Climate-Change Forcing Functions

Maria Herrmann
and
Ray Najjar

Modeling Quarterly Review Meeting
23 July 2013

Collaborators


Michael Barnes, University of Maryland, Baltimore County
Mark R. Bennett, U.S. Geological Survey
Gopal Bhatt, U. S. Environmental Protection Agency/PSU
Lauren E. Hay, U.S. Geological Survey
Lewis Linker, U. S. Environmental Protection Agency
Christopher R. Pyke, U.S. Green Building Council
Kevin G. Sellner, Chesapeake Research Consortium
Gary Shenk, U. S. Environmental Protection Agency
Denice H. Wardrop, The Pennsylvania State University

Acknowledgements:
This research was supported by the U.S. Environmental Protection Agency and the Chesapeake Research Consortium

Motivation

- Changes in air temperature and precipitation associated with climate change are likely to alter inputs of fresh water, sediment, and nutrients from the watershed to the bay

- Climate-induced changes in streamflow and loads of nutrients and sediments have been identified as some of the largest uncertainties in the Chesapeake Bay's response to climate forcing (Najjar et al., 2010).

- OBJECTIVE: to assess how future climate change will affect streamflow, nutrients, and sediment in the Chesapeake Bay watershed

Methods

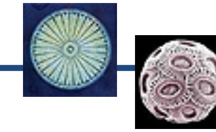

- Watershed fluxes were simulated using HSPF* 5.3.0 model of the Chesapeake Bay watershed (Bicknell et al., 1997; USEPA, 2010)
- Output of six General Circulation Models (GCMs) was used to create forcing for the climate-change runs of the hydrological model (Hay et al., 2011)
  - A2 emissions scenario (high-end, atmospheric CO_2~750 ppm by 2090)
  - only changes in the mean annual cycles of T and P; no changes in variability
- 10-year simulations of the hydrological model
  - baseline: 1990 – 1999
  - climate-change runs: 2086 – 2095
- Change (Δ) = climate run – base run
- Watershed-wide results
- Quantified separate effects of PRECIP, PET, and TEMP

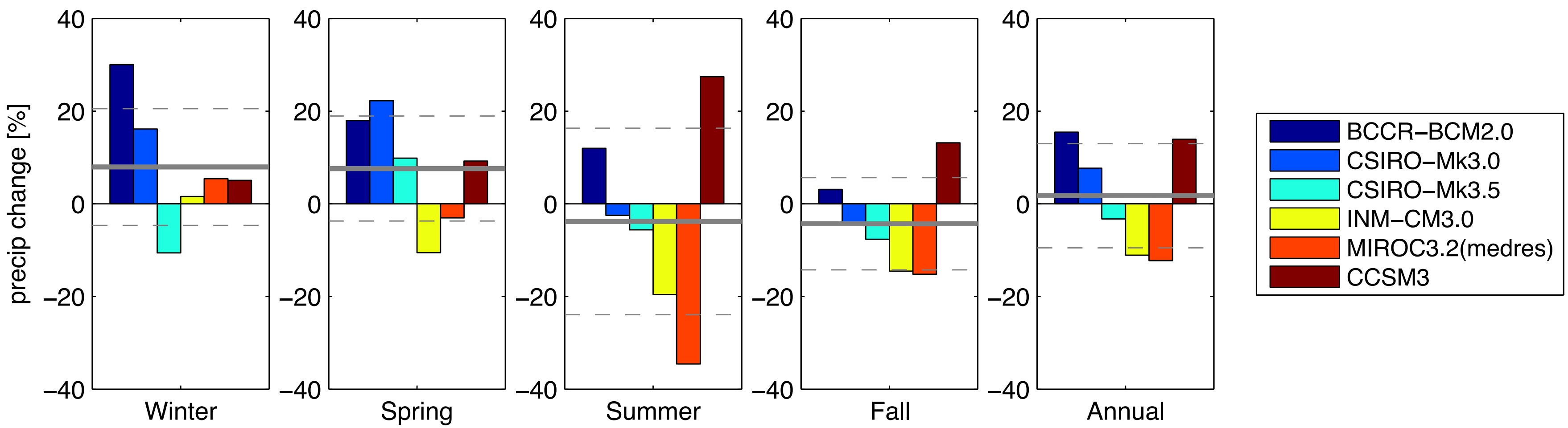
GCMs


id	GCM	Originating group
b20	BCCR-BCM2.0	Bjerknes Centre for Climate Research, Norway
c30	CSIRO-Mk3.0	Commonwealth Scientific and Industrial Research Organization, Australia
c35	CSIRO-Mk3.5	Commonwealth Scientific and Industrial Research Organization, Australia
i0x	INM-CM3.0	Institute for Numerical Mathematics, Russia
m2s	MIROC3.2(medres)	National Institute for Environmental Studies, Japan
n30	NCAR-CCSM3	National Center for Atmospheric Research, USA

- Monthly mean T and P from the multi-model dataset archive of the World Climate Research Programme Coupled Model Intercomparison Project, phase 3 (CMIP3) http://www-pcmdi.llnl.gov/ipcc/model_documentation/ipcc_model_documentation.php

Forcing: precipitation (P)



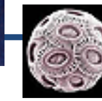


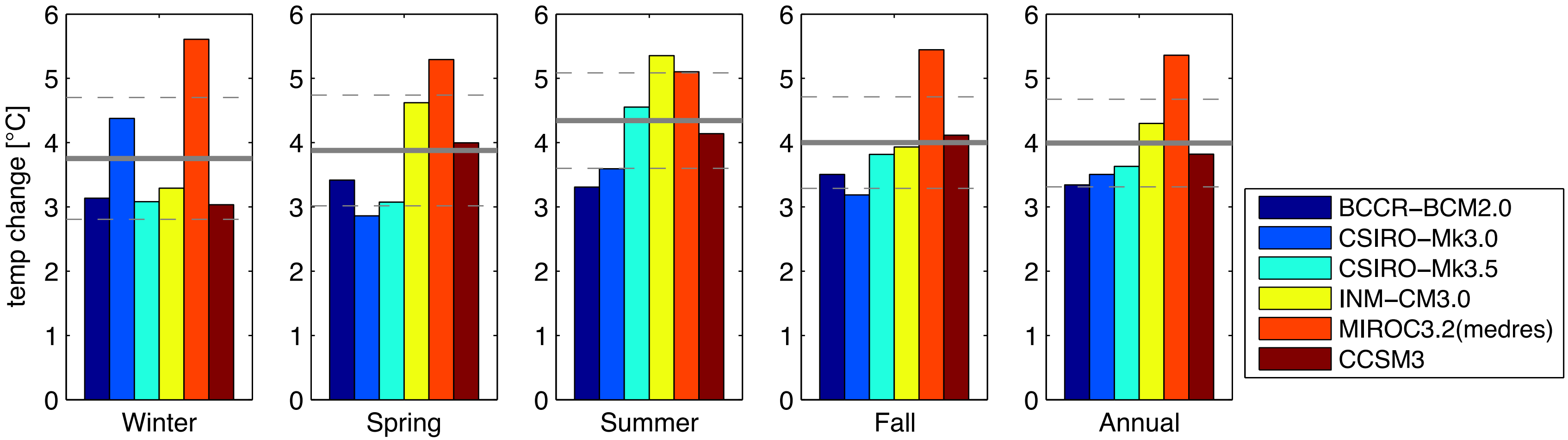
Annual summary [m yr^{-1}]	MEAN	STD	MIN	MAX
Baseline average	1.1	0.2	0.9	1.4
Projected changes	+0.02 (2 %)	0.14 (12 %)	-0.13 (12%)	+0.17 (15 %)

- Considerable variability in P projections
- Winter and spring P increases, on average
- Summer and fall P decreases, on average
- Projected changes are within the bounds of interannual variability

% changes calculated relative to the baseline annual average

Forcing: atmospheric temperature (T)

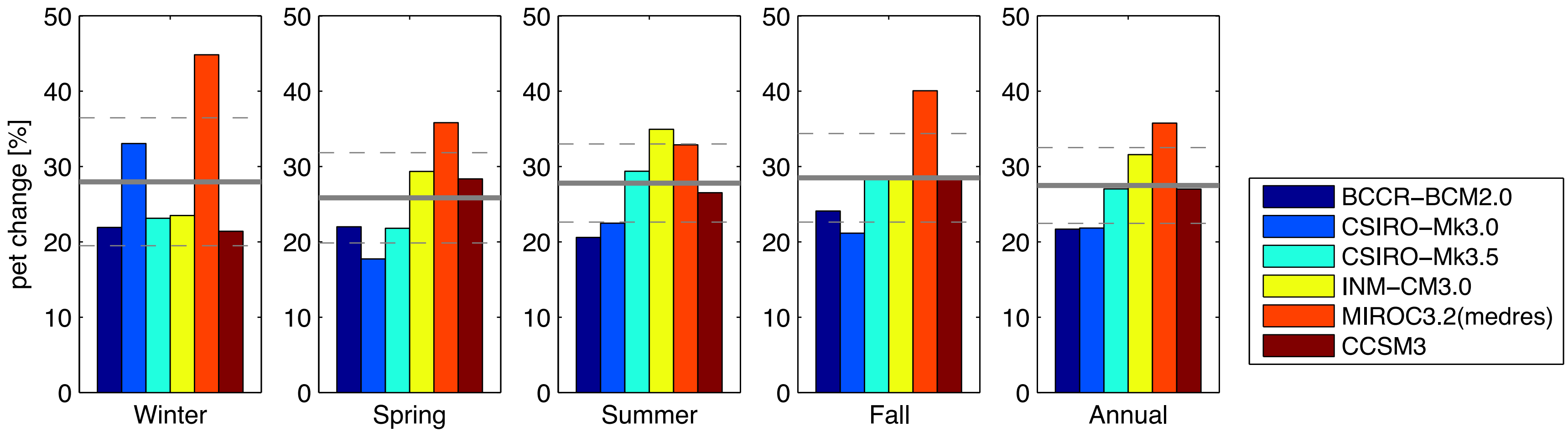




Annual summary [°C]	MEAN	STD	MIN	MAX
Baseline average	11.0	0.8	10.2	12.3
Projected changes	4.0	0.8	3.3	5.4

