Understanding the Sierra Nevada Hydrologic Response to Climate Change

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BIOGRAPHICAL SKETCH

Dr. Miller is a Hydrometeorologist at the University of California's Berkeley National Laboratory and is an Adjunct Professor in the Department of Hydrology and Water Resources at the University of Arizona-Tucson. He leads the Atmosphere and Ocean Sciences Group at Berkeley Lab. His research includes analyzing atmosphere and land surface processes at a range of scales, evaluating climate change impacts, and advancing new computational techniques for climate simulations. He has published over 50 peer reviewed journal papers and book chapters, is a contributing author of the Intergovernmental Panel for Climate Change Second and Third Assessment Reports, the Southwestern U.S. National Assessment, and the California Assessment Reports.

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In 2000, the Intergovernmental Panel on Climate Change formulated different emission scenarios for our future. These account for the demographic, socioeconomic and technological forces driving greenhouse gas (GHG) emissions. A high GHG emission scenario, designated A1fi, describes a future with continued heavy reliance on fossil fuels. In contrast, the B1 scenario envisions the development of clean, resource-efficient technology. A new approach that uses the A1fi and B1 emission scenarios as input to two Atmospheric Ocean General Circulation Models (AOGCMs) has been completed. After downscaling, analysis of the potential impacts on extreme heat, snowpack, water supply and agriculture showed that departures between the scenarios emerged before 2050. By the end of this century, annual temperature increases of 4-6^{o}C under the higher A1fi emission scenario were nearly double those seen under the lower B1 emission scenario. Snowpack in the Sierra Nevada mountains was reduced under both scenarios by 30-70% under B1 and 73-90% under A1fi, with cascading impacts on streamflow and water storage and supply. Details of the analysis and what this means to California's future hydrology are presented.

This talk provides an overview from the findings from two publications.

The first paper, Potential impacts of climate change on California hydrology (Miller et al 2003):

- Changes in temperature, precipitation, streamflow
- Changes in snow accumulation and snow melt
- Distributions by month, elevation, and latitude
- Timing of the cumulative annual streamflow
- Annual peak flow exceedance probabilities

The second paper, Emissions pathways, climate change, and impacts on California (Hayhoe et al. 2004):

- Temperature, Heat and Mortality Analysis
- Precipitation and Snowpack Projections
- Sea Level Projections and Impacts
- Projected Vegetation Distributions

In the second study, we take our analysis one dimension further by evaluating multiple emissions, as well as models.

Approach I:

(1) Evaluate Warm-Wet and a Cool-Dry GCM Projections

HadCM2 r1 PCM b06.06

Both are *forced by the* *<u>IS92a</u>* *Emission Scenario*

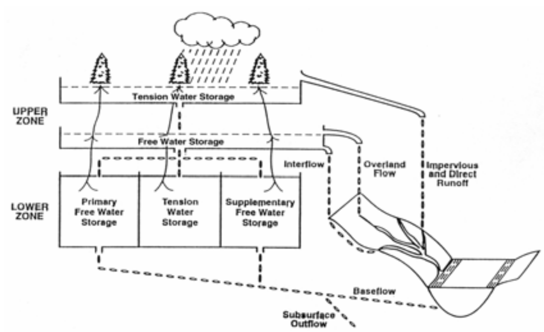
(2) Evaluate Specified Incremental Change

Temperature Shift (o C)	Precipitation Ratio (± 30%)
0.0, 1.5, 3.0, 5.0	0.70, 0.82, 091, 1.00, 1.09, 1.18, 1.30

- Impose temperature shifts and precipitation ratios to historically observed Mean Area Temperature (MAT) and Mean Area Precipitation (MAP)
- Use the 1963-1992 as climatological input forcing data
- Use the NOAA/NWS *Sacramento Soil Moisture Accounting and Anderson Snow Model*, which is a function of Temperature and Precipitation

NWS Soil Moisture Accounting and Anderson Snow Model

- ***Snow Accumulation and Ablation Energy Balance Model***
  - **Anderson Snow Model**
    - **Air Temperature is an index to energy exchange at the snow-air interface**
- ***Sacramento Soil Moisture Accounting***
  - **Spatially lumped and deterministic**
  - **2 vertical layers**
  - **5 storage compartments**
    - **upper and lower tension**
    - **upper free**
    - **lower primary free and secondary free**
  - **Inputs:**
    - **Mean Area Precipitation (MAP)**
    - **Mean Area Temperature (MAT)**



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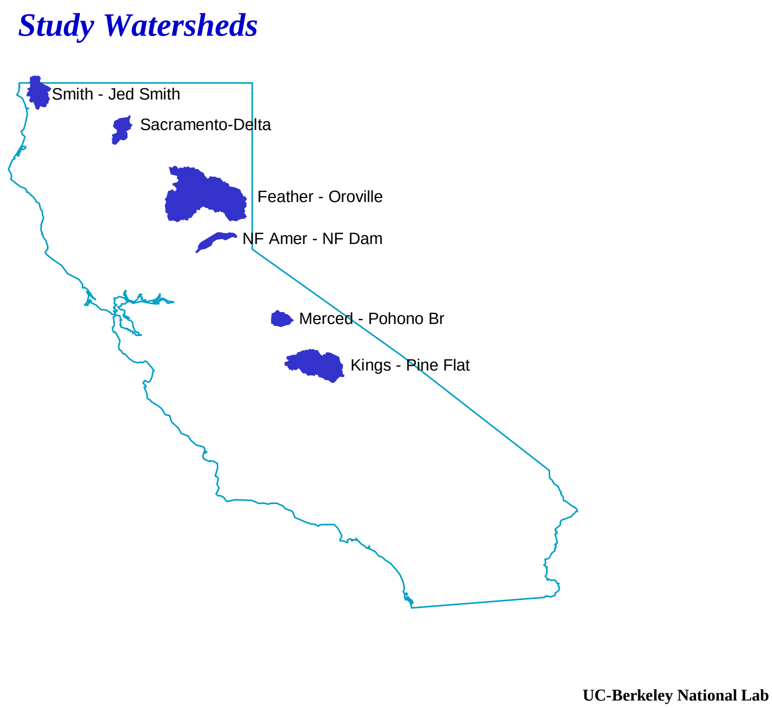
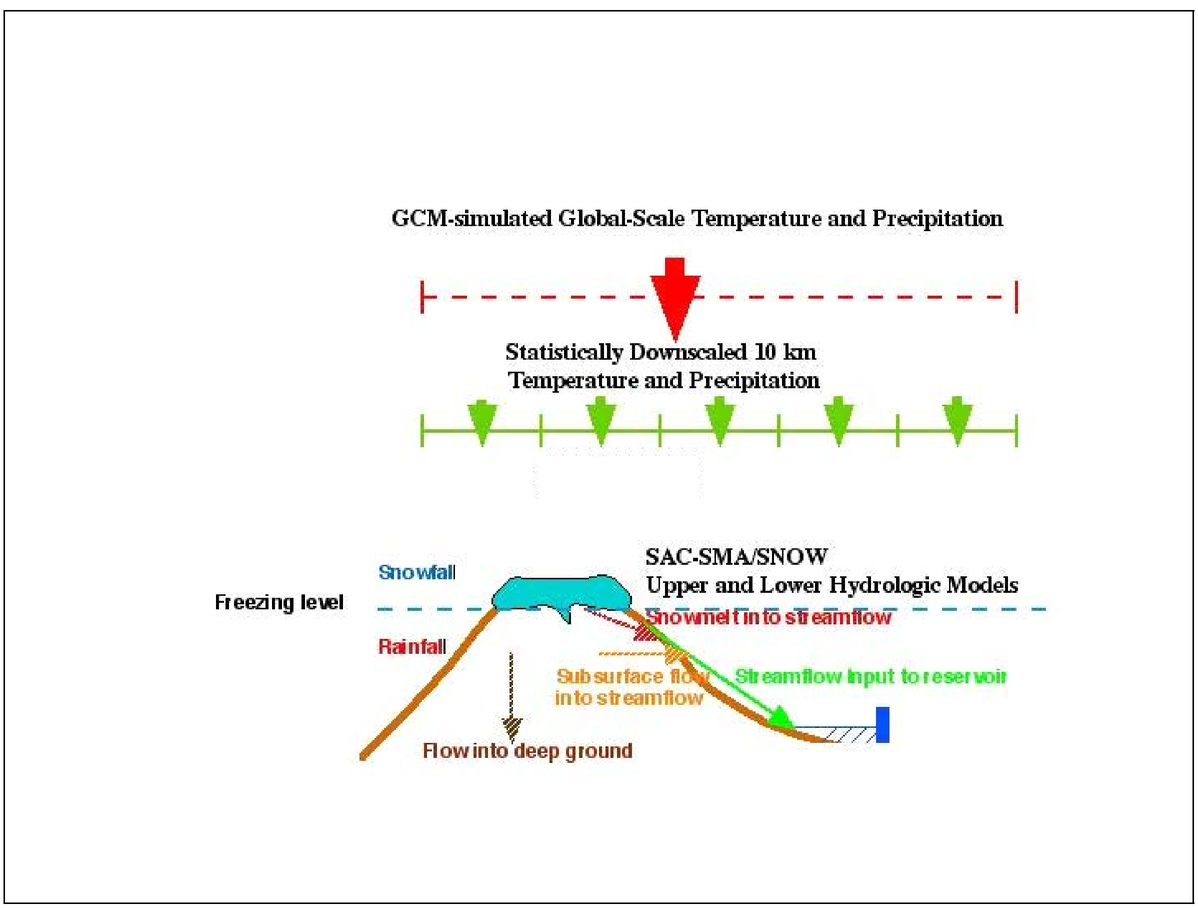
Six Study Basins were used for analysis:





