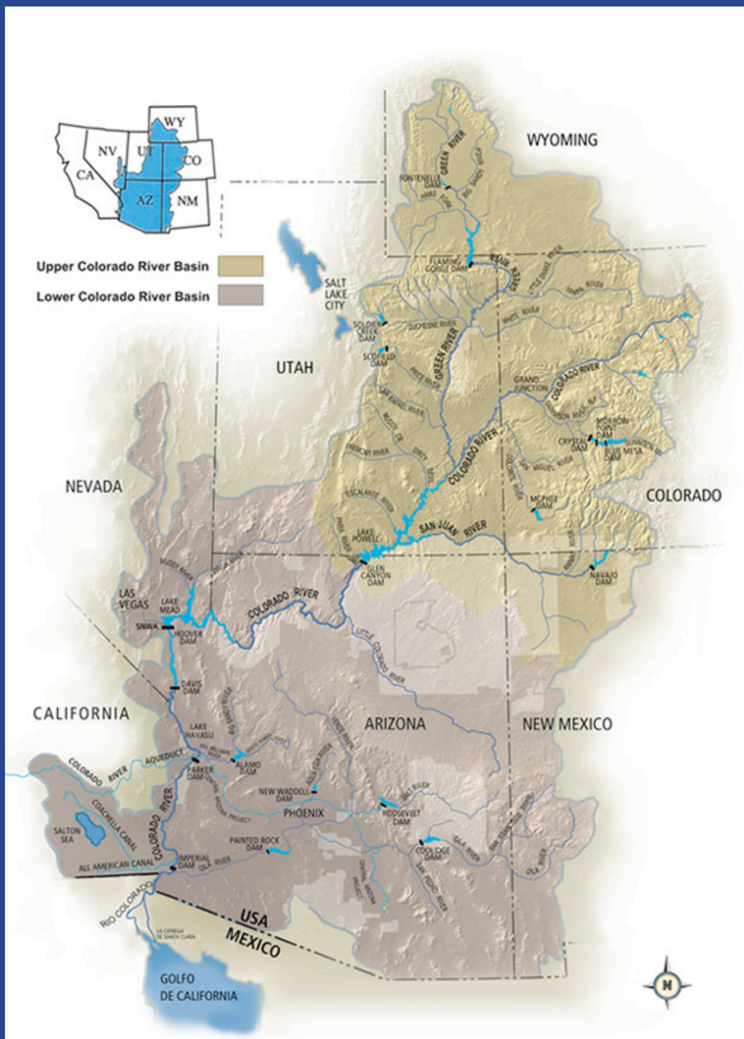
Reconciling Projections of Future Colorado River Stream Flow

**Robert Webb, Bradley Udall,
Martin Hoerling, Jonathan Overpeck,
Holly Hartman, Dennis Lettenmaier,
Julie Vano, Dan Cayan, Tapash Das
Levi Brekke, Kevin Werner
(4 RISAs and Collaborators)**

CPASW Workshop
San Diego, California
Wednesday, March 3, 2010

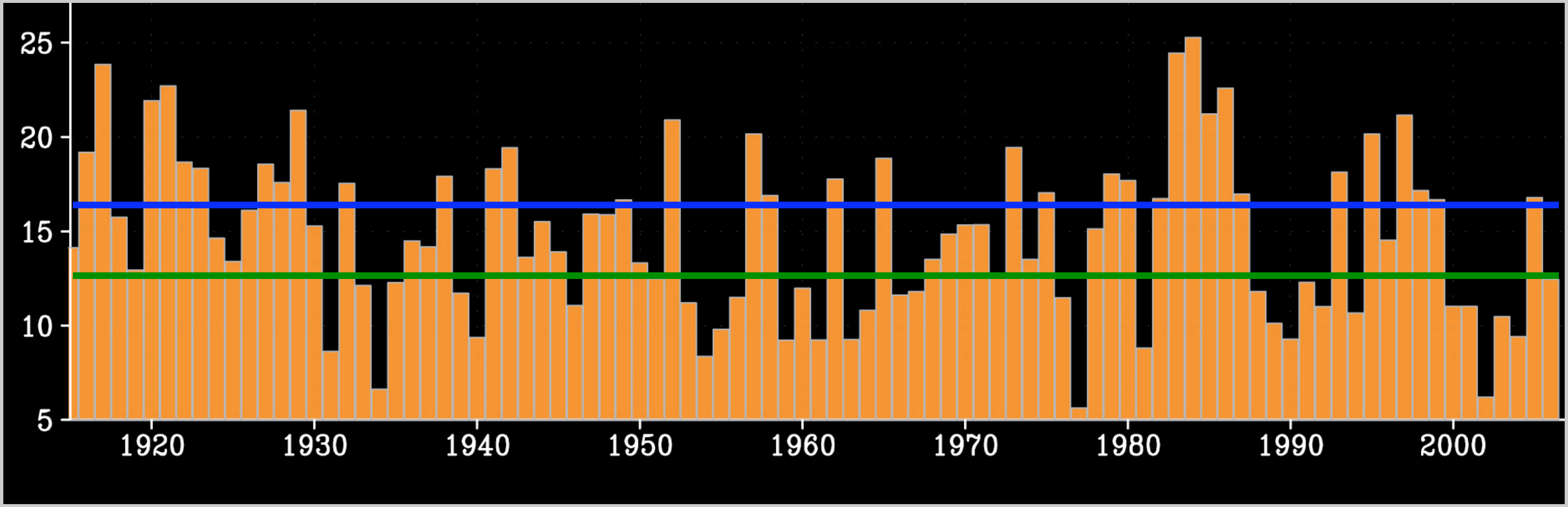
Colorado River Water



- Major water supply Southwest
- Storage to runoff ratio
  - 3.08 Upper Basin
  - 2.55 Lower Basin
- Water use (consumptive use/supply)
  - 4.2/13.9 Upper Basin
  - 10.6/10.3 Lower Basin
- Apportionments: 16.5 MAF (20.3 BCM)
  - 7.5 MAF Upper Basin
  - 7.5 MAF Lower Basin
  - 1.5 MAF Mexico
- Average annual naturalized flow: 14.8 MAF (18.3 BCM), 1975-2005

