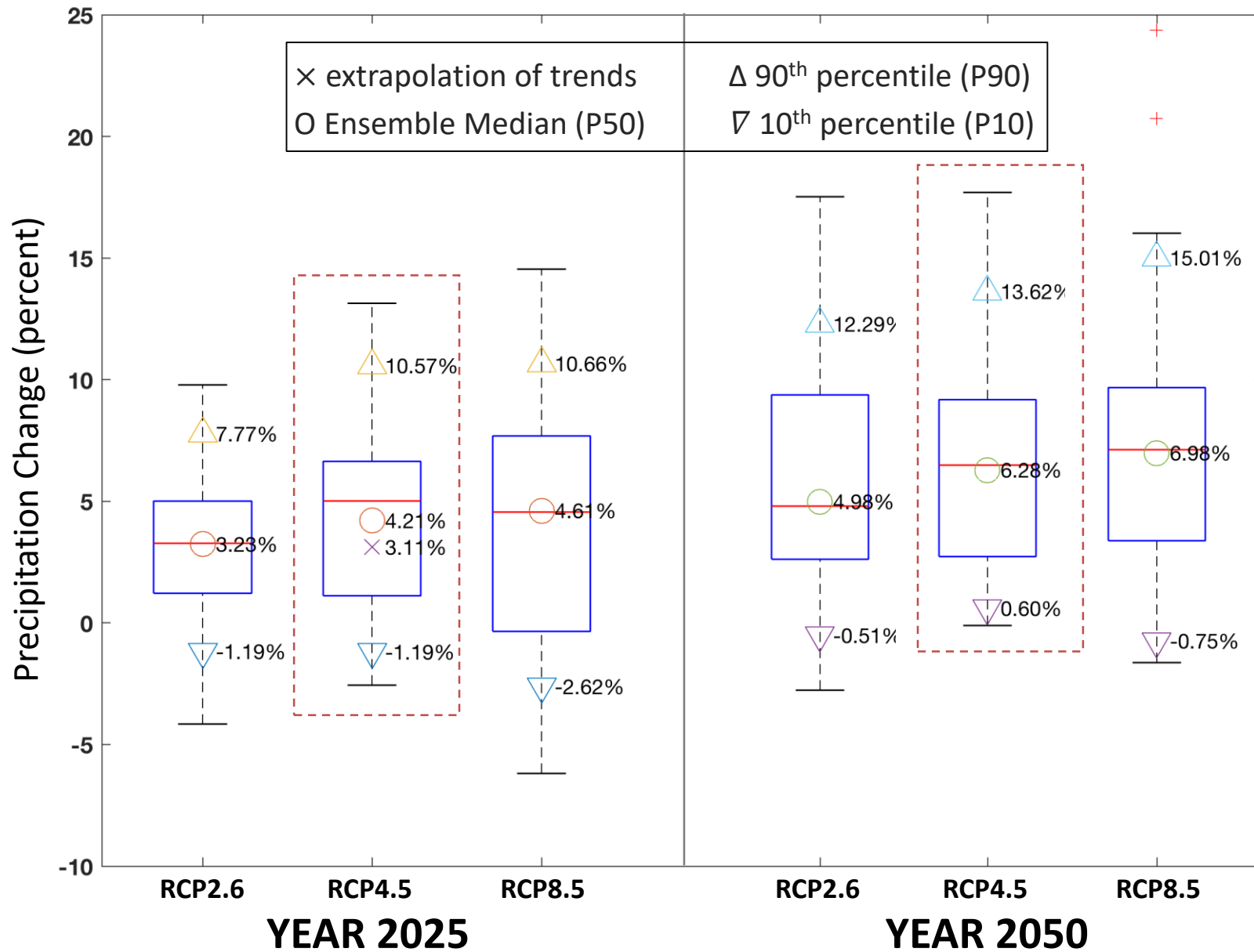
Summary of precipitation and temperature



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

Ensemble: 31-member ensemble of RCP4.5 GCMs

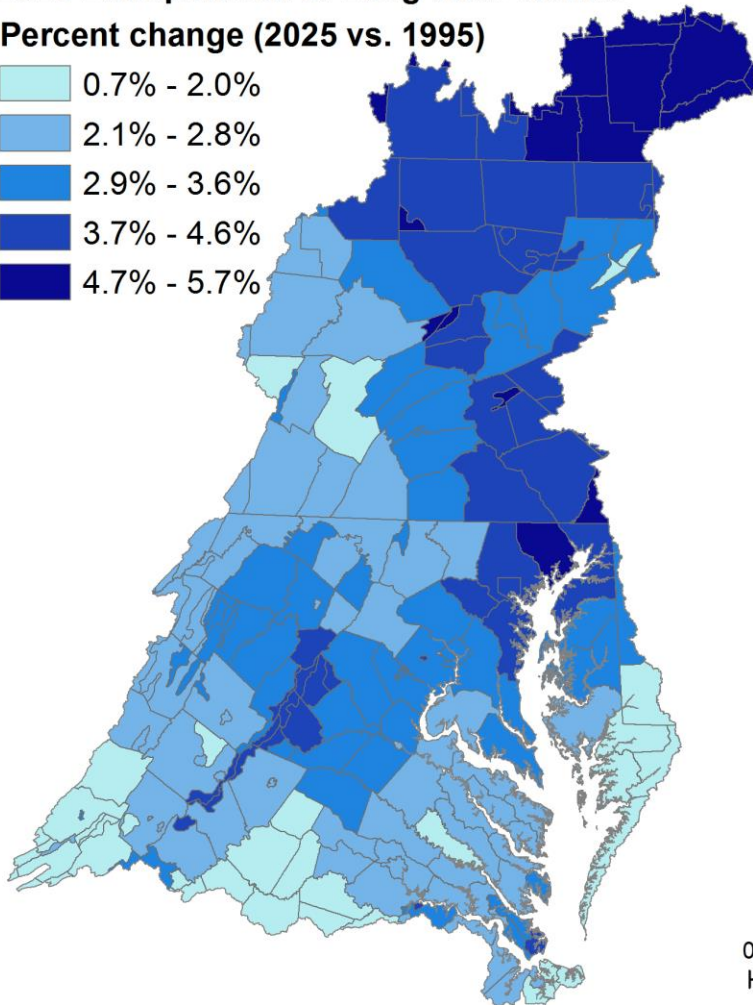
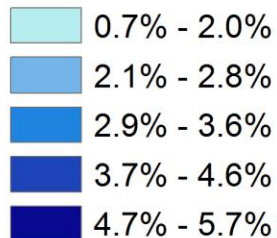
Summary of precipitation change



YEAR 2025

2025 Extrapolation of Long-term Trends

Percent change (2025 vs. 1995)

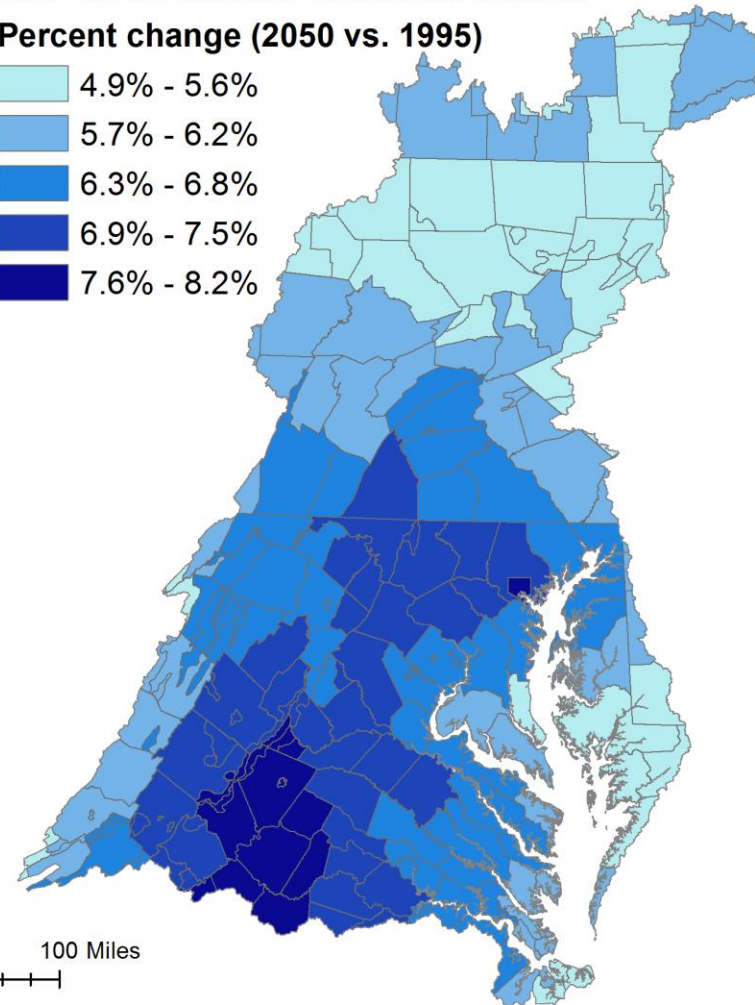
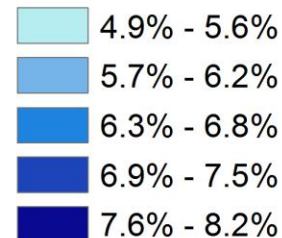


**3.11% increase in average
annual rainfall volume**

YEAR 2050

RCP 4.5 31 Member Ensemble Median

Percent change (2050 vs. 1995)



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

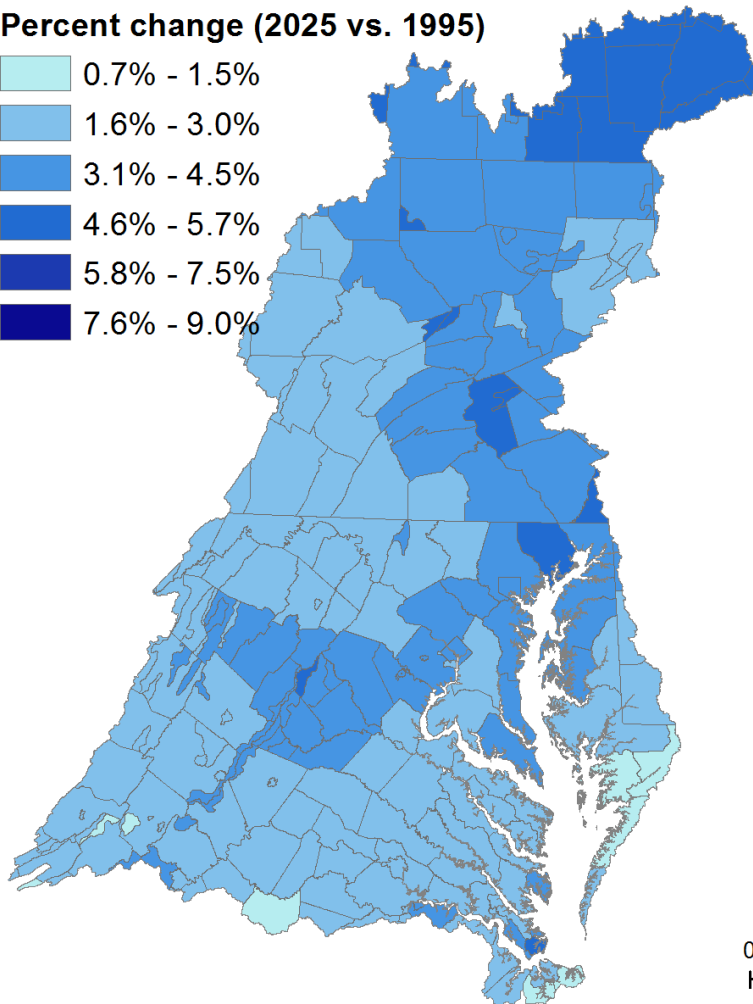
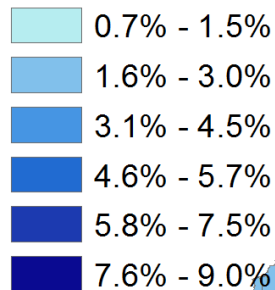


0 25 50 100 Miles

YEAR 2025

2025 Extrapolation of Long-term Trends

Percent change (2025 vs. 1995)

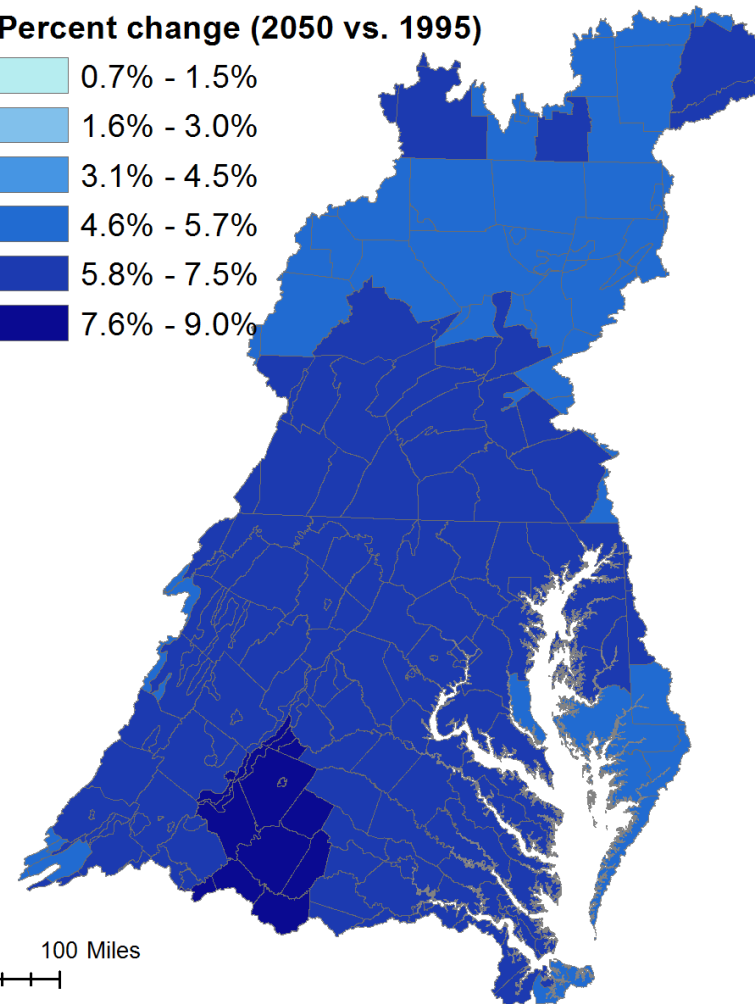
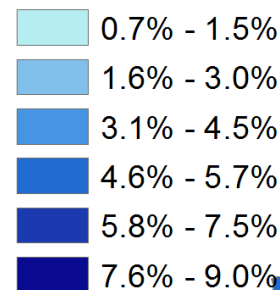


**3.11% increase in average
annual rainfall volume**

YEAR 2050

RCP 4.5 31 Member Ensemble Median

Percent change (2050 vs. 1995)



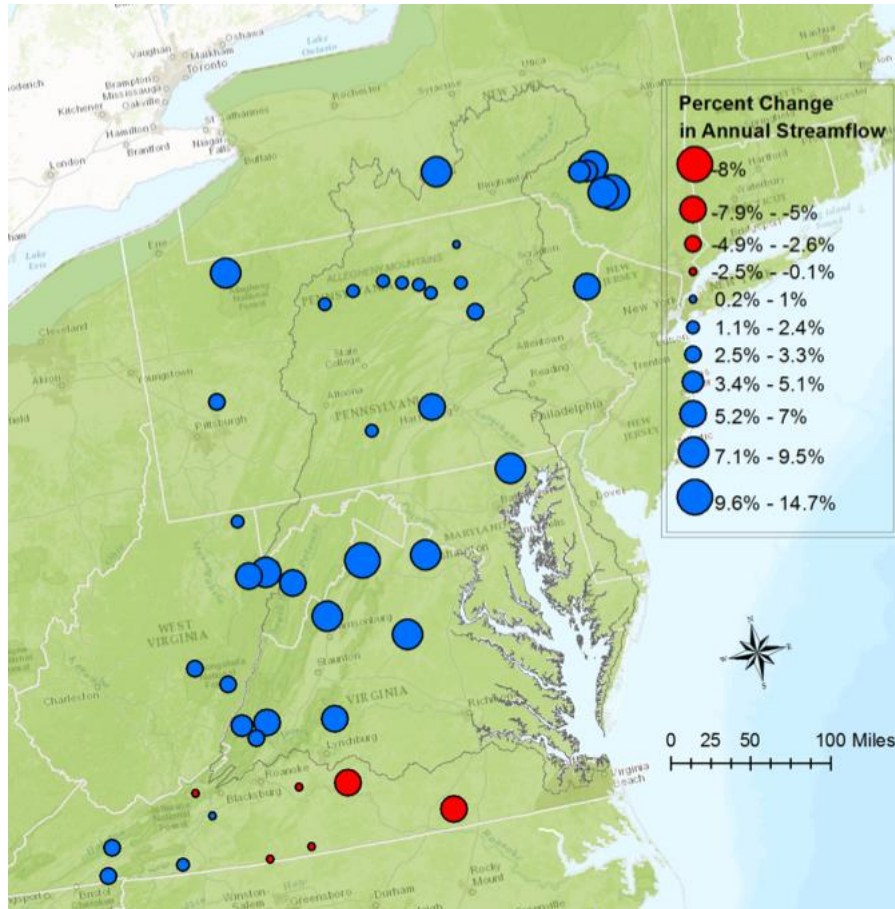
**6.28% increase in average
annual rainfall volume**



0 25 50 100 Miles

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]

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

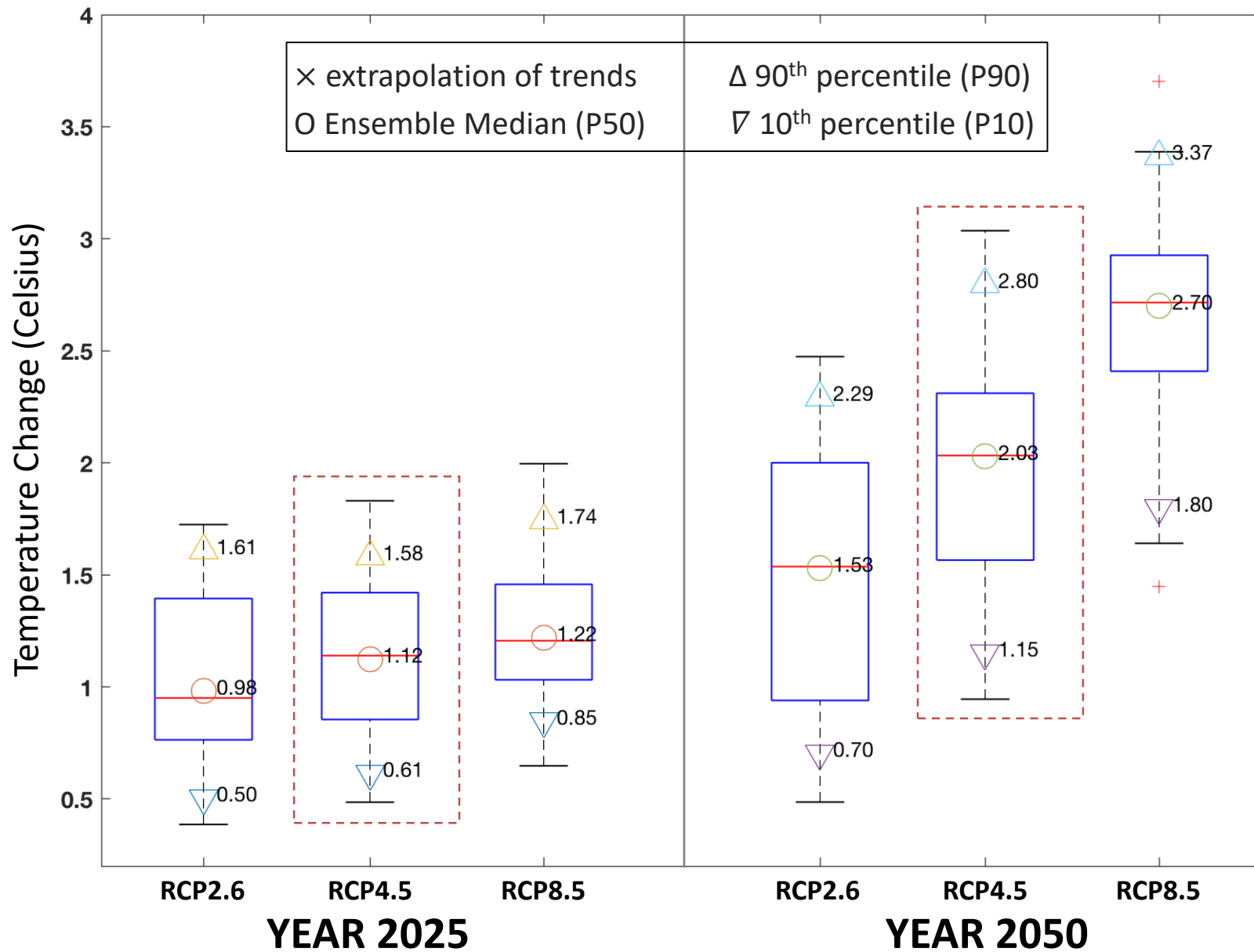
01562000	0.0004	0.1693	0.0007	0.2082
01638500	0.0004	0.1150	0.0008	0.1026
01608500	0.0004	0.1725	0.0010	0.0833
01636500	0.0005	0.1245	0.0008	0.0624
01606500	0.0003	0.1958	0.0009	0.1108
01668000	0.0006	0.0794	0.0004	0.4727
02035000	0.0003	0.2653	-0.0001	0.8243
02019500	0.0002	0.4333	0.0003	0.4836
03488000	0.0003	0.2480	0.0006	0.2841

