Impacts of Climate Change on Water Resources in Western North America

Sara A. Rauscher

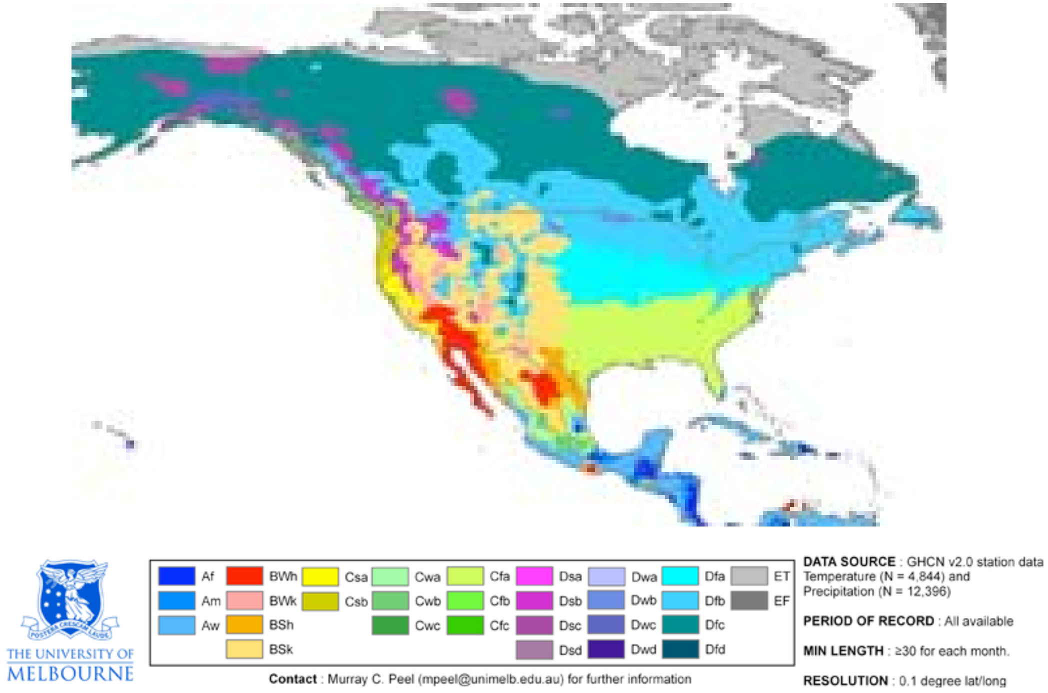
Los Alamos National Lab

Los Alamos, New Mexico USA

Michael M. Benedetti	University of North Carolina-Wilmington
Noah Diffenbaugh	Purdue University
Rosie Fisher	Los Alamos National Lab
Nate McDowell	Los Alamos National Lab
Jeremy S. Pal	Loyola Marymount University
Todd Ringler	Los Alamos National Lab
Maisa Rojas	University of Chile
Anji Seth	University of Connecticut

Climate Classification of the U.S.

- **A: Tropical/megathermal climates**
- **B: Dry (arid and semiarid) climates**
- **C: Temperate/mesothermal climates**
- **D: Continental climate**



http://en.wikipedia.org/wiki/File:World_Koppen_Map.png

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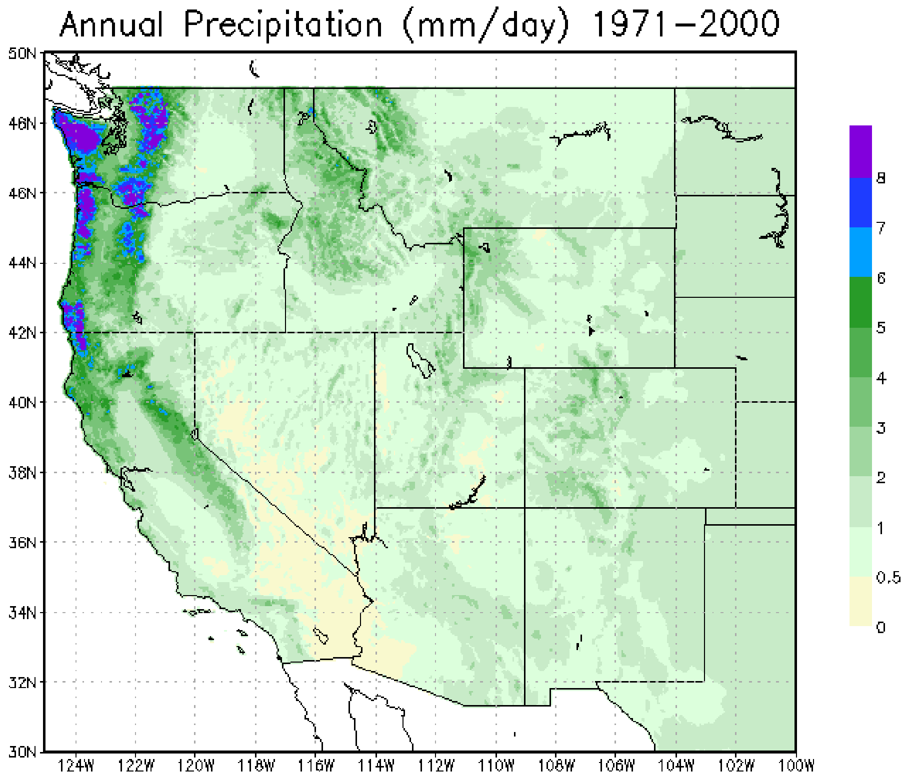
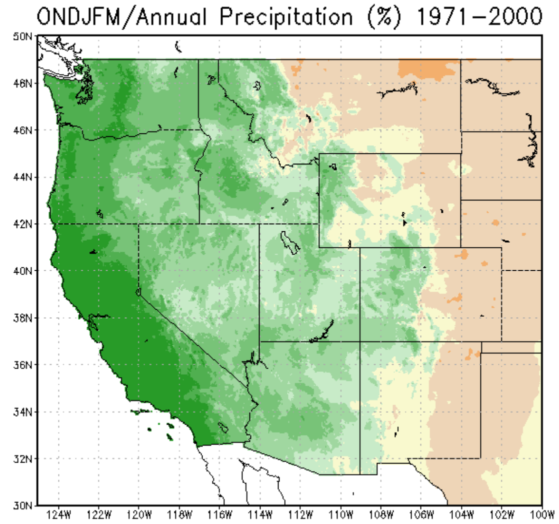
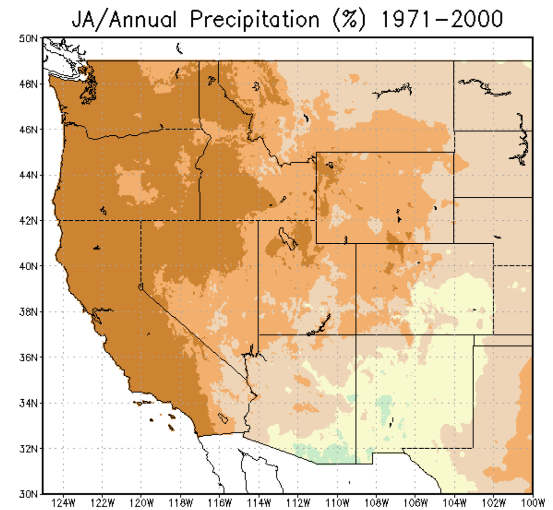
Western U.S. Precipitation
PRISM 4km data



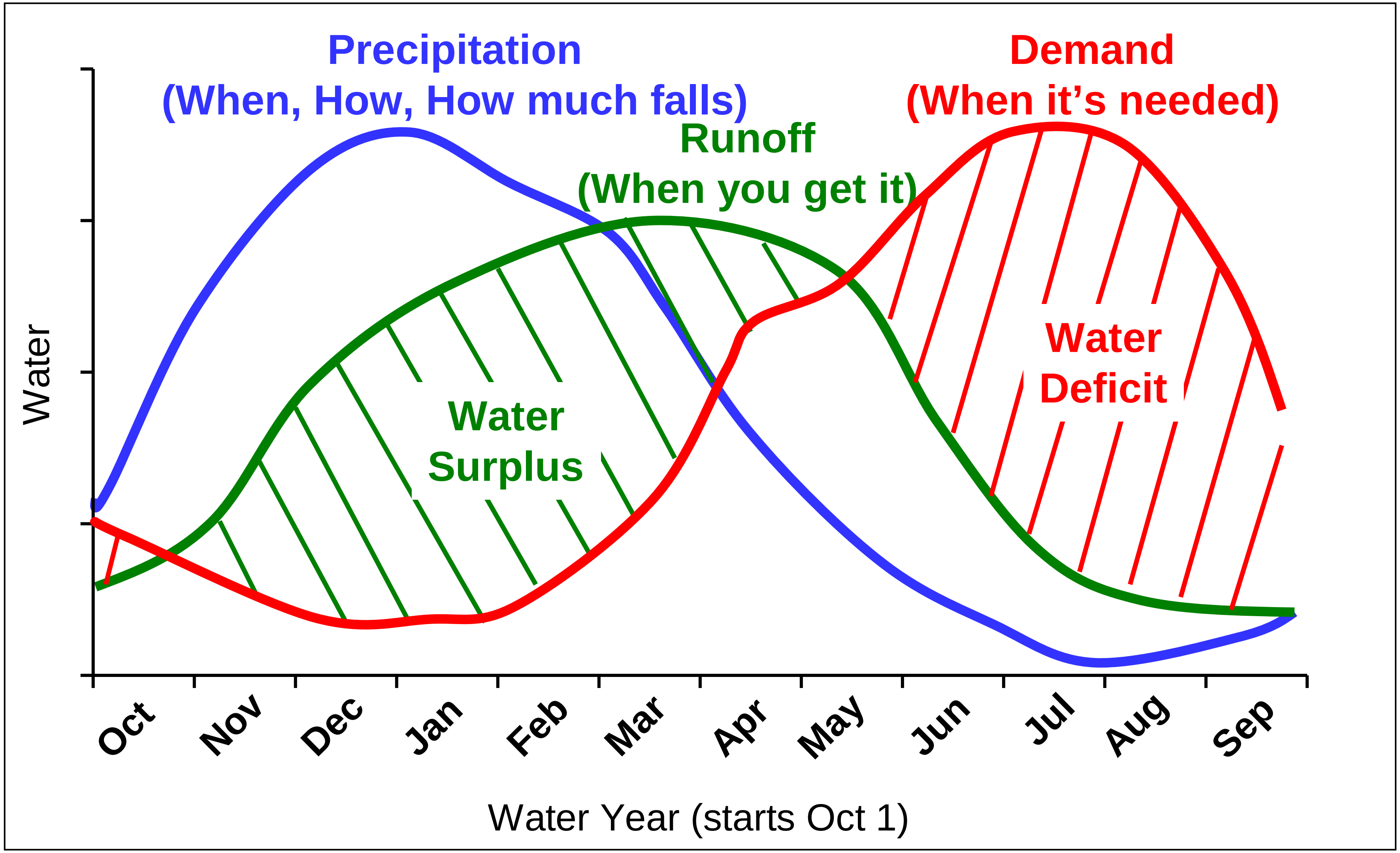




The semiarid West has too little water, spread too unevenly throughout the year.