- All GCMs project warming in every season
- Largest warming in the summer
- Projected warming is outside the bounds of interannual variability

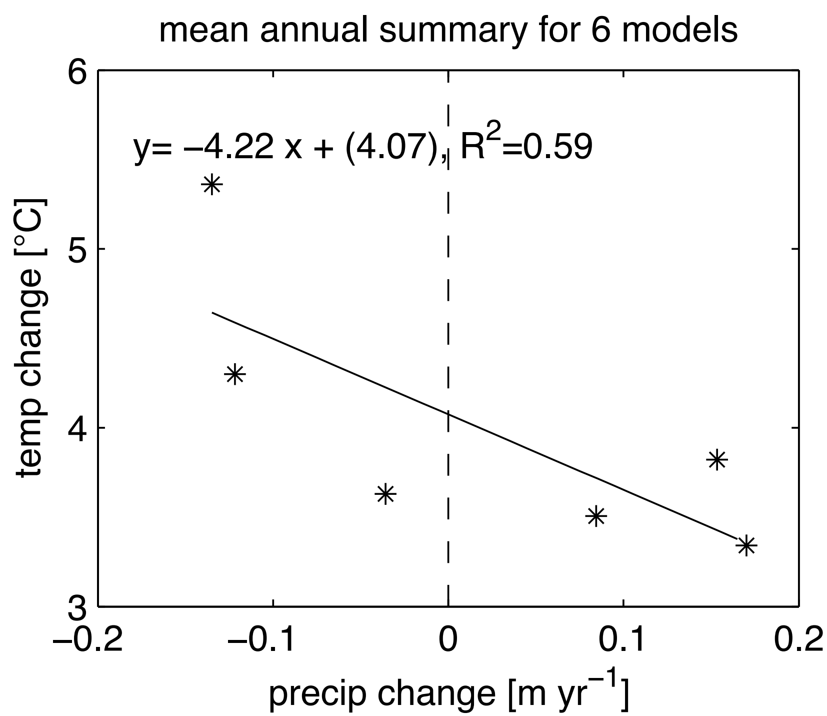
HSPF derived: potential evapotranspiration (PET)



Annual summary [m yr^{-1}]	MEAN	STD	MIN	MAX
Baseline average	0.71	0.03	0.66	0.76
Projected changes	+0.19 (27 %)	0.04 (6 %)	0.15(22%)	+0.25 (36 %)

- HSPF uses Hammon (1963) parameterization for PET
- All GCM-projected T changes result in PET increase in every season
- Model PET change is far outside the bounds of interannual variability

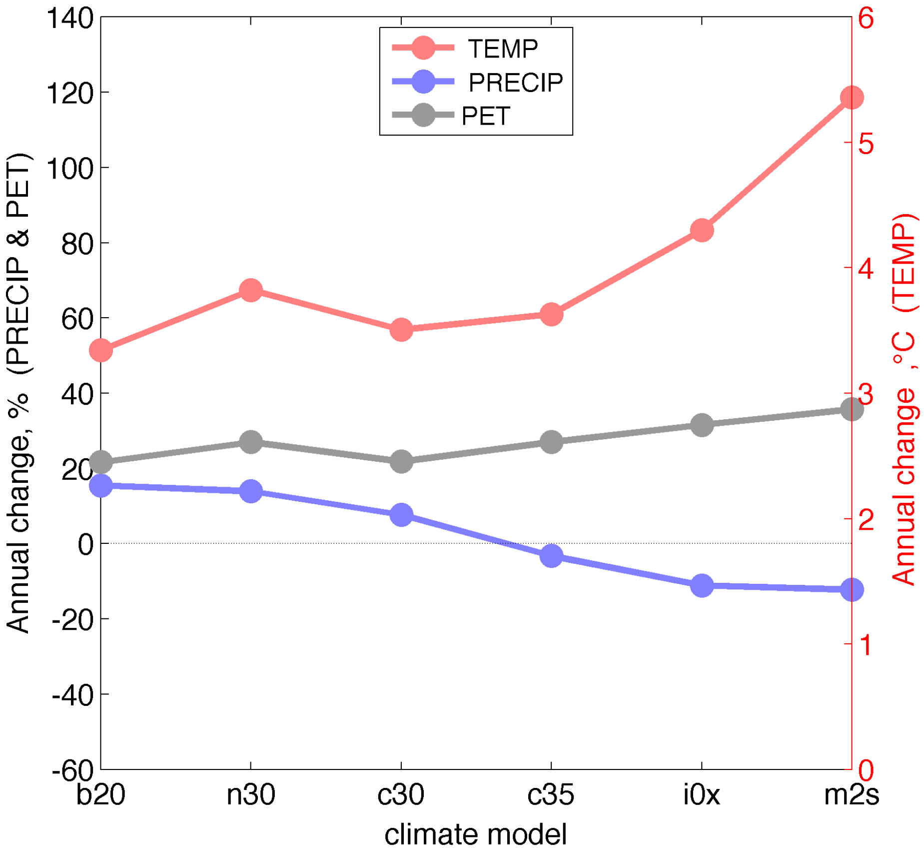
Summary of projected changes in forcing



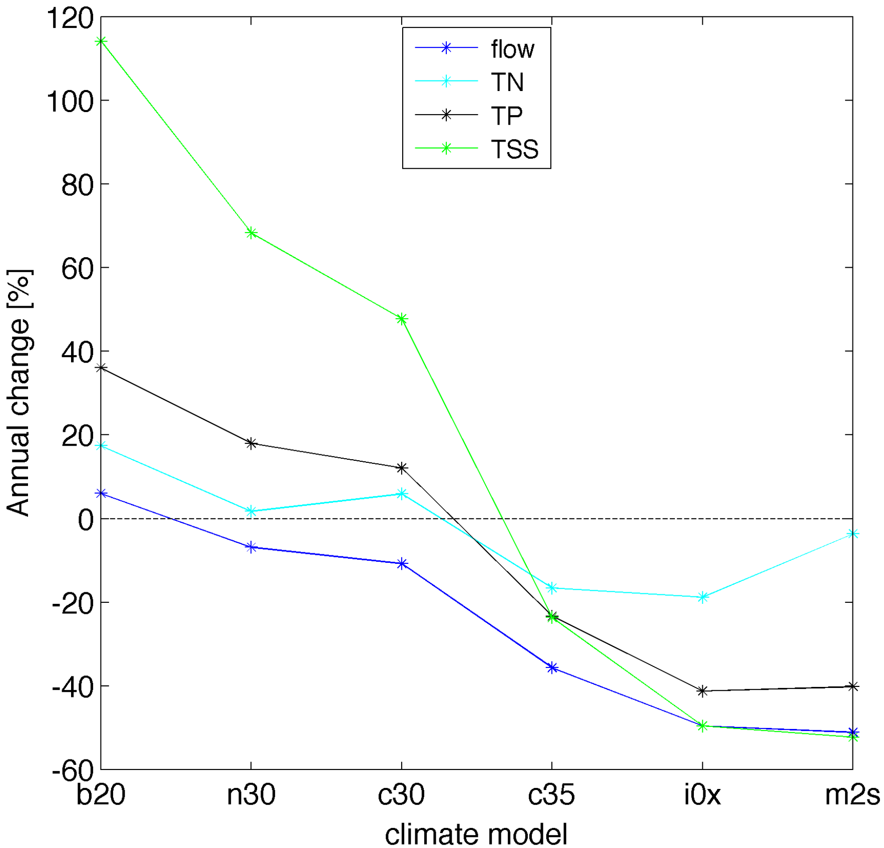
- Projected annual changes in T and P for the six models are negatively correlated, so models that get drier tend to warm more than models that get wetter
- Lower soil moisture due to lower precipitation would lead to a decreased latent cooling and, thus, more warming for a given amount of incident solar radiation

Response to full forcing

FORCING



RESPONCE



Comparison to other studies

Najjar et al. 2009

- End of 21st century
- Mid-Atlantic region, coupled models
- Large variability: ΔQ from -39 to +33 %

Meehl et al. 2007, IPCC 4AR

- End of 21st century
- Coupled models
- 15-model mean projections
- $\Delta Q = + 0.1$ mm $d^{-1} = 0.04$ m yr^{-1}