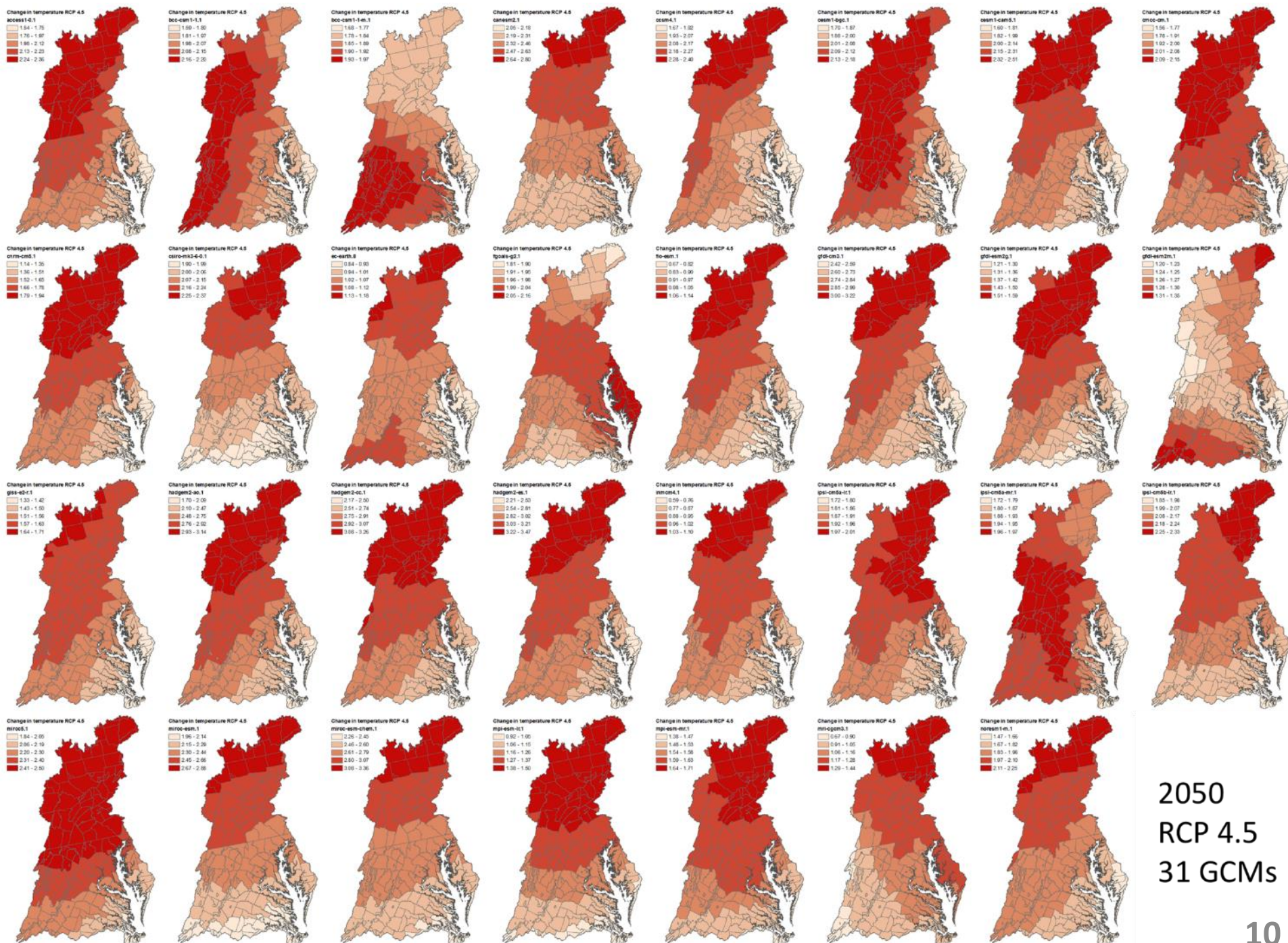
Karen C. Rice, Douglas L. Moyer, and Aaron L. Mills, 2017. Riverine discharges to Chesapeake Bay: Analysis of long-term (1927 - 2014) records and implications for future flows in the Chesapeake Bay basin *JEM* 204 (2017) 246-254

[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



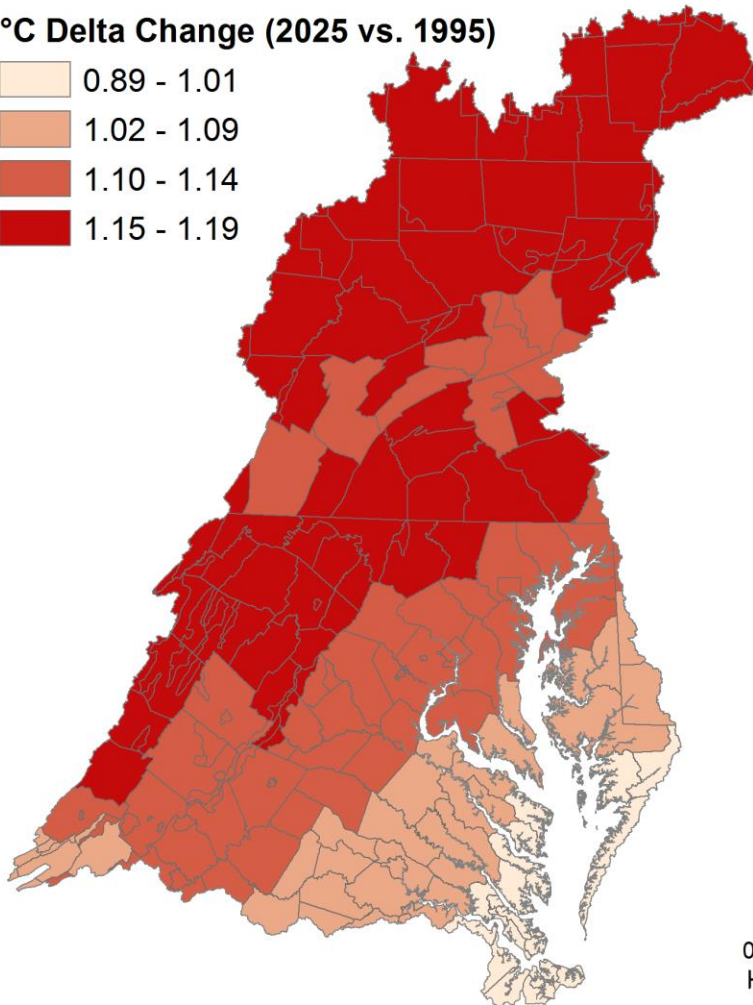
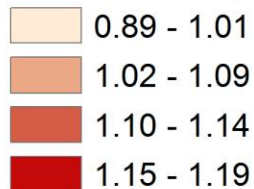


2050
RCP 4.5
31 GCMs

YEAR 2025

RCP 4.5 31 Member Ensemble Median

°C Delta Change (2025 vs. 1995)

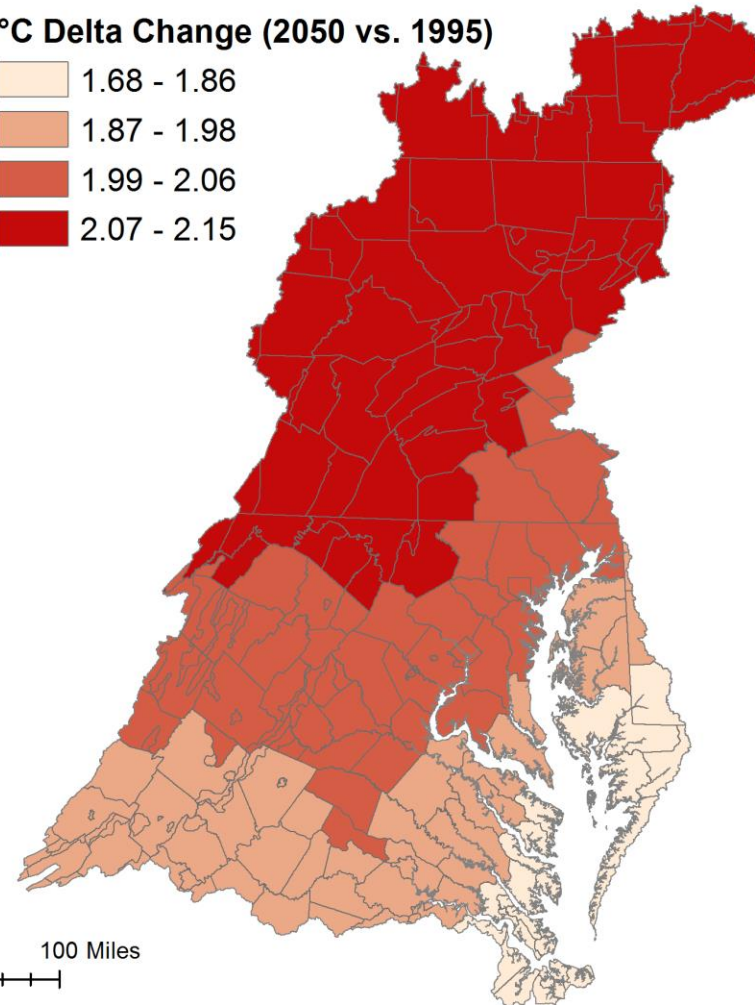
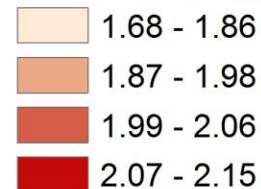


**1.12°C increase in average
annual temperature**

YEAR 2050

RCP 4.5 31 Member Ensemble Median

°C Delta Change (2050 vs. 1995)



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

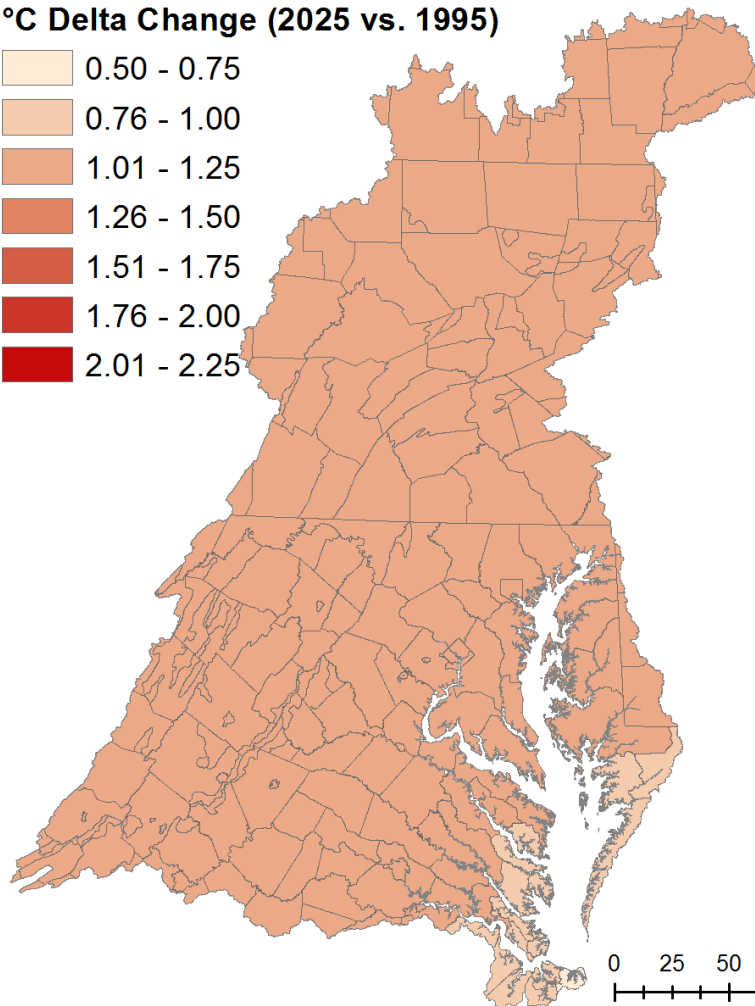
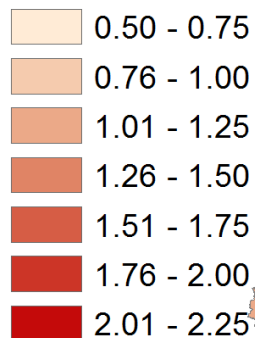


0 25 50 100 Miles

YEAR 2025

RCP 4.5 31 Member Ensemble Median

°C Delta Change (2025 vs. 1995)

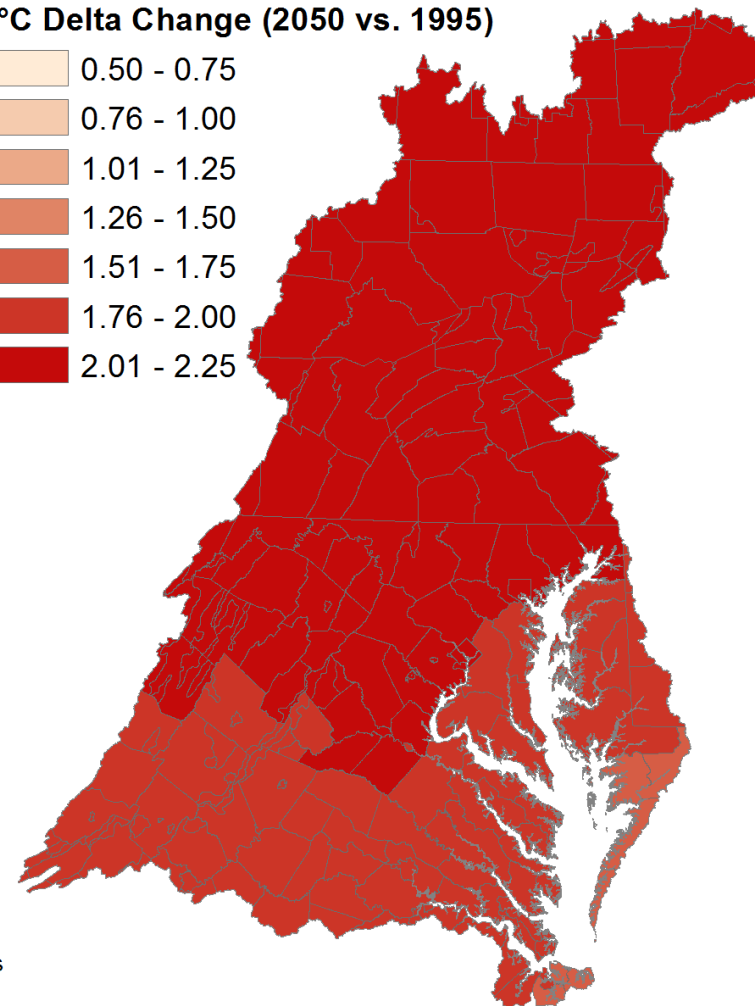
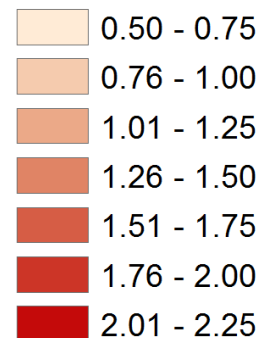


**1.12°C increase in average
annual temperature**

YEAR 2050

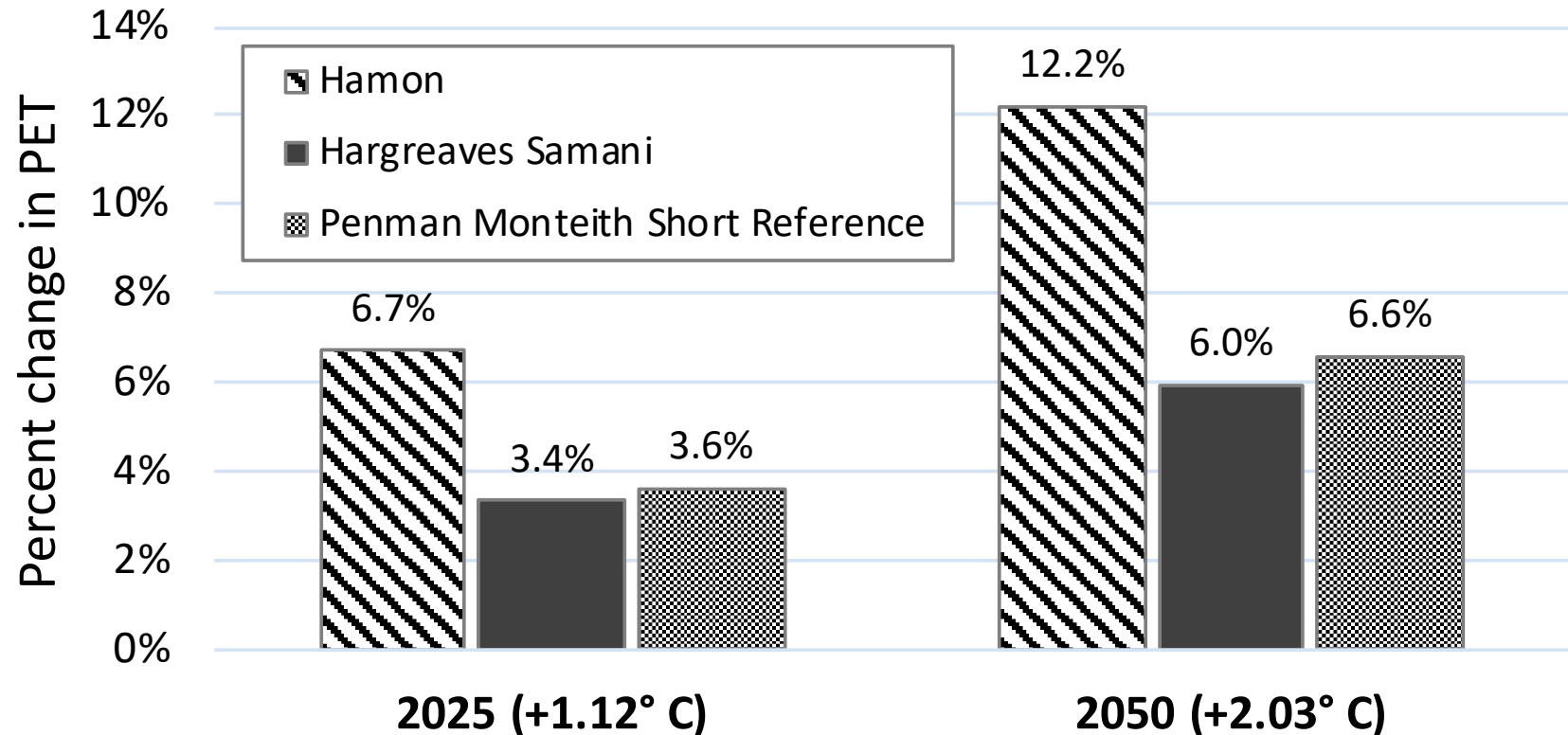
RCP 4.5 31 Member Ensemble Median

°C Delta Change (2050 vs. 1995)



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

Estimation of potential evapotranspiration (PET)

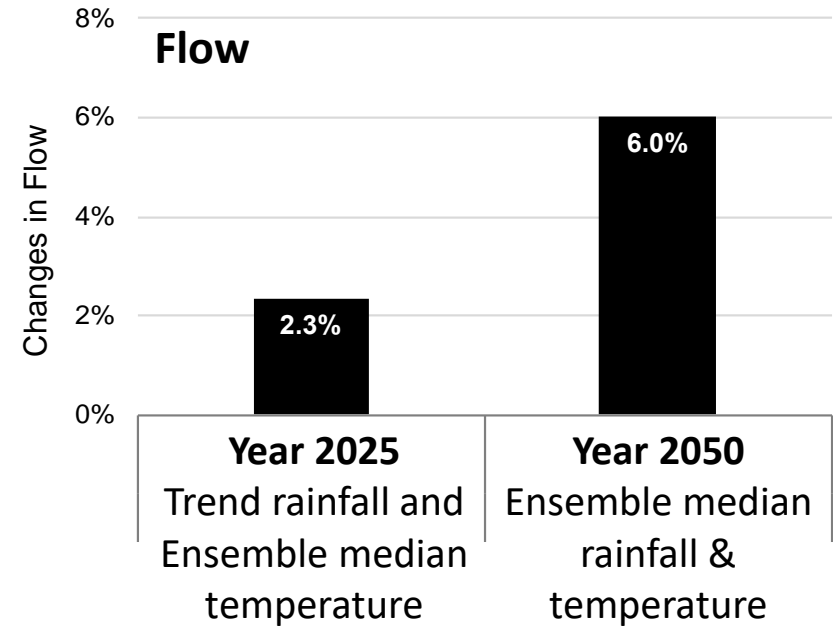
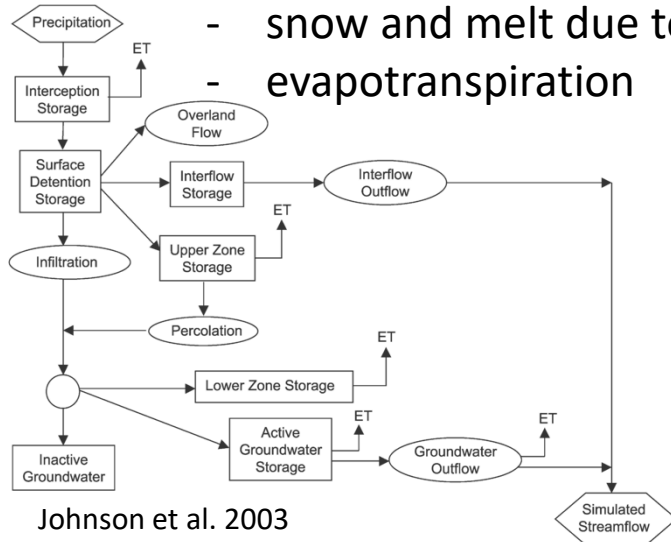


The difference in PET using the Hamon and Hargreaves-Samani methods are shown. For 2025, the Hamon method estimated an increase in PET that was 3.36% greater than that from Hargreaves-Samani method. The change was even more pronounced for 2050, where PET estimated by Hamon method 6.26 percent greater 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