Map courtesy of http://www.gcdamp.gov/aboutamp/crb.html

Natural Flow at Lee Ferry, AZ
(millions acre-feet)

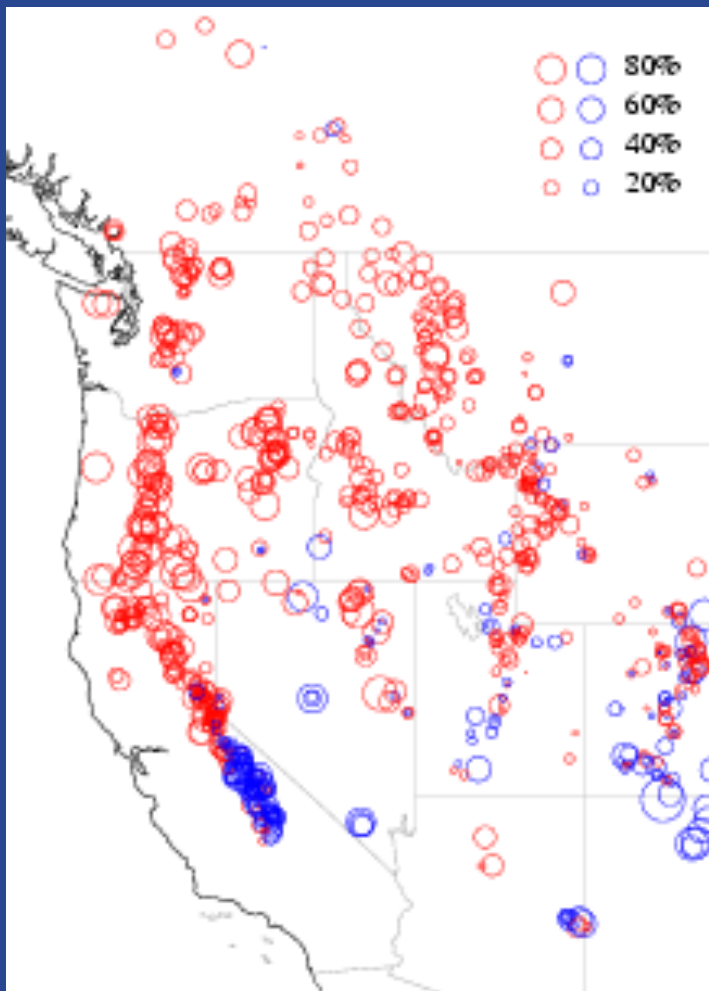


16.5 MAF allocated in Compact

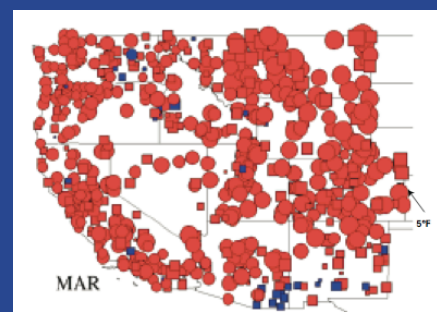
13.2 MAF currently used

1975-2005 Average Flow 14.8 MAF

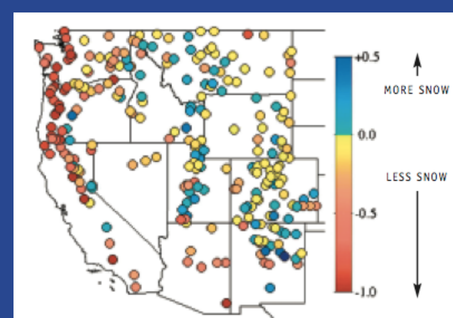
Current Climate Trends



Observed April 1 snow water equivalents, 1950-1997



March Average Min Temp on Days with Precipitation (1949-2004)