Data source: http://www.prism.oregonstate.edu

Water Cycle Schematic for the Western U.S.

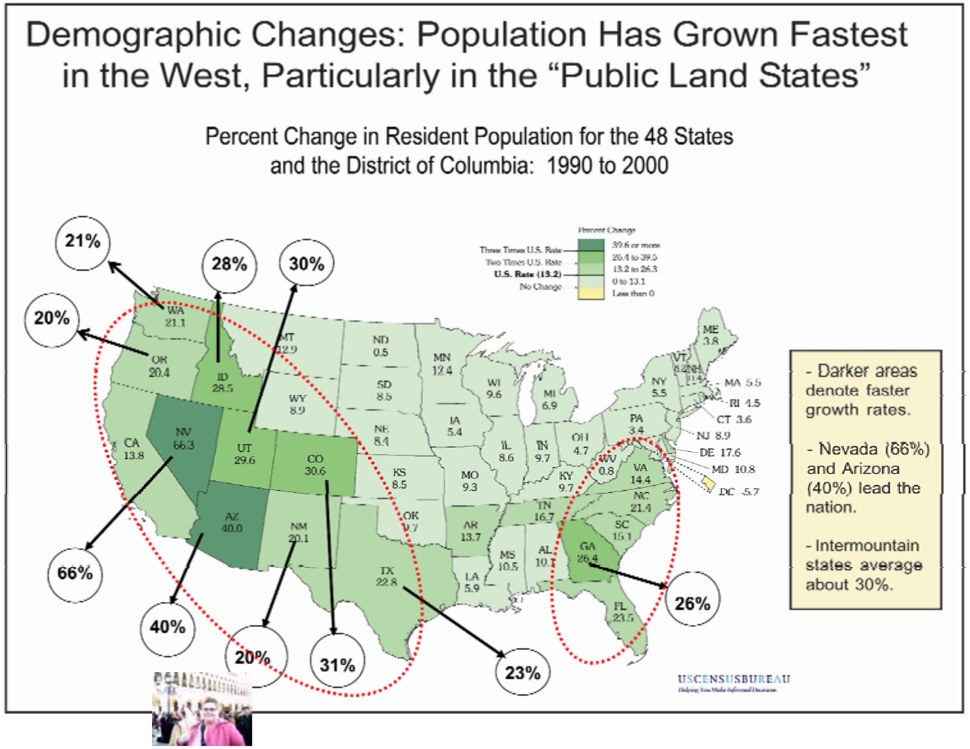


As much as 75-80% of runoff is from snowmelt in the West.

Why do we care about water resources in the Western U.S.?

- The semi-arid western United States has the fastest growing population in the U.S., increasing water needs. However:
  - Water supplies are fully or over-appropriated in many river basins.
  - All levels of government are poorly prepared for drought—reactive, crisis management approach.

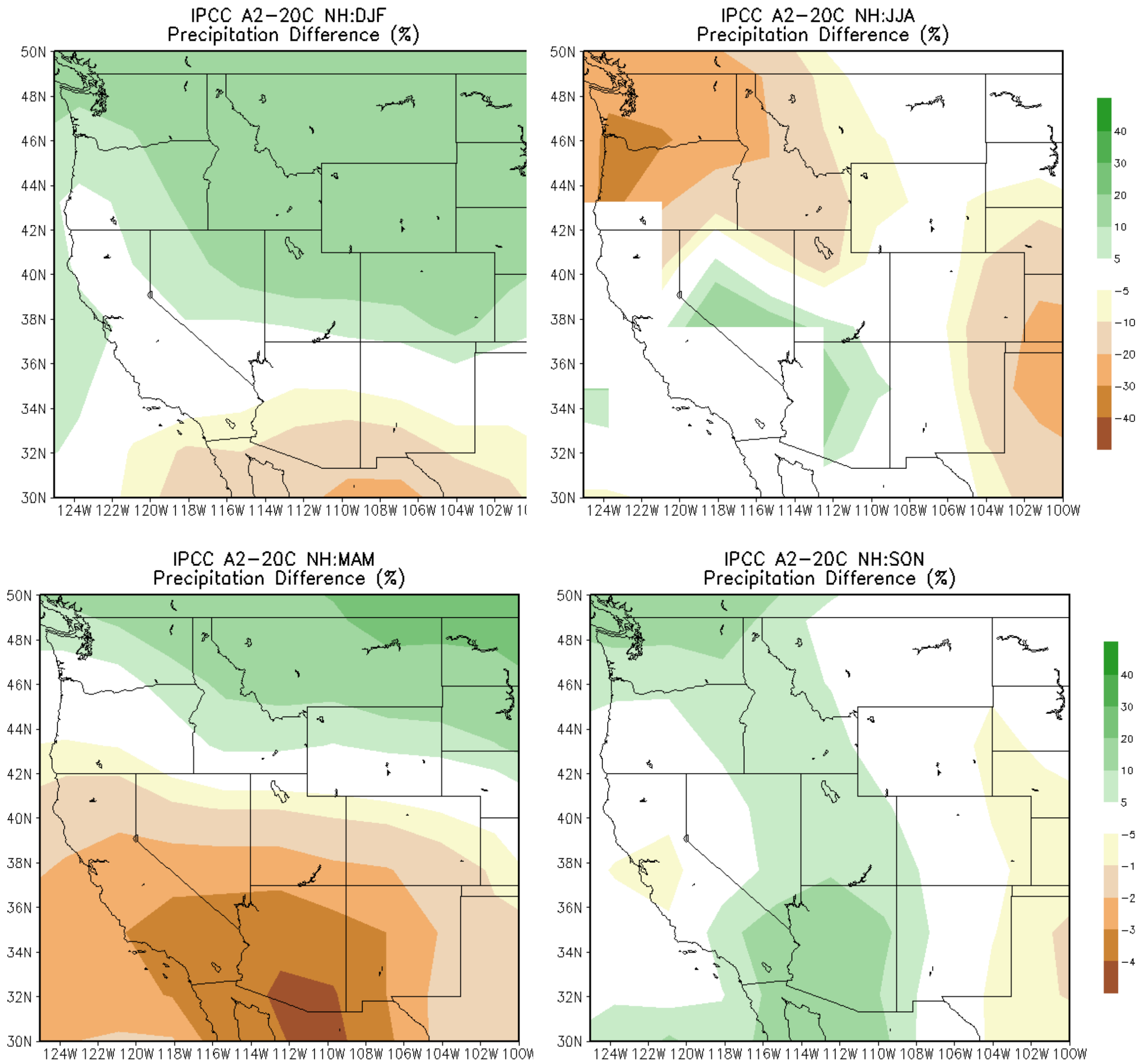
- How did this happen?
  - The western U. S. was settled in the mid-1800s, during a relatively wet period.
  - “Rain follows the plow” (not so much)



Image/text source: www.agiweb.org/gap/workgroup/briefings/Wilhite0707.ppt

Climate Change Impacts on Precipitation: How much and when? CMIP3 Models

- **Will we see changes in**
  - how much precipitation falls?
  - When it falls (timing)?
- CMIP3 Models
  - 2071-2100 – 1971-2000
  - 9 highest resolution models on T42 grid



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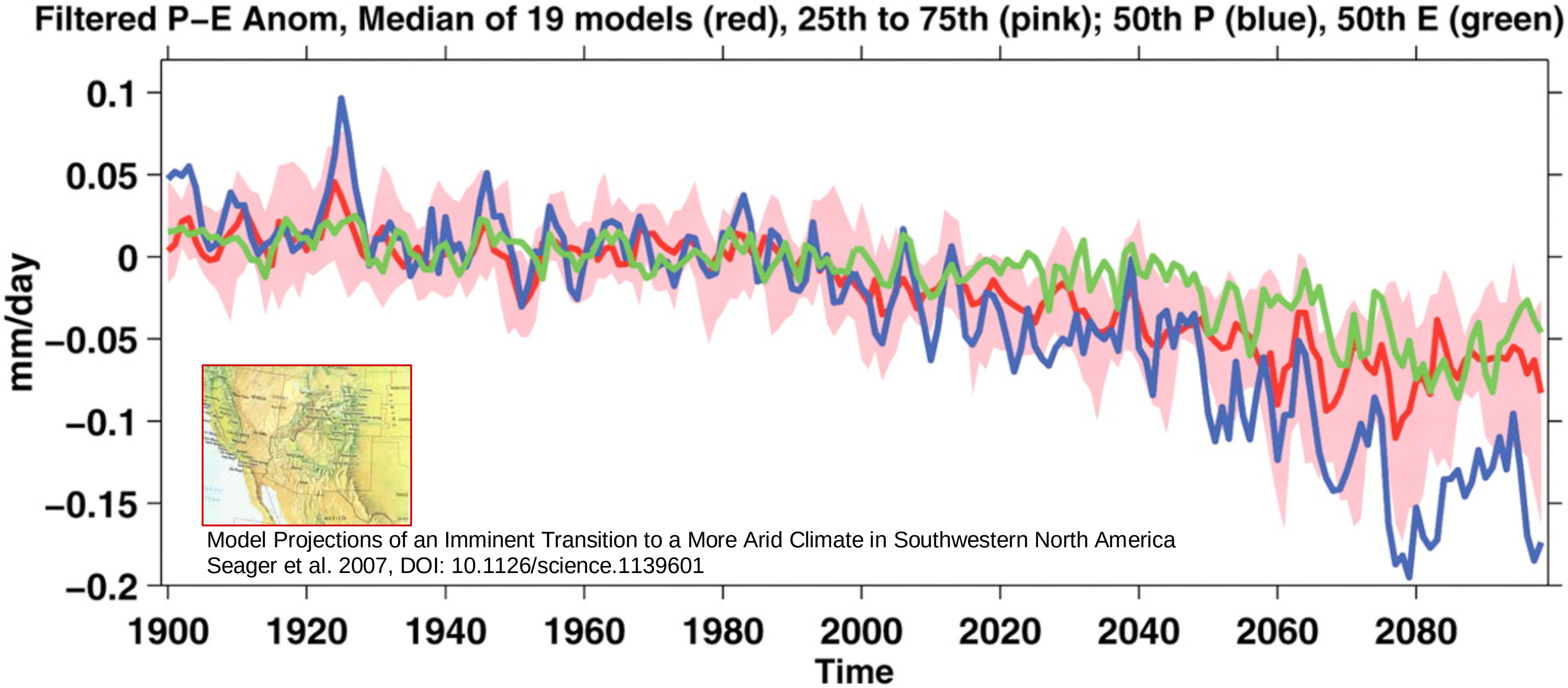
Climate Change Impacts on Precipitation: How much? Future drying over the Southwest



Modeled changes in annual mean precipitation minus evaporation over the American Southwest: average climate of SW is expected to look very similar to historic episodic drought conditions.