Hay et al. 2011

- End of 21st century projections
- Hydrological models for 14 U.S. watersheds
- $\Delta Q < 0$ for almost all watersheds

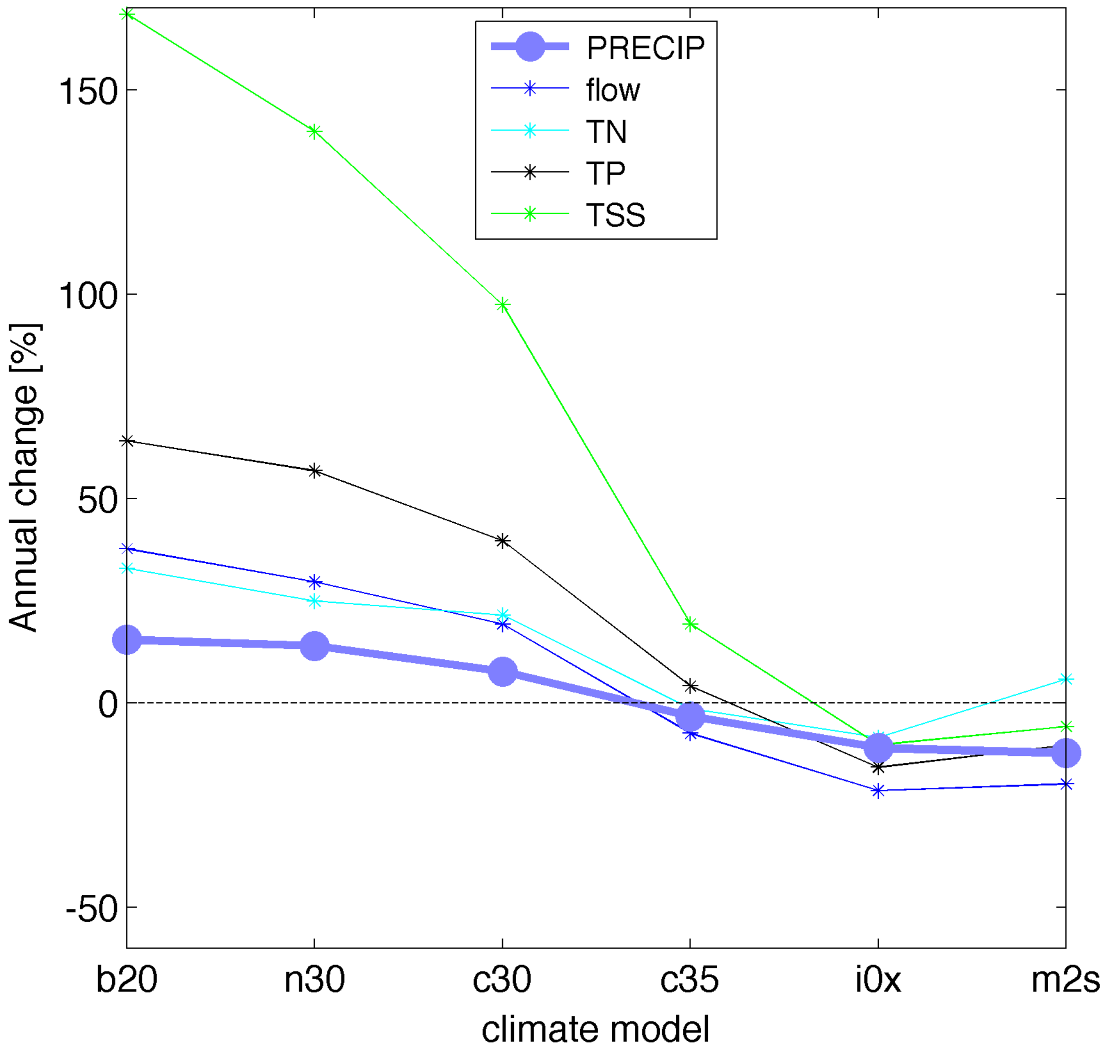
Milly and Dunne 2011

- Uncoupled simulations may lead to unrealistically large flow reductions: empirical PET formulations calibrated in the present climate might cause an overestimation of ET when used for future climate conditions

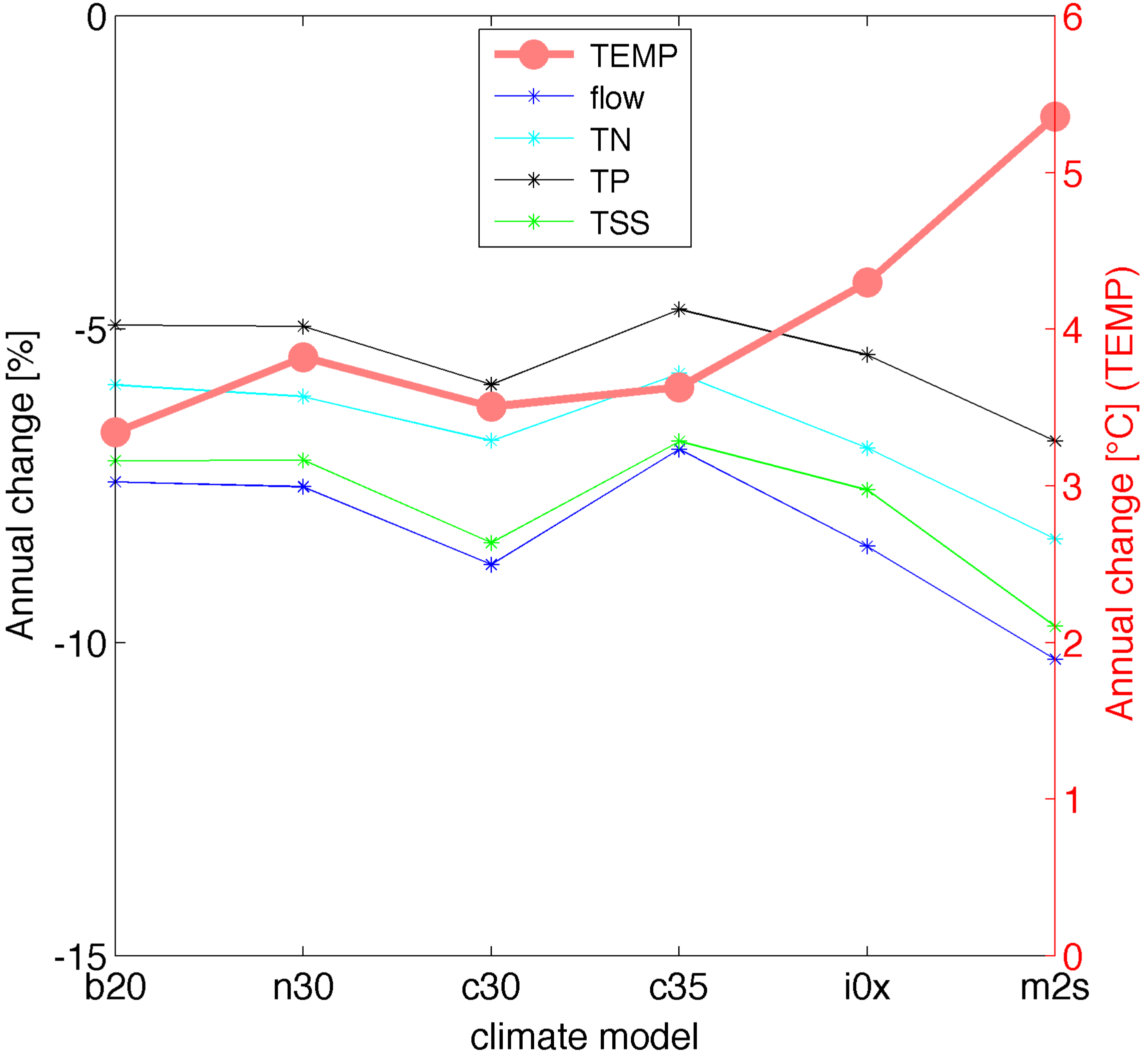
This study

Annual Q summary [m yr^{-1}]	MEAN	STD	MIN	MAX
Baseline average	0.5	0.1	0.3	0.8
HSPF projections	-0.11 (25 %)	0.11 (25 %)	-0.24 (51%)	+0.03 (6 %)