Computing MAT and MAP

$$T_{change} = T_{historical} + T_{sensitivity}$$
$$T_{sensitivity} = T_{sim,\ projected} - T_{sim,\ baseline}$$

$$P_{change} = P_{historical} * P_{sensitivity}$$
$$P_{sensitivity} = T_{sim,\ projected} / T_{sim,\ baseline}$$

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Adjusted Potential Evapotranspiration

Use the Hamon Formula:

PET hamon = F (Temperature, Julian Day, Latitude)

Generate ET_Demand Curve Adjustment Ratios:

$$ET\_Demand * PET(T_{projected})/PET(T_{baseline})$$

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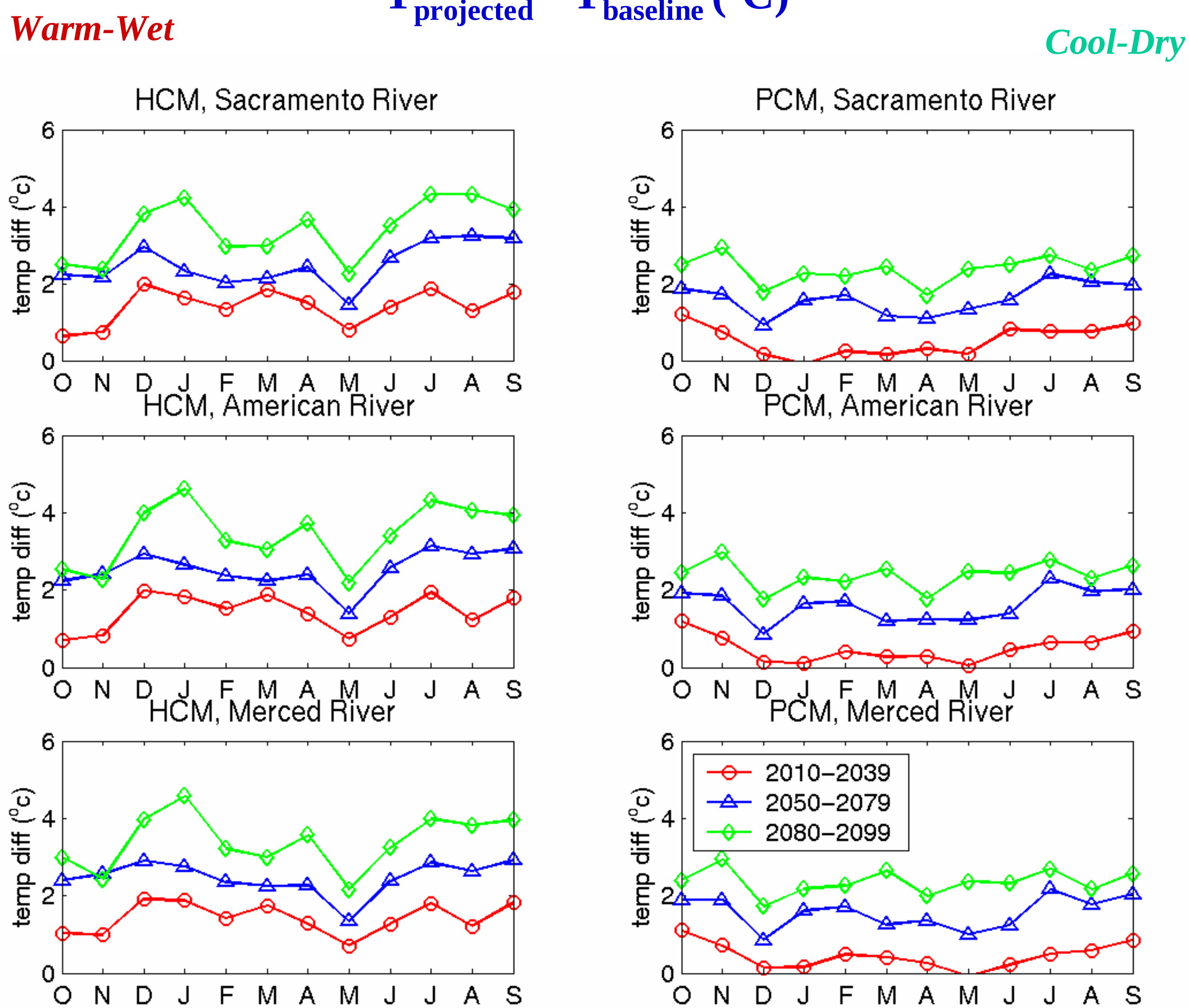
Temperature Sensitivity

$T_{projected} - T_{baseline}$ (°C)



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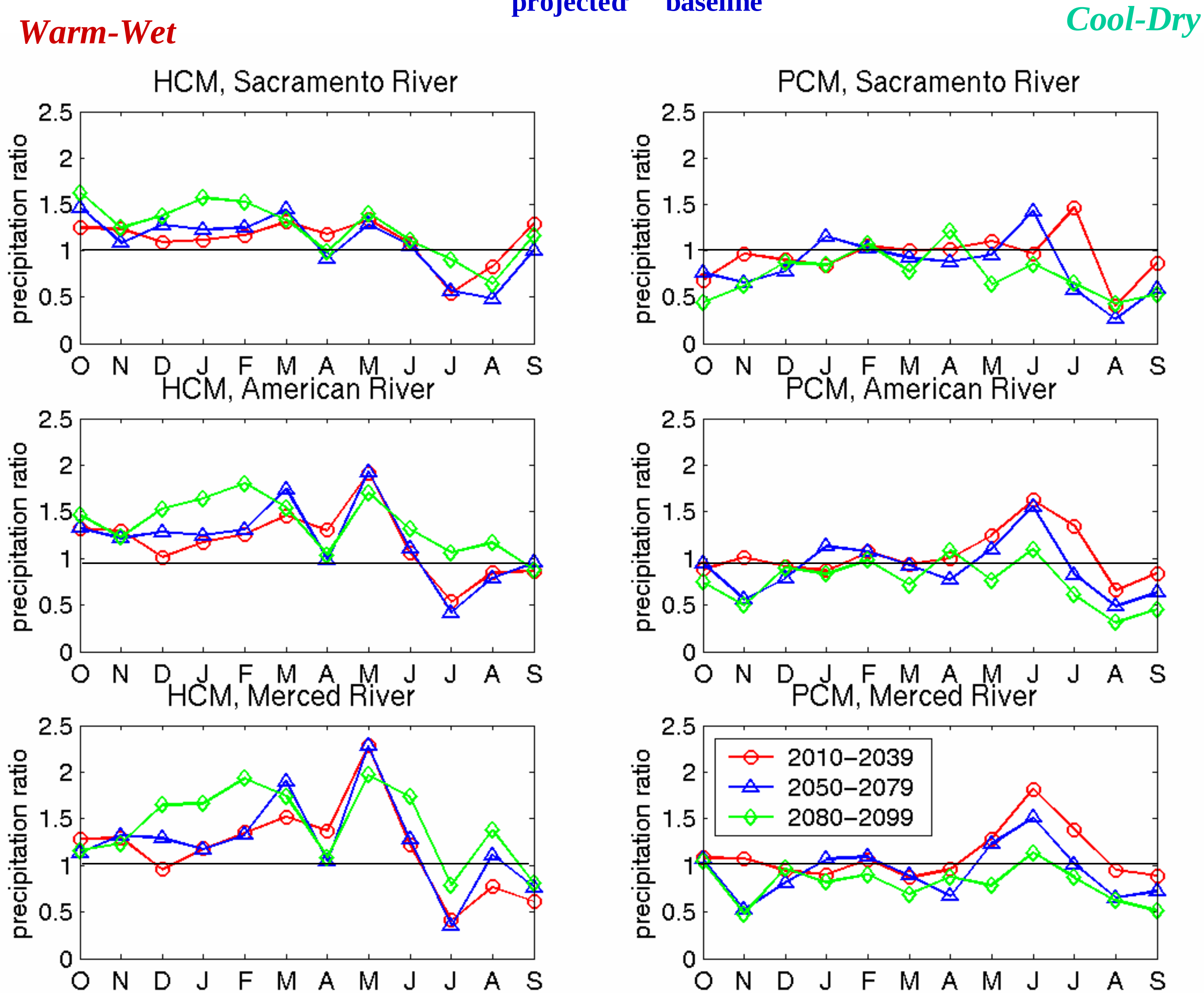
Precipitation Sensitivity