125°W to 95°W and 25°N to 40°N, land areas only

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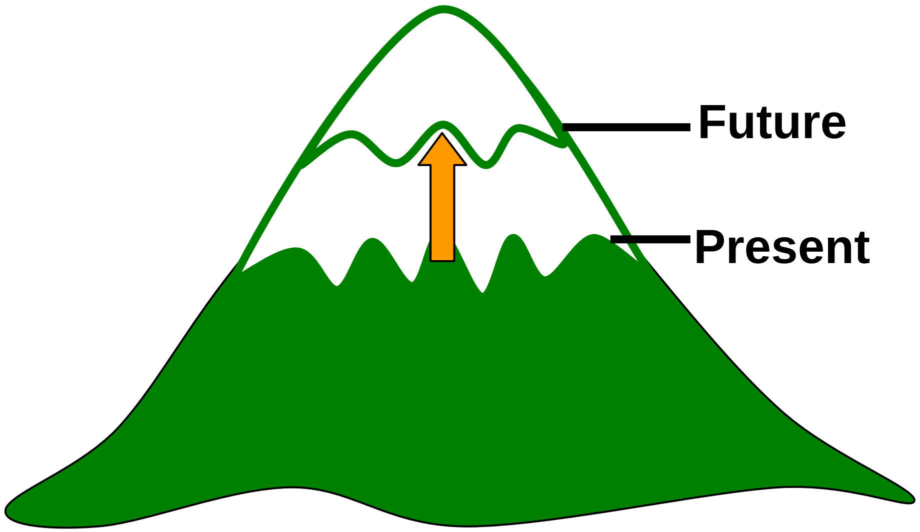
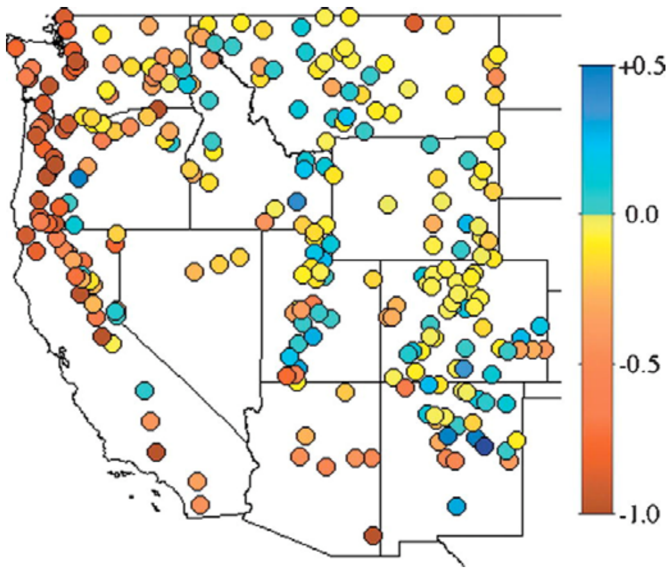
Climate Change Impacts on Precipitation: How it falls (rain or snow?)



The largest decreases in snowfall are happening and low and mid elevations, suggesting that the warming is raising the freezing level.

Fractional change in winter snowfall water equivalent after removing the effects of trends in precipitation (1949-2004).

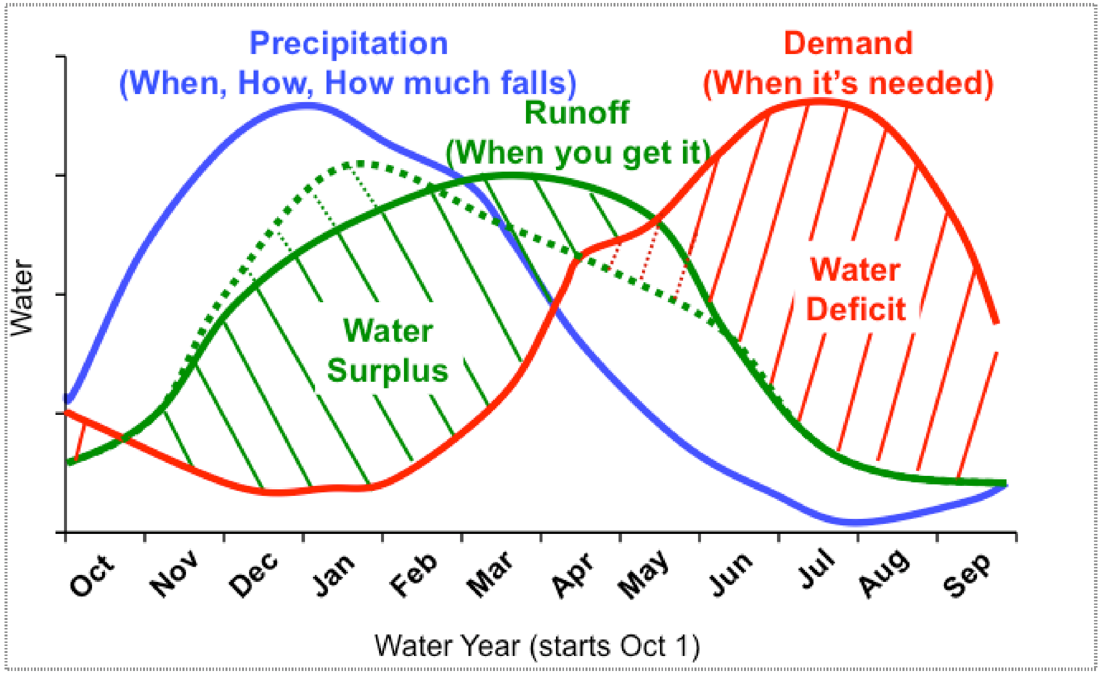


A total of 75% of stations have experienced snowfall reductions as a result of widespread warming (1-2 degrees over past ~50 years).

Knowles, N., M.D. Dettinger, and D.R. Cayan, 2006: Trends in Snowfall versus Rainfall in the Western United States. J. Climate, 19, 4545–4559.

Climate Change Impacts on Runoff: When you get it

- **Streamflow in the western US is highly seasonal, and dominated by snowmelt runoff in the boreal spring**
- **Higher future temperatures should be expected to cause major changes in snowpack.**
  - Reduced storage in snowpack (rain instead of snow)
  - Earlier release of snowpack
- **Earlier/less snowmelt runoff**
  - Reservoirs still in flood control mode
  - Longer summer drought
  - Impacts on water availability, agriculture



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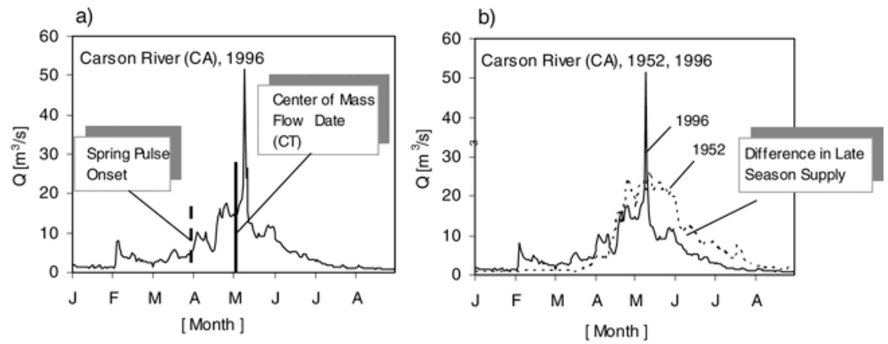
Climate Change Impacts on Runoff: When you get it: Observed changes in runoff

Earlier snowmelt runoff

- Linked to increase in winter and spring temperatures by 1-3 degrees C
- Temperature changes overwhelm precipitation changes (positive in some areas)
- Part of the signal due to warm phase of Pacific Decadal Oscillation (does not fully explain trend)



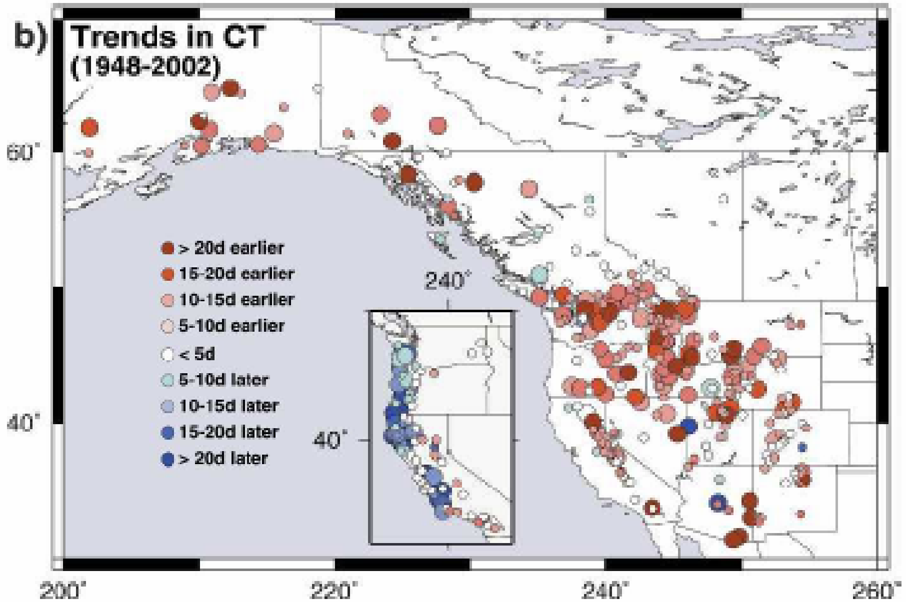


FIG. 2. Trends in (a) spring pulse onset and (b) date of center of mass of annual flow (CT) for snowmelt- and (inset) non-snowmelt-dominated gauges. Shading indicates magnitude of the trend expressed as the change (days) in timing over the 1948–2000 period. Larger symbols indicate statistically significant trends at the 90% confidence level. Note that spring pulse onset dates could not be calculated for Canadian gauges.