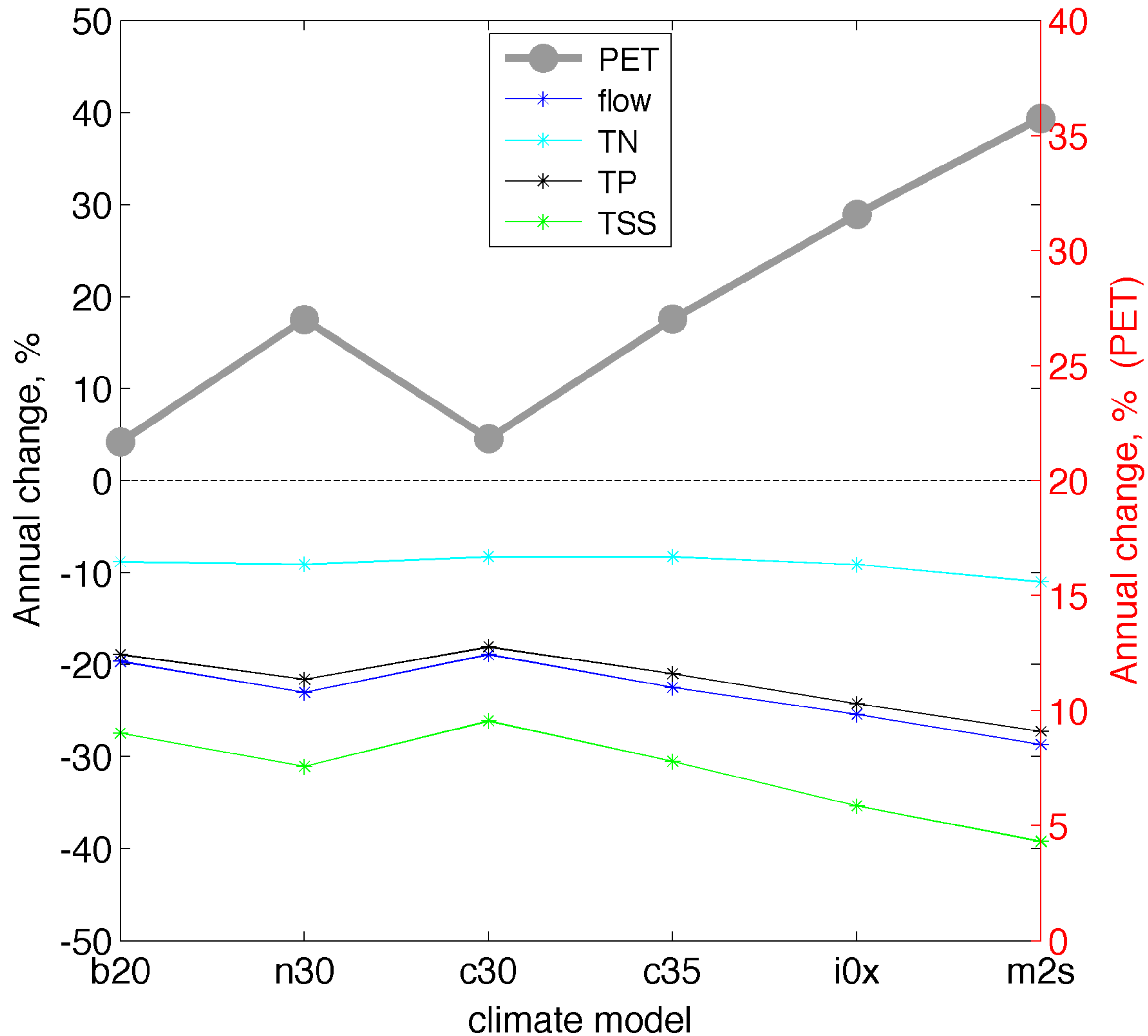
Response to PRECIP forcing



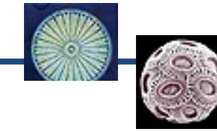
Response to TEMP forcing

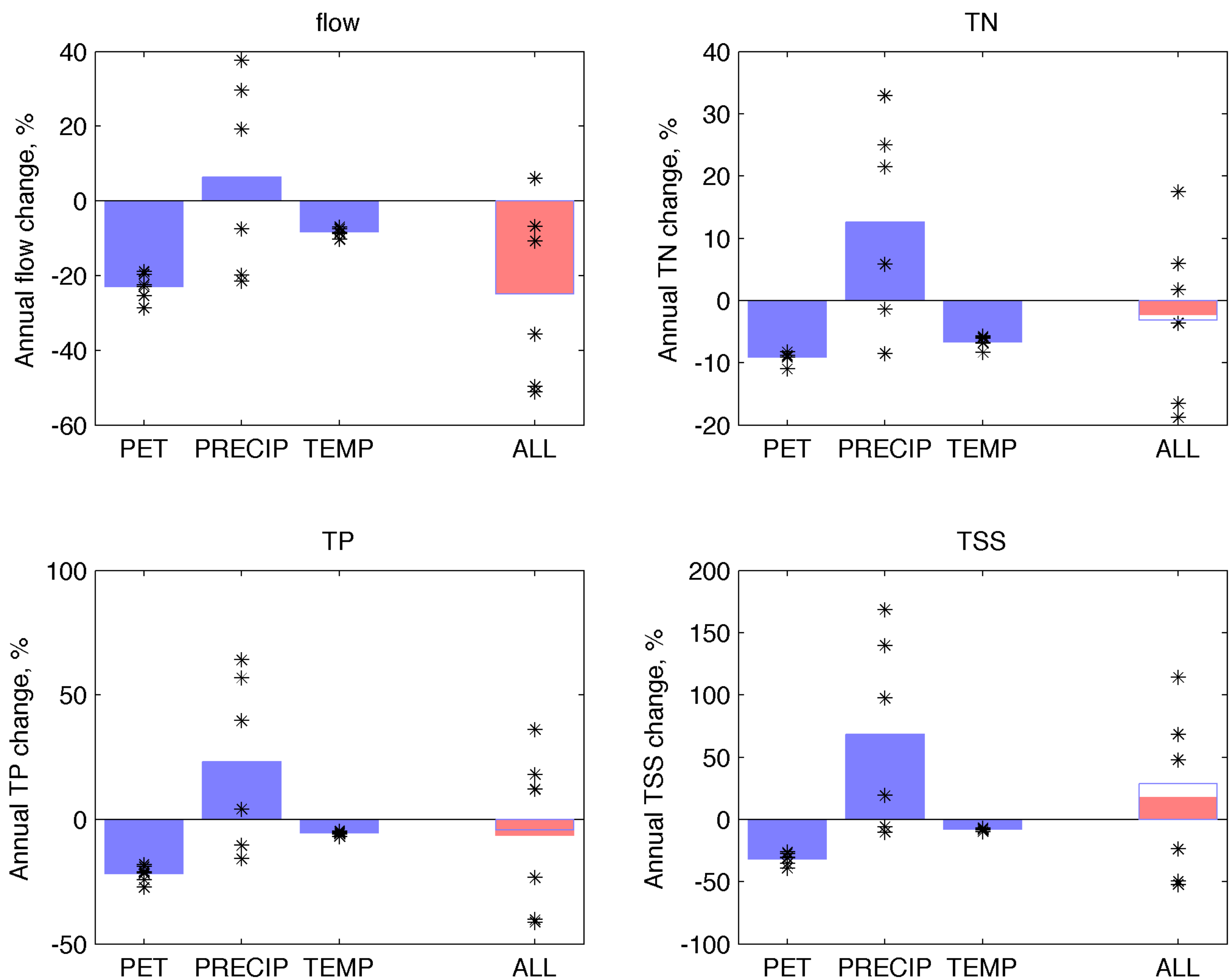


Response to PET forcing



Response summary





individual models are shown as stars; means of all models are shown as bars

Summary


- ΔT = + 4 °C ➔ outside the bounds of interannual variability
- ΔP range from -12 % to +15 %
- Annual ΔT and ΔP for the 6 GCMs are negatively correlated
- Dramatic decline in streamflow: annual ΔQ = -25%
- ΔTSS range from -56% to + 139%
- ΔTN range from -20% to + 20%
- ΔTP range from -40% to + 40%
- PET appears to dominate ΔQ projections
- Things to think about:
  - Why TEMP forcing alone results in relatively large ΔQ (-8%) ?
  - Why TP, TSS, and TN are strongly responsive to an increase in PRECIP, but only slightly to a decrease in PRECIP? Is this related to erosion treatment in HSPF?

Thank you.

SUPPLEMENTARY

References


Bicknell, B.R., Imhoff, J.C., Kittle, J.L., Jr., Donigian, A.S., Jr., and Johanson, R.C., 1997. Hydrological Simulation Program - Fortran, User's manual for version 11. U.S. Environmental Protection Agency. EPA/600/R-97/080, 755 p. Athens, GA.

Hamon, W.R., 1961. Estimating potential evapotranspiration. Proceedings of the American Society of Civil Engineers 87, 107–120 .

Hamon, W.R., 1963. Computation of direct runoff amounts from storm rainfall. International Association of Scientific Hydrology 63, 52–62.

Hay, L.E., Markstrom, S.L., and Ward-Garrison, C., 2011. Watershed-scale response to climate change through the twenty-first century for selected basins across the United States. Earth Interactions, 15, 1-37.

McKenney, M.S. and Rosenberg, N.J., 1993. Sensitivity of some potential evapotranspiration estimation methods to climate change. Agricultural and Forest Meteorology, 64, 81-110.

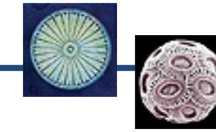
Meehl, G.A., Stocker, T.F., Collins, W.D., Friedlingstein, P., Gaye, A.T., Gregory, J.M., Kitoh, A., Knutti, R., Murphy, J.M., Noda, A., Raper, S.C.B., Watterson, I.G., Weaver, A.J., Zhao, Z.-C., 2007. Global climate projections. In: S. Solomon, D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor, H.L. Miller (Editors), Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 747-845.