$P_{projected}/P_{baseline}$



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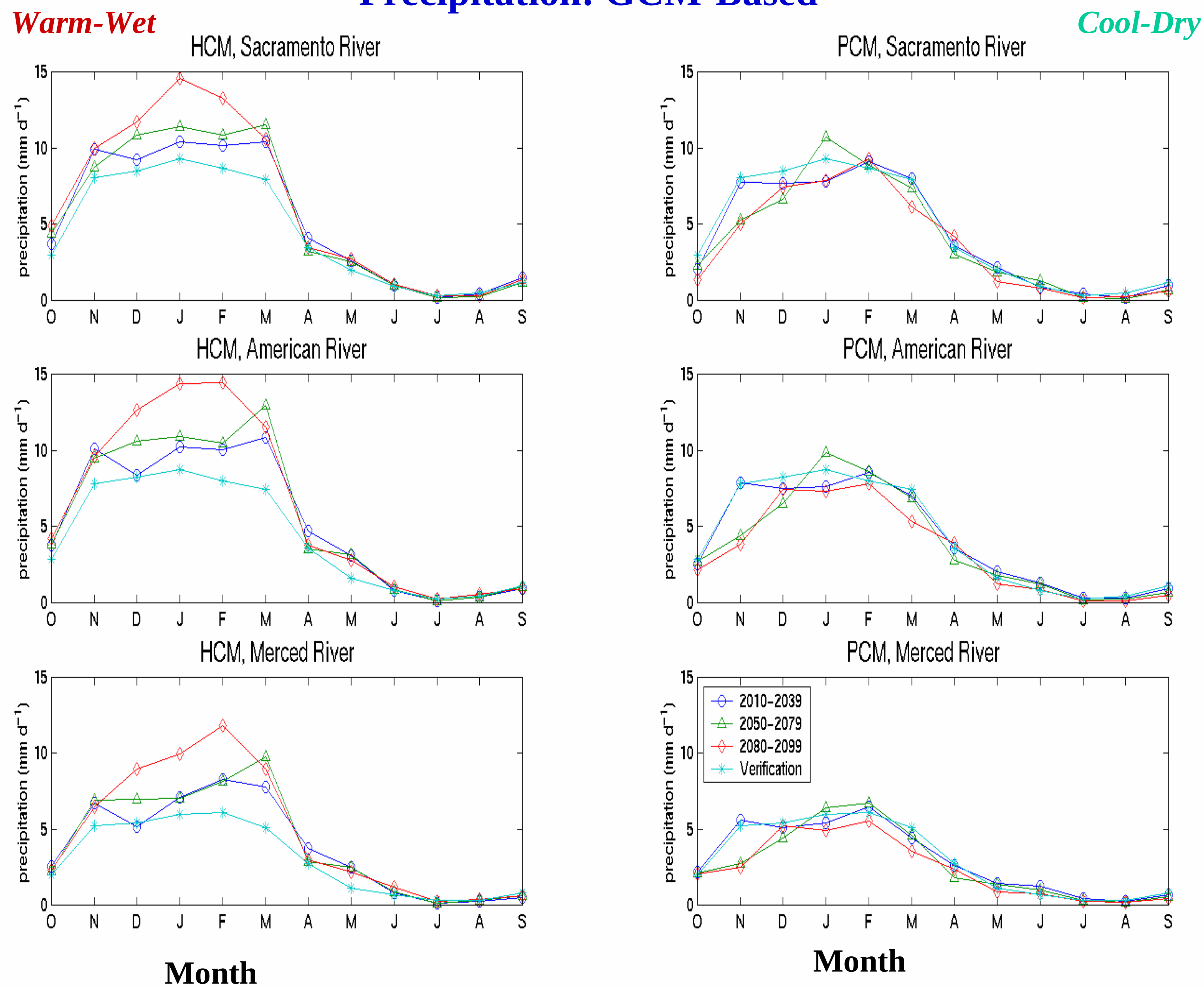
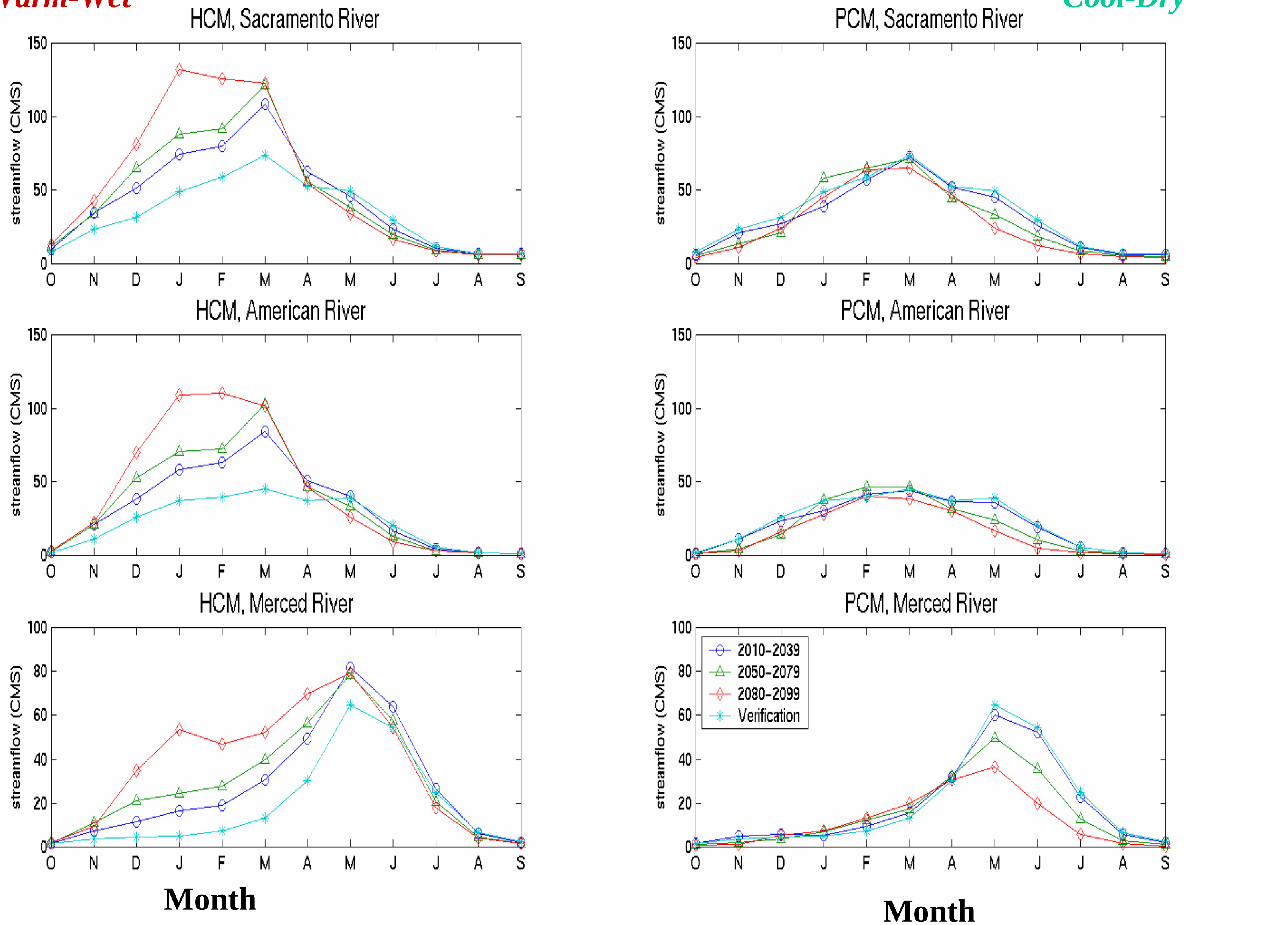
Precipitation: GCM-Based