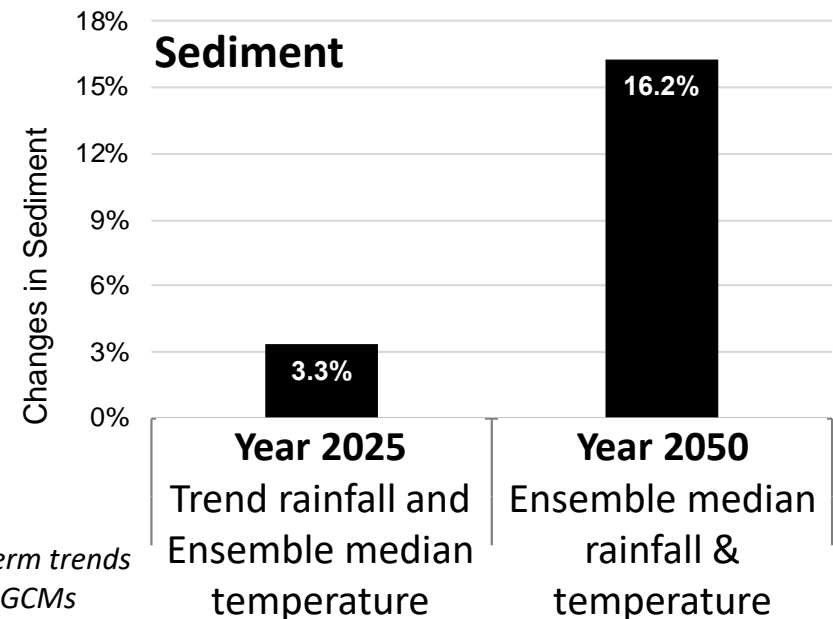
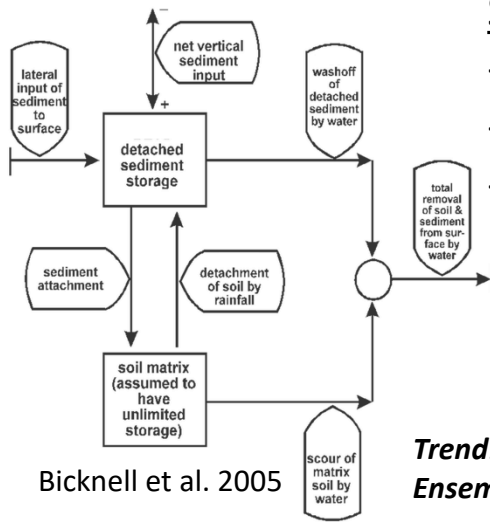
Hydrologic response:

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



Sediment response:

- rainfall intensity
- surface runoff
- riverine scour and deposition

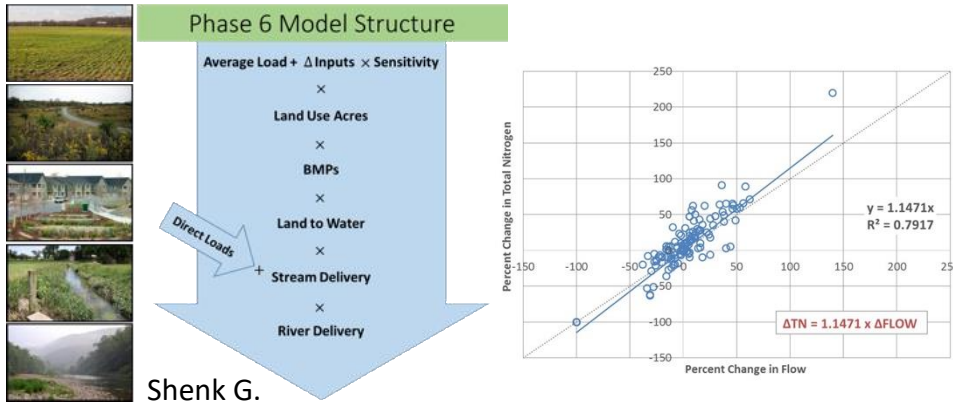


Trend: projection of extrapolation of long-term trends
Ensemble: 31-member ensemble of RCP4.5 GCMs

Summary of changes in delivery

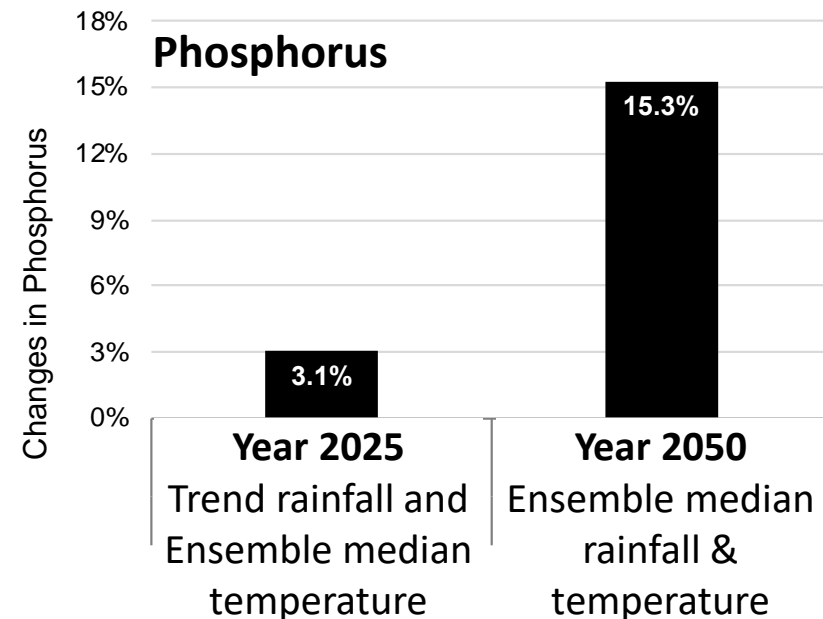
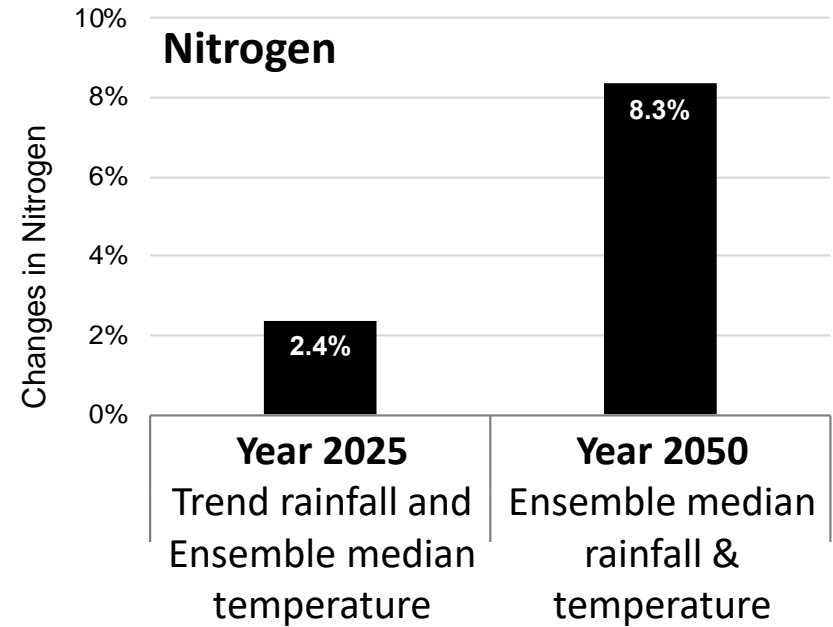
Nitrogen response:

- 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)

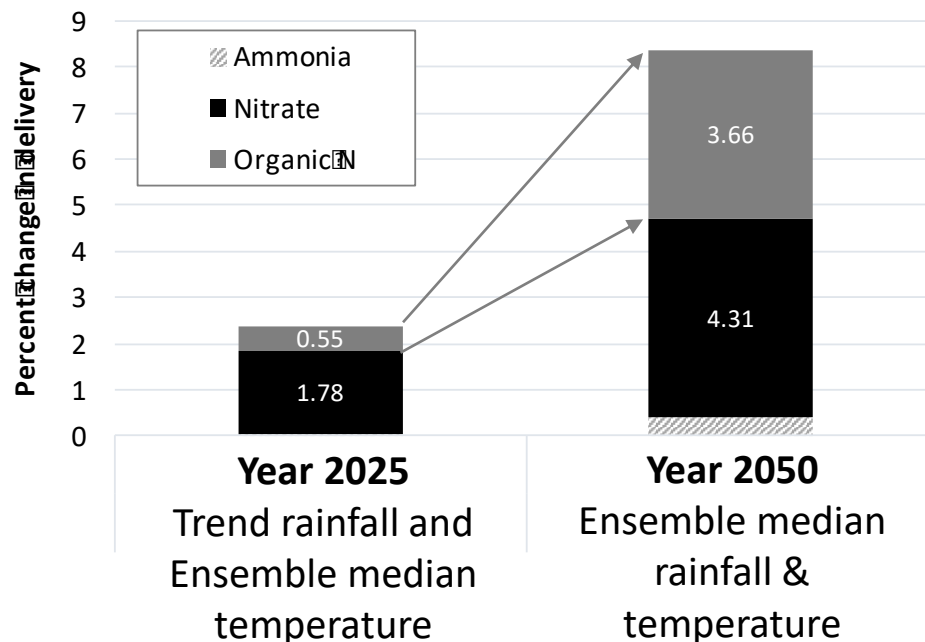


Trend: projection of extrapolation of long-term trends

Ensemble: 31-member ensemble of RCP4.5 GCMs

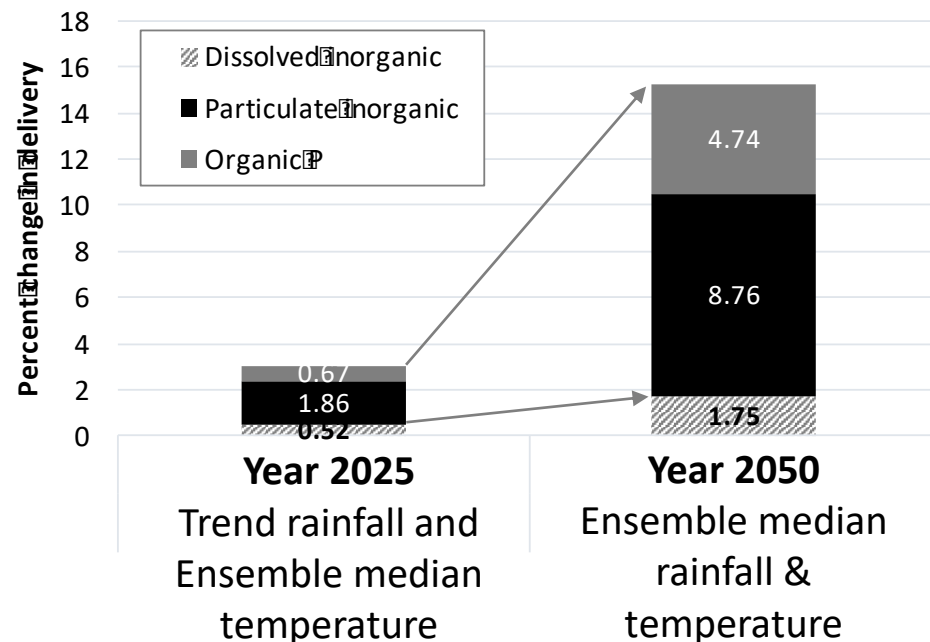
Nitrogen and phosphorus species

Simulated changes in nitrogen delivery



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

Simulated changes in phosphorus delivery



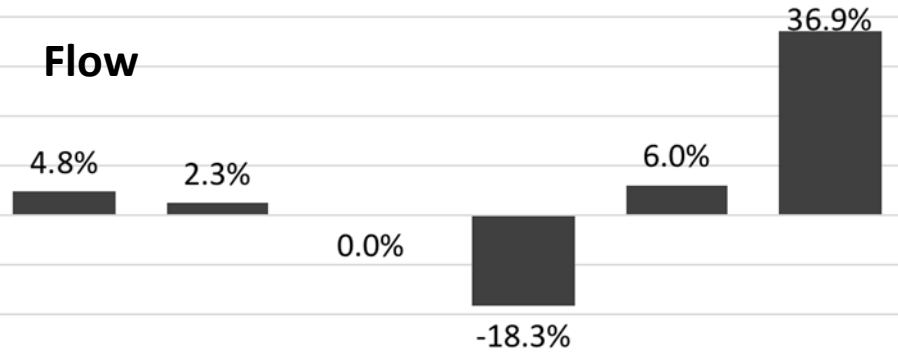
Arrows show relatively more increase in particulate phosphorus as compared to dissolved inorganic phosphorus.

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

Trend rainfall, Ensemble median
temperature

Trend rainfall, Ensemble 90%
temperature

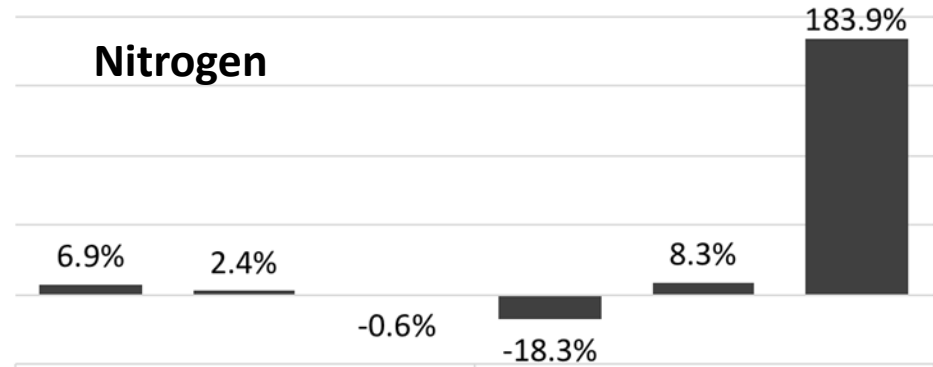
Year 2050

Ensemble 10% rainfall & temperature

Ensemble median rainfall & temperature

Ensemble 90% rainfall & temperature

Nitrogen



Year 2025

Trend rainfall, Ensemble 10%
temperature

Trend rainfall, Ensemble median
temperature

Trend rainfall, Ensemble 90%
temperature

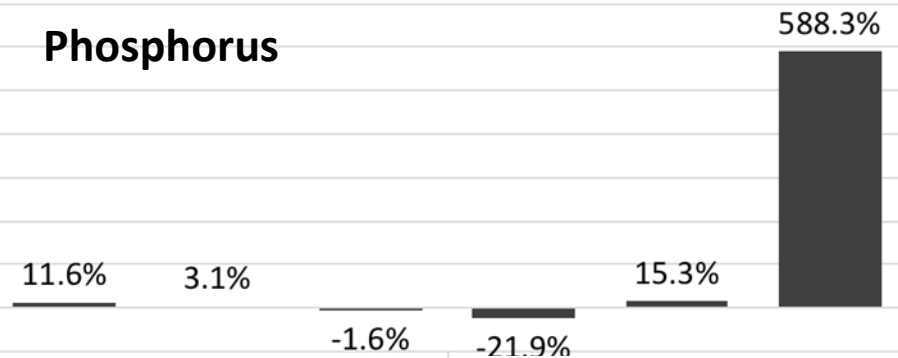
Year 2050

Ensemble 10% rainfall & temperature

Ensemble median rainfall & temperature

Ensemble 90% rainfall & temperature

Phosphorus



Year 2025

Trend rainfall, Ensemble 10%
temperature

Trend rainfall, Ensemble median
temperature

Trend rainfall, Ensemble 90%
temperature

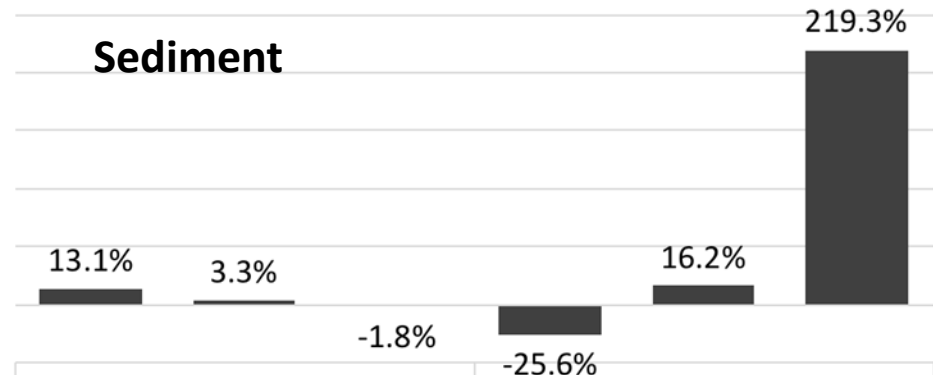
Year 2050

Ensemble 10% rainfall & temperature

Ensemble median rainfall & temperature

Ensemble 90% rainfall & temperature

Sediment



Year 2025

Trend rainfall, Ensemble 10%
temperature

Trend rainfall, Ensemble median
temperature

Trend rainfall, Ensemble 90%
temperature

Year 2050

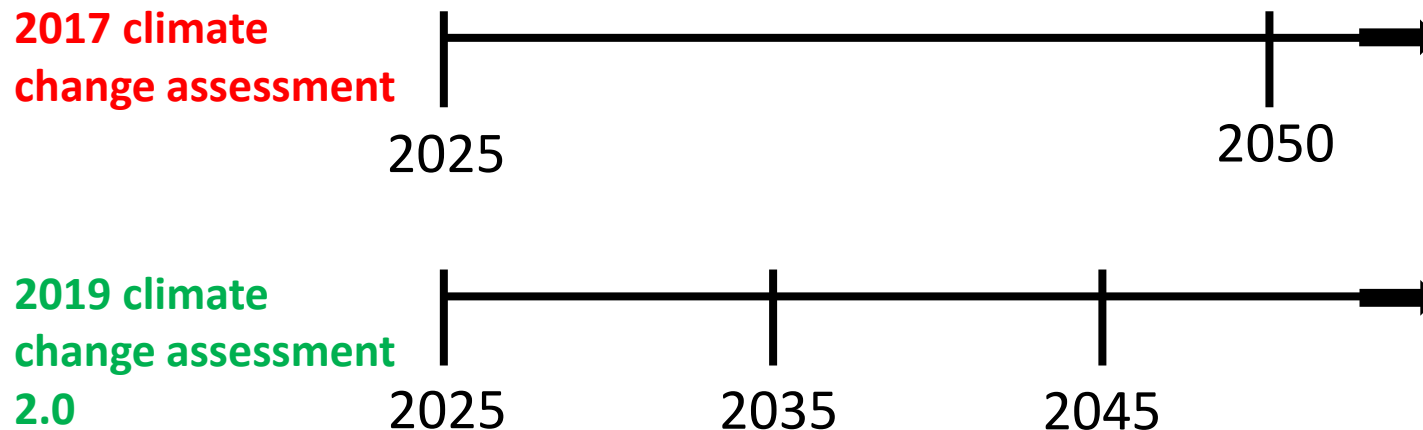
Ensemble 10% rainfall & temperature

Ensemble median rainfall & temperature

Ensemble 90% rainfall & temperature

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



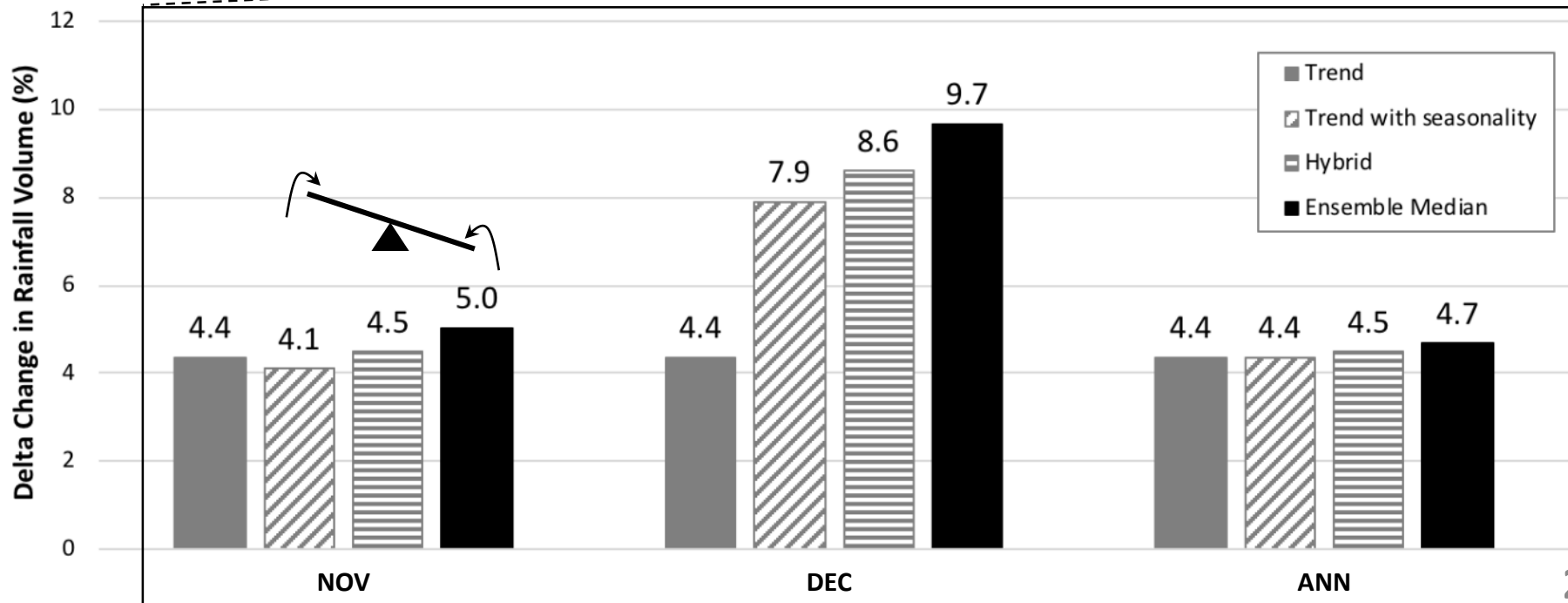
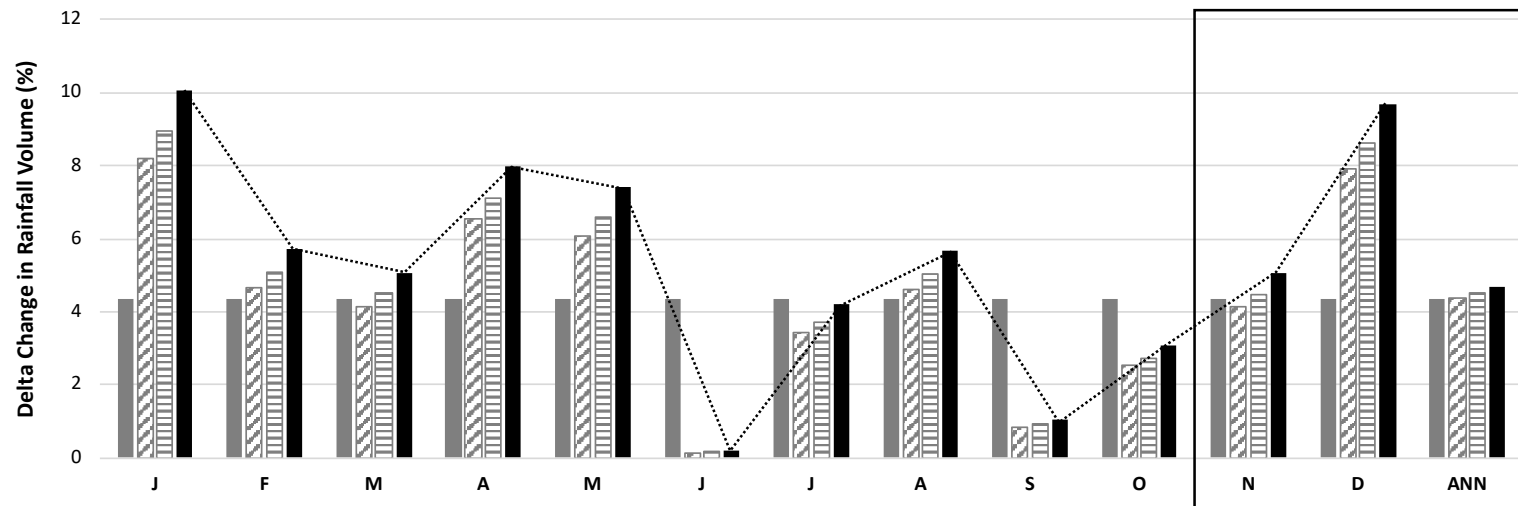
Year	Precipitation		Temperature	
	Trend	Ensemble	Trend	Ensemble
2025	x	—	—	x
2035	?	?	?	?
2045	?	?	?	?
2050	—	x	—	x