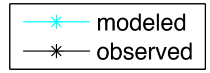
References (cont'd)


Milly, P.C.D., Dunne, K.A., 2011. On the hydrologic adjustment of climate-model projections: the potential pitfall of potential evaportraspiration. Earth Interactions, 15, 1-15.

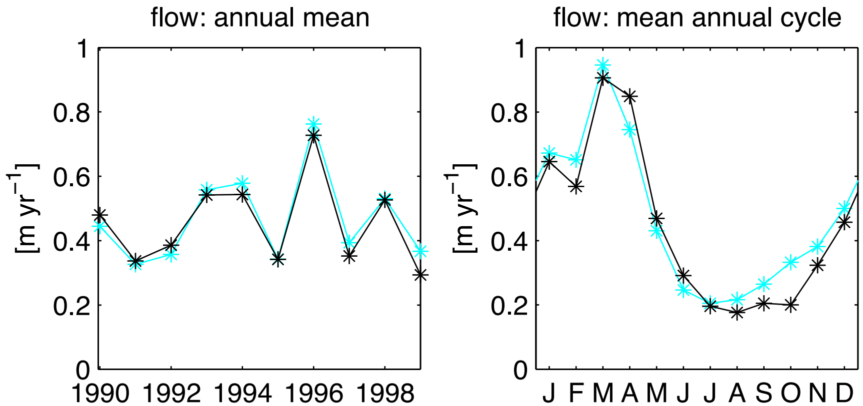
Najjar, R.G., Pyke, C.R., Adams, M.B., Breitburg, D., Hershner, C., Kemp, M., Howarth, R., Mulholland, M.R., Paolisso, M., Secor, D., Sellner, K., Wardrop, D., Wood, R., 2010. Potential climate-change impacts on the Chesapeake Bay. Estuarine, Coastal and Shelf Science 86, 1–20. USEPA, 2010. Chesapeake Bay Phase 5.3 Community Watershed Model (No. EPA 903S10002 - CBP/TRS-303-10). U.S. Environmental Protection Agency, Chesapeake Bay Program Office, Annapolis, MD. Environmental Protection Agency. EPA/600/R-97/080, 755 p. Athens, GA.

Hydrological model evaluation

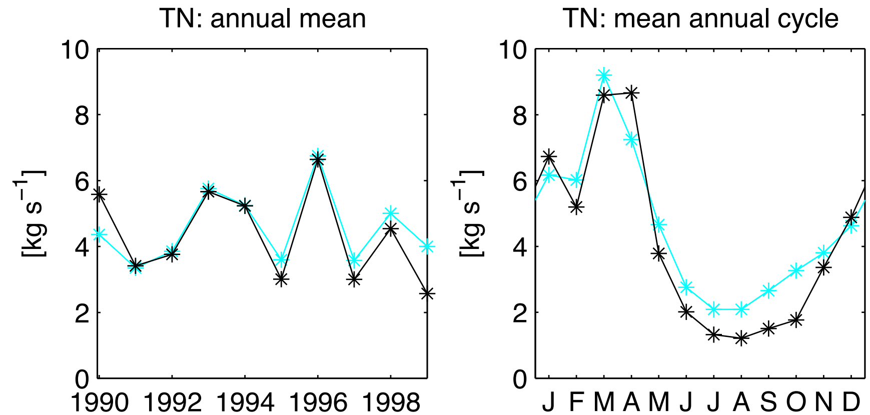




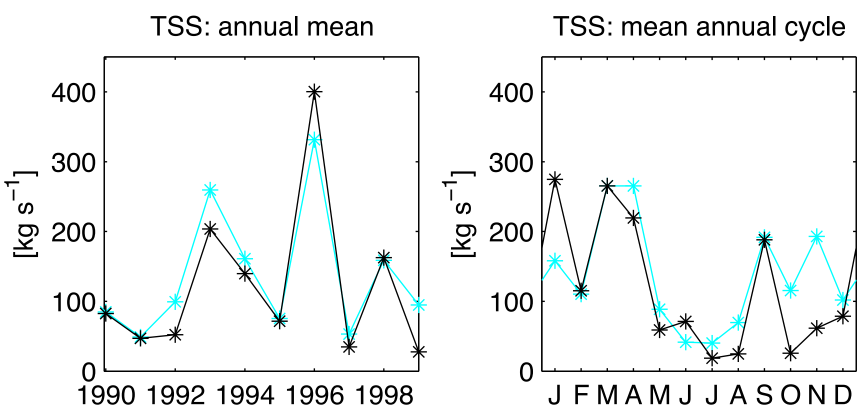
A. Streamflow (Q)



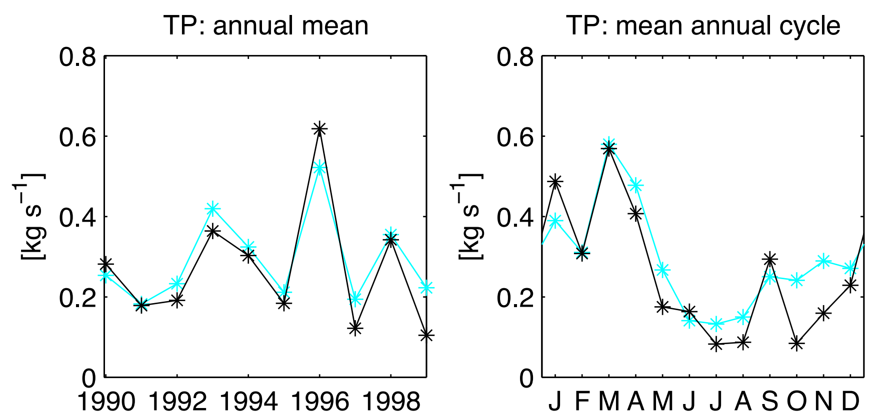
C. Total nitrogen (TN)



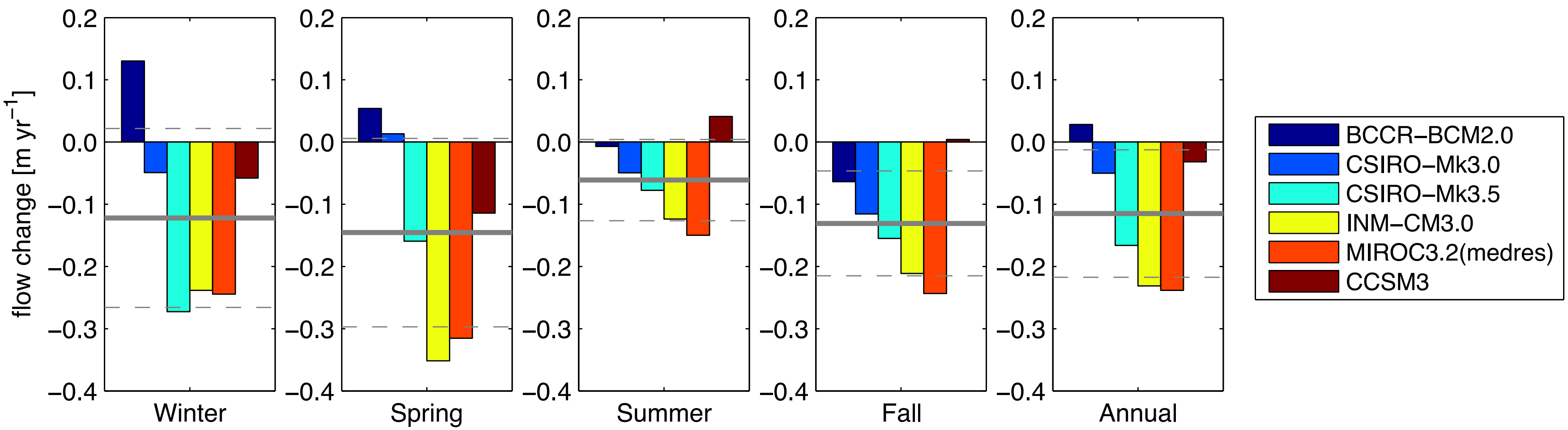
B. Sediment (TSS)



D. Total phosphorus (TP)



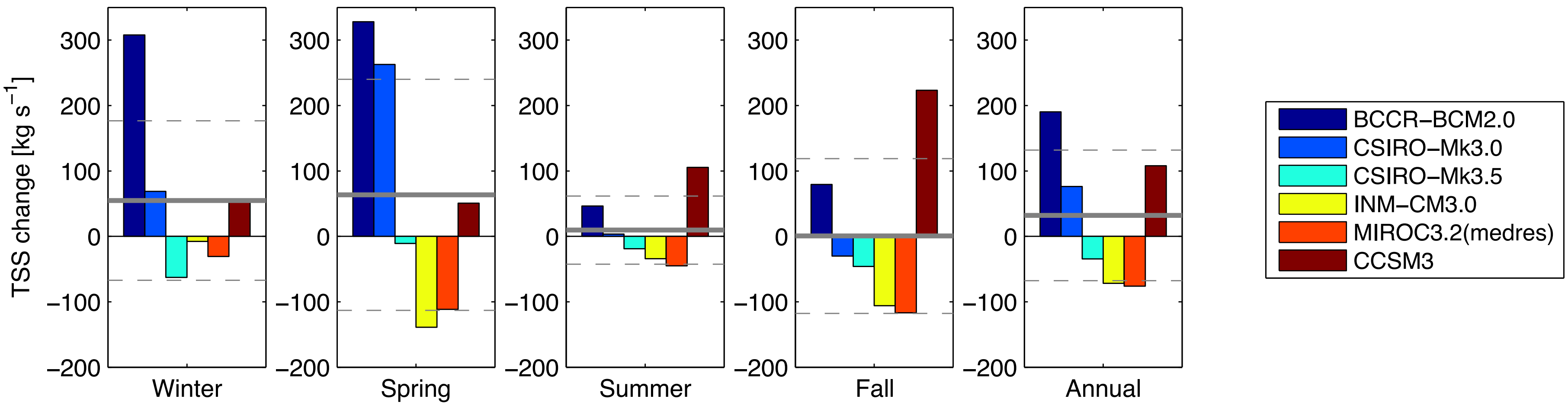
Simulated Q response



Annual summary [m yr^{-1}]	MEAN	STD	MIN	MAX
Baseline average	0.5	0.1	0.3	0.8
Projected changes	-0.11 (25 %)	0.11 (25 %)	-0.24 (51%)	+0.03 (6 %)