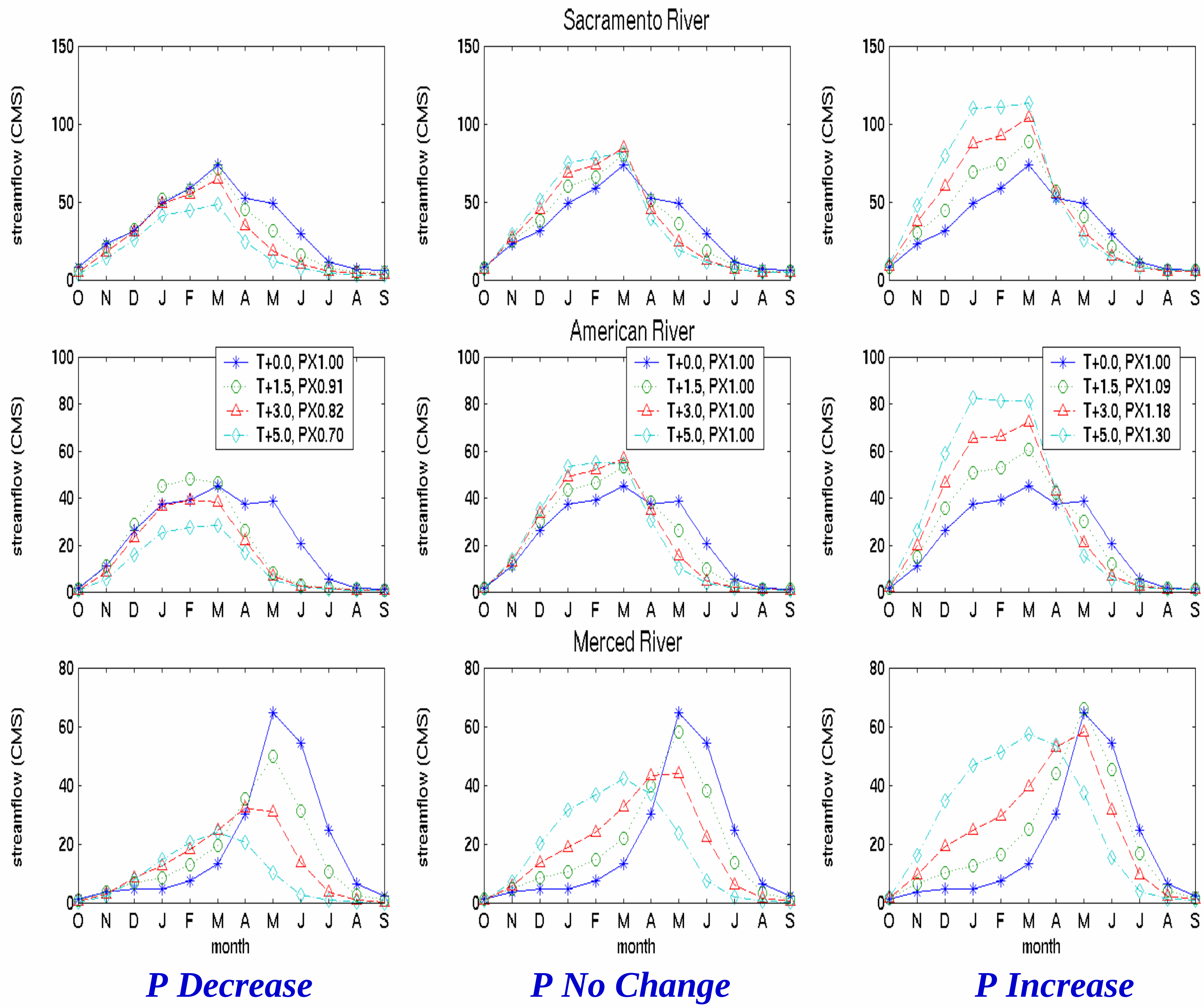


Streamflow: GCM-Based

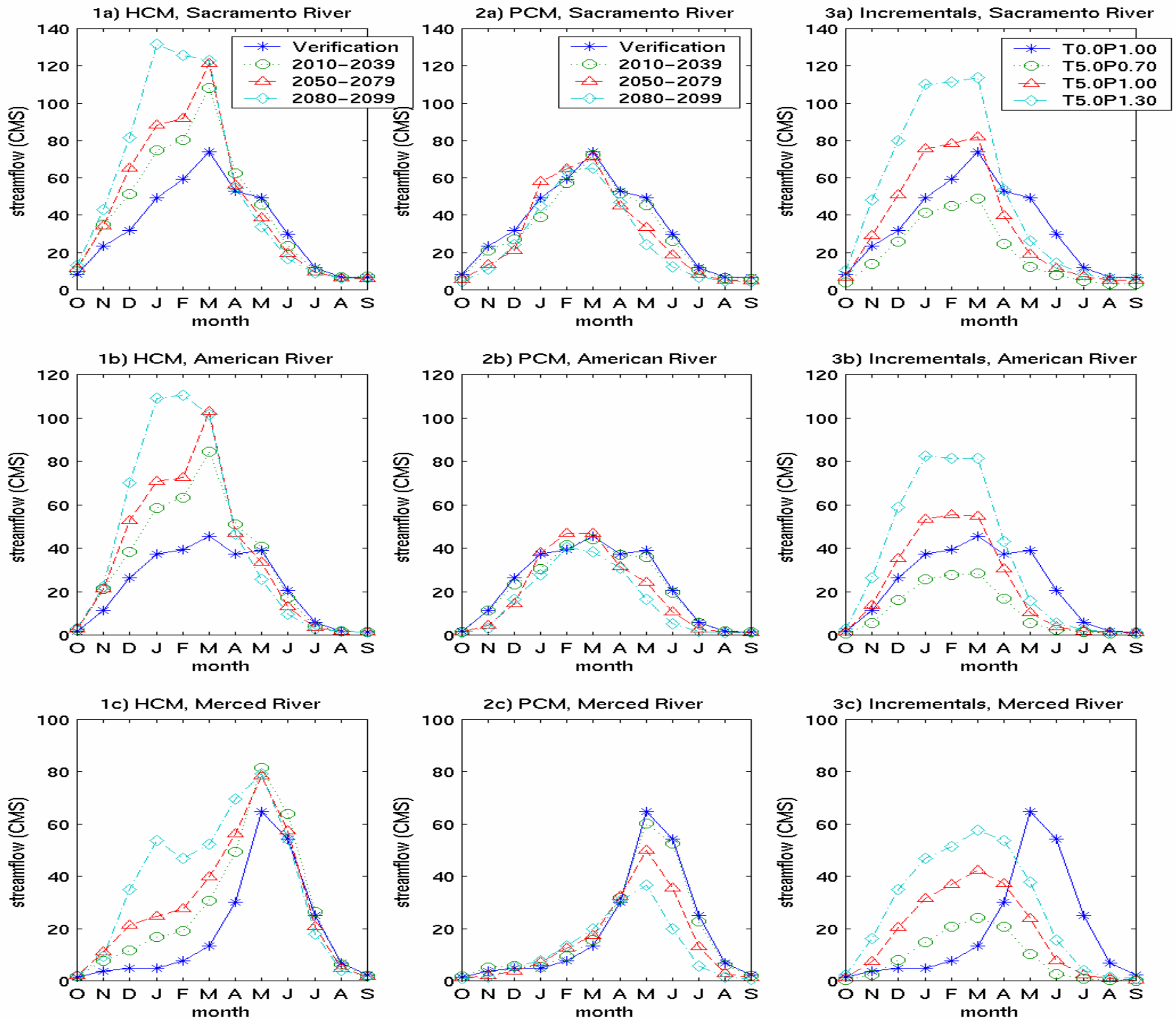
Warm-Wet ***Cool-Dry***



Mean-Monthly Streamflow

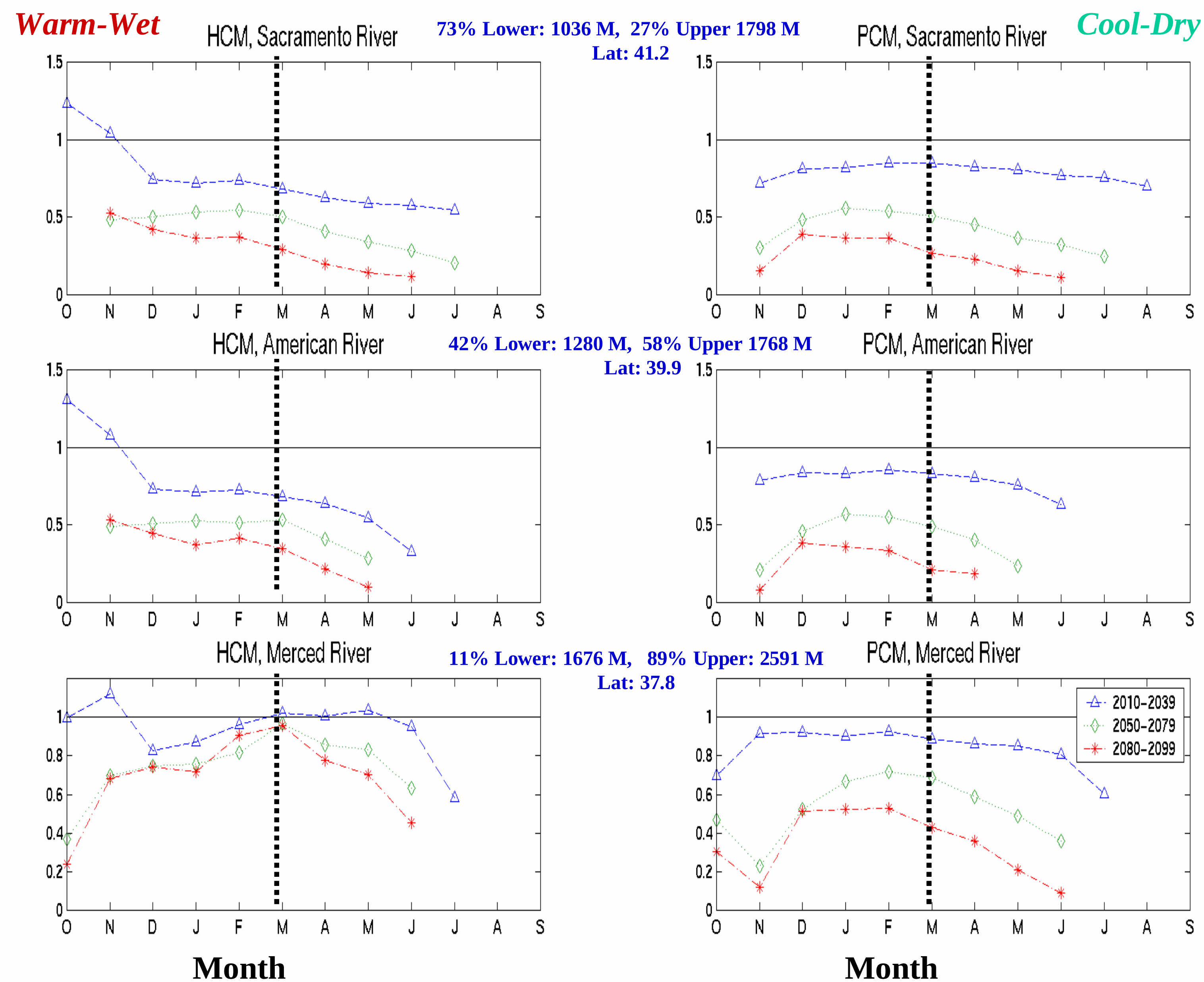


Mean-Monthly Streamflow

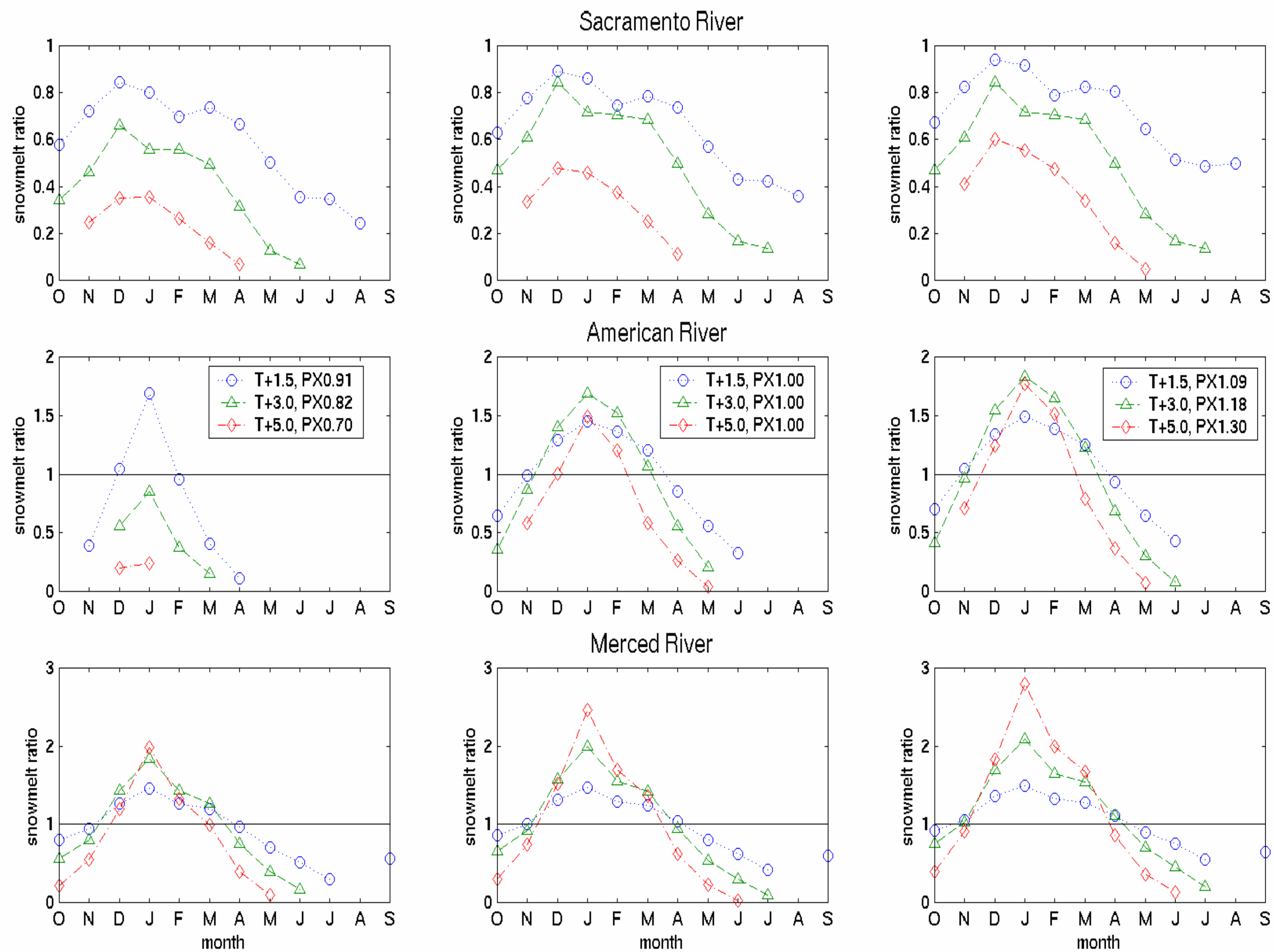


Results indicate that projected shifts in streamflow are primarily due to changes in temperature. The timing will play the most significant role in extreme events. Specified future scenarios, such as a 5°C increase and a 30% precipitation decrease suggest a situation similar to a drought.

Ratio of Mean-Monthly Projected Snow Water Equivalent to Baseline Snow Water Equivalent