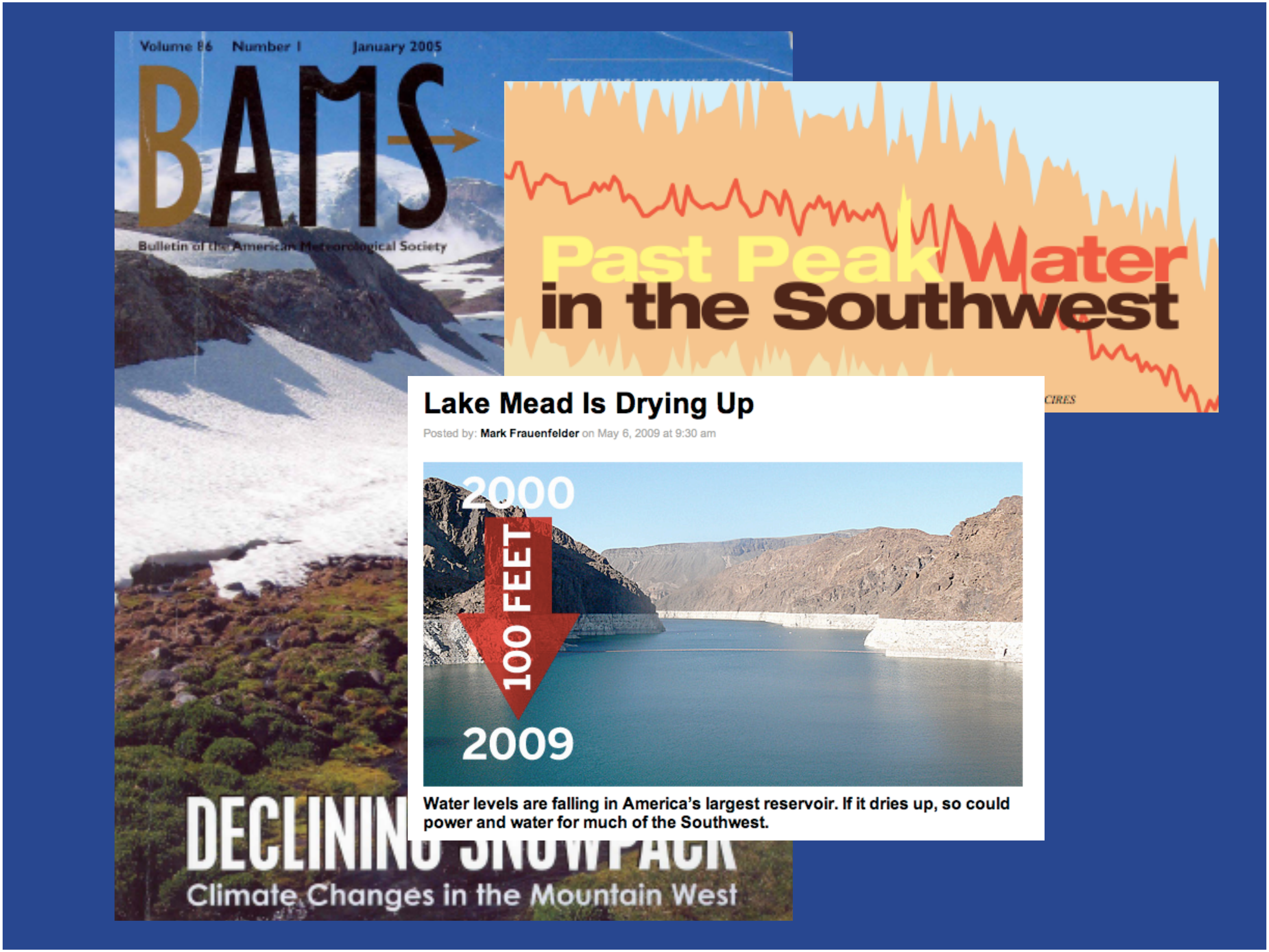


Trends in Snow vs. Rain in Winter (1949-2004)

and many more…

Mote P.W.,Hamlet A.F., Clark M.P., Lettenmaier D.P., 2005, Declining mountain snowpack in western North America, BAMS, 86 (1): 39-49

Knowles, N., Dettinger, M.D., and D.R. Cayan, 2006, Trends in Snowfall verse Rainfall in the Western United States, Journal of Climate 19: 4545-4559.



Volume 86 Number 1 January 2005
BAMS
Bulletin of the American Meteorological Society
DECLINING SNOWPACK
Climate Changes in the Mountain West
Past Peak Water
in the Southwest
CIRES
Lake Mead Is Drying Up
Posted by: Mark Frauenfelder on May 6, 2009 at 9:30 am
2000
100 FEET
2009
Water levels are falling in America's largest reservoir. If it dries up, so could power and water for much of the Southwest.

Past Studies

TABLE 5-1. Projected Changes in Colorado River Basin Runoff or Streamflow in the Mid-21st Century from Recent Studies

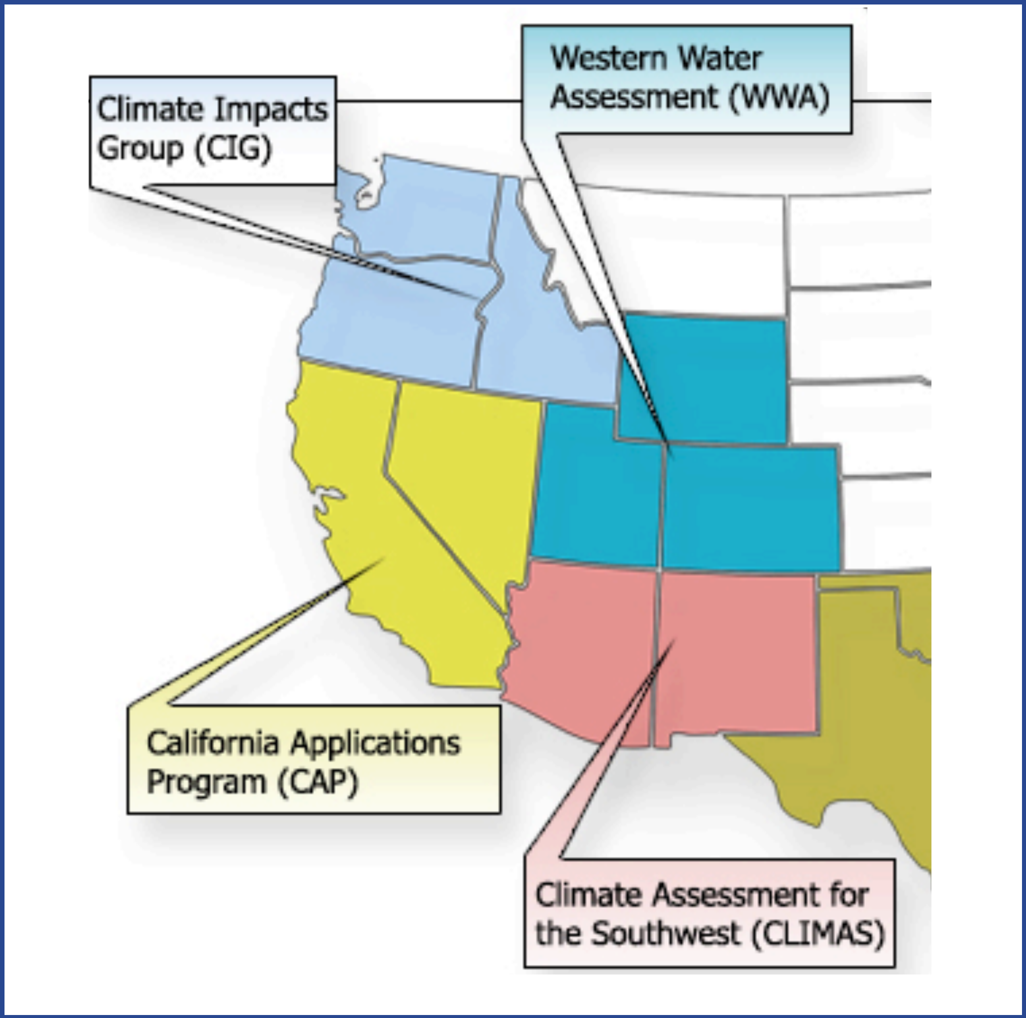
Study	*GCMs (runs)*	*Spatial Scale*	*Temperature*	*Precipitation*	*Year*	*Runoff (Flow)*	*Risk Estimate*
Christensen et al. 2004	1 (3)	VIC model grid (~8 mi)	+3.1°F	-6%	2040–69	-18%	Yes
Milly 2005, replotted by P.C.D. Milly	12 (24) (~100–300 mi)	GCM grids —	—		2041–60	-10 to -20% 96% model agreement	No
Hoerling and Eischeid 2006	18 (42)	NCDC Climate Division	+5.0°F	~0%	2035–60	-45%	No
Christensen and Lettenmaier 2007	11 (22)	VIC model grid (~8 mi)	+4.5°F (+1.8 to +5.0)	-1% (-21% to +13%)	2040–69	-6% (-40% to +18%)	Yes
Seager et al. 2007*	19 (49)	GCM grids (~100–300 mi)	—	—	2050	-16% (-8% to -25%)	No
McCabe and Wolock 2008	—	USGS HUC8 units (~25–65 mi)	Assumed +3.6°F	0%	—	-17 %	Yes
Barnett and Pierce 2008*	—	—	—	—	2057	Assumed -10% to -30%	Yes