Stewart, I.T., D.R. Cayan, and M.D. Dettinger, 2005: Changes toward Earlier Streamflow Timing across Western North America. J. Climate, 18, 1136–1155.

Let’s investigate these climate-hydrology relationships further using a regional climate model for a present-day and future climate change scenario…

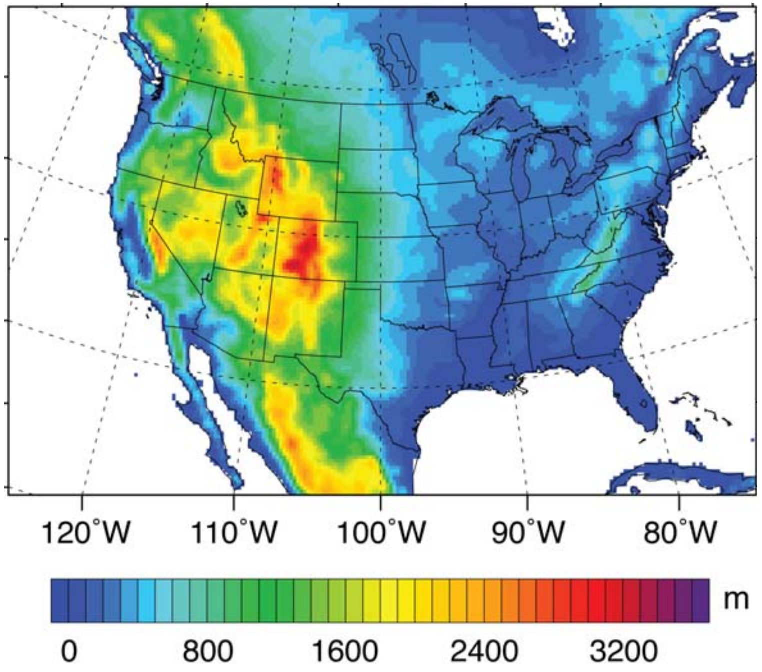
Models and Data

Regional Climate Model: RegCM3 (Pal et al. 2007)

- 25-km horizontal grid point spacing
- BATS Land Surface Model (Dickinson et al. 1993)
- Initial and Lateral Boundary Conditions: NASA Finite Volume GCM (FVGCM)
- Reference simulation: 1961-1985
- Future Simulation: 2071-2095, A2

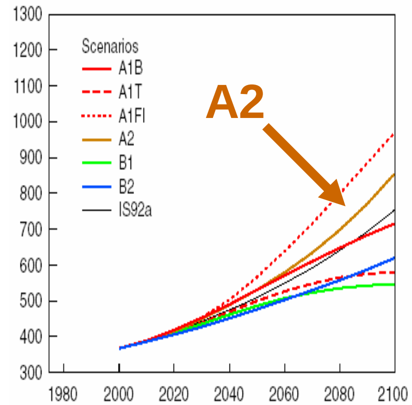
Observed Runoff Data: USGS Hydro-Climatic Data Network (HCDN) (Slack and Landwehr 1992)

- Daily streamflow observations from the USGS least affected by anthropogenic influences
- Station selection:
  - Stations with missing data during the reference period were excluded.
  - Stations are **snowmelt-dominated:** greater than 50% of annual flow occurs from April-July (AMJJ/annual fractional flow).
  - 141 stations, 100-2800 m elevation, basin drainage areas between 100–1000 km^2



Diffenbaugh et al. 2005, PNAS

CO_2 Concentrations (ppm)

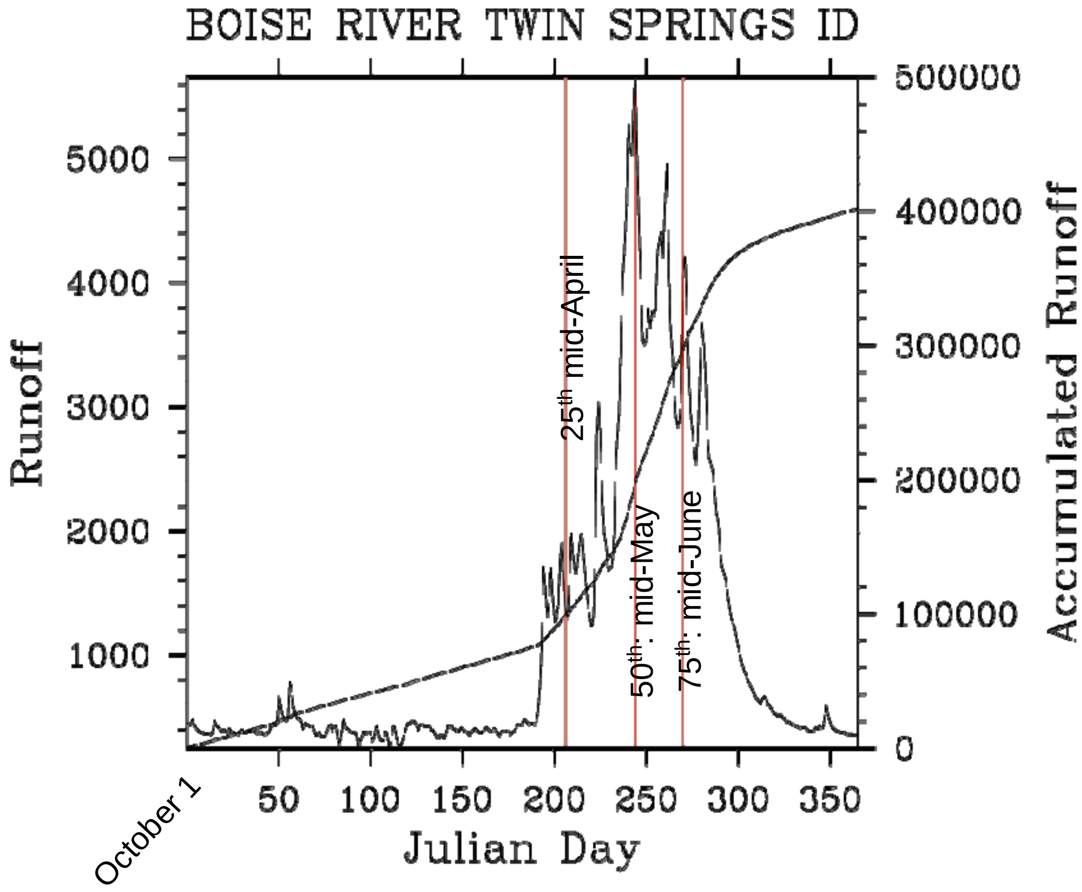


Rauscher, S. A., J. S. Pal, N. S. Diffenbaugh, and M. M. Benedetti (2008) Future changes in snowmelt-driven runoff timing over the western US, Geophys. Res. Lett., 35, L16703, doi:10.1029/2008GL034424.

Methods

- **D**ay of **Q**uantile of **F**low (**DQF**): day that the first X% of the year's total flow passed a station or grid point
  - 25^{th} DQF: early season/spring pulse
  - 50^{th} DQF: mid-season (similar to centroid)
  - 75^{th} DQF: late-season

- **Snowmelt-dominated** stations/model gridpoints: greater than 50% of annual flow occurs from April-July (AMJJ/annual fractional flow).



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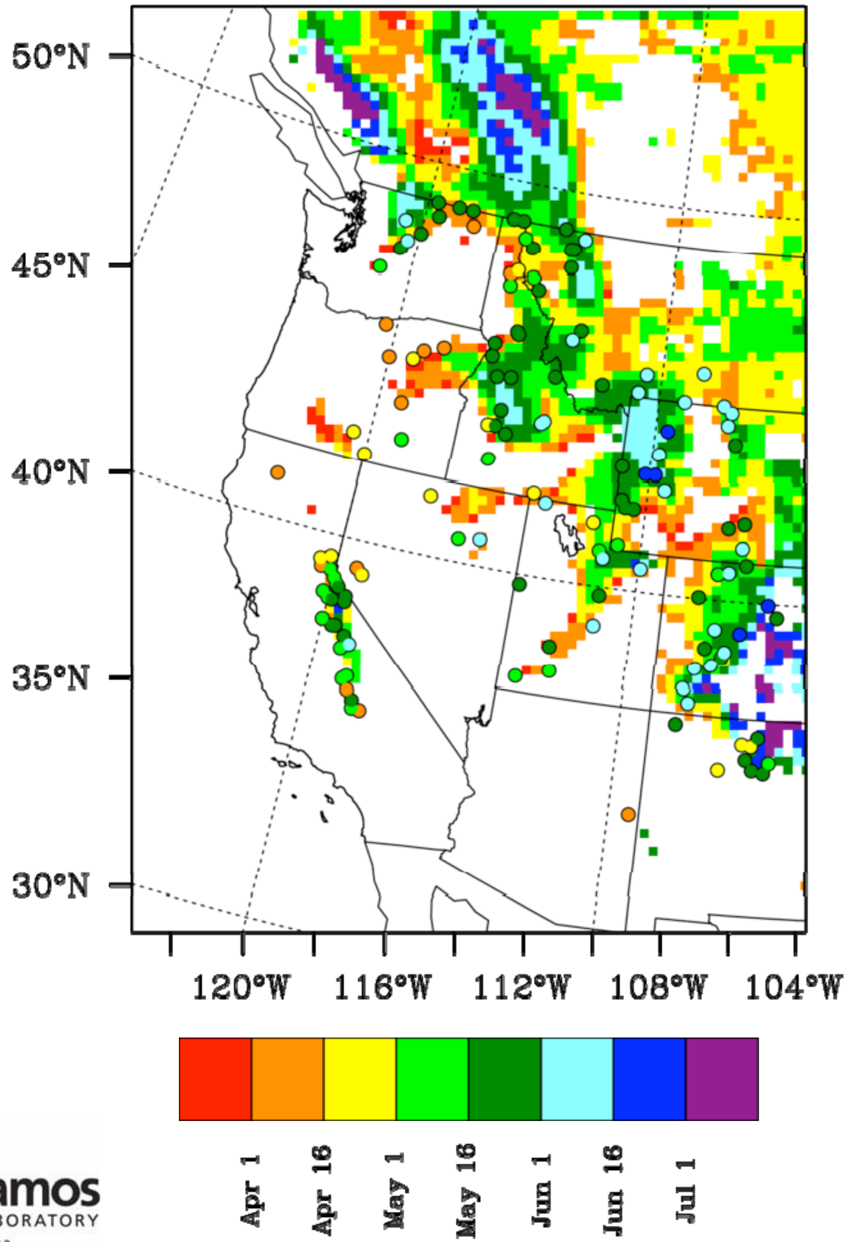
50th DQF: Model vs. Observations