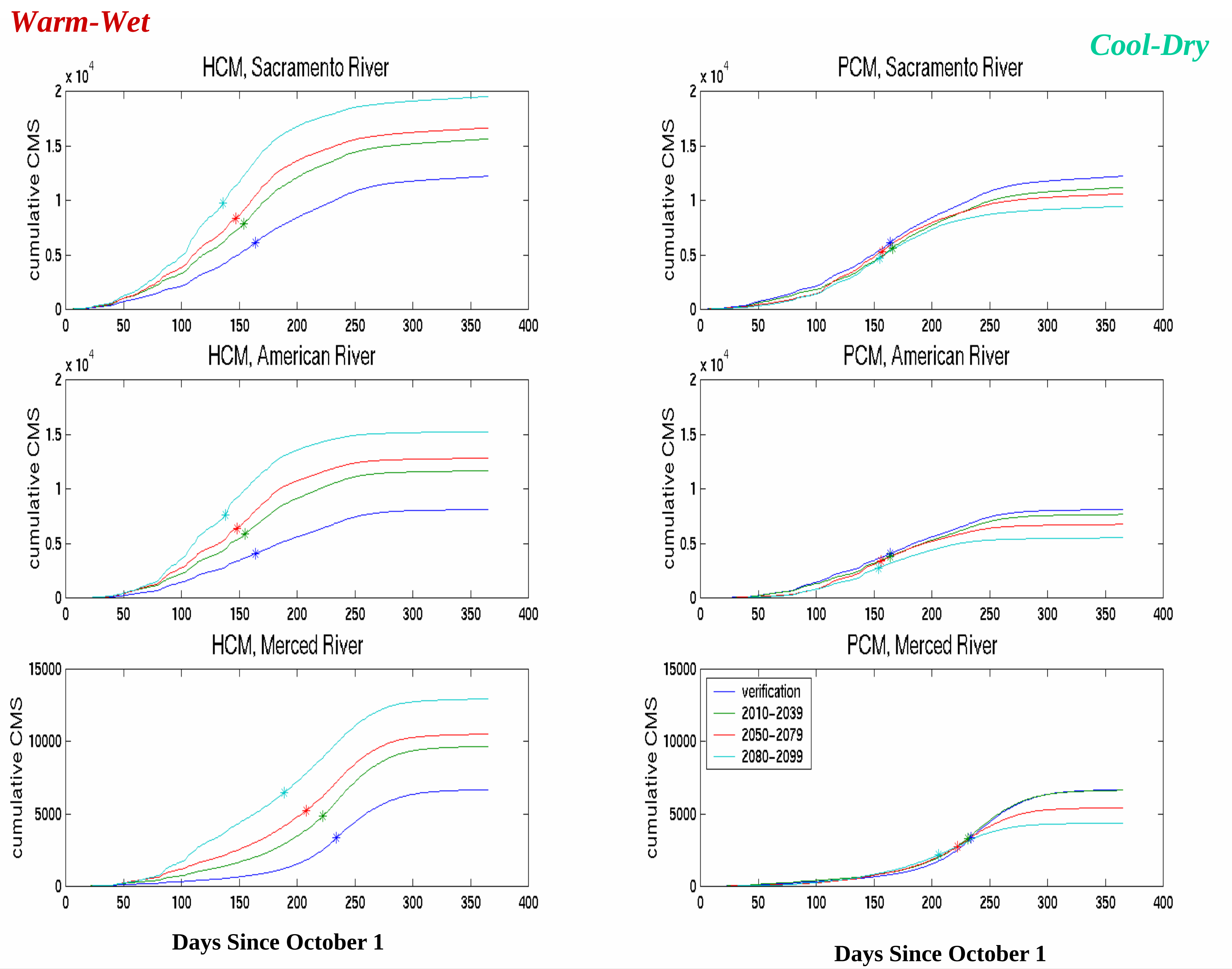


Ratio of Mean-Monthly Projected Snow Melt to Baseline Snow Melt



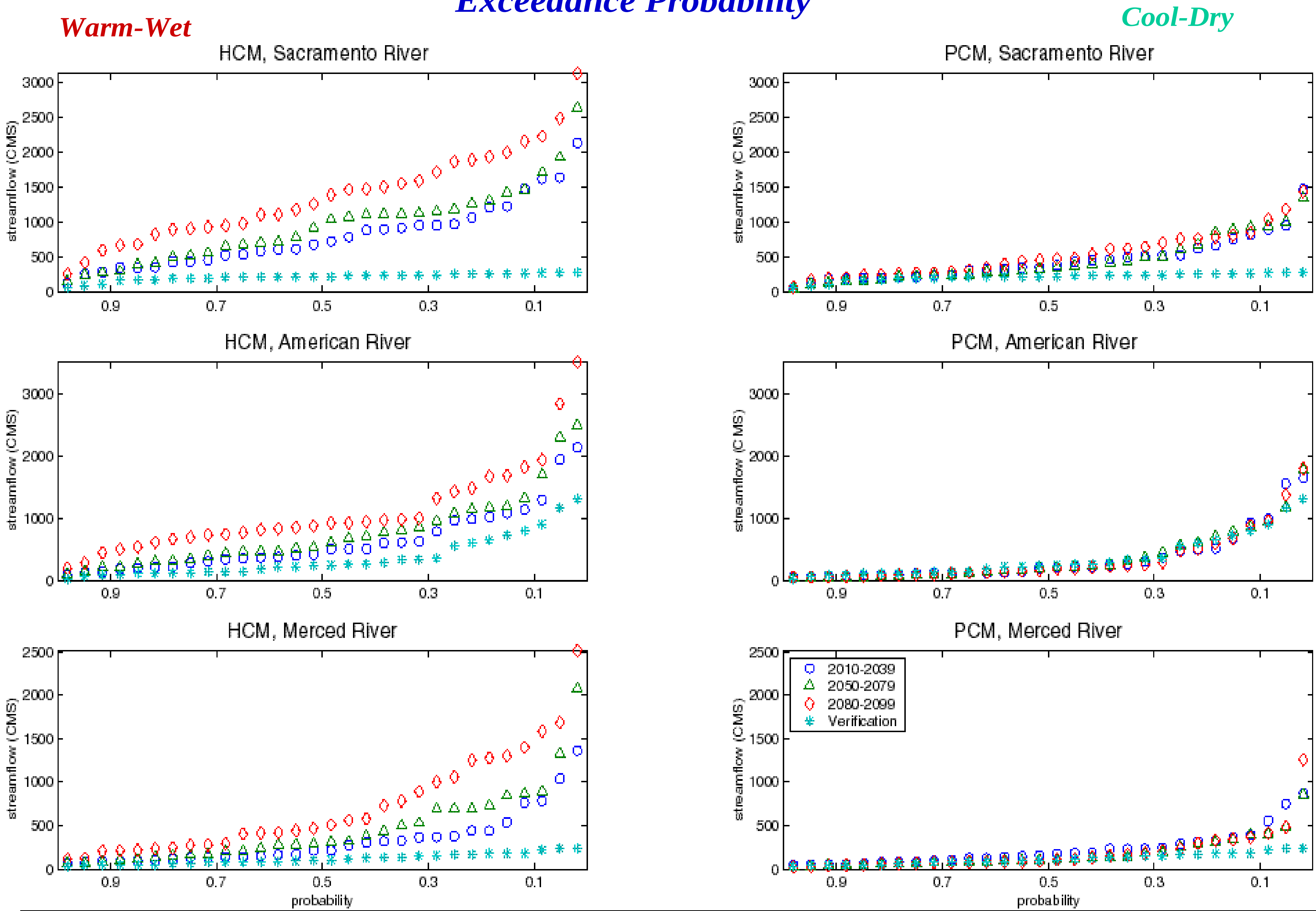
The projected mean monthly snowmelt indicates that the American River may flood during winter months, which is especially true for warm rain on snow events.

Cumulative Streamflow October to September



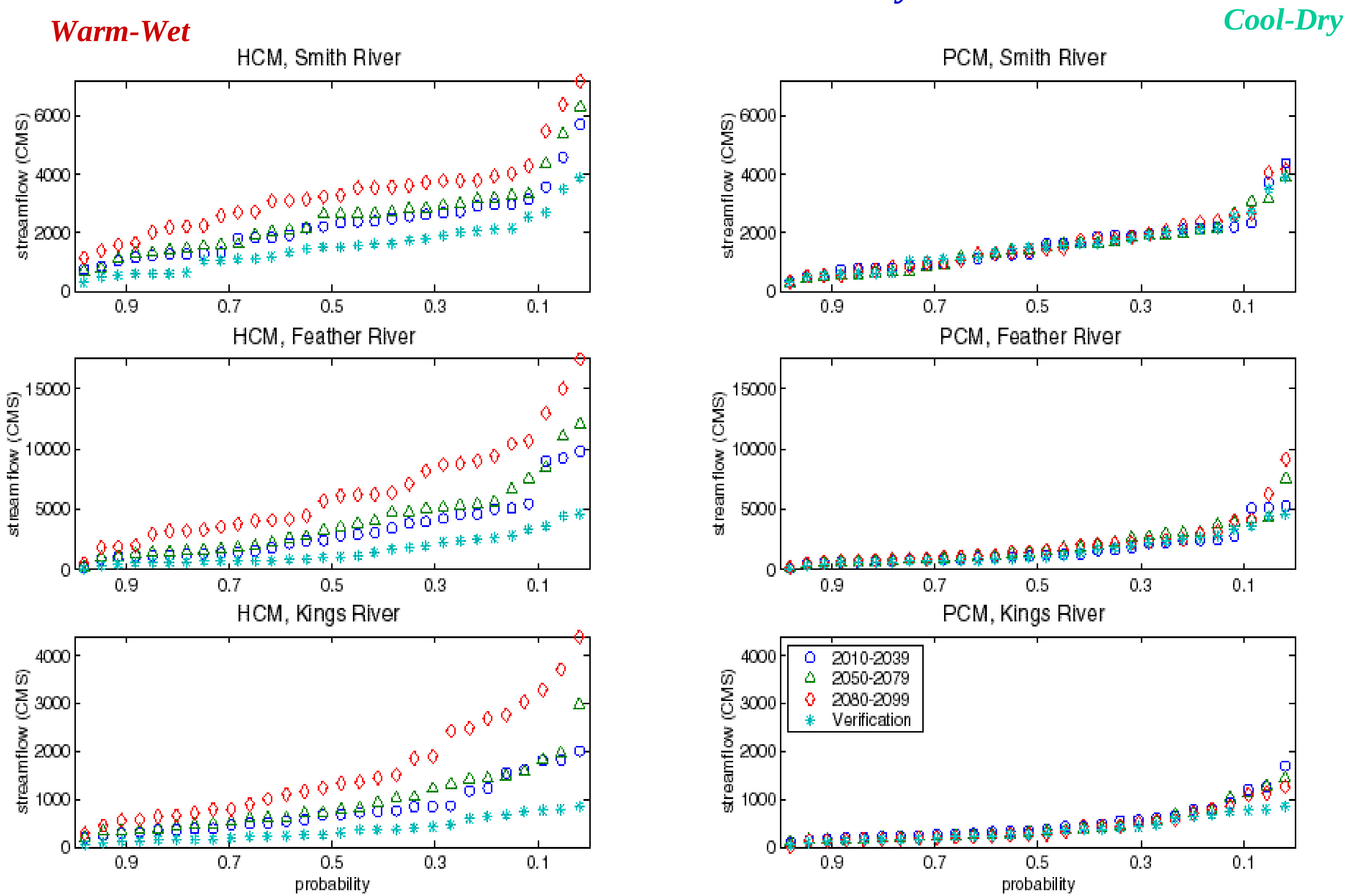
Future projections suggest 50% of the annual flow volume will occur earlier.