Values and ranges (where available) were extracted from the text and figures of the references shown. Columns provide the number of climate models and individual model runs used to drive the hydrology models, the spatial scale of the hydrology, the temperature and precipitation changes that drive the runoff projections, and whether or not the study quantified the risk these changes pose to water supply (e.g., the risk of a compact call or of significantly depleting reservoir storage).

* Two studies do not specifically make projections of Upper Basin runoff or streamflow. Seager et al. (2007) average over a large area (95°W–125°W, 25°N–40°N) that only partially overlaps with the Upper Basin. Barnett and Pierce (2008) assume Lees Ferry streamflow changes to drive their water balance model of reservoir storage.

Table from Colorado Water Conservation Board (CWCB) report " Colorado Climate Change: A Synthesis to Support Water Resource Management and Adaptation." Oct 2008 (available online at: http://cwcb.state.co.us/NR/rdonlyres/8118BBDB-4E54-4189-A354-3885EEF778A8/0/CCSection5.pdf)

Regional Integrated Sciences & Assessments



Goal:
Research that addresses complex climate sensitive issues of concern to decision-makers and policy planners at a regional level.

Collaborators:

Brad Udall, Robert Webb (WWA)
Dan Cayan, Tapash Das (CAP)
Jonathan Overpeck, Holly Hartman (CLIMAS)
Dennis Lettenmaier, Julie Vano (CIG)
Martin Hoerling, Kevin Werner (NOAA)
Levi Brekke (Reclamation)

More info at: http://www.climate.noaa.gov/cpo_pa/risa

Project Objectives

1) Reconcile discrepancies in projected Colorado River flow changes.

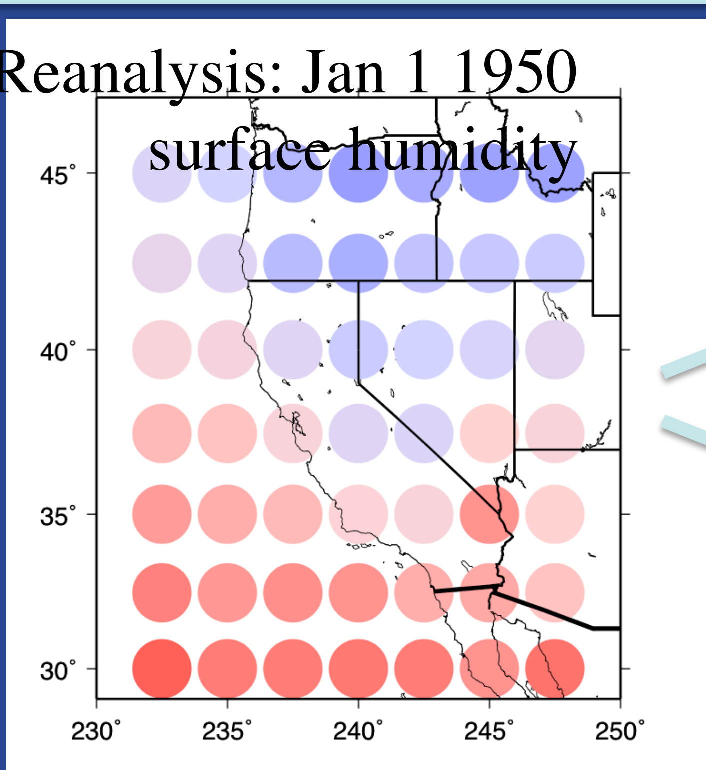
2) Assess the basins sensitive in runoff to changes in temperature, in precipitation, or in both.

5) Identify the underlying mechanisms for these sensitivities (e.g. soil moisture, ET).

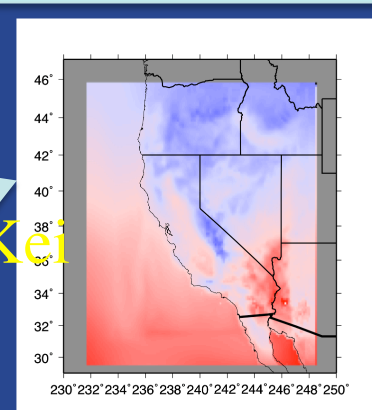
6) Provide meaningful information for water managers and policymakers that incorporate uncertainties in future climate change projections.