- 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

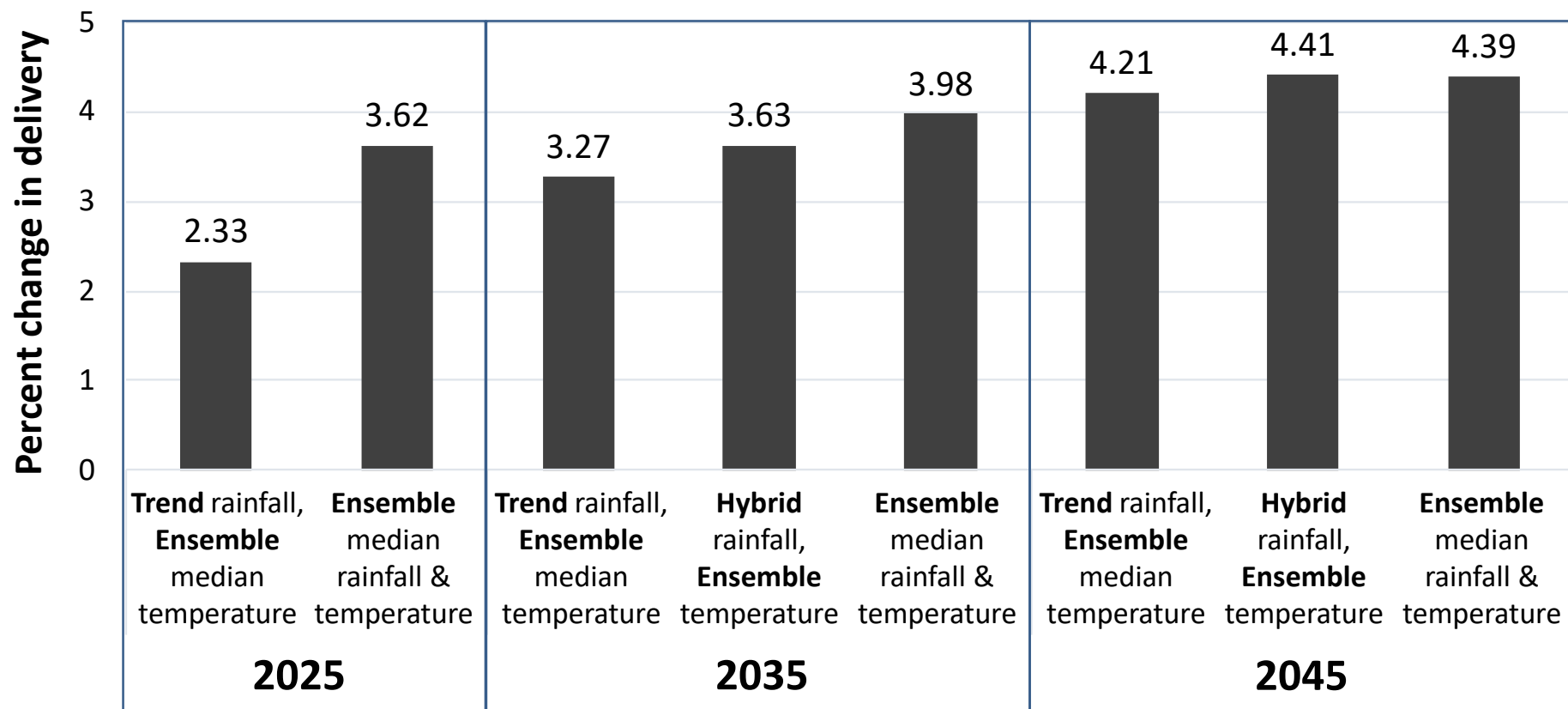
*Separately for
each land segment*

*showing data for
one of the land
segment*



Flow response

Simulated Changes in Flow Delivery



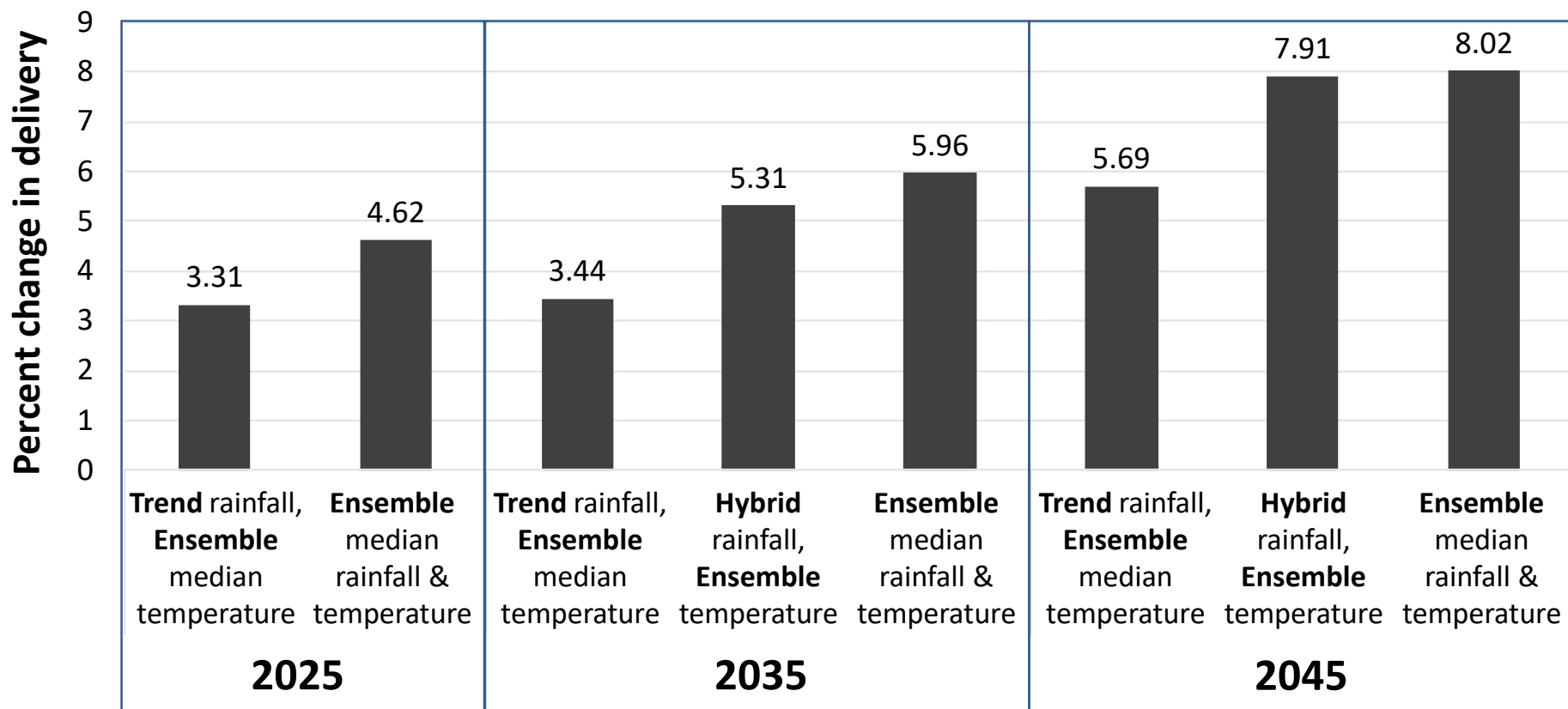
Trend: projection of extrapolation of long-term trends

Ensemble: 31-member ensemble of RCP4.5 GCMs

Hybrid: weighted average of trend and ensemble

Sediment response

Simulated Changes in Sediment Delivery



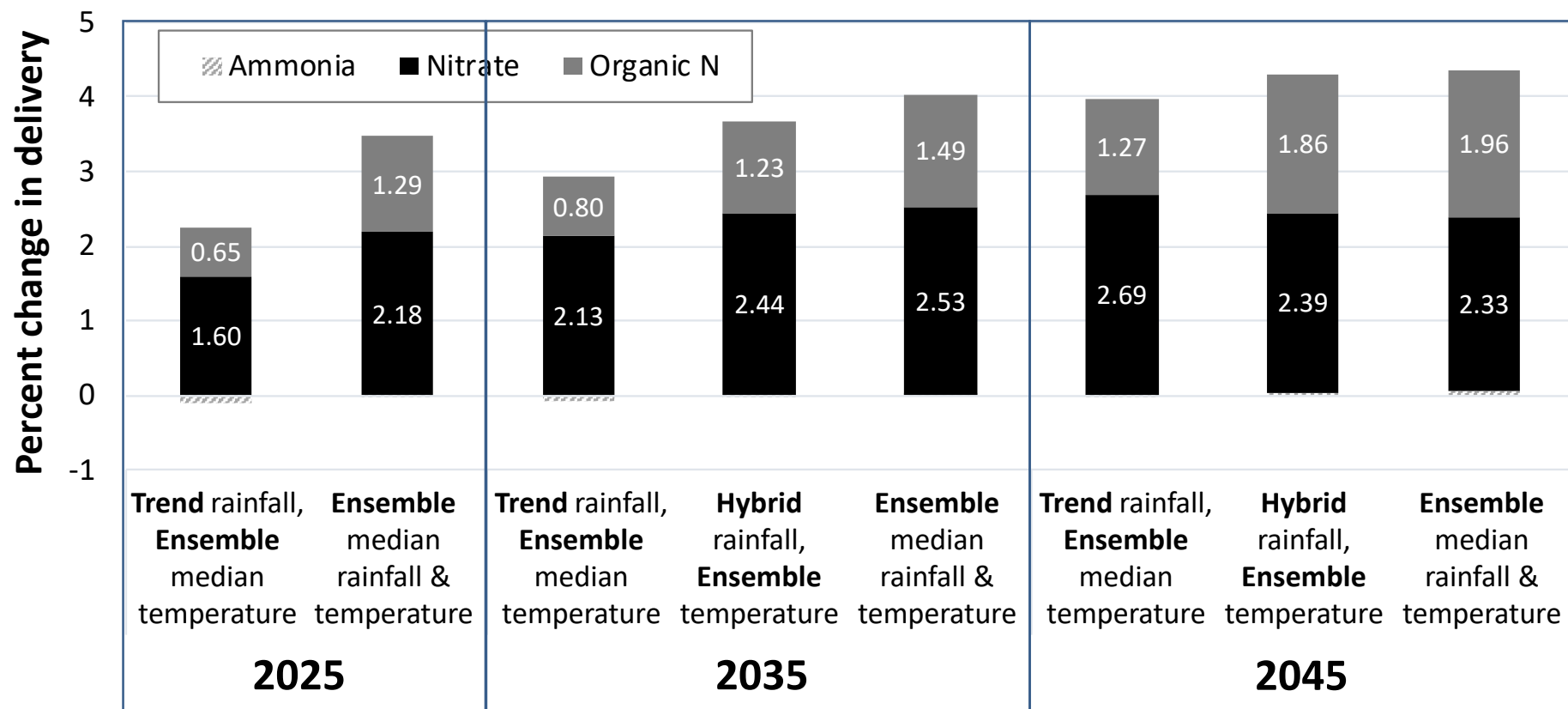
Trend: projection of extrapolation of long-term trends

Ensemble: 31-member ensemble of RCP4.5 GCMs

Hybrid: weighted average of trend and ensemble

Nitrogen response

Simulated Changes in Nitrogen Delivery

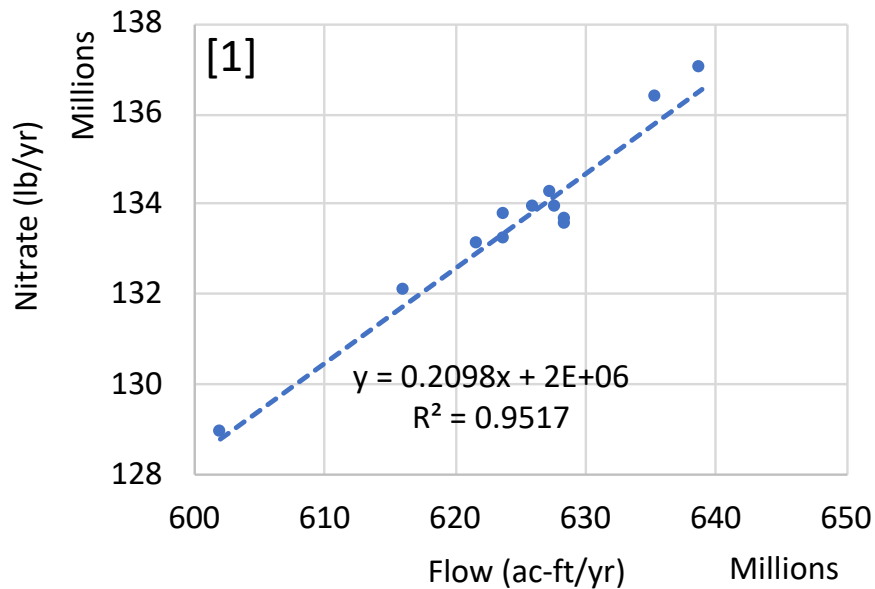


Trend: projection of extrapolation of long-term trends

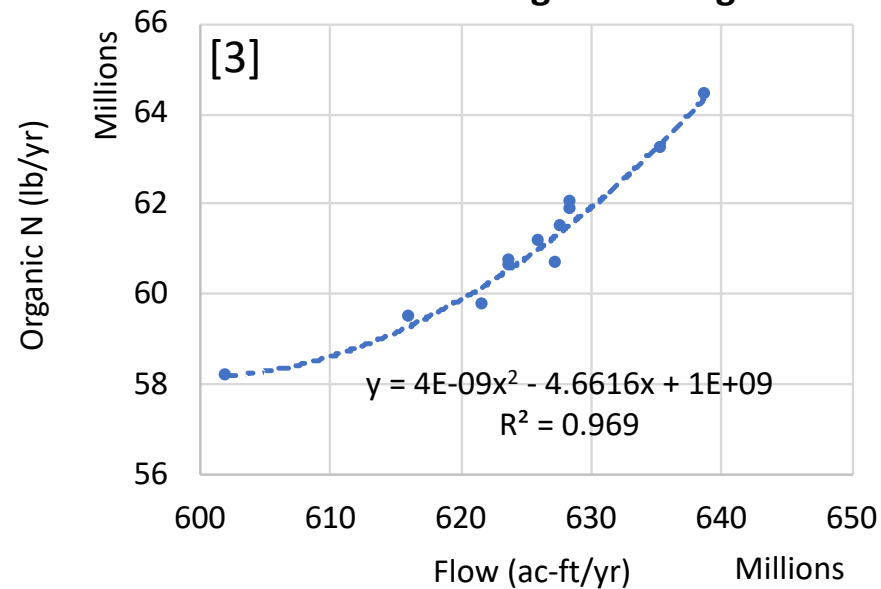
Ensemble: 31-member ensemble of RCP4.5 GCMs