- Dramatic decline in all seasons
  - 5 out of 6 runs show a decrease in winter, summer and fall
  - 4 out of 6 runs show a decrease in spring
- Summer decline is the least pronounced
- Projected changes are comparable to interannual variability

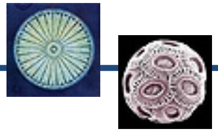
Simulated TSS response

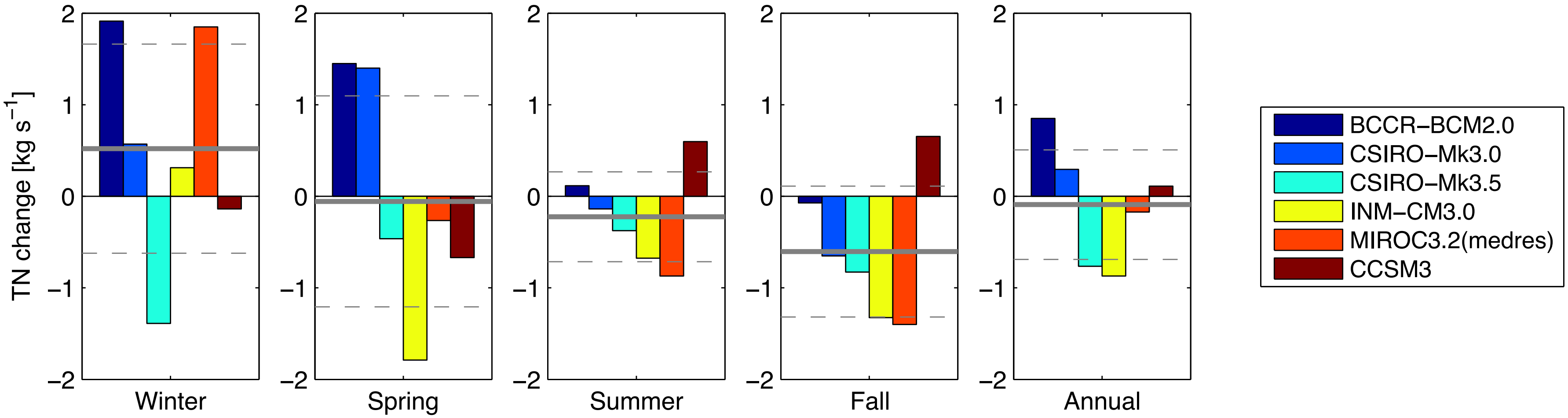


Annual summary [kg s^{-1}]	MEAN	STD	MIN	MAX
Baseline average	137	93	49	331
Projected changes	+32 (23 %)	109 (80 %)	-76 (56%)	+190 (139 %)

- Projected changes are highly variable
- Winter and spring fluxes increase, on average
- Summer and fall fluxes remain essentially unchanged, on average
- Projected changes are comparable to interannual variability

Simulated TN response

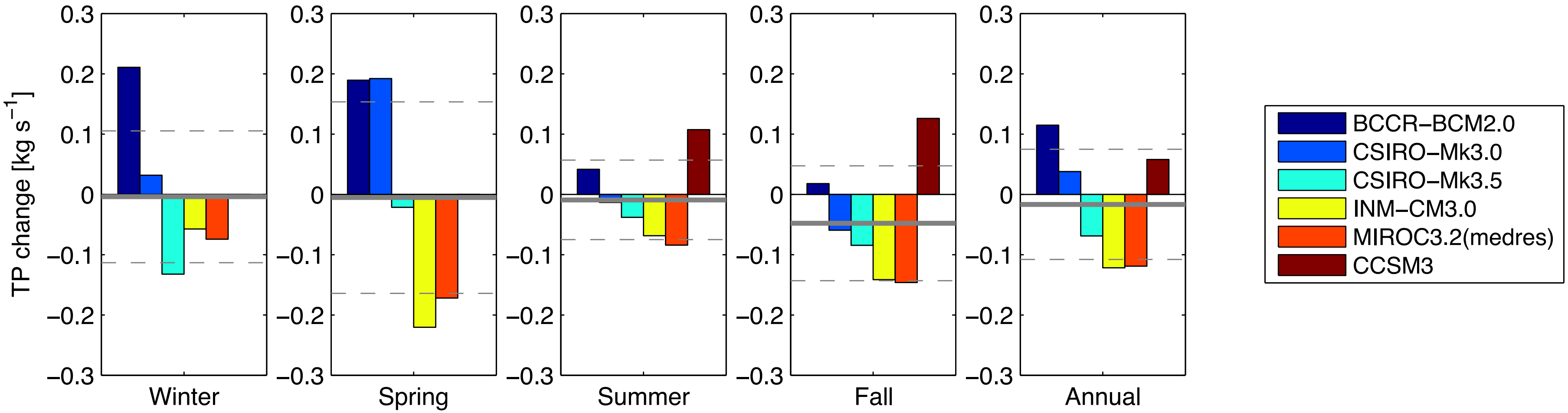




Annual summary [kg s-1]	MEAN	STD	MIN	MAX
Baseline average	4.6	1.1	3.4	6.8
Projected changes	-0.1 (2 %)	0.7 (14 %)	-0.9 (20 %)	+0.9 (20 %)

- Projected changes are highly variable
- Winter fluxes increase, on average
- Spring, summer and fall fluxes decrease, on average
- Projected changes are comparable to interannual variability

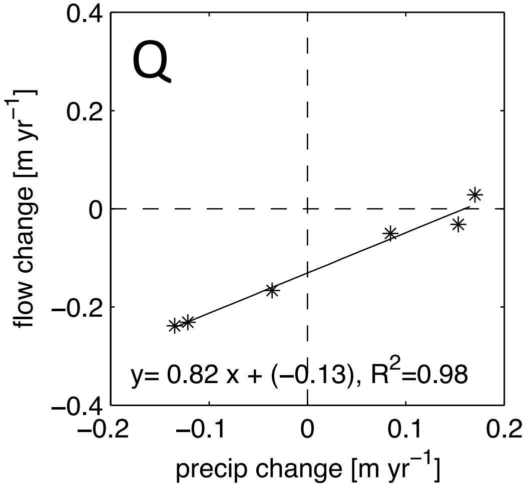
Simulated TP response

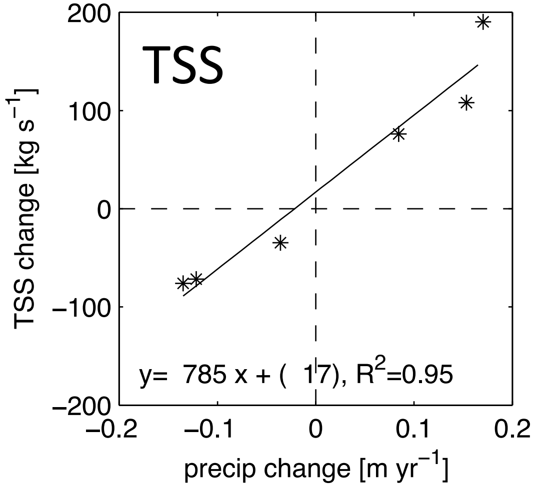


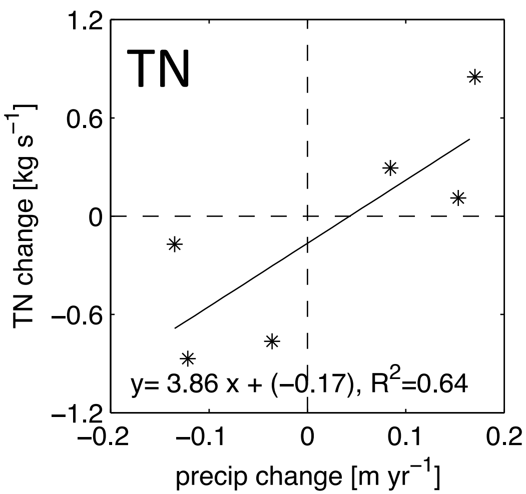
Annual summary [kg s^{-1}]	MEAN	STD	MIN	MAX
Baseline average	0.29	0.11	0.18	0.52
Projected changes	-0.02 (6 %)	0.10 (34 %)	-0.12 (40 %)	+0.12 (40 %)