Downscaling & probabilities at CCCC

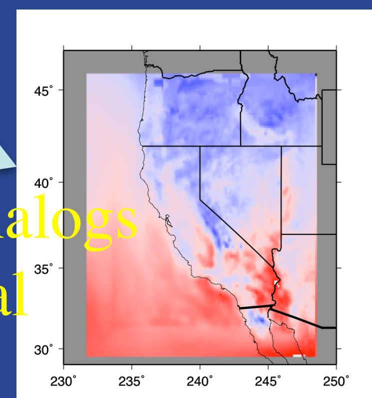
Reanalysis: Jan 1 1950 surface humidity

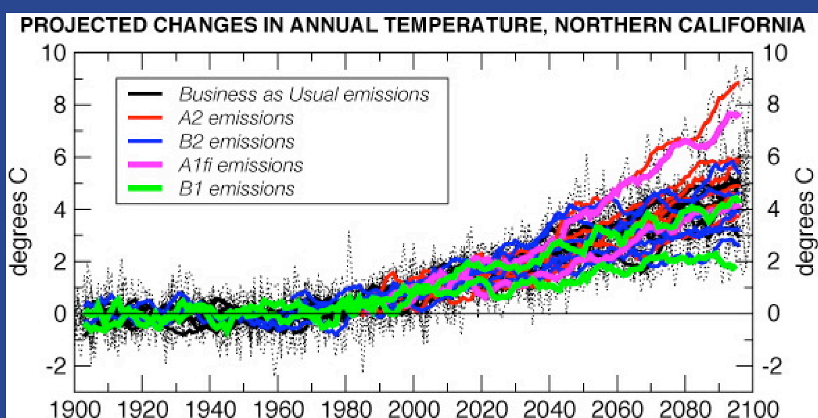


Dynamical: CARD10 by Kanamitsu & Kei

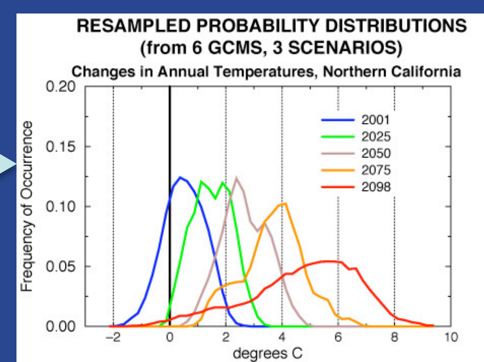


Statistical: Constructed analogs by Hidalgo et al

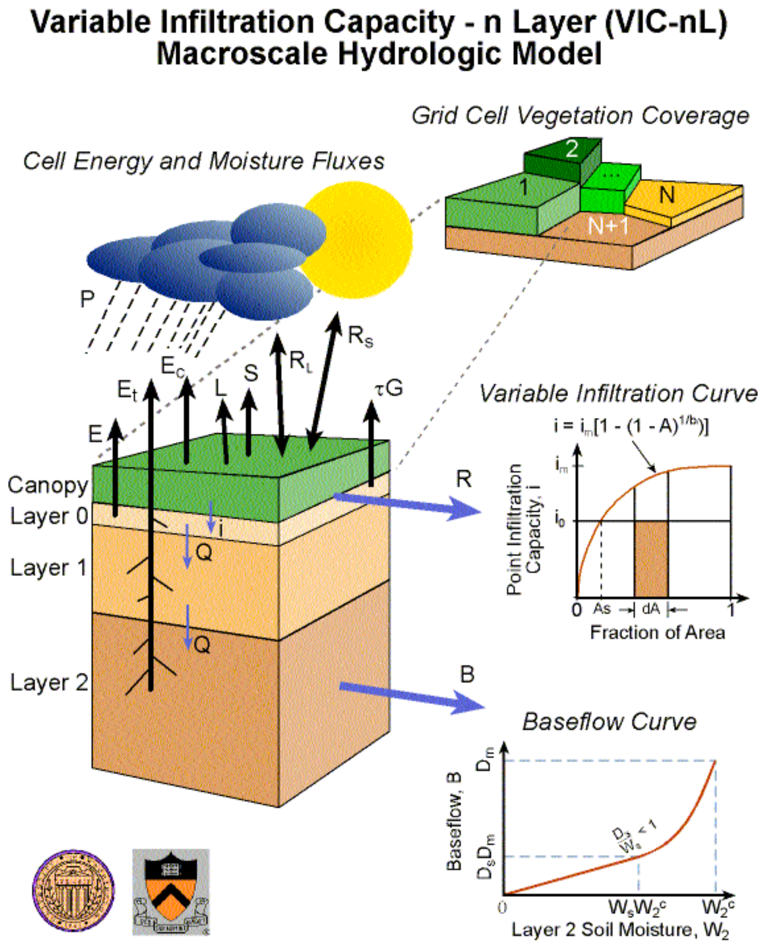


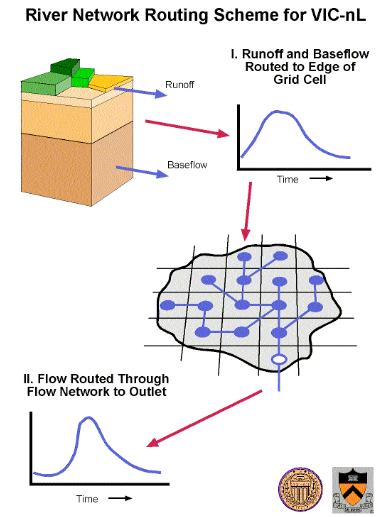


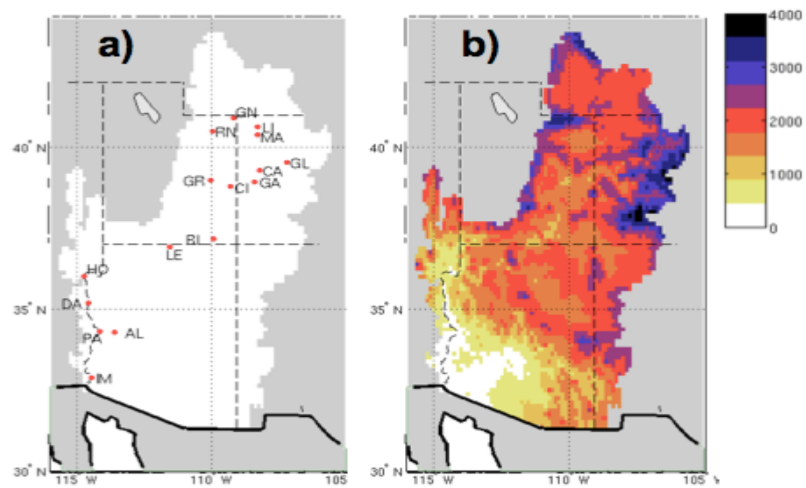
Resampling by Dettinger et al



Land surface hydrologic models