Exceedance Probability



The 30 year highest annual daily flow is dramatically increased as the climate warms.

Exceedance Probability



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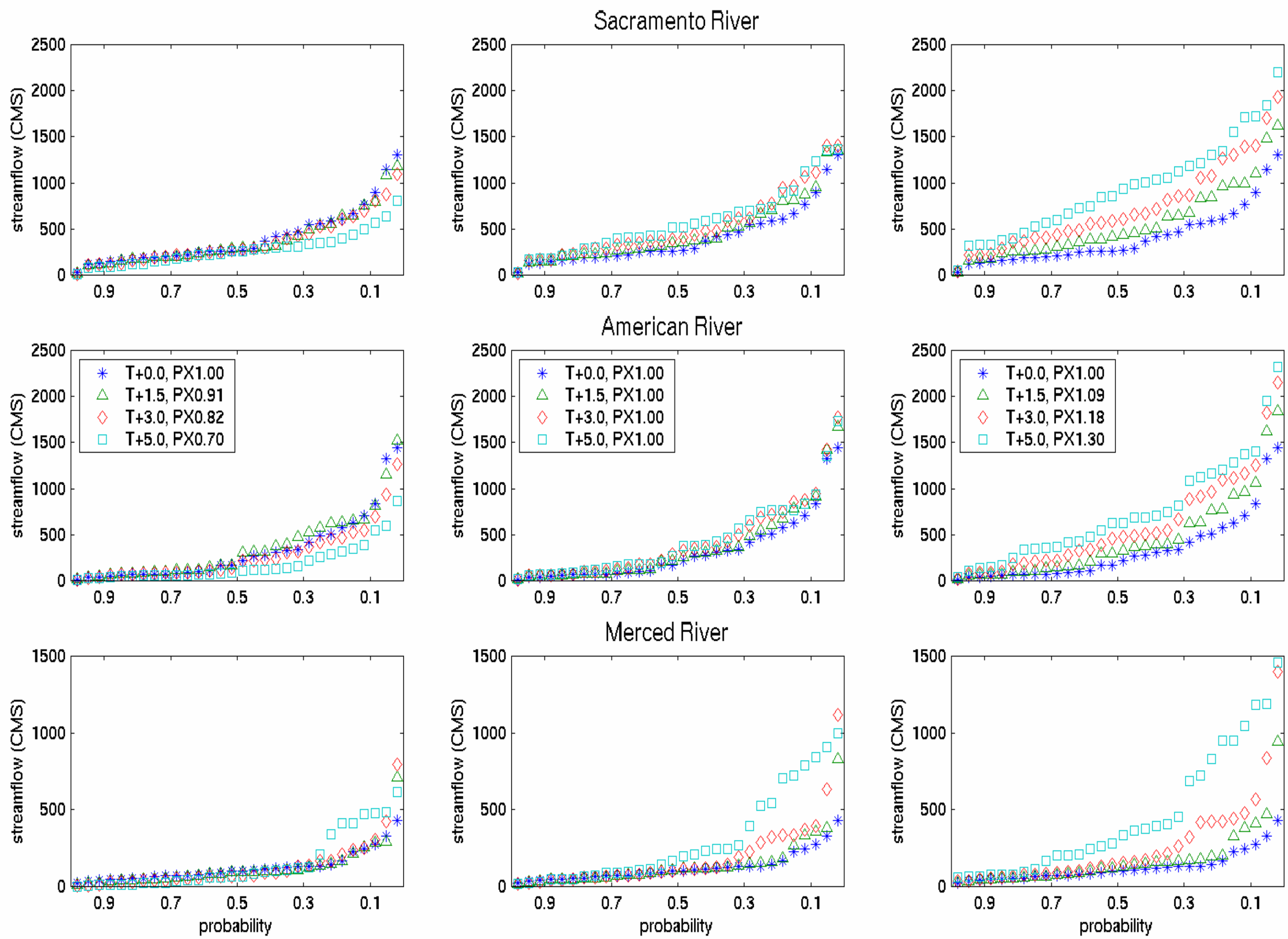
Exceedance Probability



P Decrease | **P No Change** | **P Increase**

Conclusions: Part I

- **Results suggest a continued trend for increasing early snowmelt and streamflow due to:**
  - **Rates of change in temperature and precipitation**
  - **Watershed elevation, latitude, and local weather pattern**
  - **The most important sensitivity is the elevation of the snow line and the historical snow area.**

- **Peak climatological runoff shift in magnitude occurs by mid-century, but the timing does not shift significantly until late 21st century using the GCM output.**

- **Snow water equivalent ratio decreases for all but the very high elevation Kings River by the mid-century. April 1st snow amount is reduced by about 50% by 2100.**

- **Snow melt rate ratio increases during DJF and significantly decreases during AMJ.**

- **The cumulative 50% streamflow occurs earlier for all snowmelt driven basins and annual high flow days increase for all snow melt basins.**

- **Annual peak flow magnitudes increase for both the warm-wet and the cool-dry simulations.**

- **Exceedance probabilities imply increased likelihood of high flow (floods) by mid-to-late century. This may be much higher if the study was not an imposed historical analysis.**

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Part II

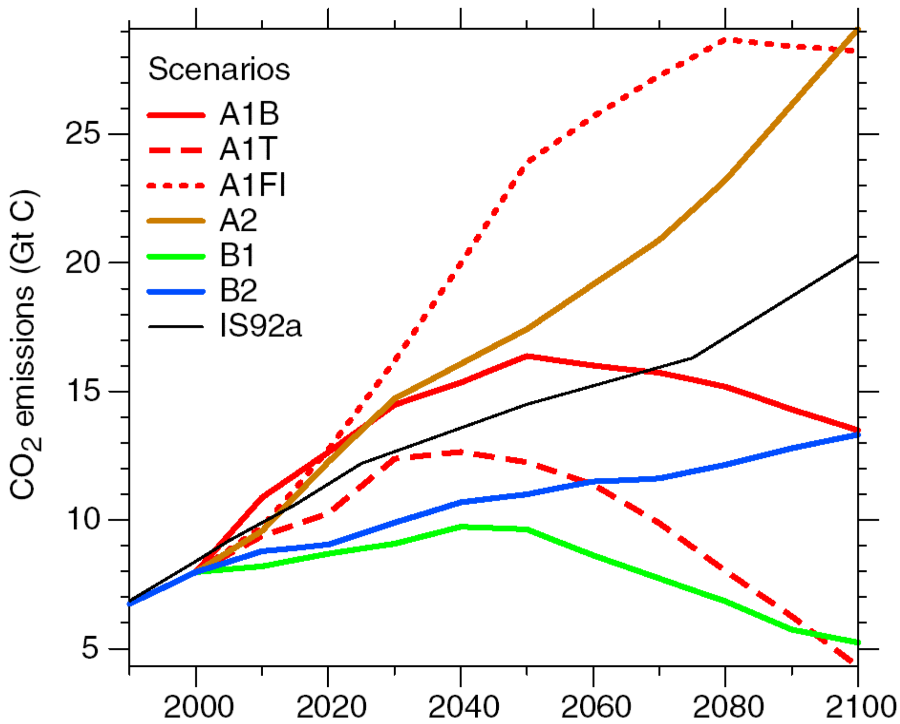
What are the consequences of following different emissions pathways?

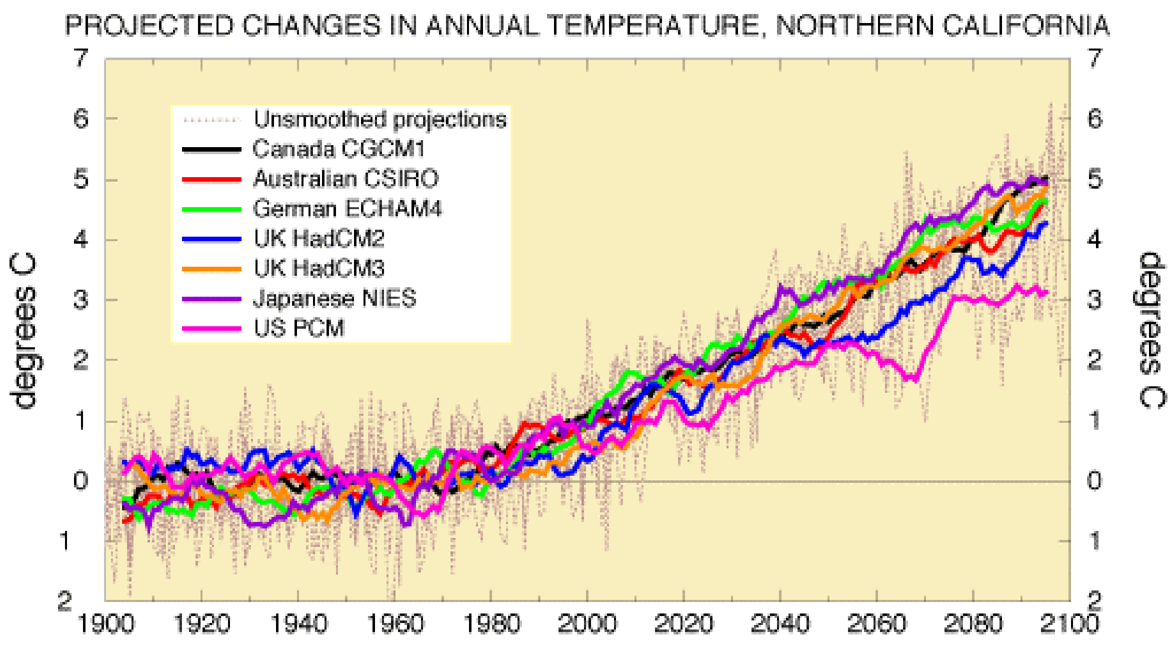
- **for temperature and precipitation**
- **for key climate-sensitive sectors**