Differences due to

- **Model climate**
  - Cold/wet biases (too much snow)
- **Basin size**
  - Model should lead obs
    - Why? In reality, flood wave takes time to collect in a channel and travel downstream to the gauge while in BATS, runoff is produced instantaneously at a grid point
    - Bigger problem for larger basins (HCDN is mostly small basins)
  - …but model lags obs
    - Why? Cold/wet bias
- **Local factors**
  - topography resolution
  - slope aspect
  - vegetation
  - soil moisture

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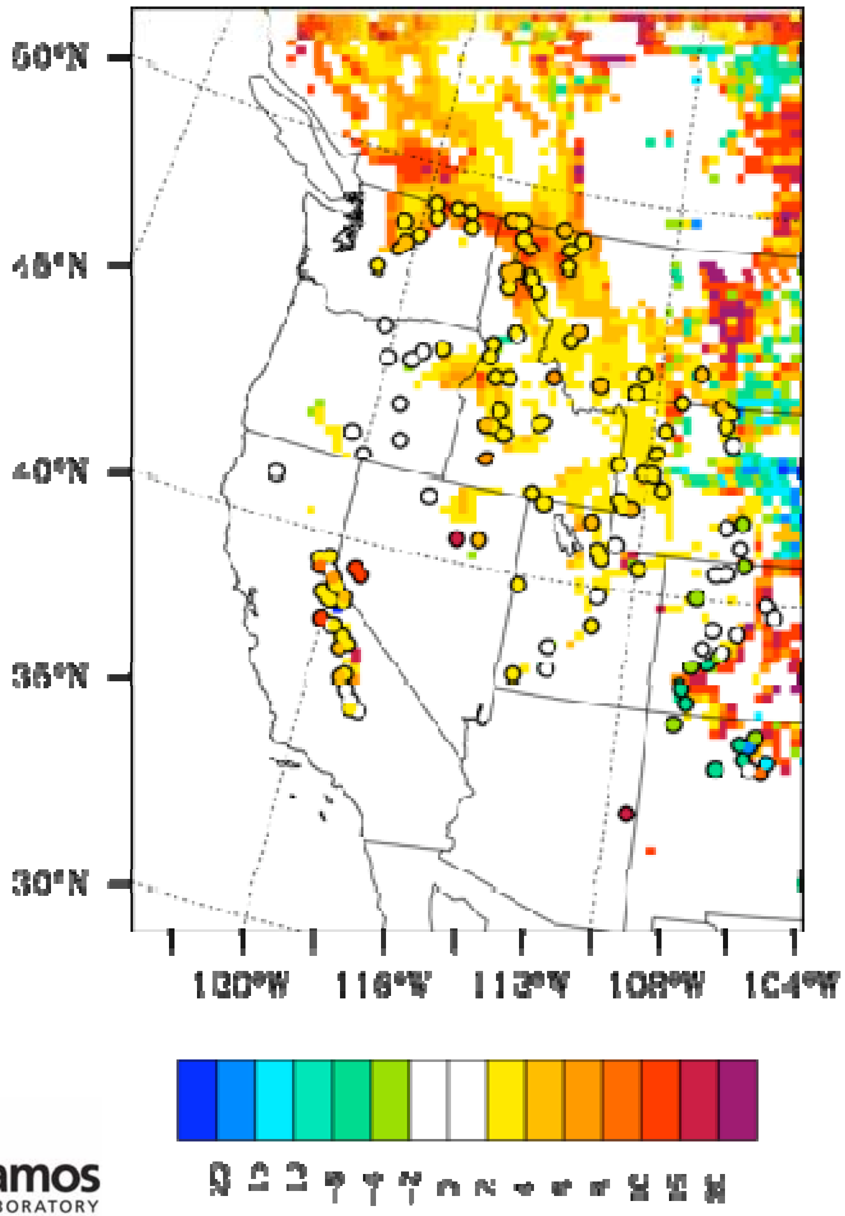
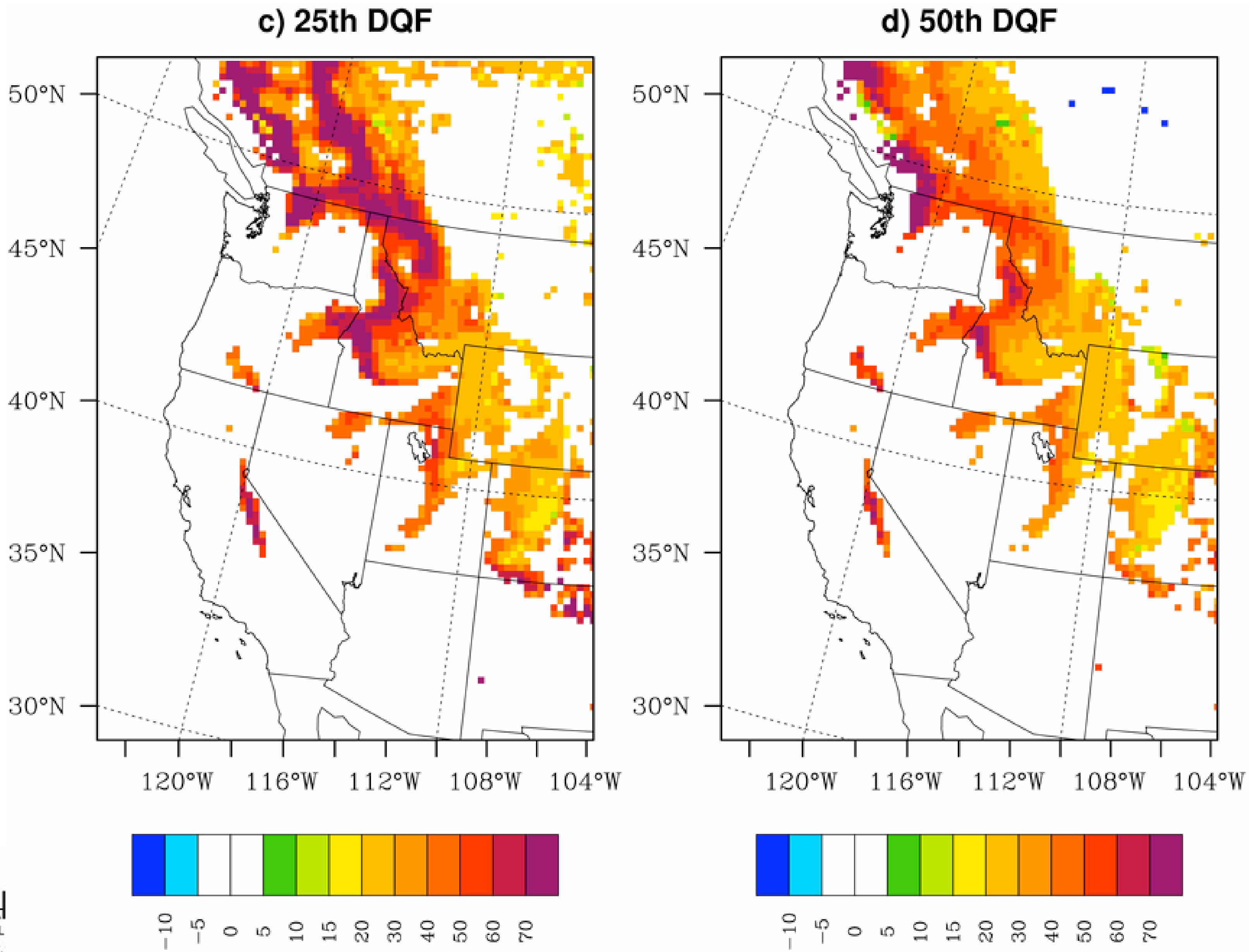
50th DQF: Model vs. Observations: Linear Trend (days/decade)