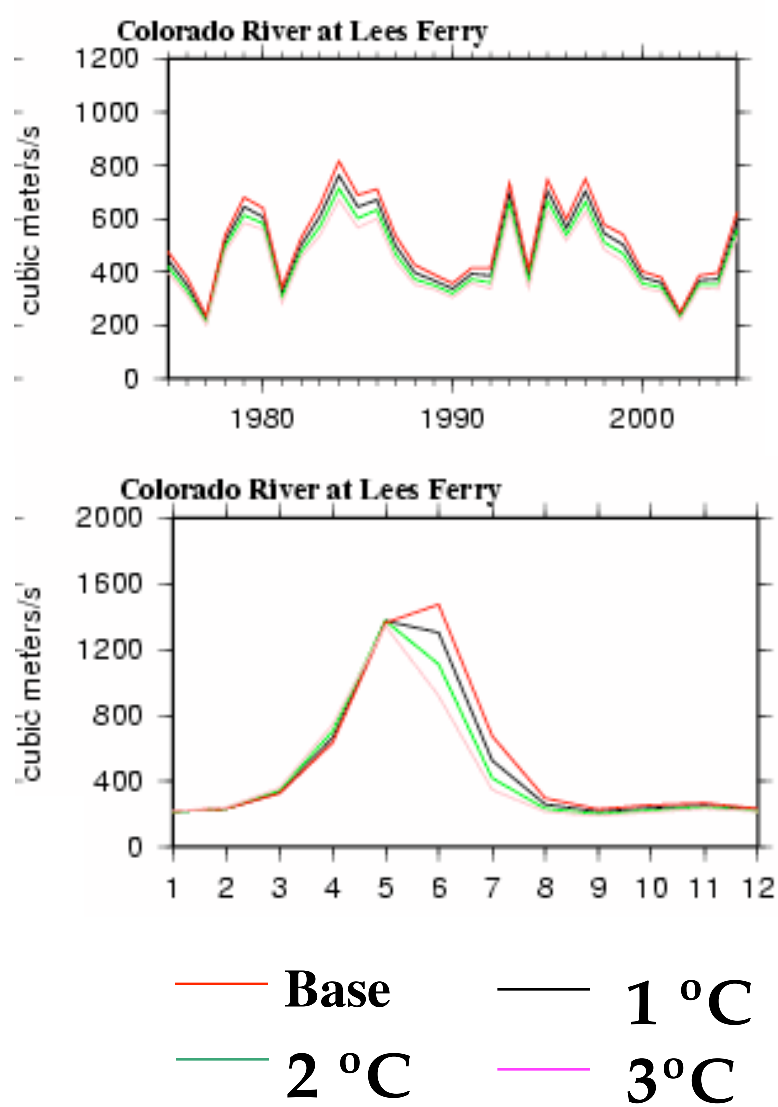




a) Locations of Colorado River main stem stations and tributaries b) Elevations, in meters

Delta method climate forcings

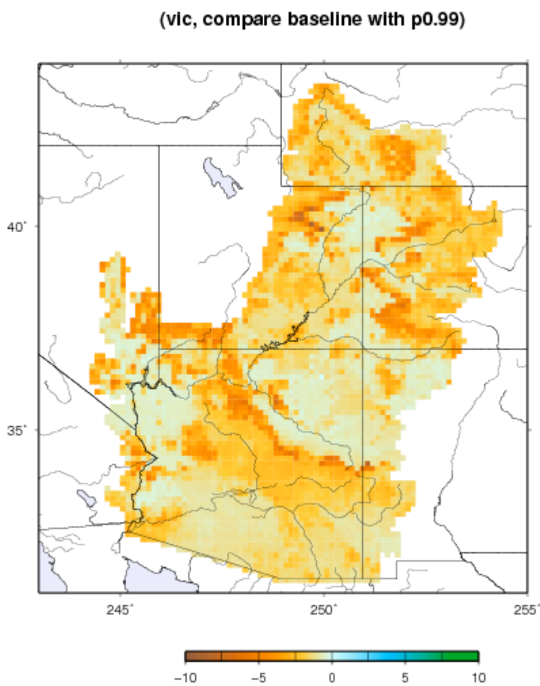
- Applied uniform perturbations in temperature and/or precipitation at every timestep in historic record
- Temp increases: streamflow decreases annually, primarily because decreases flow in spring/summer
- Where are these changes occurring? Specific land-surface characteristics? Thresholds?