Hybrid: weighted average of trend and ensemble

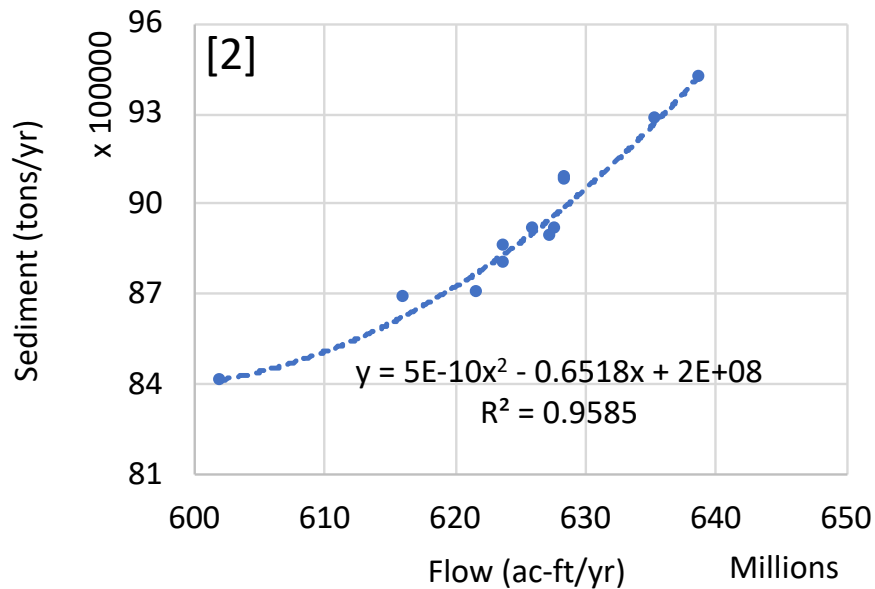
Flow vs. Nitrate



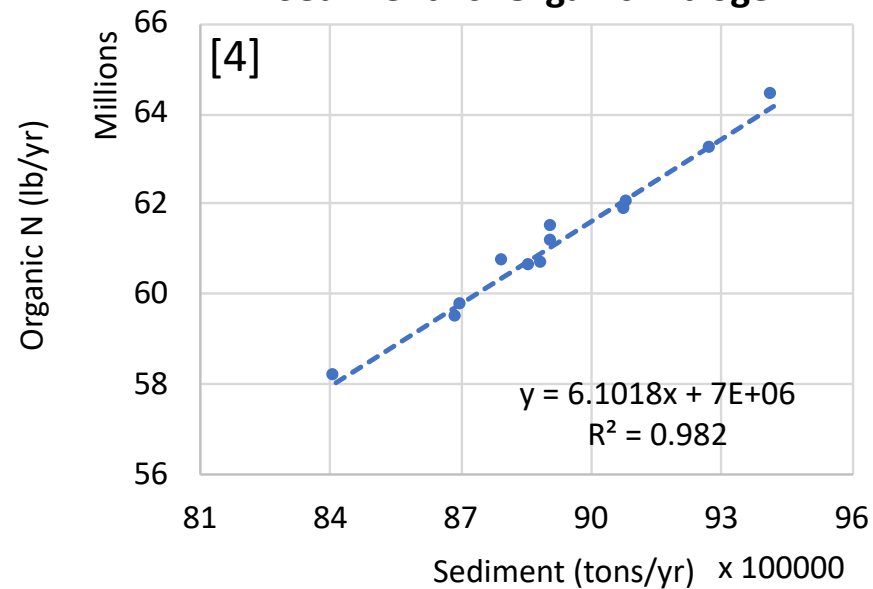
Flow vs. Organic Nitrogen



Flow vs. Sediment

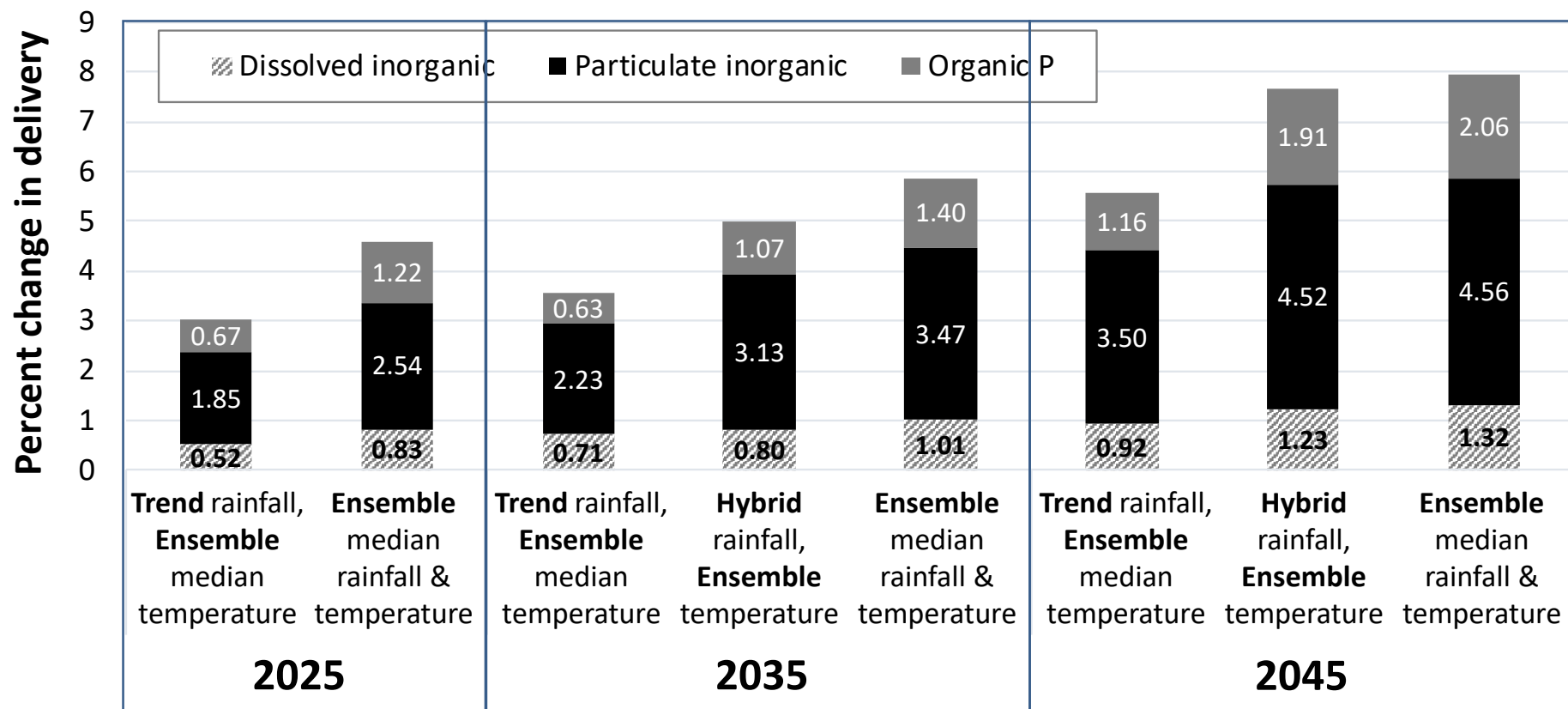


Sediment vs. Organic Nitrogen



Phosphorus response

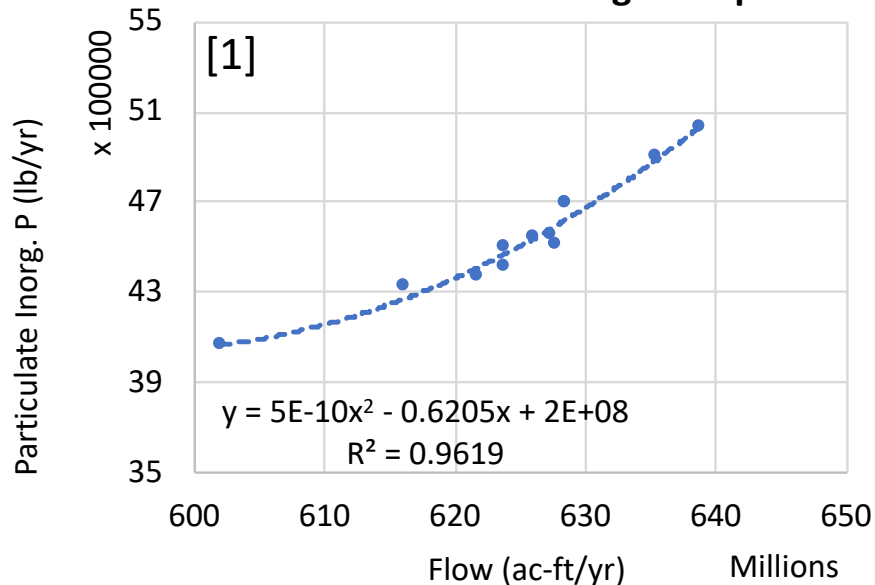
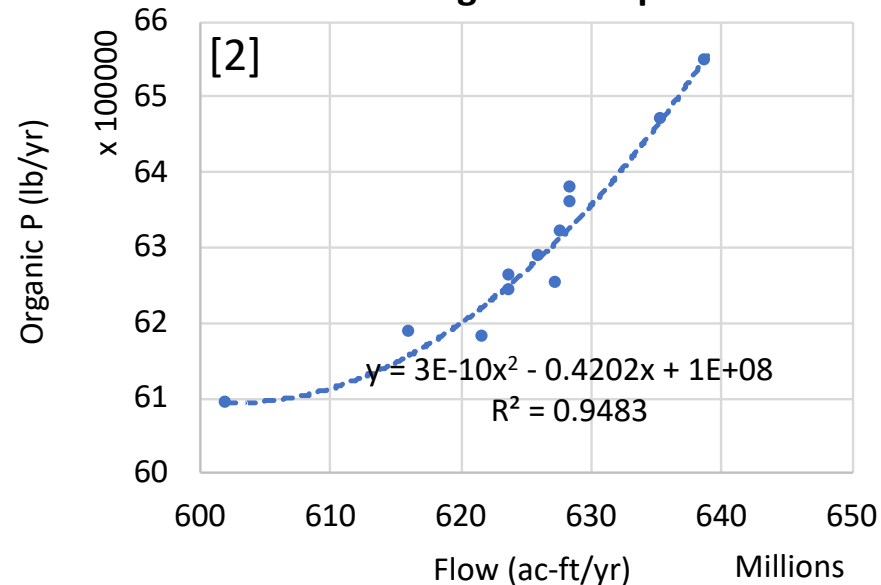
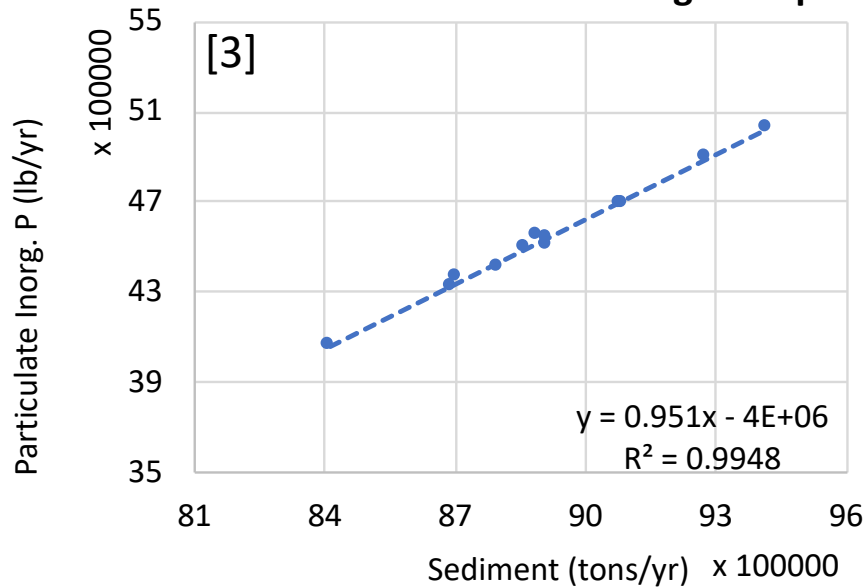
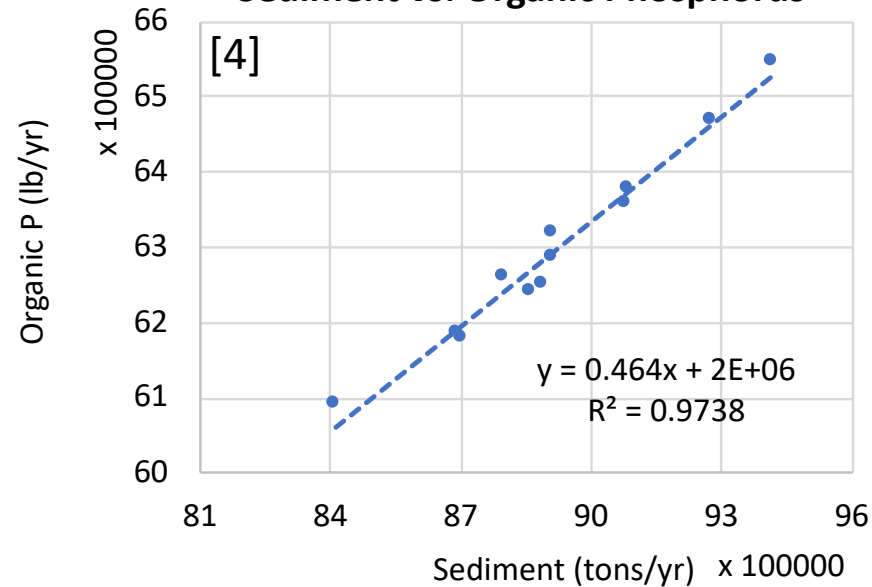
Simulated Changes in Phosphorus Delivery



Trend: projection of extrapolation of long-term trends

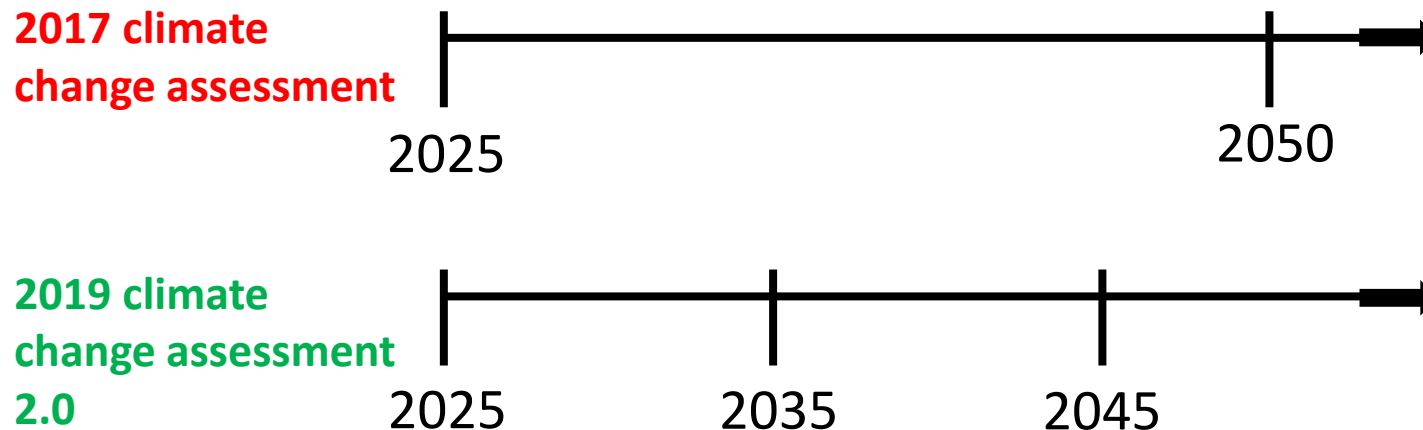
Ensemble: 31-member ensemble of RCP4.5 GCMs

Hybrid: weighted average of trend and ensemble

Flow vs. Particulate Inorg. Phosphorus**Flow vs. Organic Phosphorus****Sediment vs. Particulate Inorg. Phosphorus****Sediment vs. Organic Phosphorus**

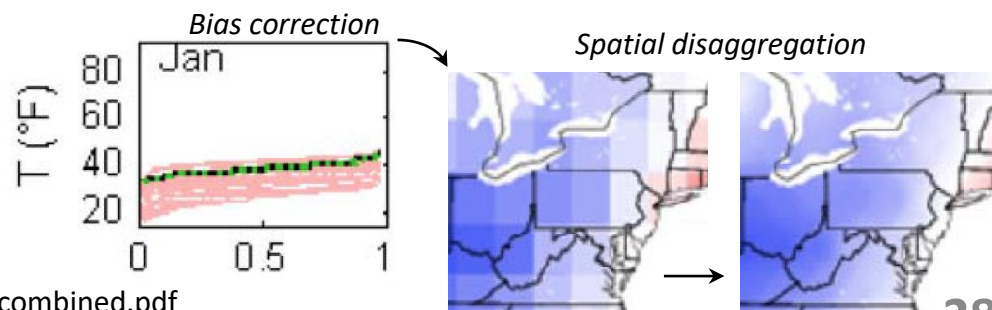
Presentation outline

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- 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

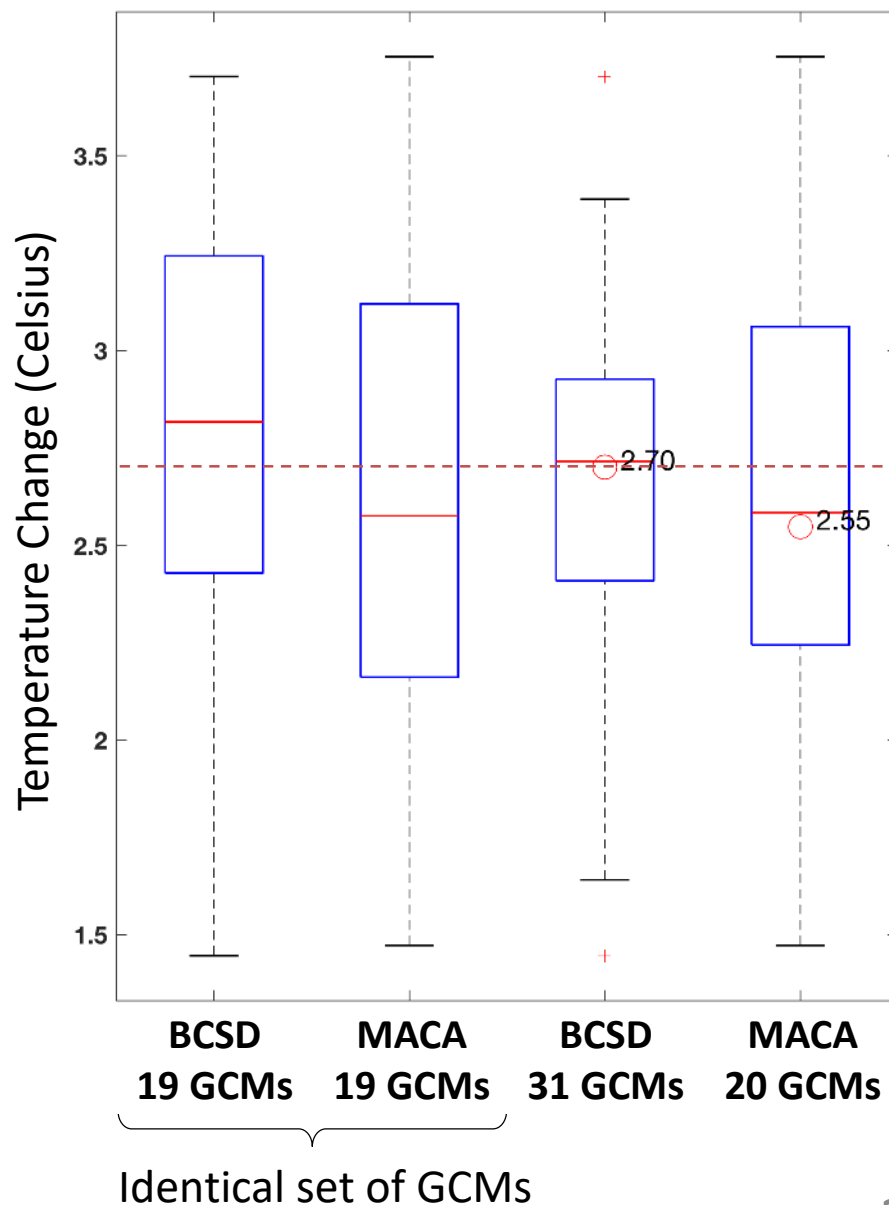
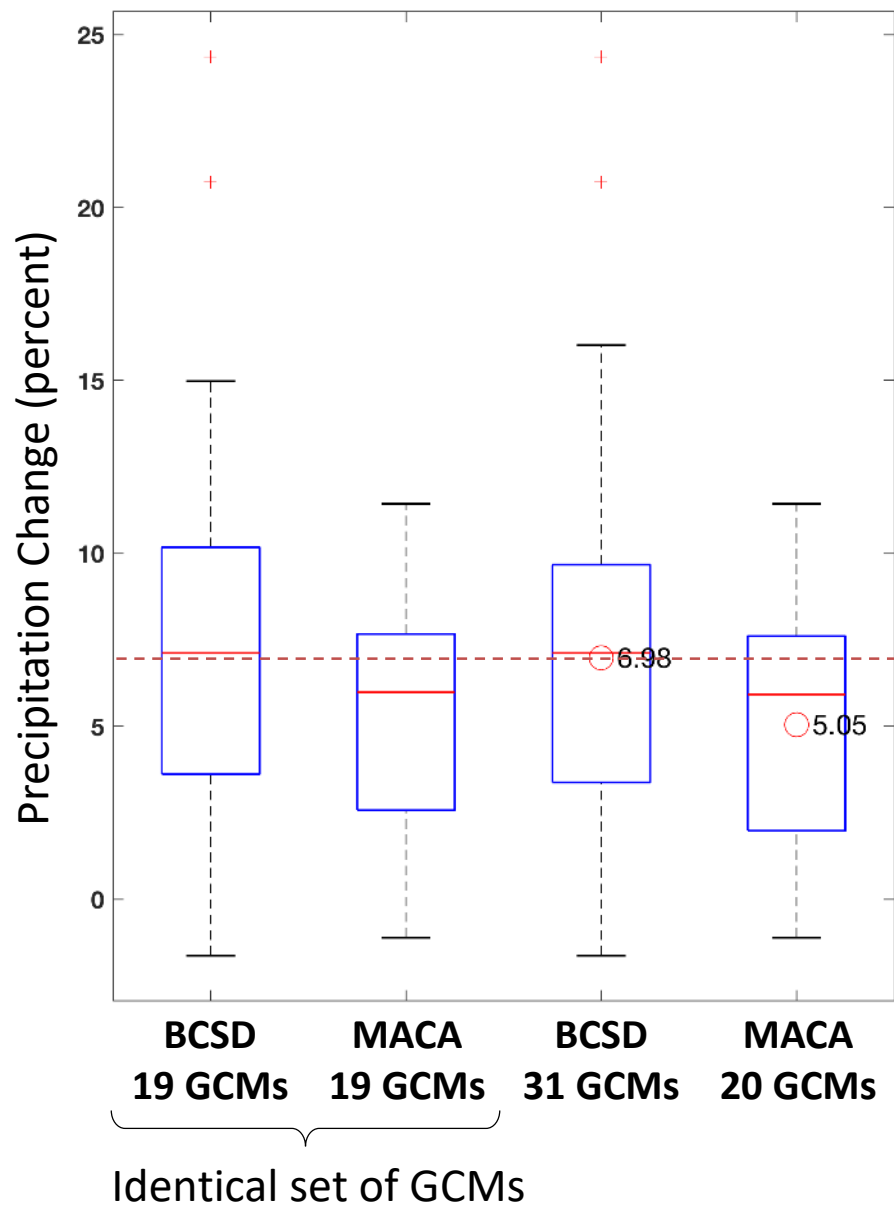
	MACA	BCSD
Source	Processed by PSU (Herrmann and Najjar); University of Idaho Abatzoglou and Brown, 2012 ^[1]	Processed at CBPO Bureau of Reclamation, Technical Services Center, Denver ^[2]
GCMs	20 models	31 models
RCPs	RCP 4.5 , RCP 8.5	RCP 2.6, 4.5 and 8.5
Period	1981-2065 (1950-2099)	1950-2099
Spatial	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



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.

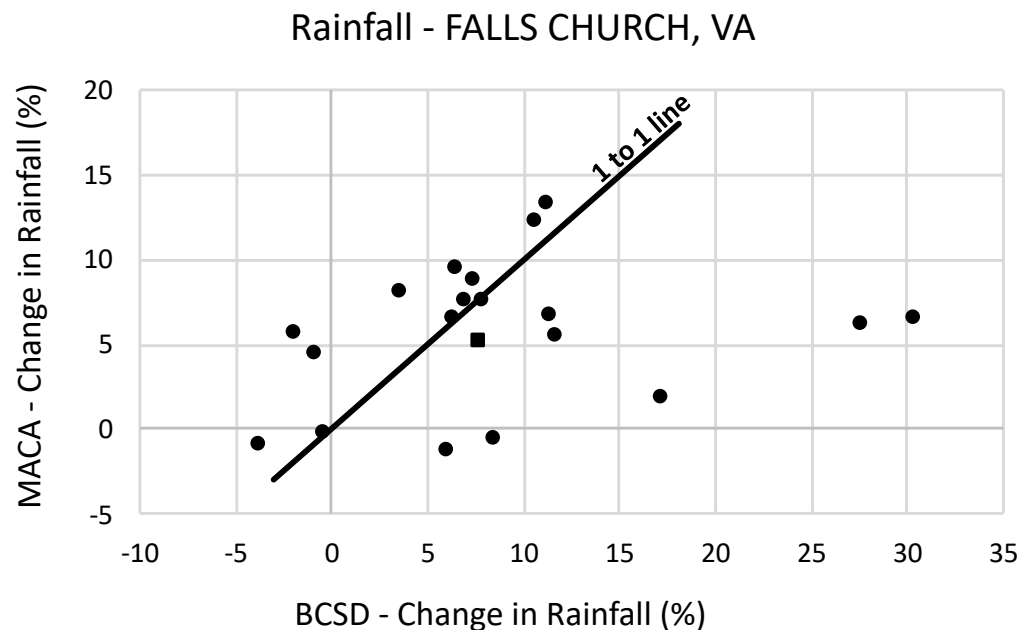


Figure shows delta % change in annual rainfall volume from 19 matching GCMs after downscaling.