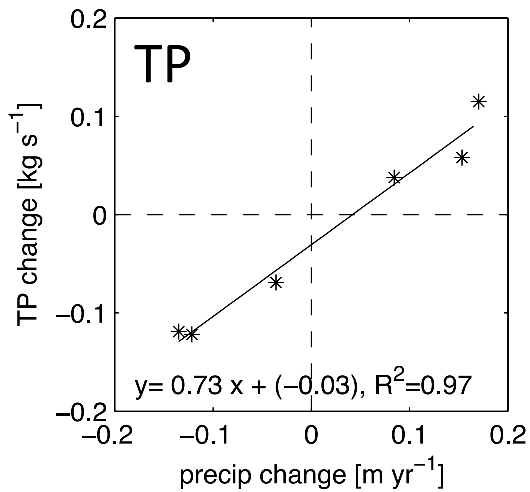
- Projected changes are highly variable
- Winter and spring fluxes remain essentially unchanged, on average
- Sumer and fall fluxes decrease, on average
- Projected changes are comparable to interannual variability

Sensitivity to P

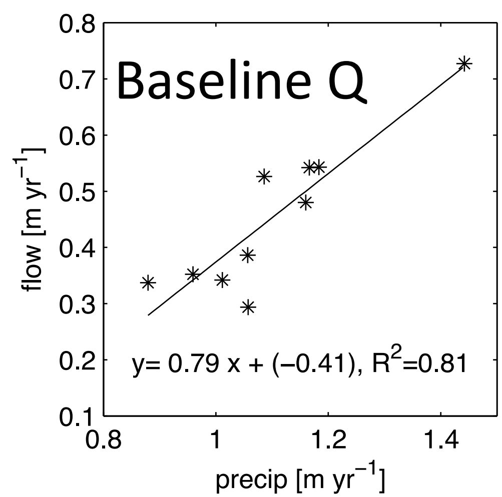





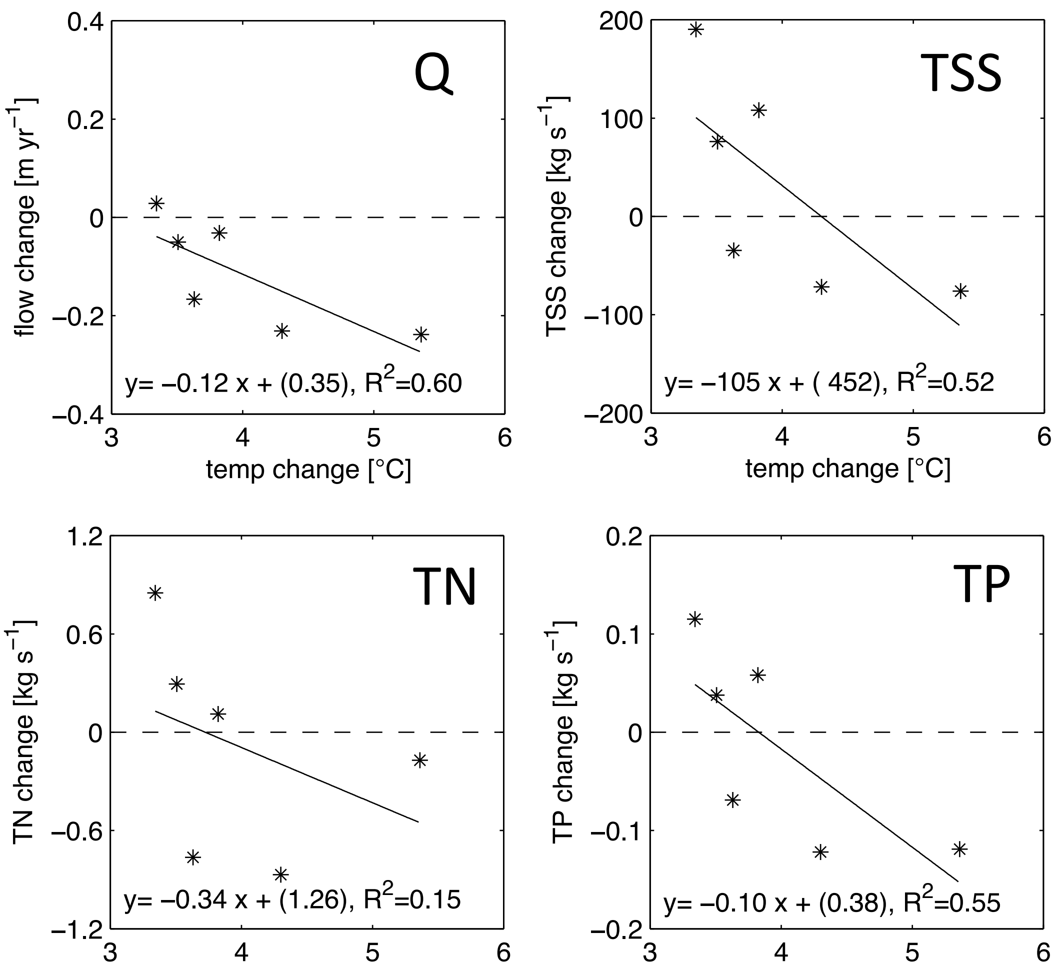




- Positive correlation with P
- P accounts for a considerable fraction of variability
- The y-intercepts can be interpreted as the projected flux changes due to T alone
- The slope of the Q vs. P is similar to what was found for the baseline interannual variability (slope = 0.79, R^2 = 0.81)