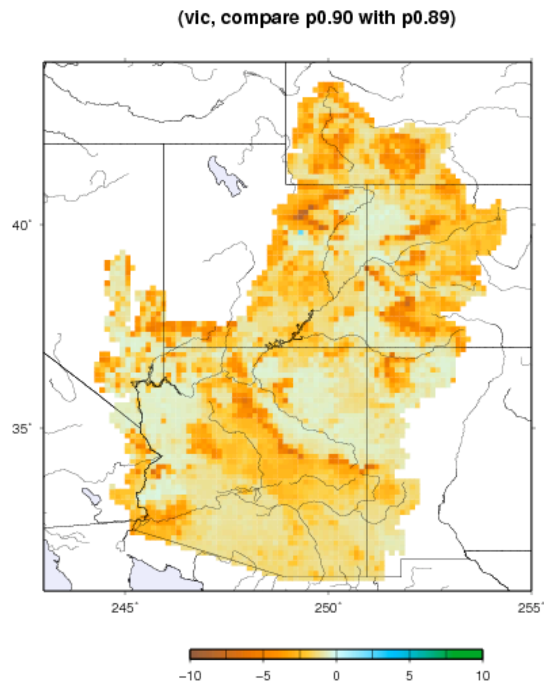


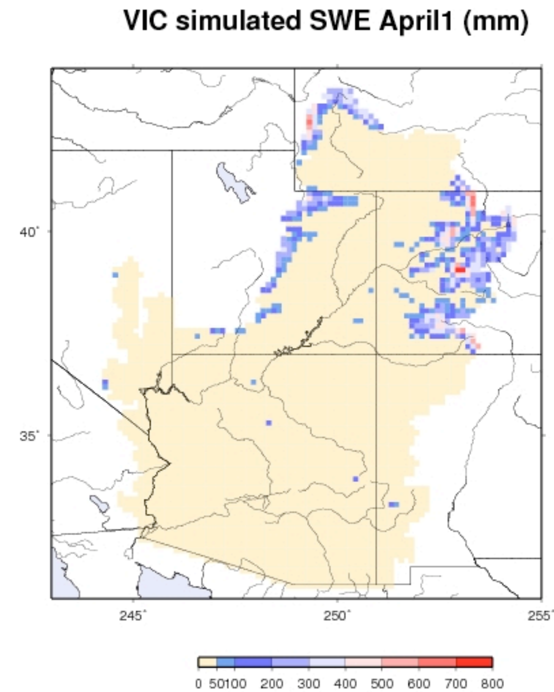
Analysis of Hydrologic Models

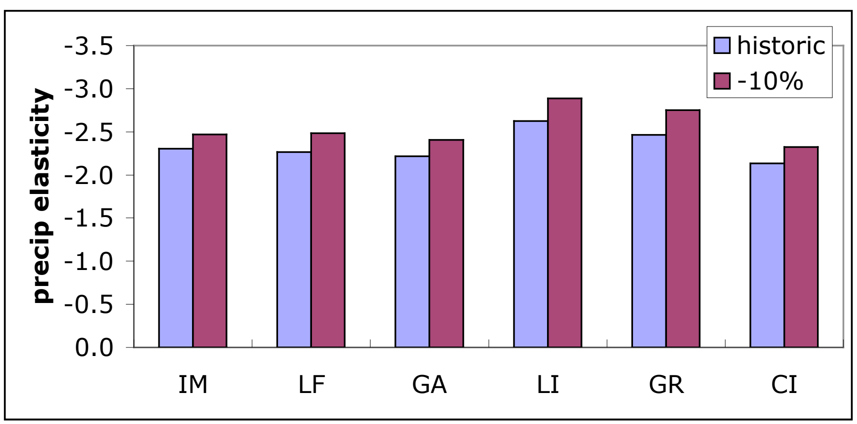
Climate Forcings	Land-surface Hydrologic Models	Measures
Historic Delta changes GCM scenarios	Variable Infiltration Capacity (VIC) McCabe 2-Layer Soil Water Balance Noah LSM Sacramento (SAC) Catchment LSM Community Land Model SAC operational others…	temp sensitivity $= \dfrac{\dfrac{Q_{ref+1} - Q_{ref}}{Q_{ref}}}{\text{deg C}}$ precip elasticity $= \dfrac{\dfrac{Q_{ref-1\%} - Q_{ref}}{Q_{ref}}}{\%}$

Preliminary precip elasticities









Station Key:

GA: Gunnison River near Grand Junction

CI: Colorado River near Cisco

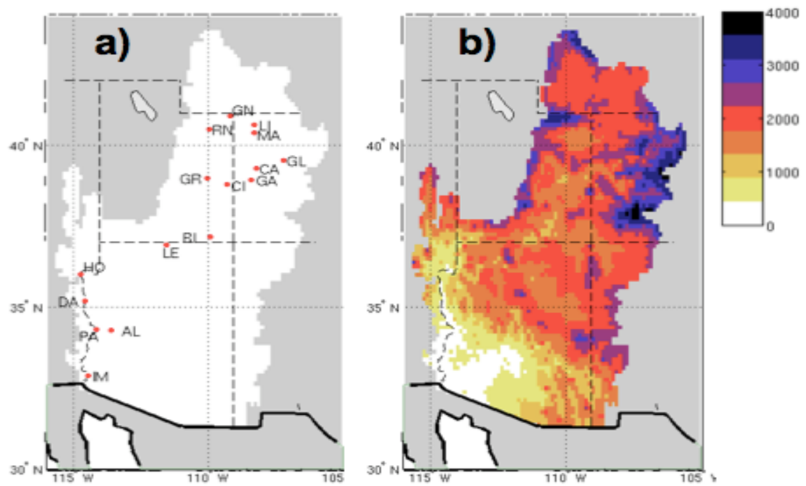
GR: Green River at Green River

LI: Snake River near Lilly, CO

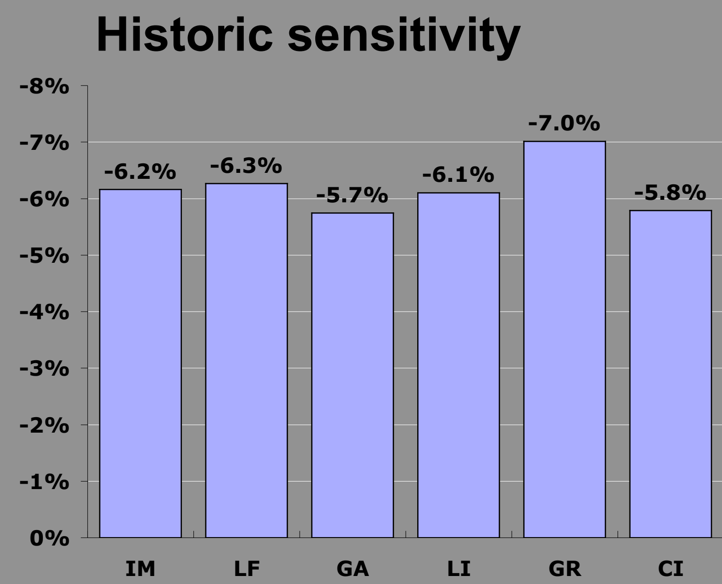
LE or LF: Colorado River at Lees Ferry

IM: Colorado River below Imperial Dam

Colorado River Flows highly Sensitive to Warming



a) Locations of Colorado River main stem stations and tributaries b) Elevations, in meters



Station Key:
GA: Gunnison River near Grand Junction
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LE or LF: Colorado River at Lees Ferry
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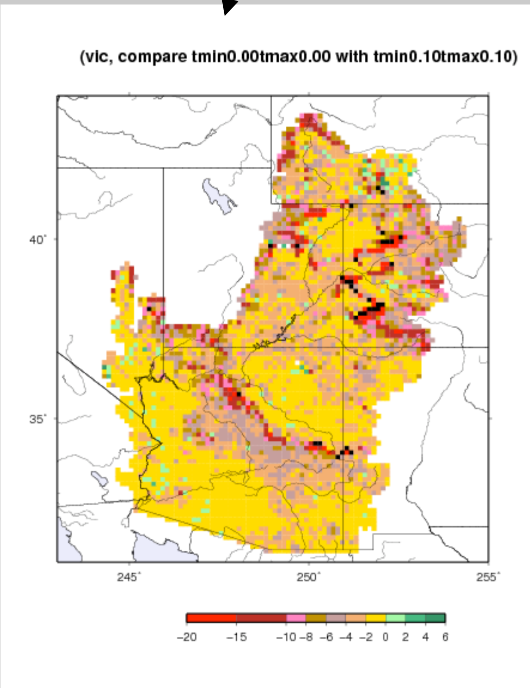
Greatest sensitivities appear in zones of snow and snow-rain transition.