- **IPCC SRES High and Medium Range Emission scenarios:**
  - **High emission scenario: A1fi (High Industry, Fossil Energy Intensive)**
    ~970 ppm CO2 by 2100, 6 x 1990 levels
  - **Medium Range Emission Scenario: B1 (Local Government, Soft/Efficient Energy Use)**
    ~550 ppm CO2 by 2100, 2 x 1990 levels

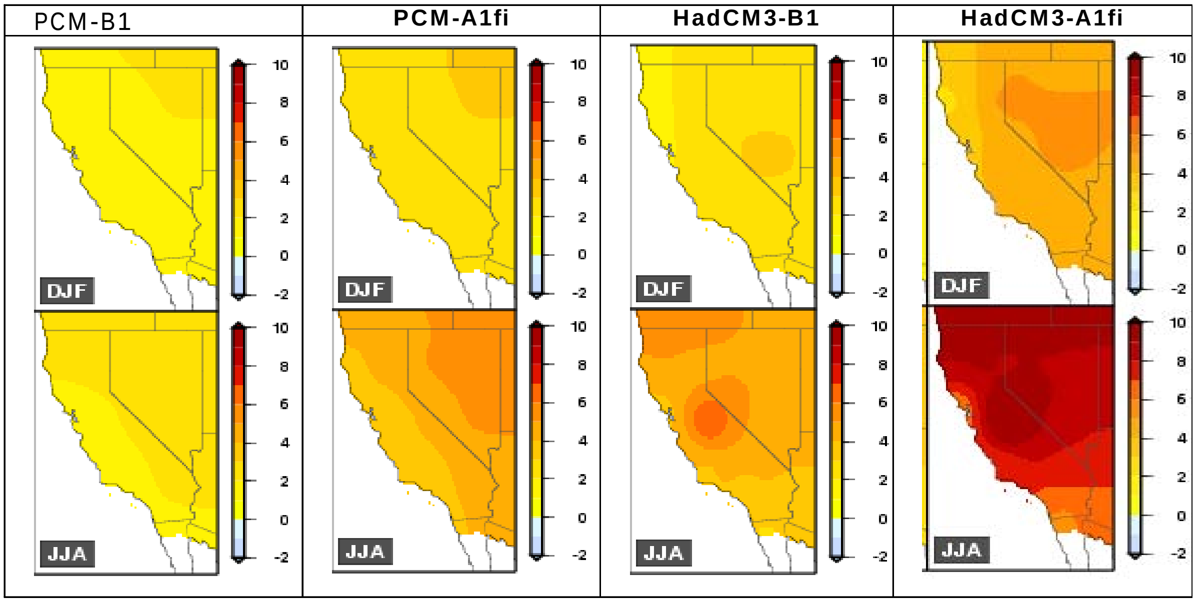
- **Global Climate System Models**
  - **U.S. Parallel Climate Model (PCM) Low Temperature Sensitivity**
  - **U.K. Hadley Centre Climate Model (HadCM3) Medium Temperature Sensitivity**

- **The four simulations (1900-2100) provide a new outcome envelope**
  - **Outcomes based on amount of Fossil Fuel use.**
  - **Reduced uncertainty**

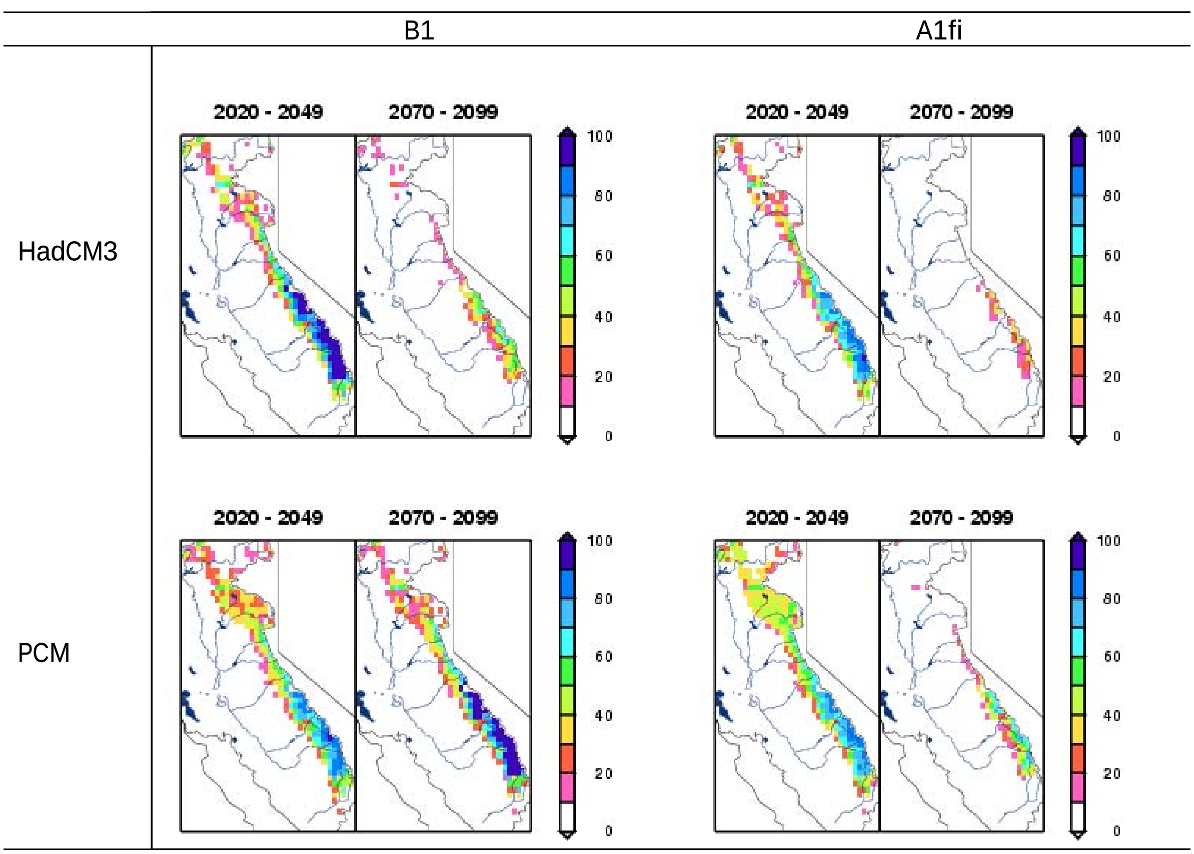




Using the B1 and A1fi emission scenarios as inputs to the PCM and HadCM3 models gives four outcomes for analysis.



The winter (DJF) and summer (JJA) mean temperature for the four outcomes indicates a significant warming in the Sierras, leading to a snowpack reduction of up to 80 % in the worse case scenario (HadCM3, A1fi) at the end of this century.



Conclusions: Part II

- Temperature increases more rapidly with higher emissions
- Summer temperatures are higher than previously projected, accompanied by more heat waves and extreme temperatures
- Precipitation is more variable, tends towards slight decrease, and is not notably affected by emissions pathway.

Impacts on Key Sectors

- Substantial impacts occur under both emissions scenarios.
- More severe impacts result from the higher emissions pathway after mid-century, but are entrained by higher emissions in preceding decades.
- Adaptation costs will increase with higher emissions; for some impacts, adaptation options are greatly limited.
- Higher emission pathway (A1fi) and the lower emissions pathway (B1) are not upper and lower limits.

References:

Miller, N.L., K.E. Bashford, and E. Strem, : Potential impacts of climate change on California hydrology, *Journal of the American Water Resources Association*, August 2003, 771-784.

Hayhoe, K., DC Cayan, CB Field, PC Frumhoff, EP Mauer, NL Miller, SC Moser, SH Schneider, and others, Emissions pathways, climate change, and impacts on California. *Proceedings of the National Academy of Sciences*, 101, 12422-12427, August. 2004.