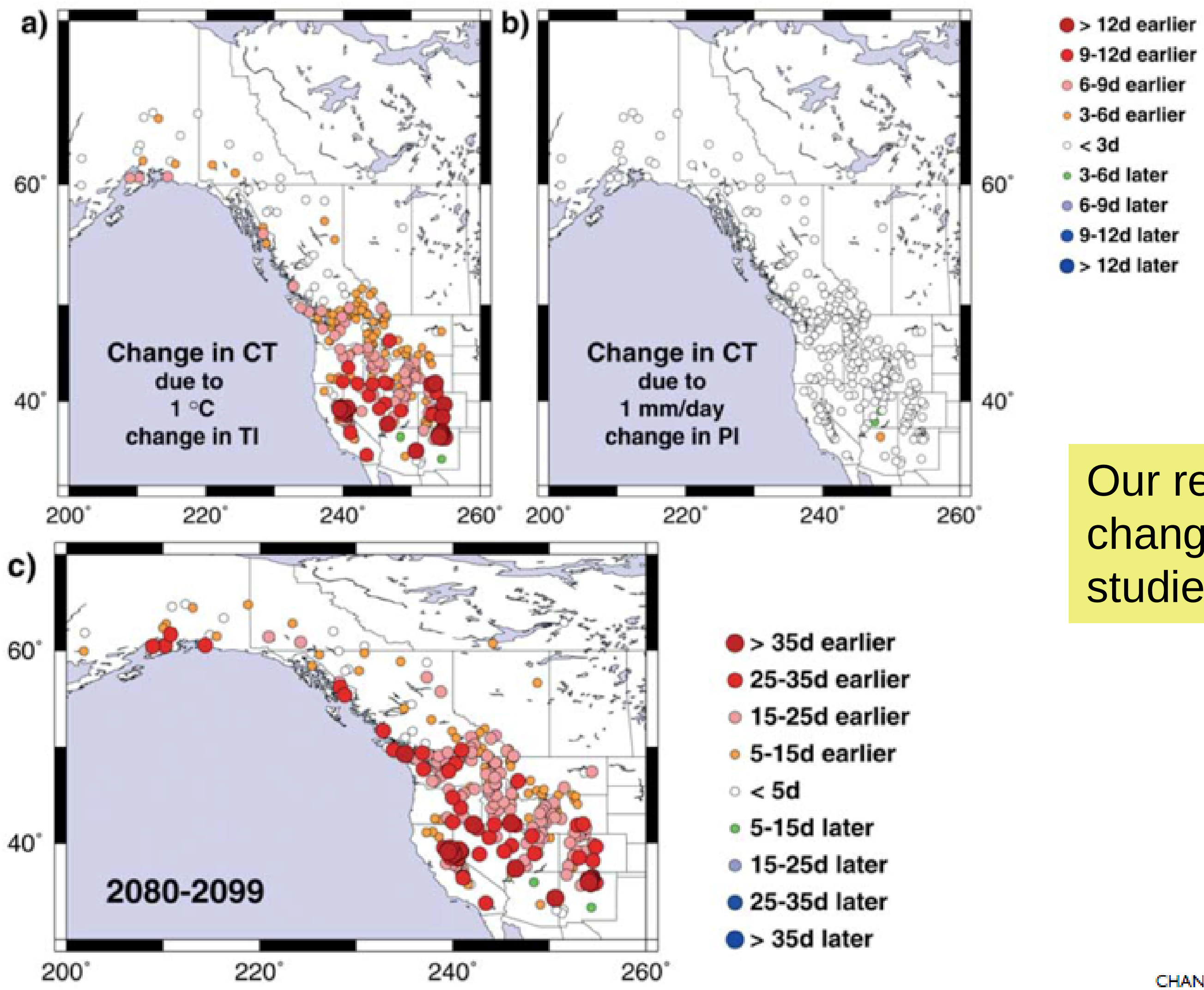
- **Model captures geographical distribution of trend**
  - Stronger trend in Washington State and California
  - Weak/mixed in interior
- **Observed SSTs used in FVGCM boundary conditions**
  - Trend due to PNA/PDO/ENSO variations or warming?
  - RF Period simulates spans cold PDO to warm PDO transition

Future changes (days, A2-RF)



Comparison with Other Studies

CT = Center Timing, "center of mass of run-off"



Note from a) and b) that temperature has a significantly greater impact on CT than precipitation.

Our results show larger changes in timing than most studies…why?

CHANGES IN SNOWMELT RUNOFF TIMING IN WESTERN NORTH AMERICA UNDER A 'BUSINESS AS USUAL' CLIMATE CHANGE SCENARIO.

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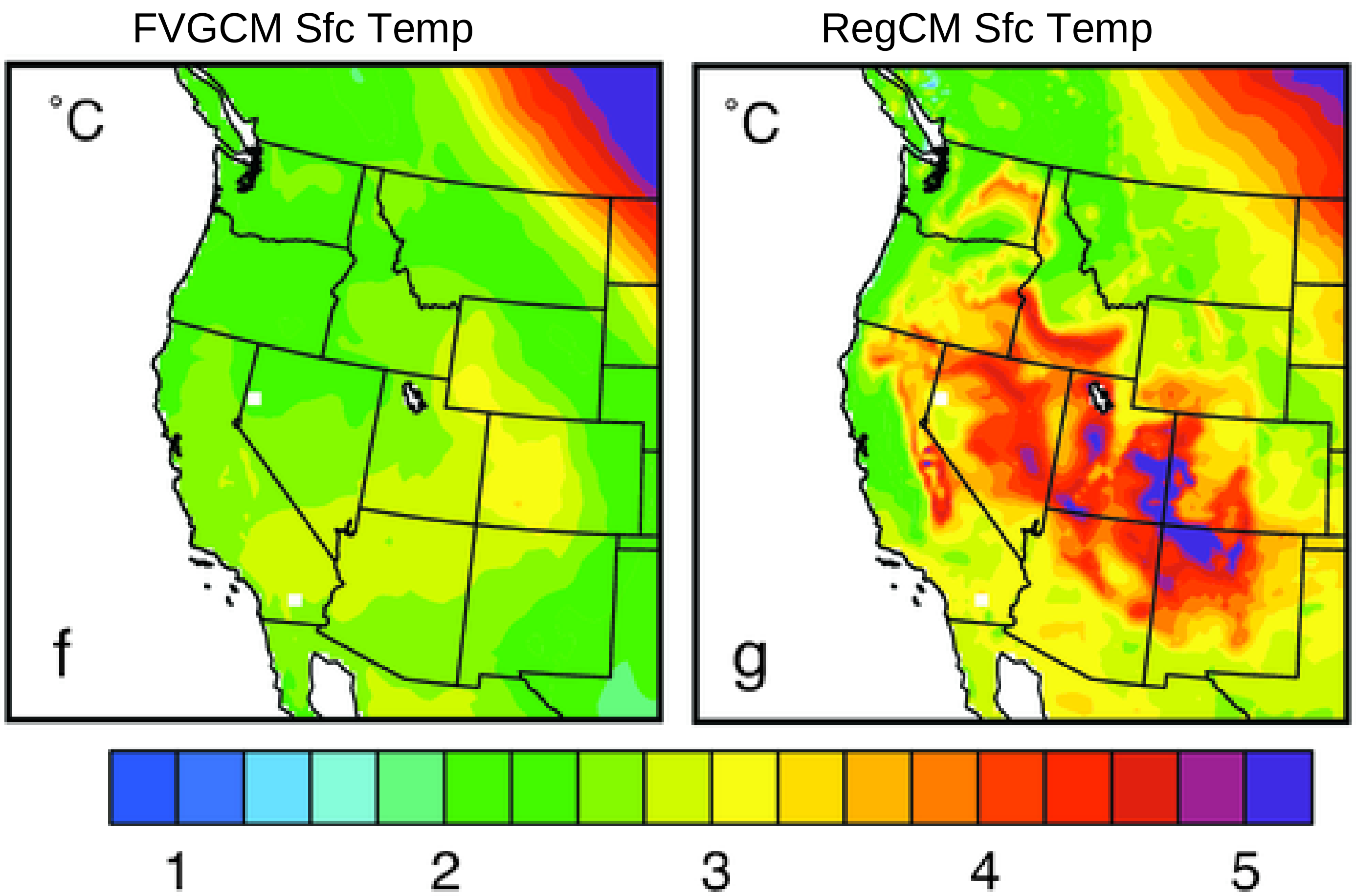
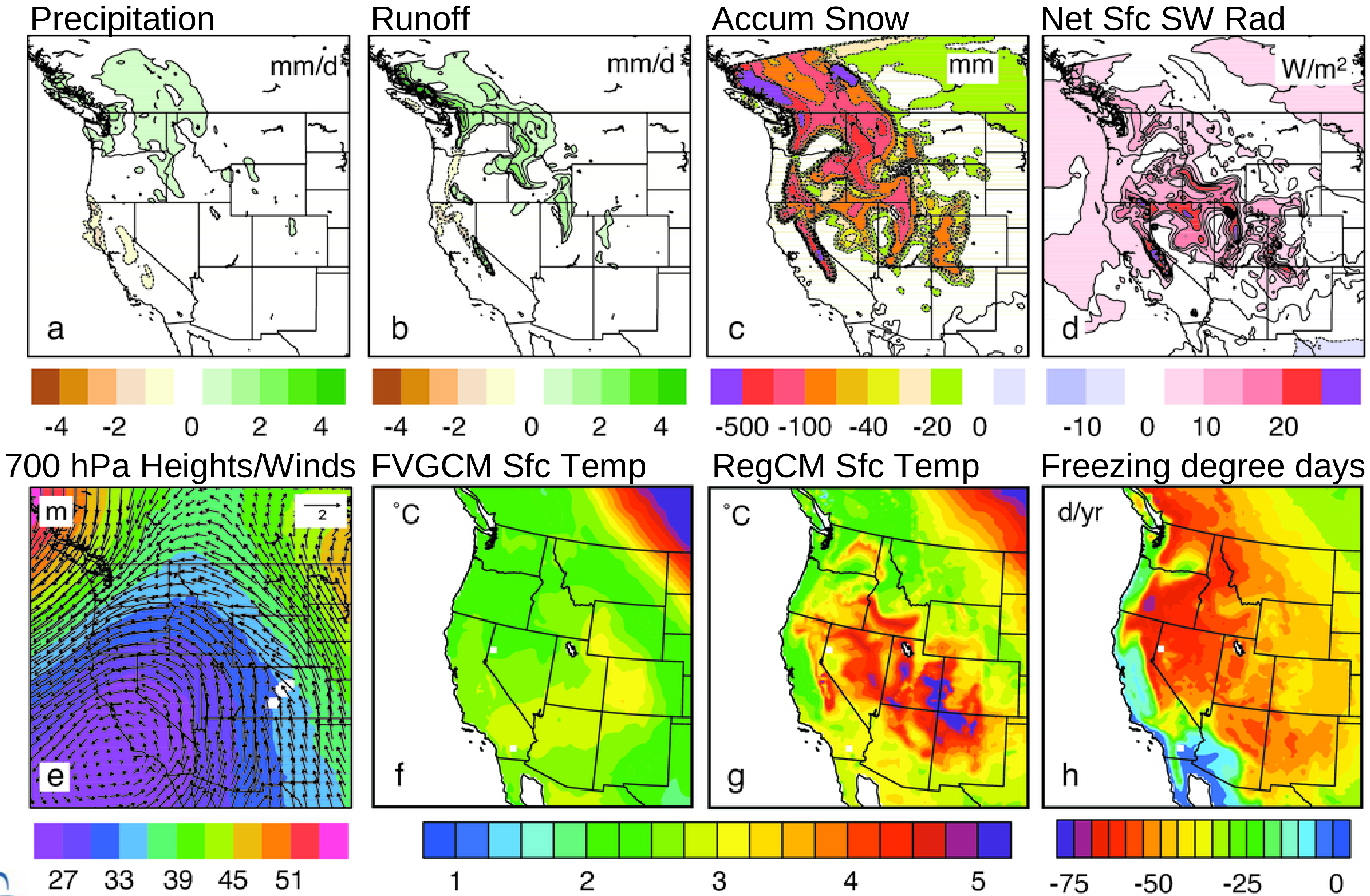
Regional Model vs. GCM: Temperature Change A2-RF JFM



Much larger response in RegCM – WHY?