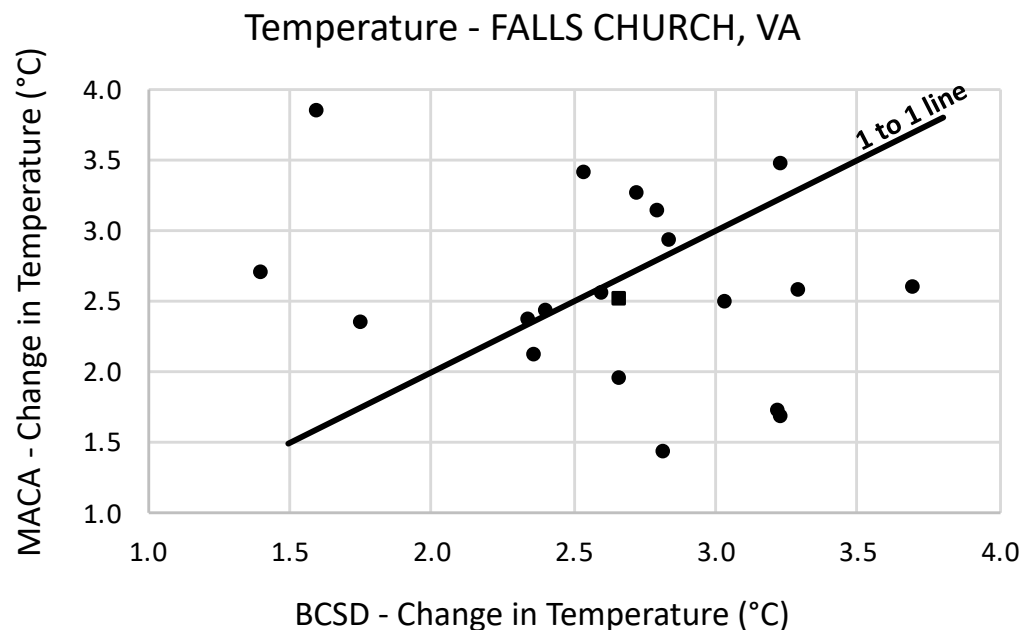
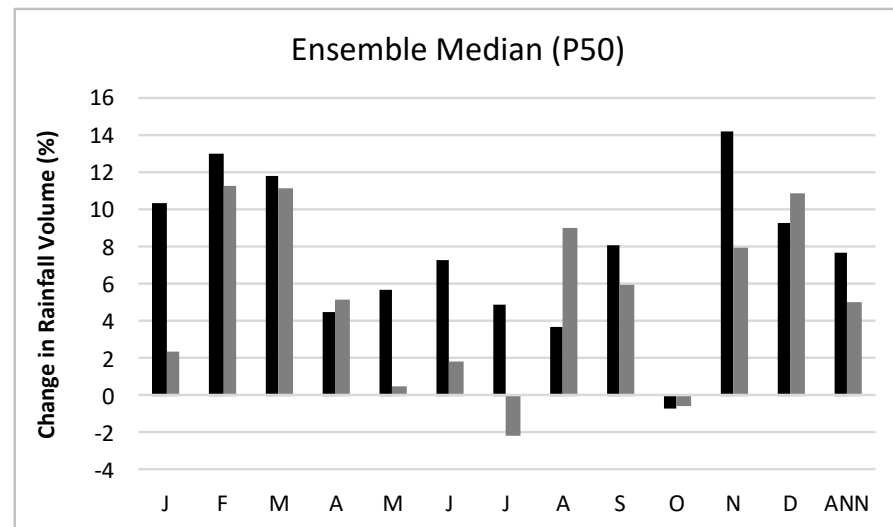
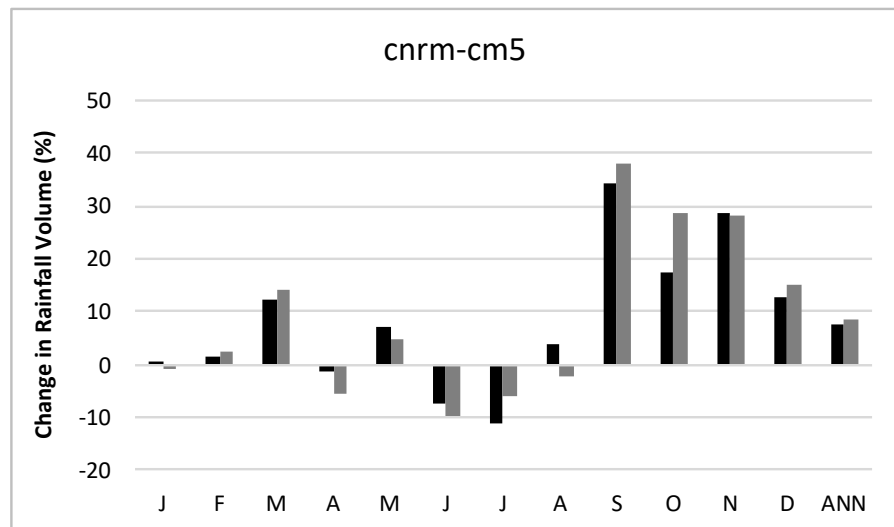
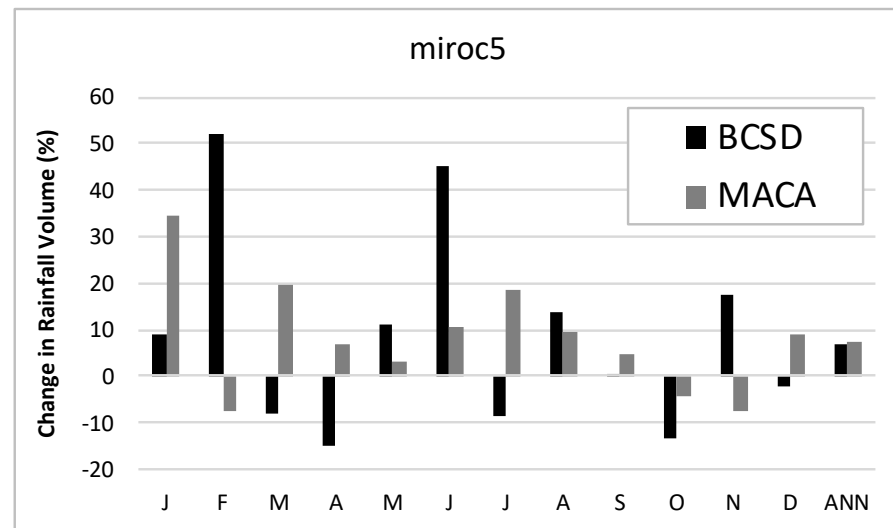
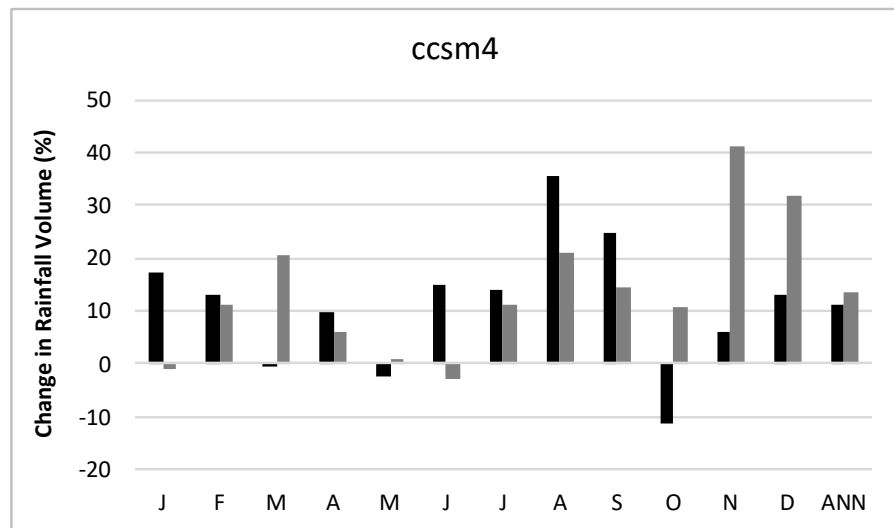


Figure shows delta degree Celsius change for temperature from 19 matching GCMs after downscaling.

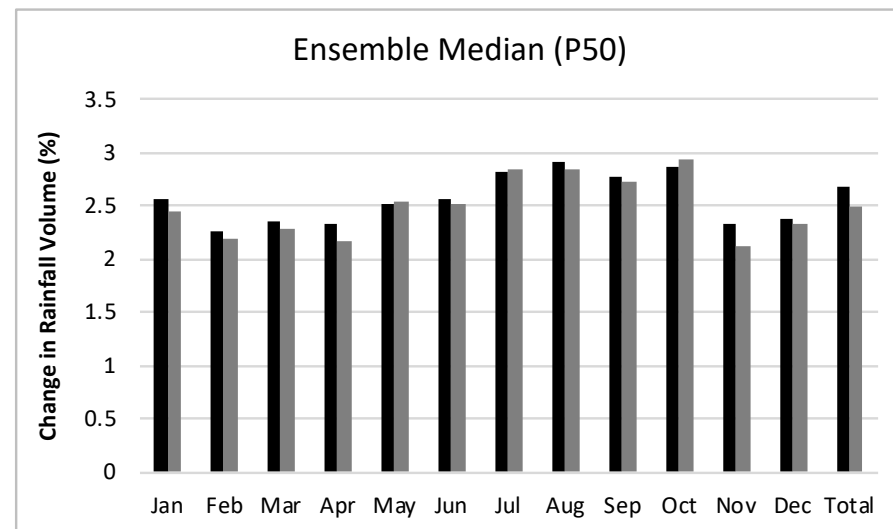
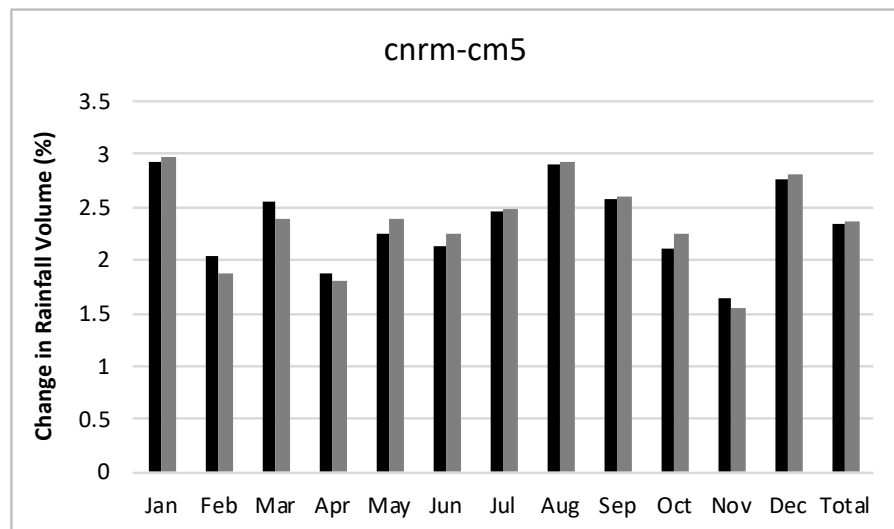
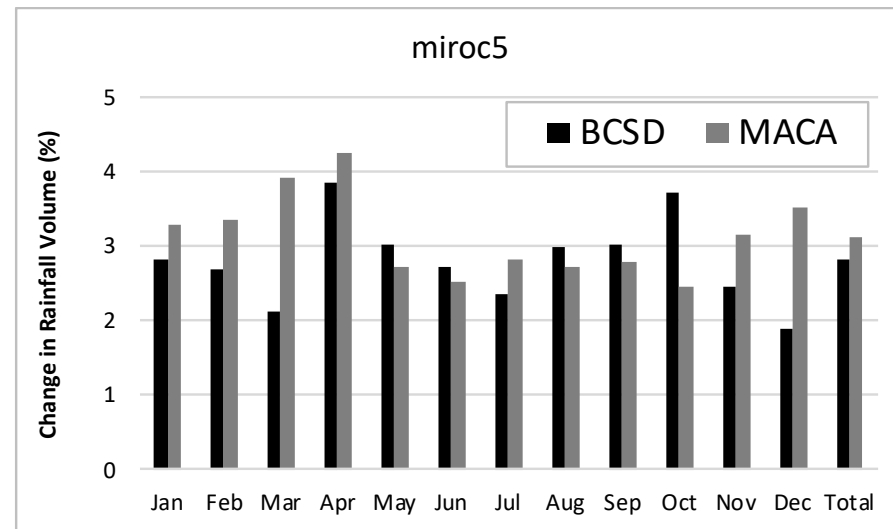
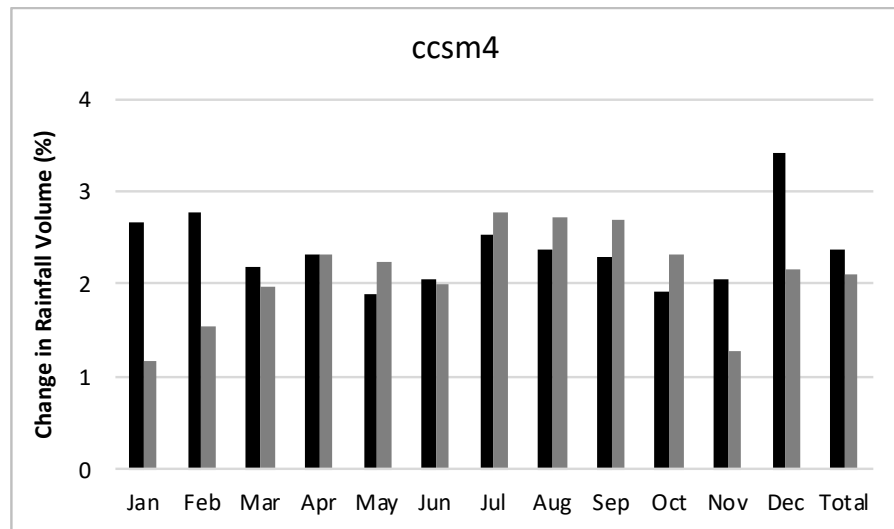
Falls Church, VA – Rainfall

RCP 8.5
2050 vs. 1995



Falls Church, VA – Temperature

RCP 8.5
2050 vs. 1995



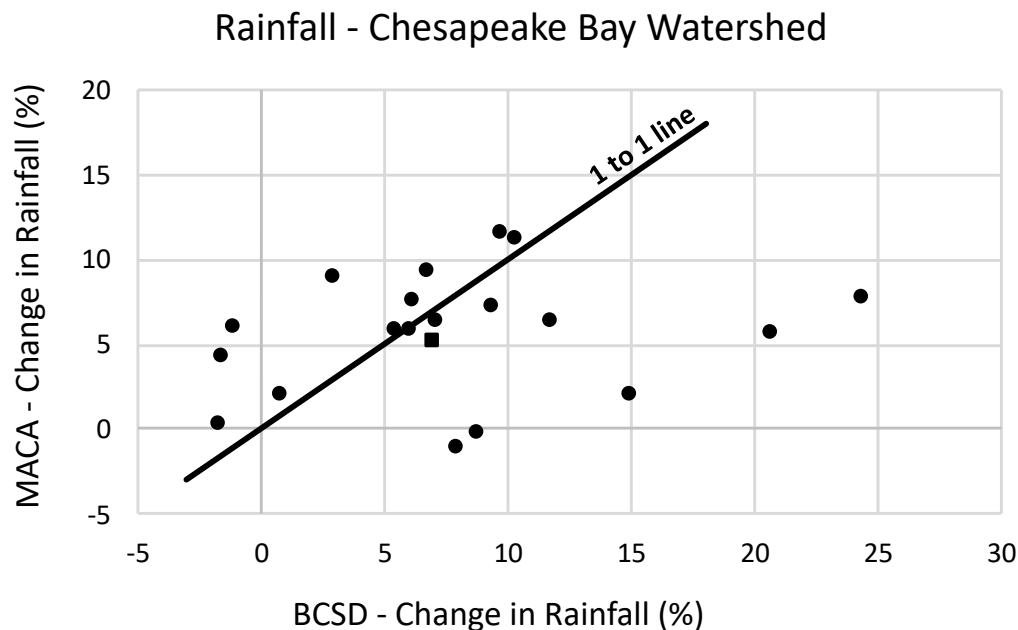


Figure shows delta % change in annual rainfall volume from 19 matching GCMs after downscaling.

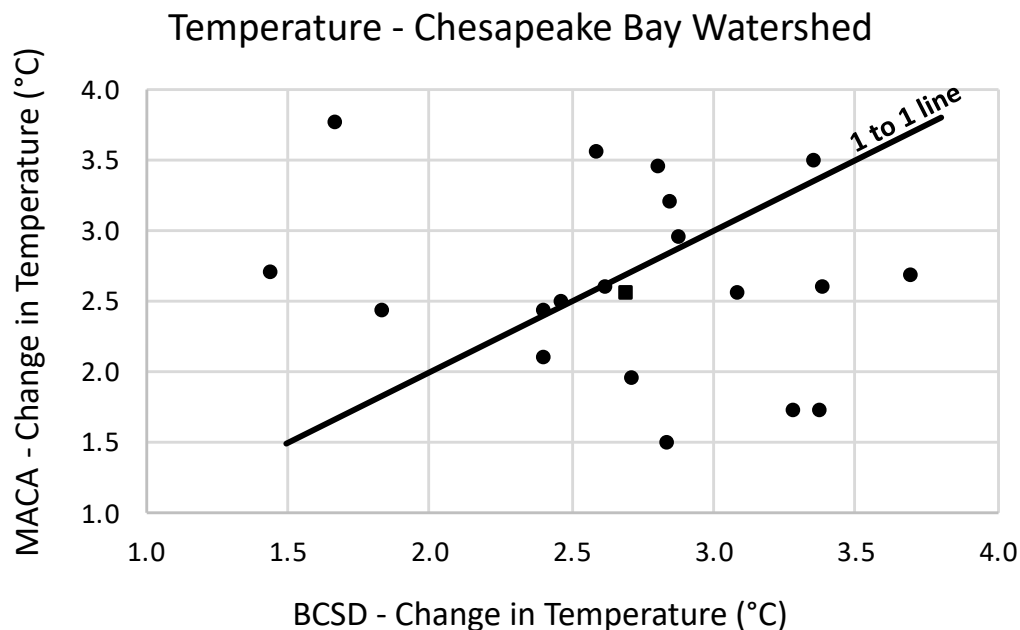
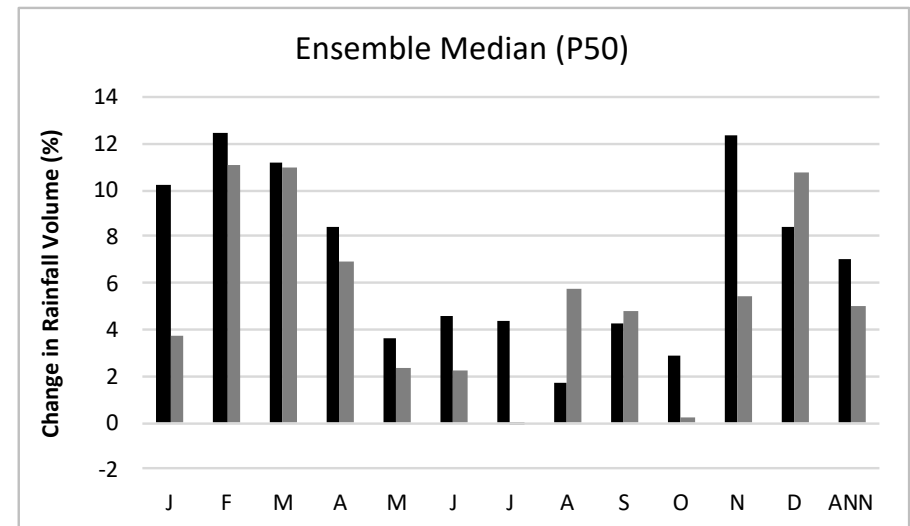
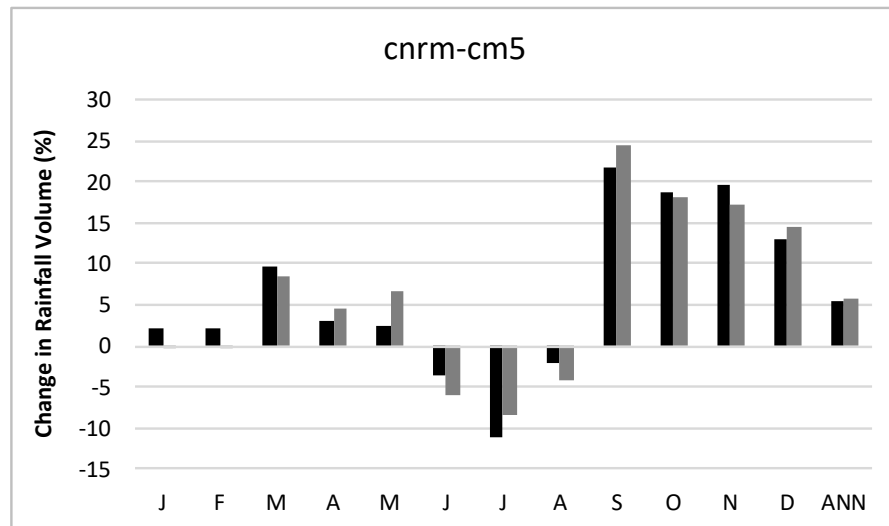
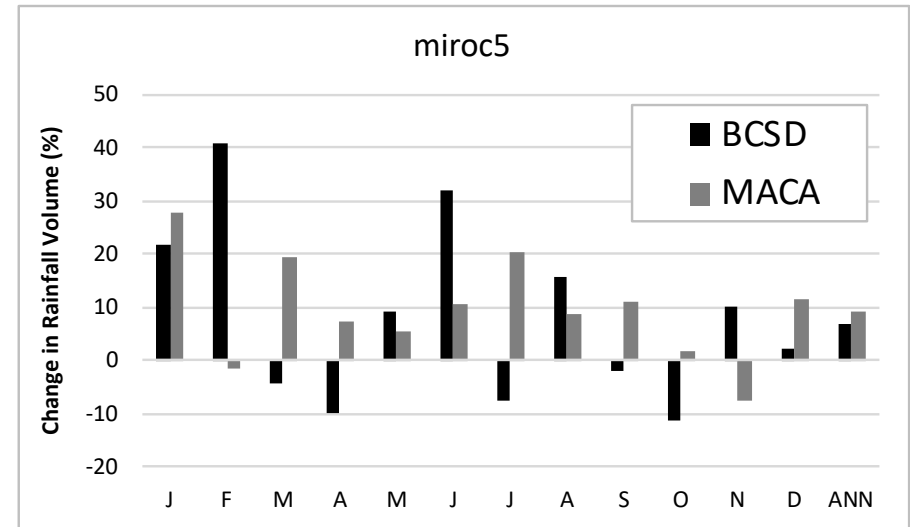
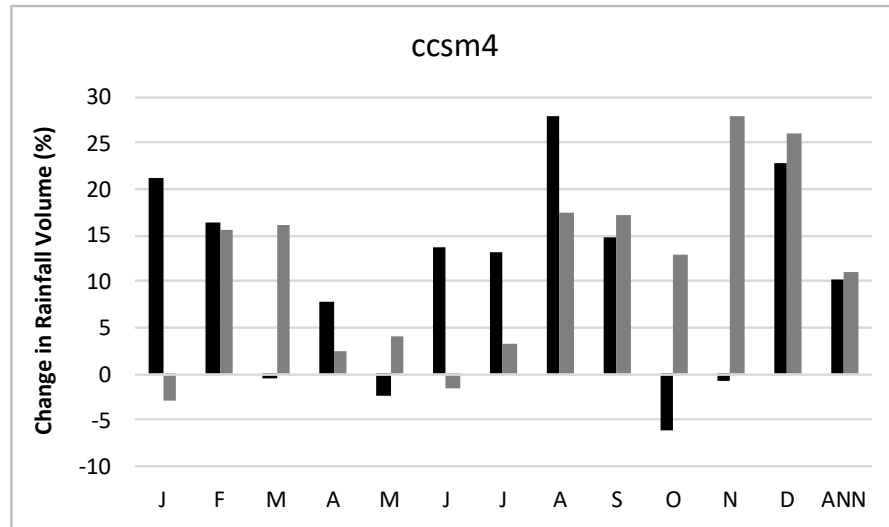