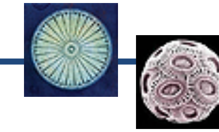


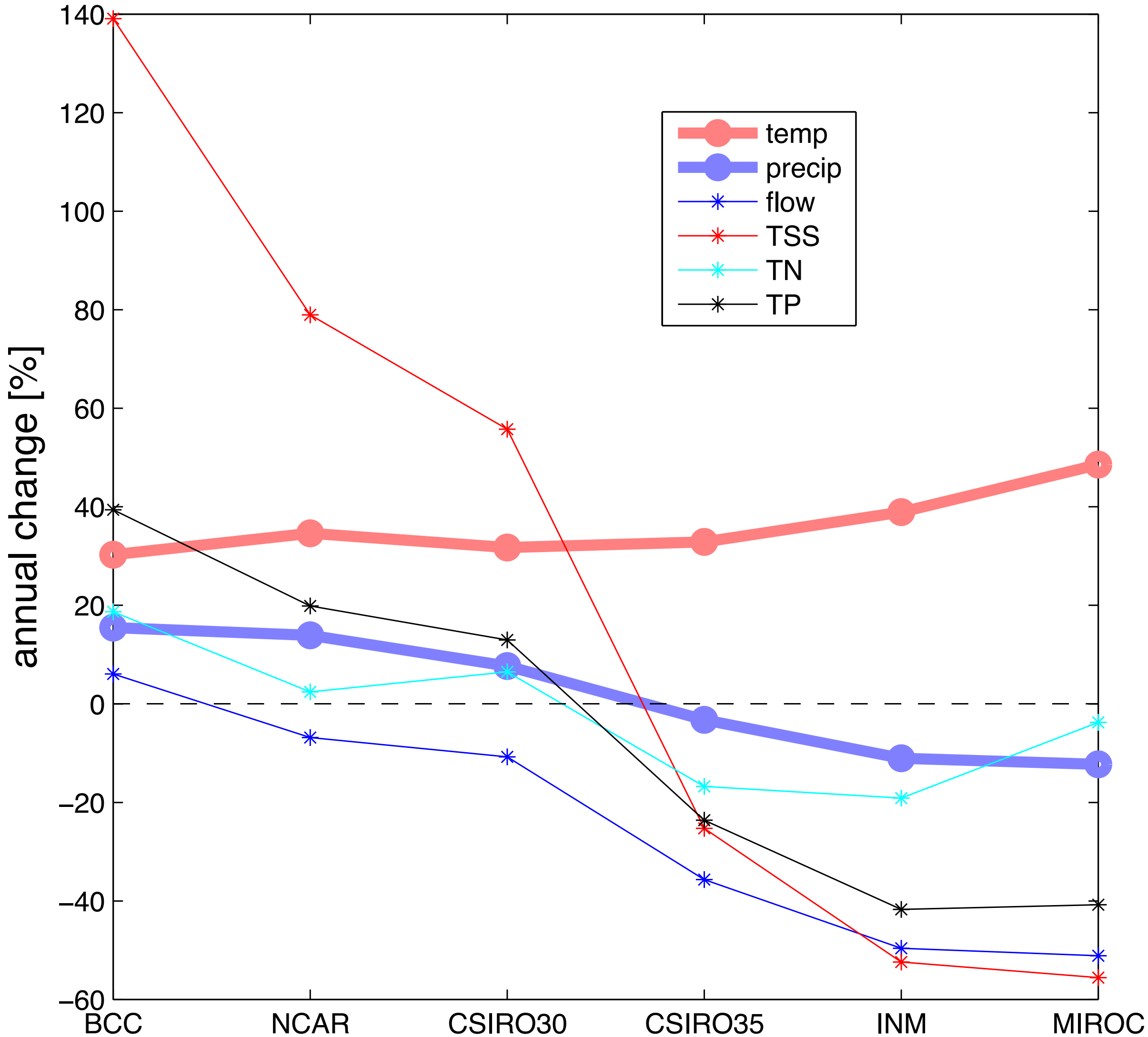
Sensitivity to T

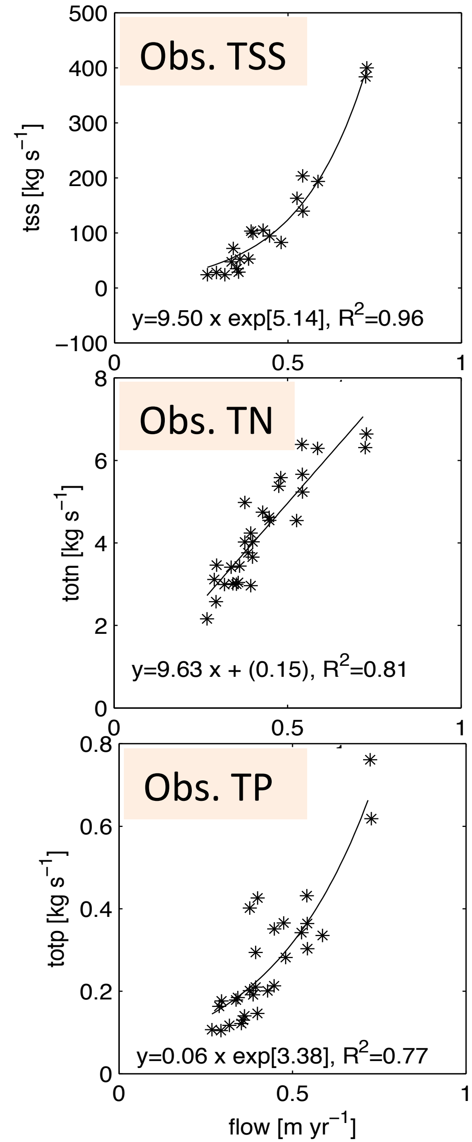


- Negative correlation with T
- T accounts for a smaller fraction of variability compared with P
- For TN, the relationship is particularly week
- For Q, have the strongest relationship

Summary of annual response to climate forcing







Comparison to other Q projections

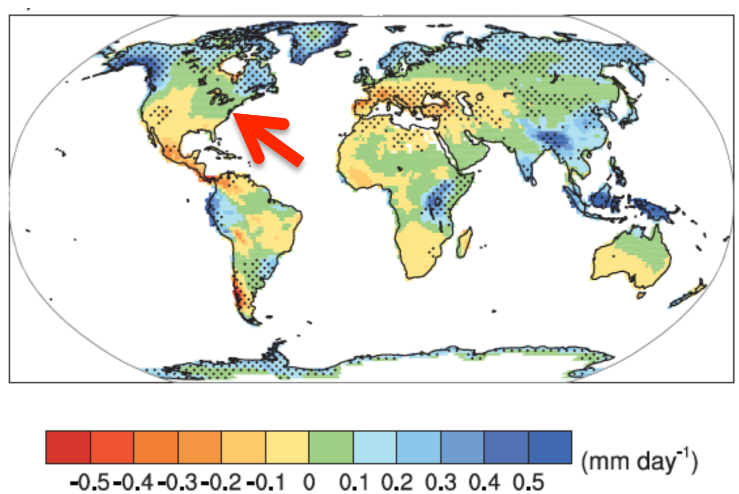
Najjar et al. 2009

- End of 21^{st} century
- Mid-Atlantic region
- Coupled models
- Large variability ΔQ

Reference	Region	Annual streamflow change (%)
McCabe and Ayers (1989)	Delaware River Basin	−39 to 9
Moore et al. (1997)	Mid-Atlantic/New England	−32 to 6
Najjar (1999)	Susquehanna River Basin	24 ± 13
Wolock and McCabe (1999)	Mid-Atlantic	−25 to 33
Neff et al. (2000)	Susquehanna River Basin	−4 to 24
Frei et al. (2002)	Southeastern New York	−28 to 10
Hayhoe et al. (2007)	Pennsylvania and New Jersey	9 to 18

Meehl et al. 2007, IPCC 4AR

- End of 21^{st} century
- Coupled models
- 15-model mean projections
- $\Delta Q = + 0.1 \text{ mm d}^{-1} = 0.04 \text{ m yr}^{-1}$

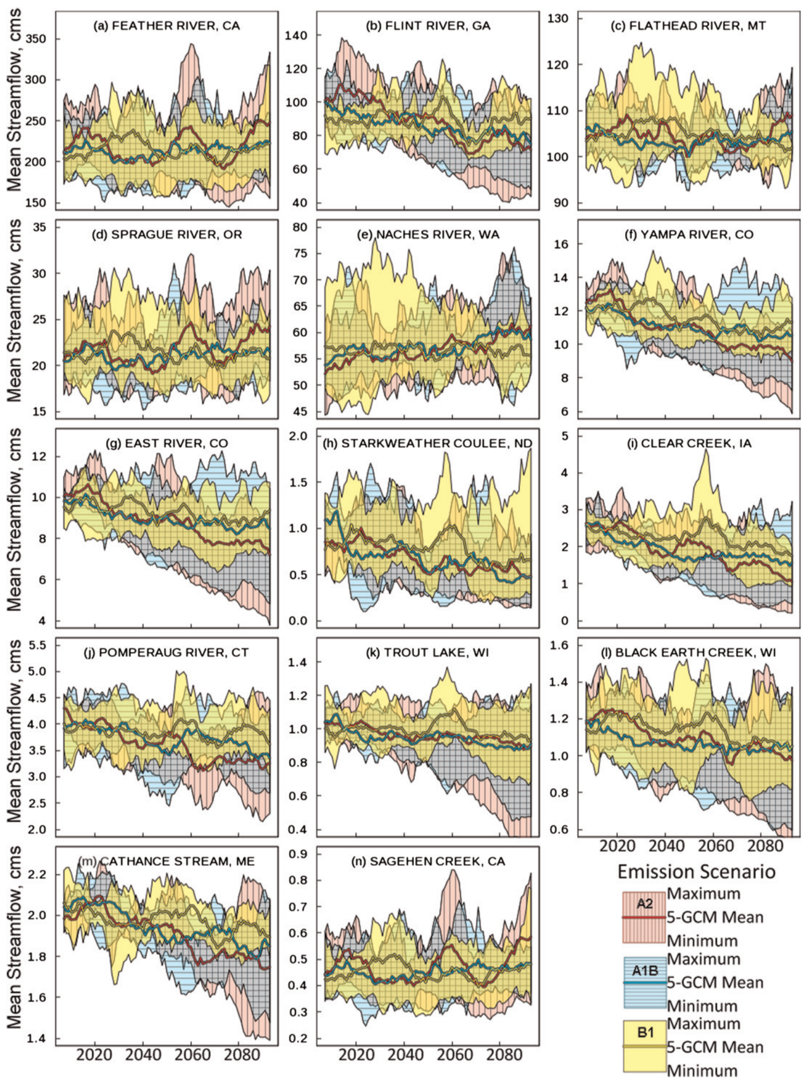


Annual Q summary [m yr^{-1}]	MEAN	STD	MIN	MAX
Baseline average	0.5	0.1	0.3	0.8
HSPF projections	-0.11 (25 %)	0.11 (25 %)	-0.24 (51%)	+0.03 (6 %)

Comparison to other Q projections (contd.)

Hay et al. 2011

End of 21st century projections for 14 U.S. watersheds: hydrological model



Milly and Dunne 2011

- used Hay et al. 2011 hydrological model projections
- compared to climate – land surface coupled models (Coupled Model Intercomparison Project, CMIP)
- ΔPET according to T-based empirical formulation was typically 3 times larger than that of the explicit calculation of the surface energy balance
- uncoupled simulations may lead to unrealistically large flow reductions: empirical PET formulations calibrated in the present climate might cause an overestimation of ET when used for future climate conditions

Summary

- ΔT = + 4 °C ➔ outside the bounds of interannual variability
- ΔP range from -12 % to +15 %
- Annual ΔT and ΔP for the 6 GCMs are negatively correlated
- Dramatic decline in stramflow: annual ΔQ = -25%
- ΔTSS range from -56% to + 139%
- ΔTN range from -20% to + 20%
- ΔTP range from -40% to + 40%
- All parameters are strongly correlated with P
- All parameters are weakly anti-correlated with T
- Q has the strongest anti-correlation with T: real or due to PET parameterization?

Plans for future work

- What are the separate effects of PET, T, and P?
  - T change only (6 runs)
  - P change only (6 runs)
  - PET change only (6 runs)

- Are HSPF-based projections flows comparable to those from coupled models?
  - use best regional hydrological model predictions available for our study region from coupled climate-land surface models: mid-century (2041-2070) projections are available from the North American Regional Climate Change Assessment Program (NARCCAP)
  - for comparison with Milly and Dunne (2011), also use Couple Model Intercomparison Project (CMIP) models
  - 6 additional HSPF simulations that overlap with the NARCCAP period