Physical Mechanisms (A2-RF JFM)



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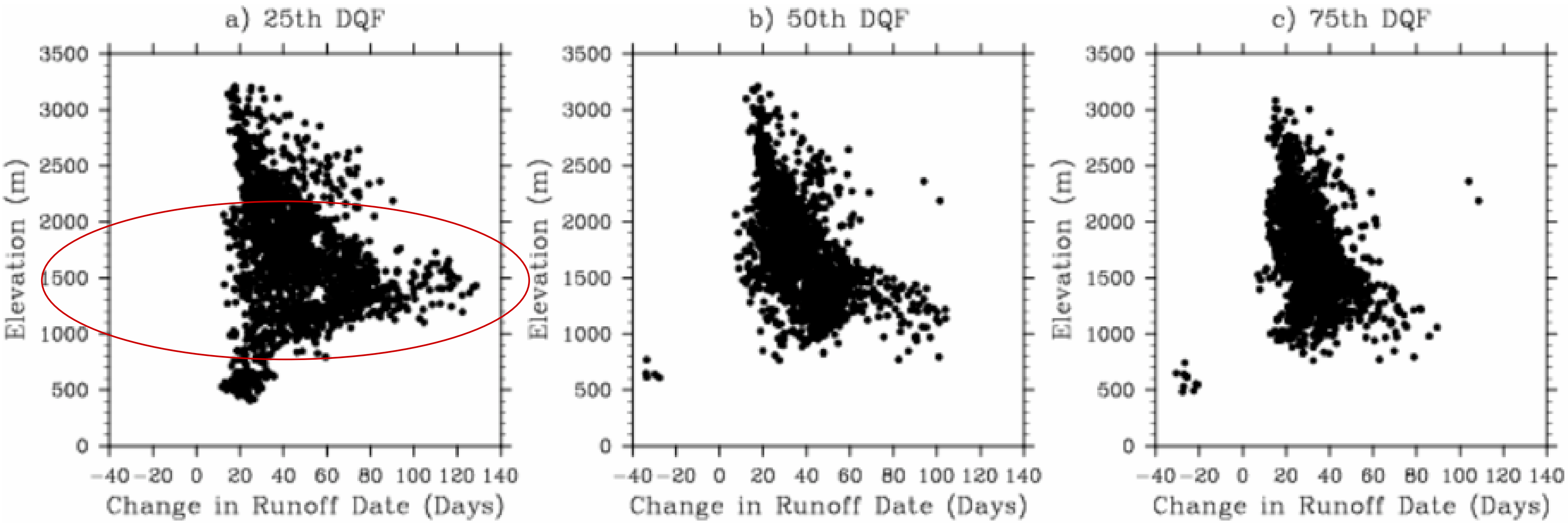
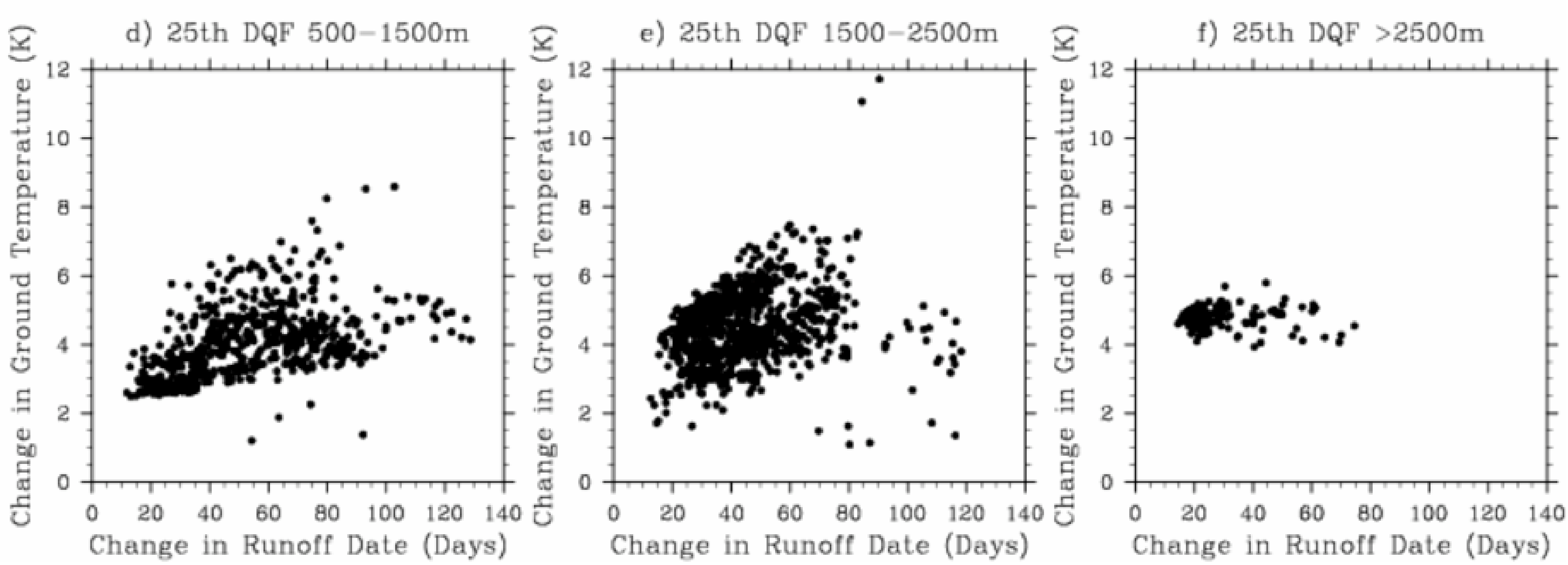
Changes in Runoff Date (Days) vs. Elevation (m)



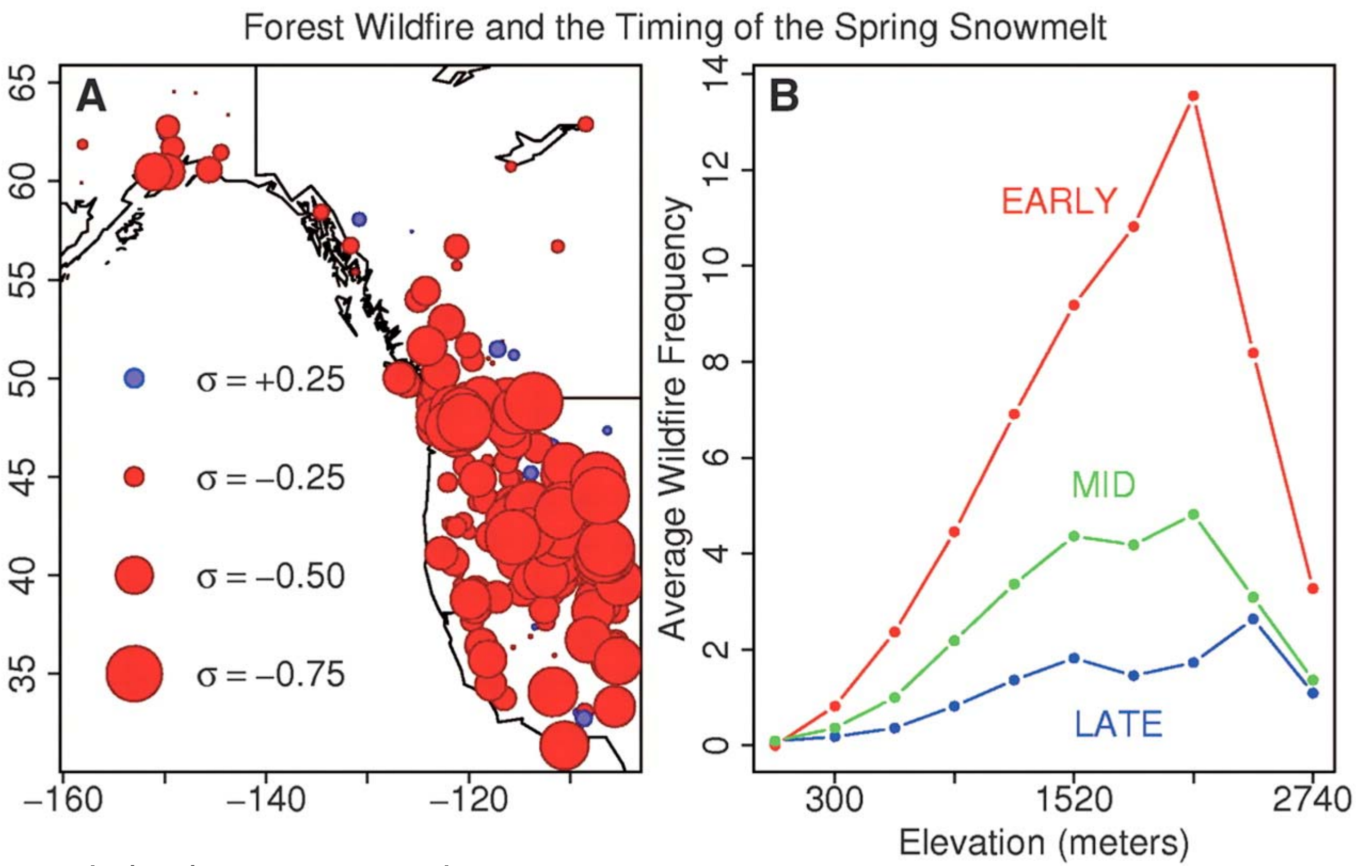
Greatest changes occur at mid-elevations (1200-1700 m),
Consistent with 20th C. observed changes: even though greater temperature changes may occur at higher elevations, overall temperatures remain below freezing to maintain snow cover.