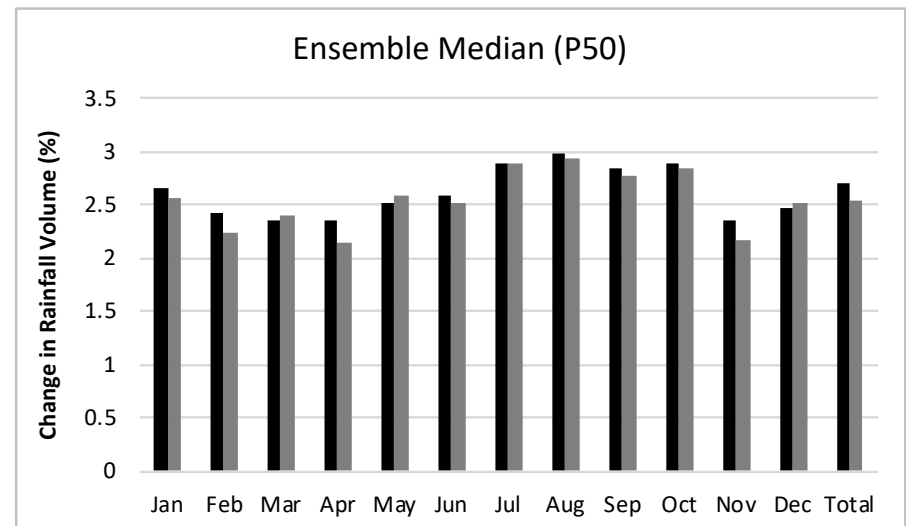
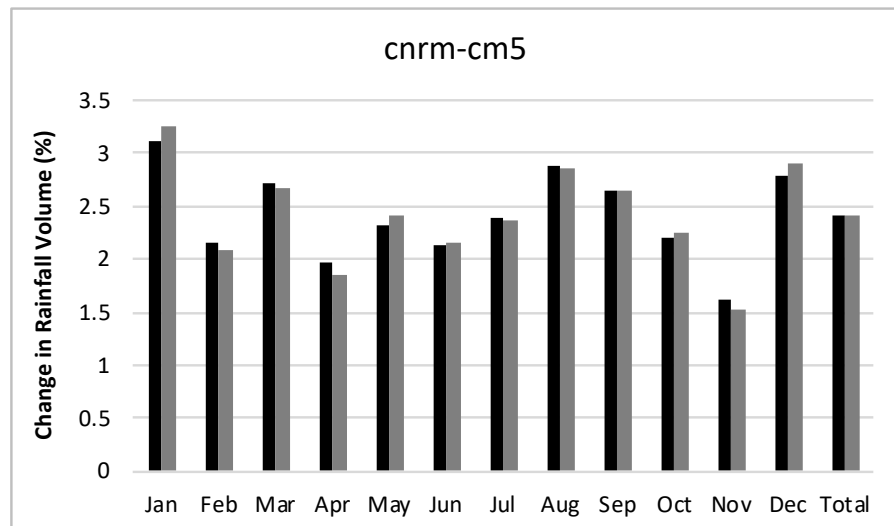
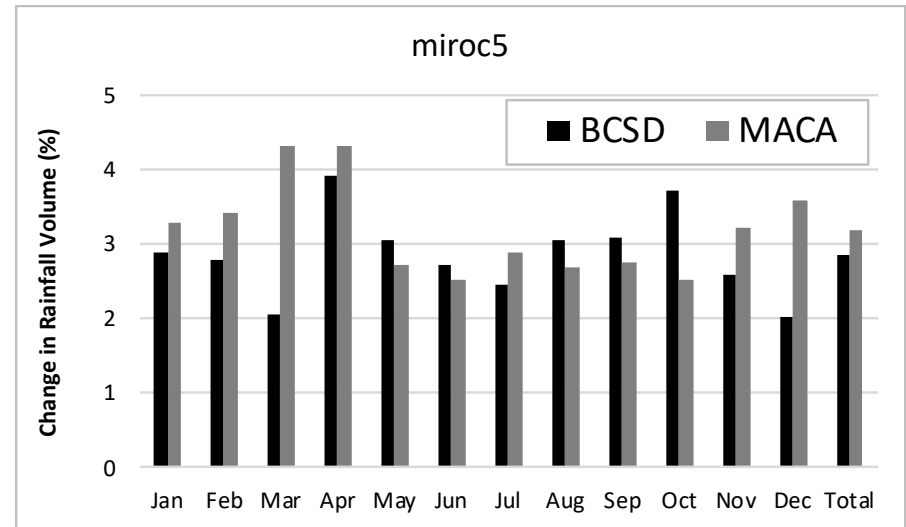
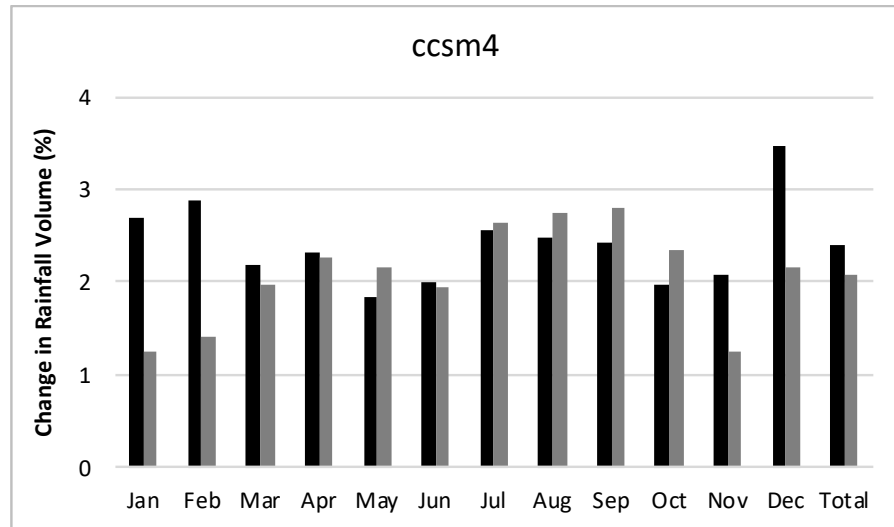
Figure shows delta degree Celsius change for temperature from 19 matching GCMs after downscaling.

Chesapeake Bay Watershed – Rainfall

RCP 8.5
2050 vs. 1995



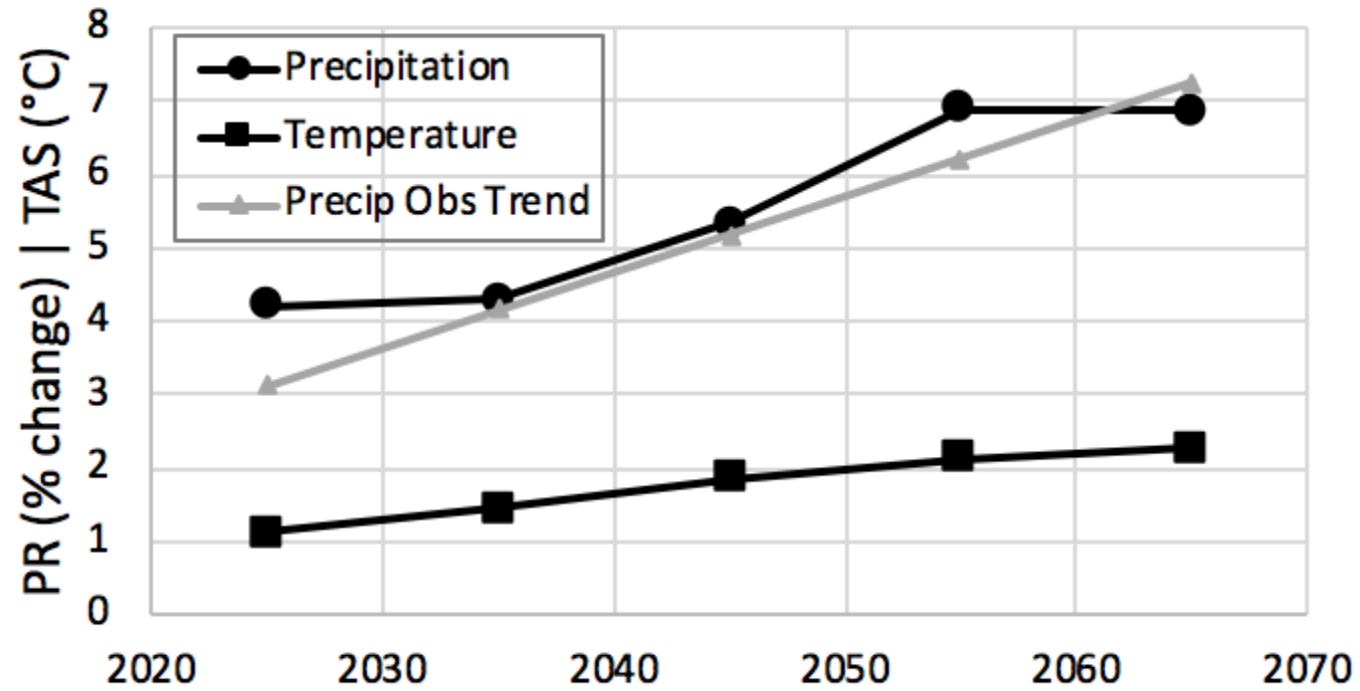
Chesapeake Bay Watershed – Temperature RCP 8.5 2050 vs. 1995

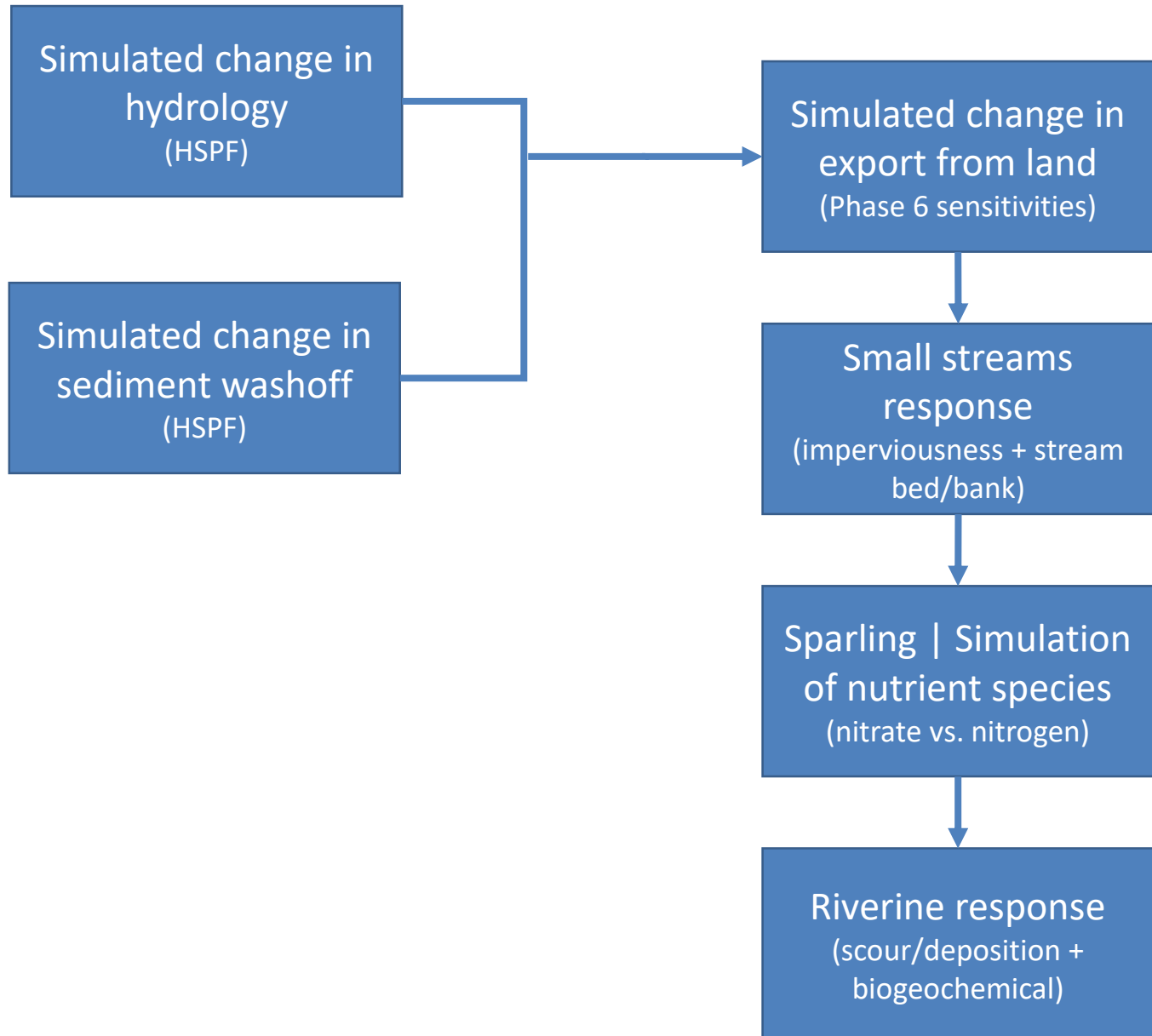


Summary and Conclusions

- 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.

RCP 4.5 Ensemble Median





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 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



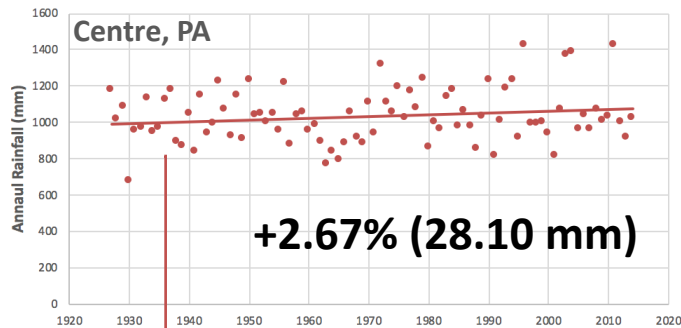
STAC Workshop Report
March 7-8, 2016
Annapolis, MD



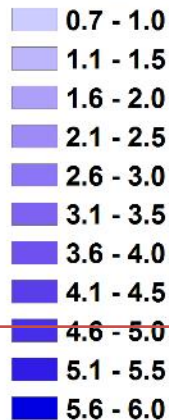
STAC Publication 16-006

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

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



2025 Rainfall Projection (percent change)

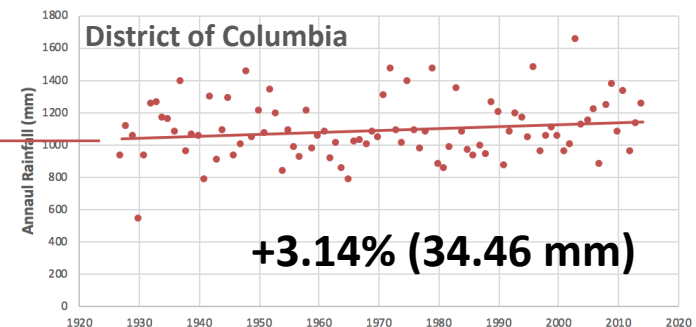


[1] Parameter-elevation Relationships on Independent Slopes Model

0 25 50 100 Miles

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%



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

[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;

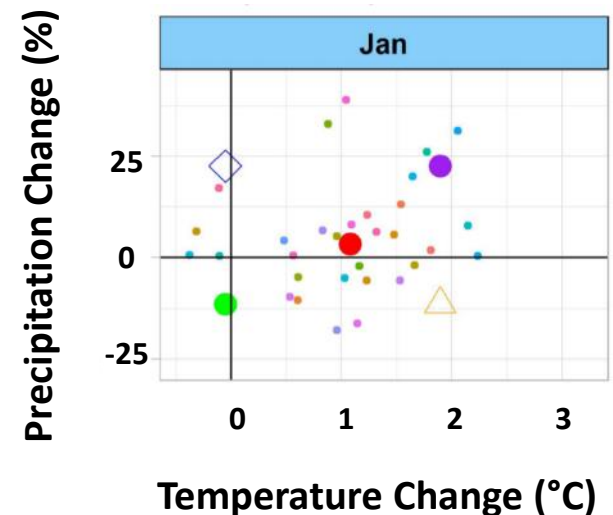
[1] CMIP5 – Coupled Model Intercomparison Project 5

Data[?] unavailable[?]

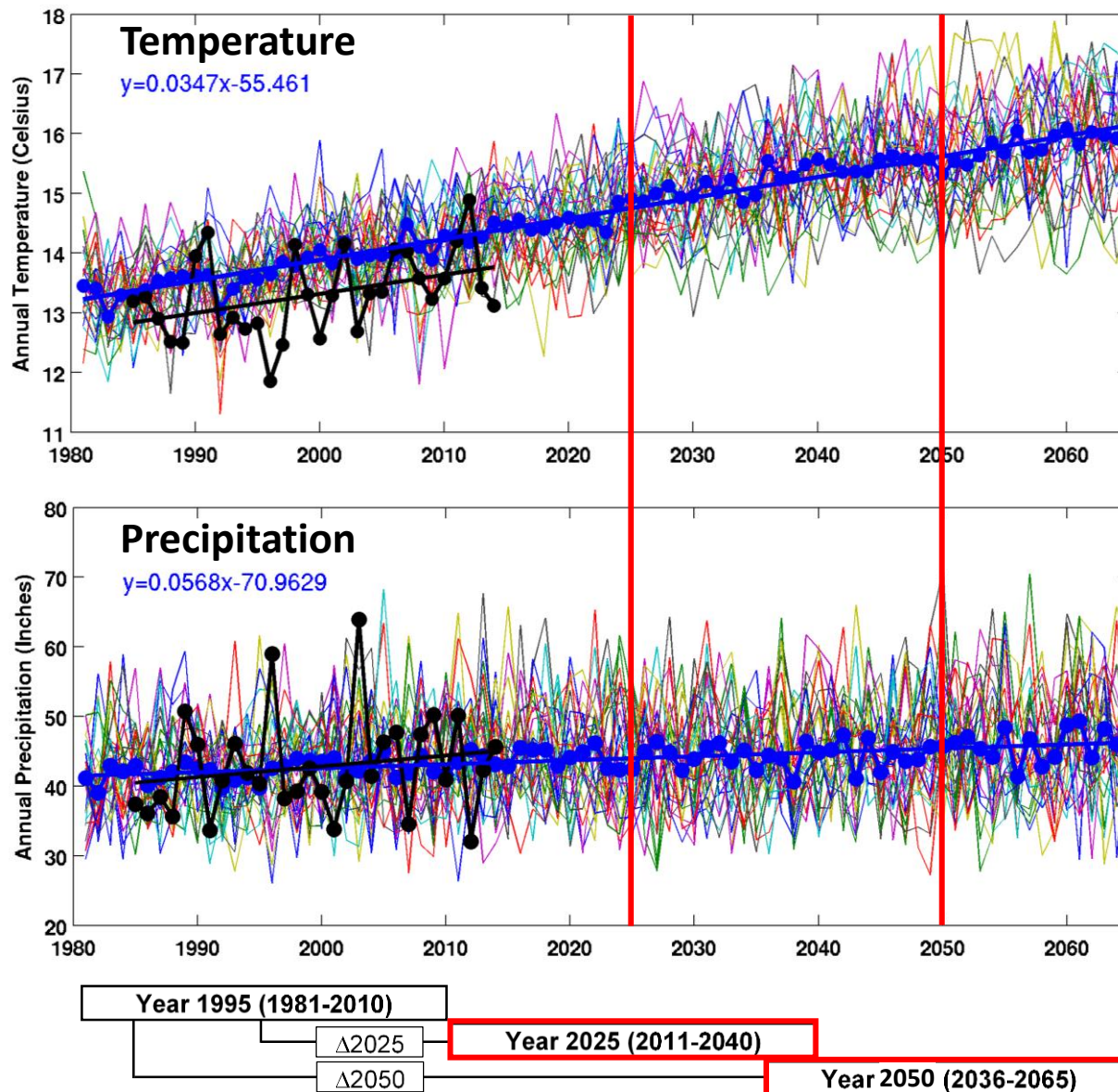
GCM[?] Used[?]