Changes in 25th DQF (days) vs. Temperature (K)



Again, strongest linear relationship at low-mid elevations.

Early Snowmelt Impacts: Increased Wildfire



1970-2002

Correlation between annual western U.S. large (>400 ha) forest wildfire frequency and streamflow center timing.

Average frequency of western U.S. forest wildfire by elevation and early, mid-, and late snowmelt years.

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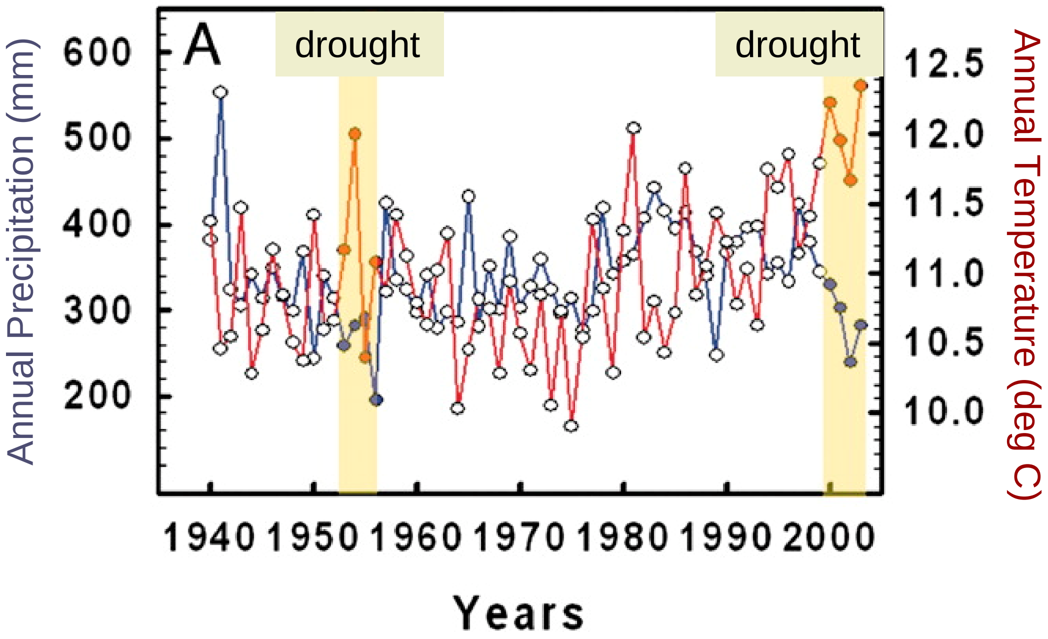
A. L. Westerling et al. (2006) Warming and Earlier Spring Increase Western U.S. Forest Wildfire Activity. Science, DOI: 10.1126/science.1128834

Summary

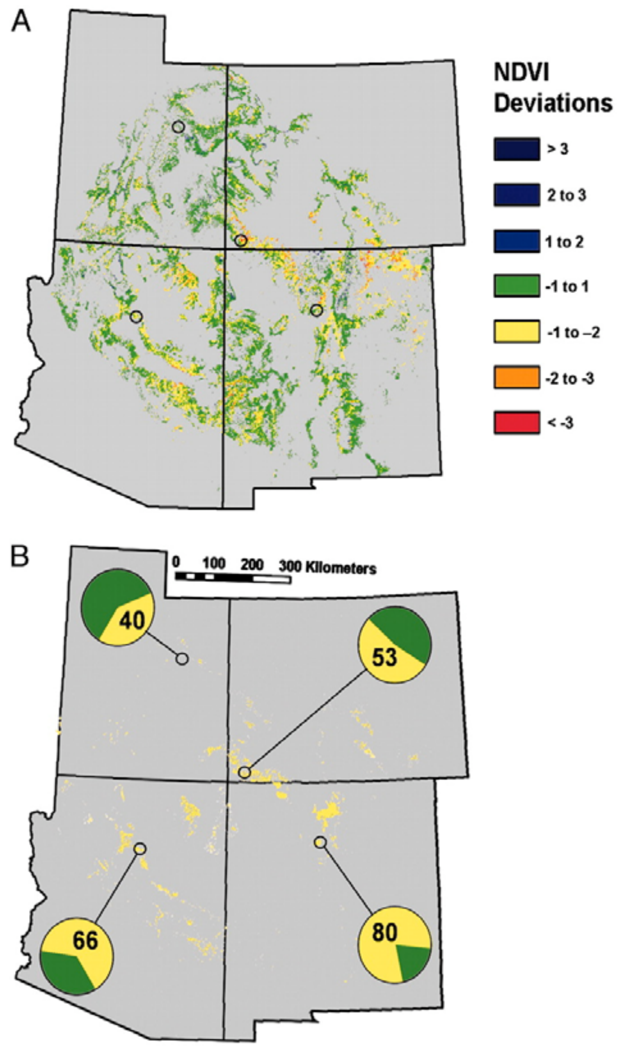
- **Already limited water resources in the western U.S. are likely to be affected by**
  - potential future drying
  - reduced storage of water in the snowpack (less snow and early melting)
- **High-resolution RCM simulations suggest snowmelt-driven runoff timing could occur 1-2 months (or more) earlier than present.**
  - This is a larger change than seen in previous (GCM/statistical downscaling) studies.
  - Large response due to amplified snow-albedo feedback (high resolution effect)
  - While based on a single model, the results emphasize the need for high spatial resolution studies to identify important processes.
- **Potential impacts are HUGE: agriculture, tourism, hydropower generation, increased risks of wildfire, and vegetation mortality…**

Vegetation Mortality in the SW U.S.

Annual Precipitation and temperature over the SW



D. D. Breshears et al. (2005) Regional vegetation die-off in response to global-change-type drought, PNAS, 15144-15148



B: Aerial survey map of piñon-juniper woodlands, delineating areas that experienced noticeable levels of tree mortality

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Future Research at LANL

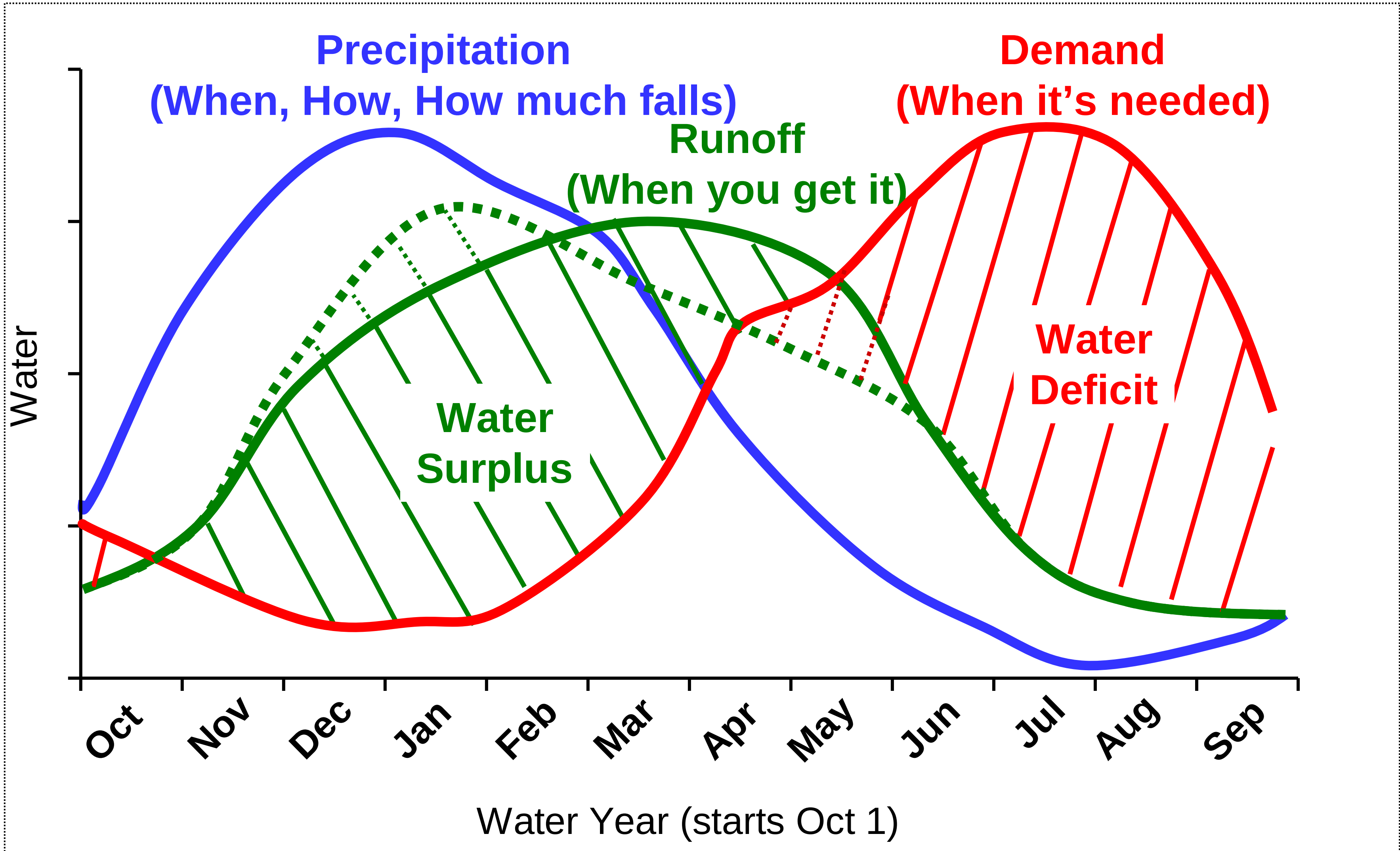
- **Test new hypotheses about drought-related mortality using regional modeling system**
  - Simulate past mortality events
  - Predict future mortality events in climate change scenarios
- **High resolution modeling system**
  - CCSM driving fields
  - WRF RCM
  - CLM land surface model coupled to new vegetation mortality model
  - High resolution (~4 km) climate change scenarios

Fig. 1. From McDowell et al. 2008

Fig. 1 Dead ponderosa pine (*Pinus ponderosa*) trees in Bandelier National Monument, New Mexico, USA. (Photograph courtesy of Craig Allen.)

Thank you

Water Cycle Schematic for the Western U.S.



As much as 75-80% of runoff is from snowmelt in the West.

Model Biases: Temperature

CRU

RegCM

FVGCM