Selection[?] updated[?]

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



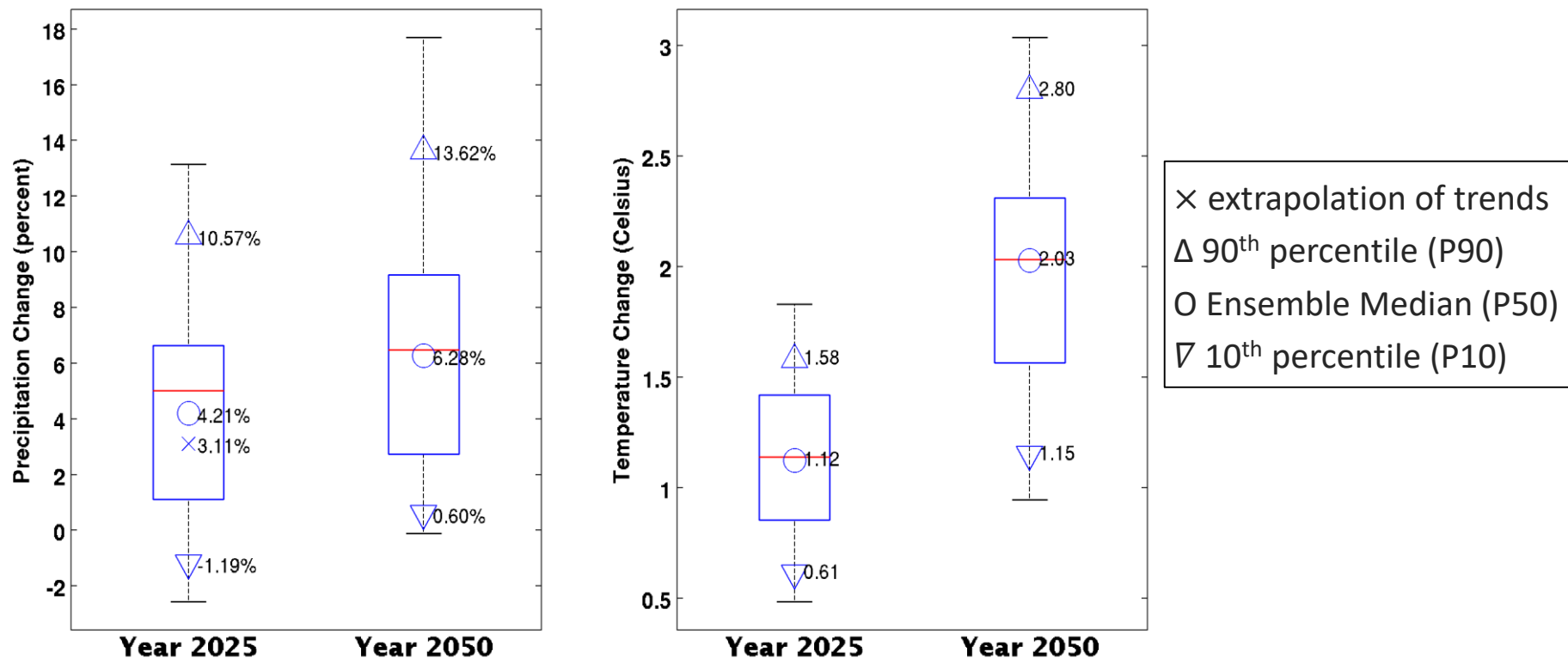
● Ensemble_Median
● Ensemble_P10
△ Ensemble_P10T90
● Ensemble_P90
◇ Ensemble_T10P90



Data shown
for the District
of Columbia
for illustration.

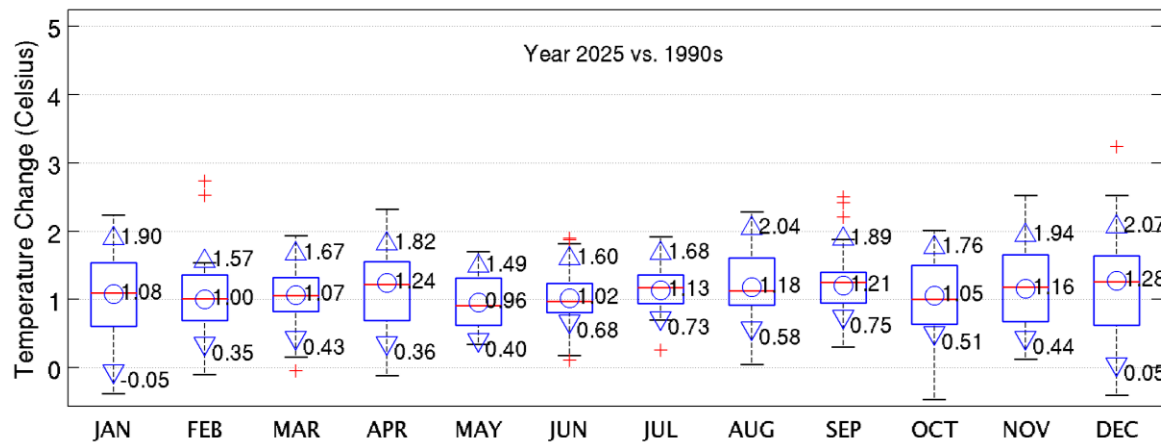
Average annual precipitation and temperature from the 31 bias-corrected downscaled global circulation models are shown for a land segment (N11001). Shown in blue line is the ensemble median. Data used in model calibration from NLDAS-2 are shown in black 46

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

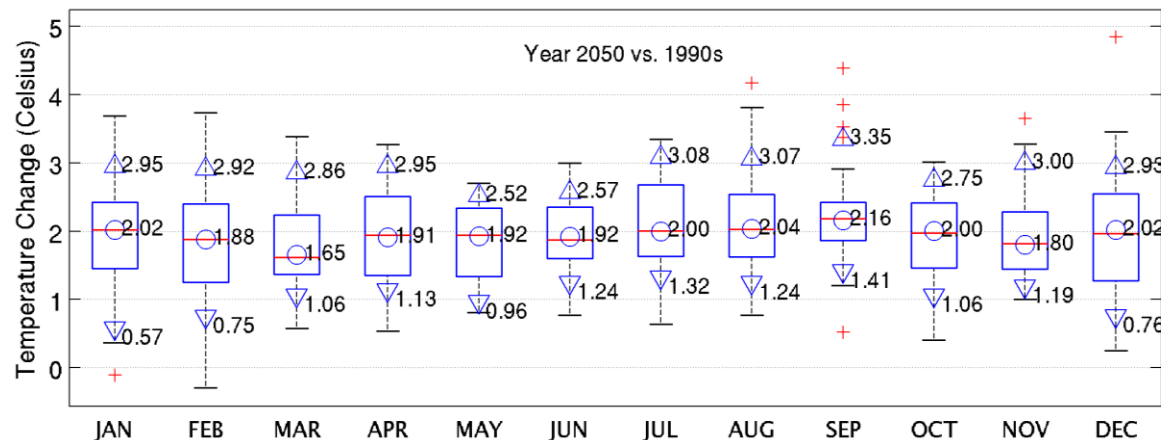


Summary of RCP4.5 average annual rainfall and temperature change for the Chesapeake Bay watershed are shown. Then range for 10th percentile (P10), ensemble median (P50), and 90th percentile (P90) are shown. The estimated change in rainfall volume based on the extrapolation of long-term trends are also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

Projected changes in temperature (RCP 4.5)



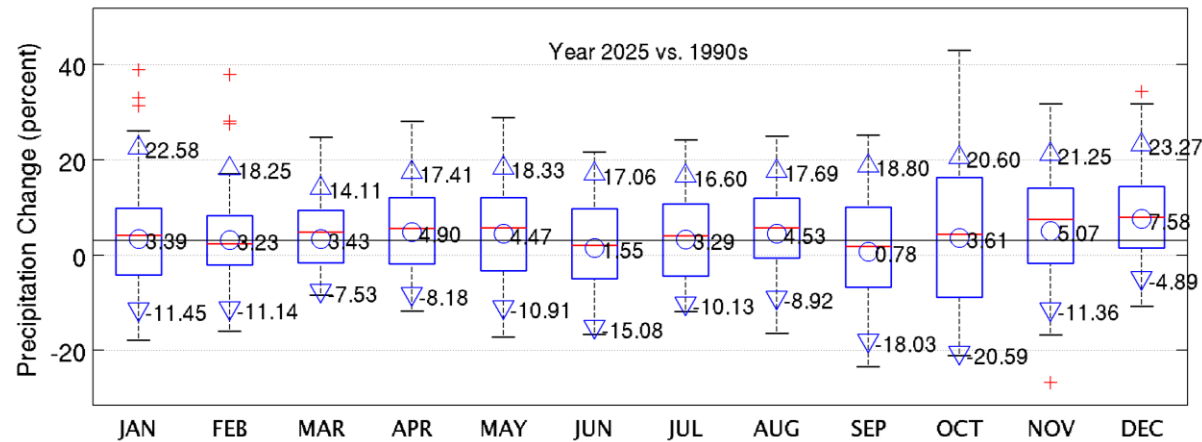
**Watershed average
of ensemble
median is +1.12 °C**



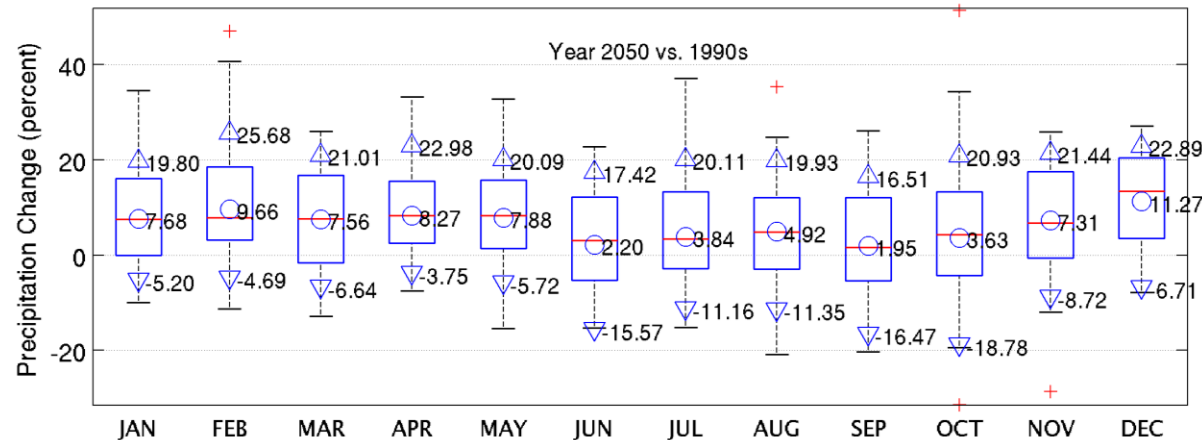
**Watershed average
of ensemble
median is +2.02 °C**

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)



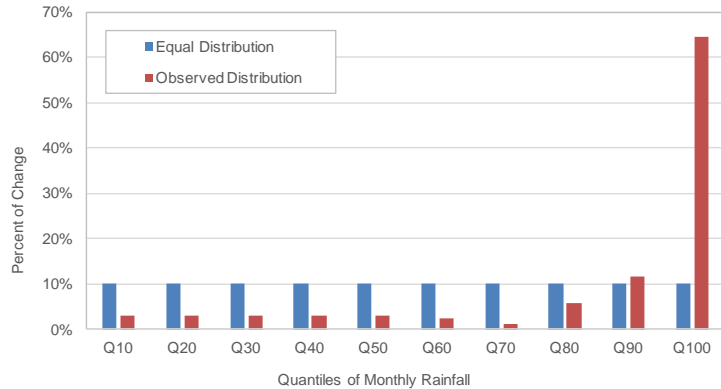
Watershed average of ensemble median is +4.21% (+3.11% estimated using extrapolation of long term trend)



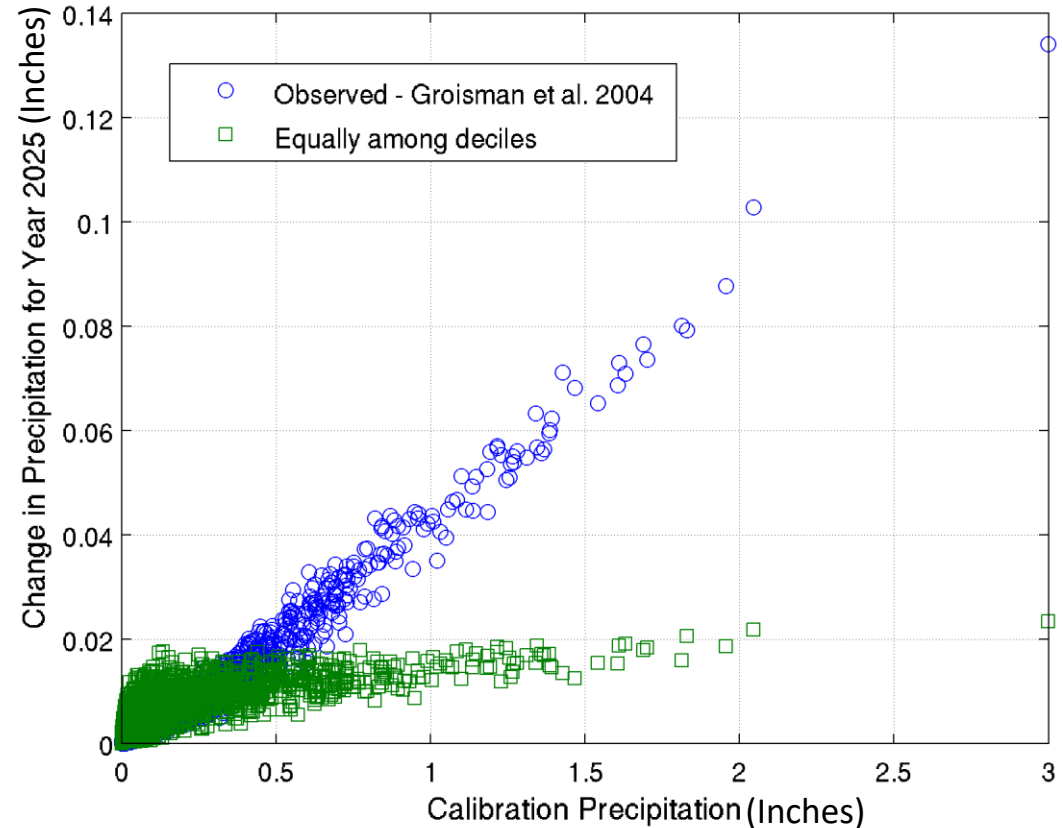
Watershed average of ensemble median is +6.28%

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

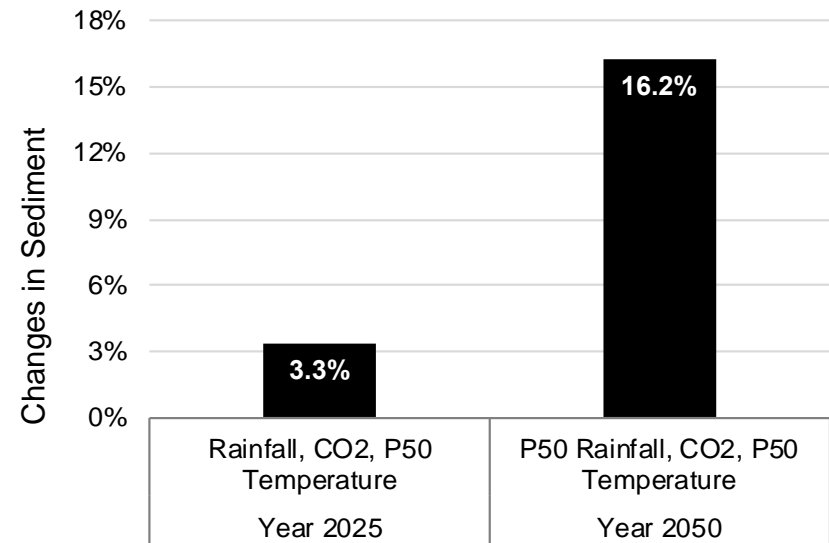
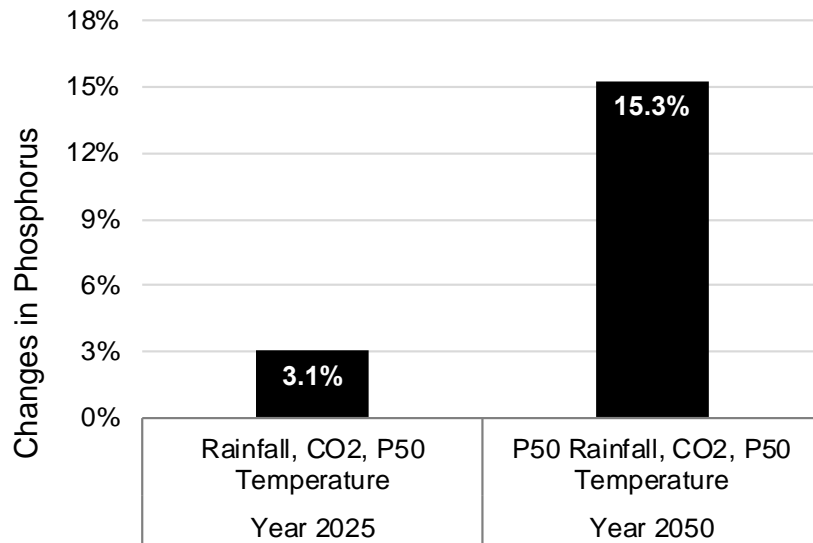
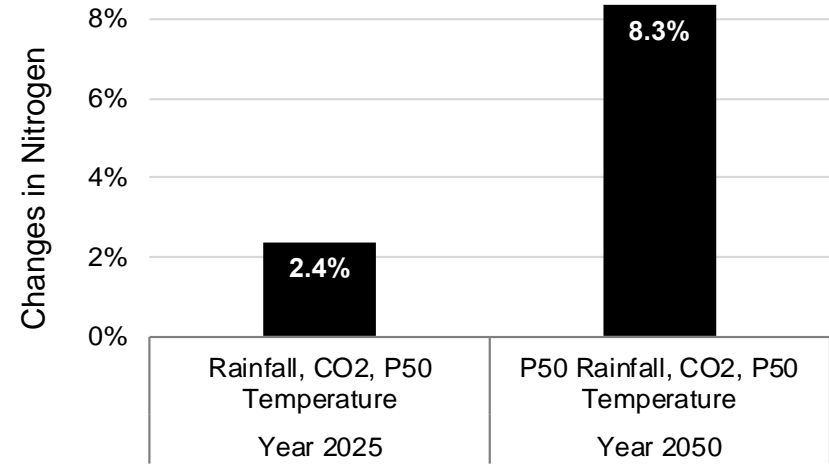
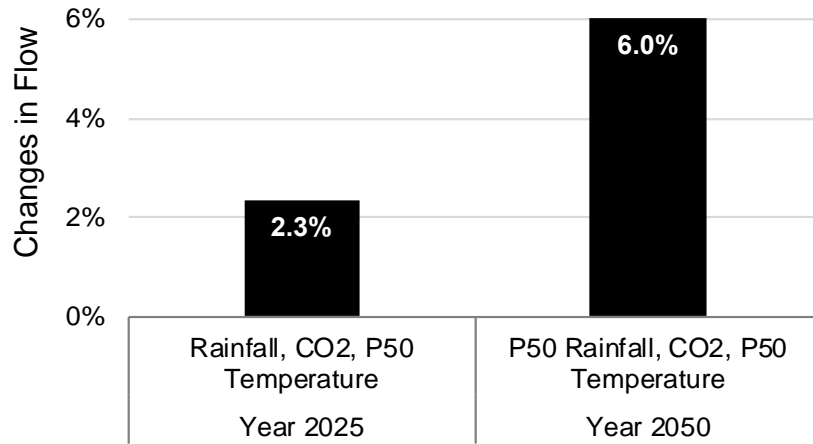


Observed changes in rainfall intensity over the last century (based on Figure 10 in Groisman et al. 2004). The equal allocation distribution (blue) is contrasted with the distribution obtained based on observed changes (red).



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.

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

Trend: projection of extrapolation of long-term trends

Ensemble: 31-member ensemble of RCP4.5 GCMs