Overall sensitivity approx 6% decline in flow per 1°C warming

Temperatures sensitivities for Colorado River Flow at Lees Ferry

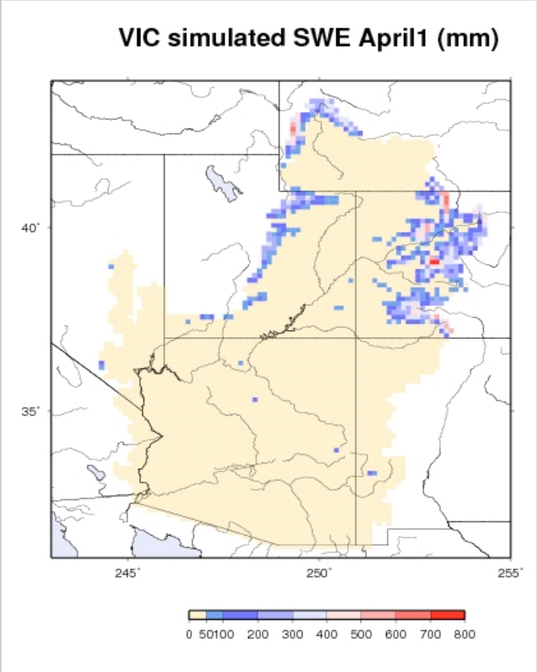
VIC T_{max} and T_{min}	-5.9%
VIC T_{max}	-10.8%
2-Layer Model	-9.0%



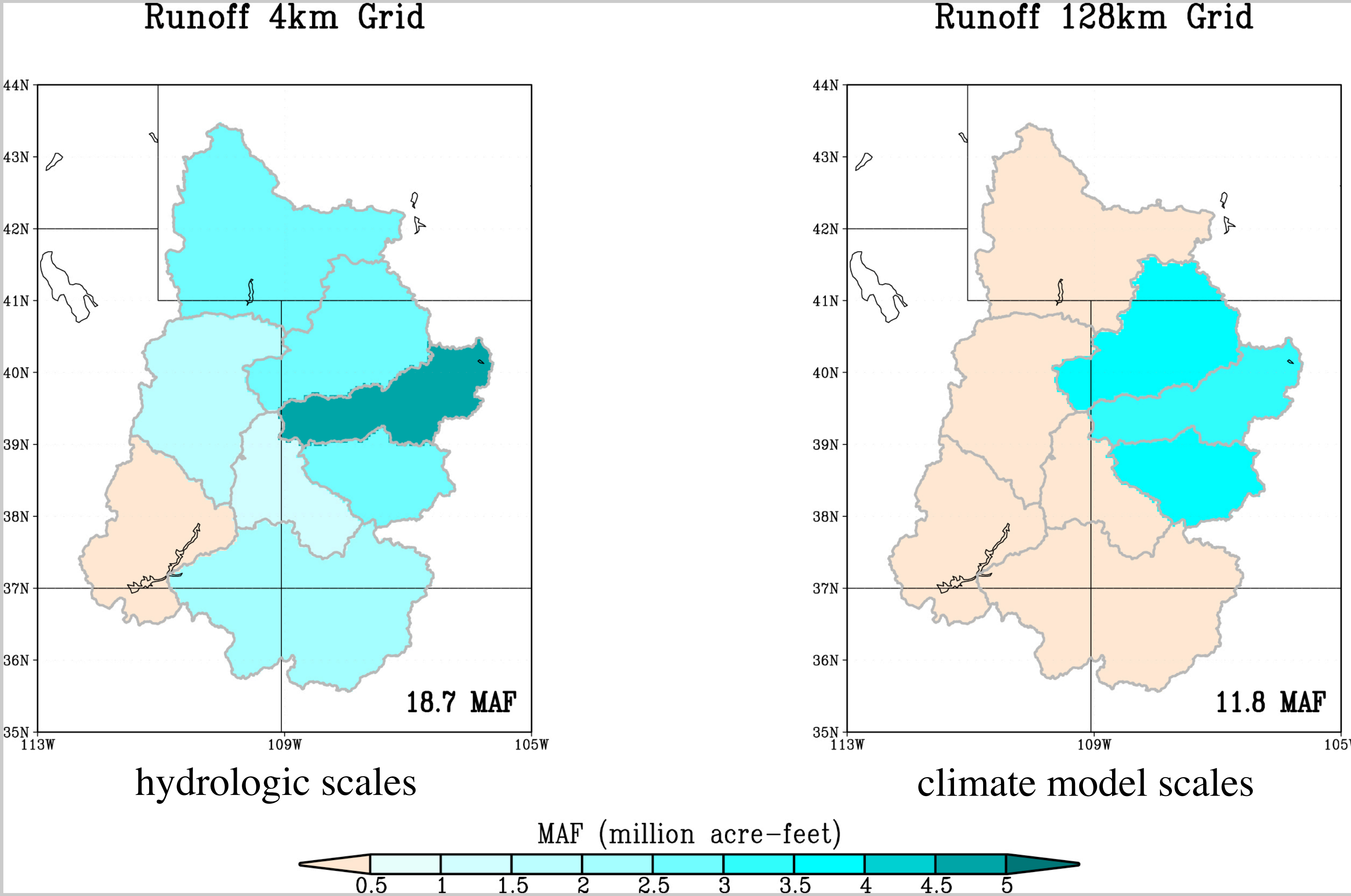
Sensitivity between models is dependant on how PET is calculated:

Penman-Monteith versus Thornthwaite

How temperature applied (T_{max} vs $T_{max\&min}$) changes radiation budget



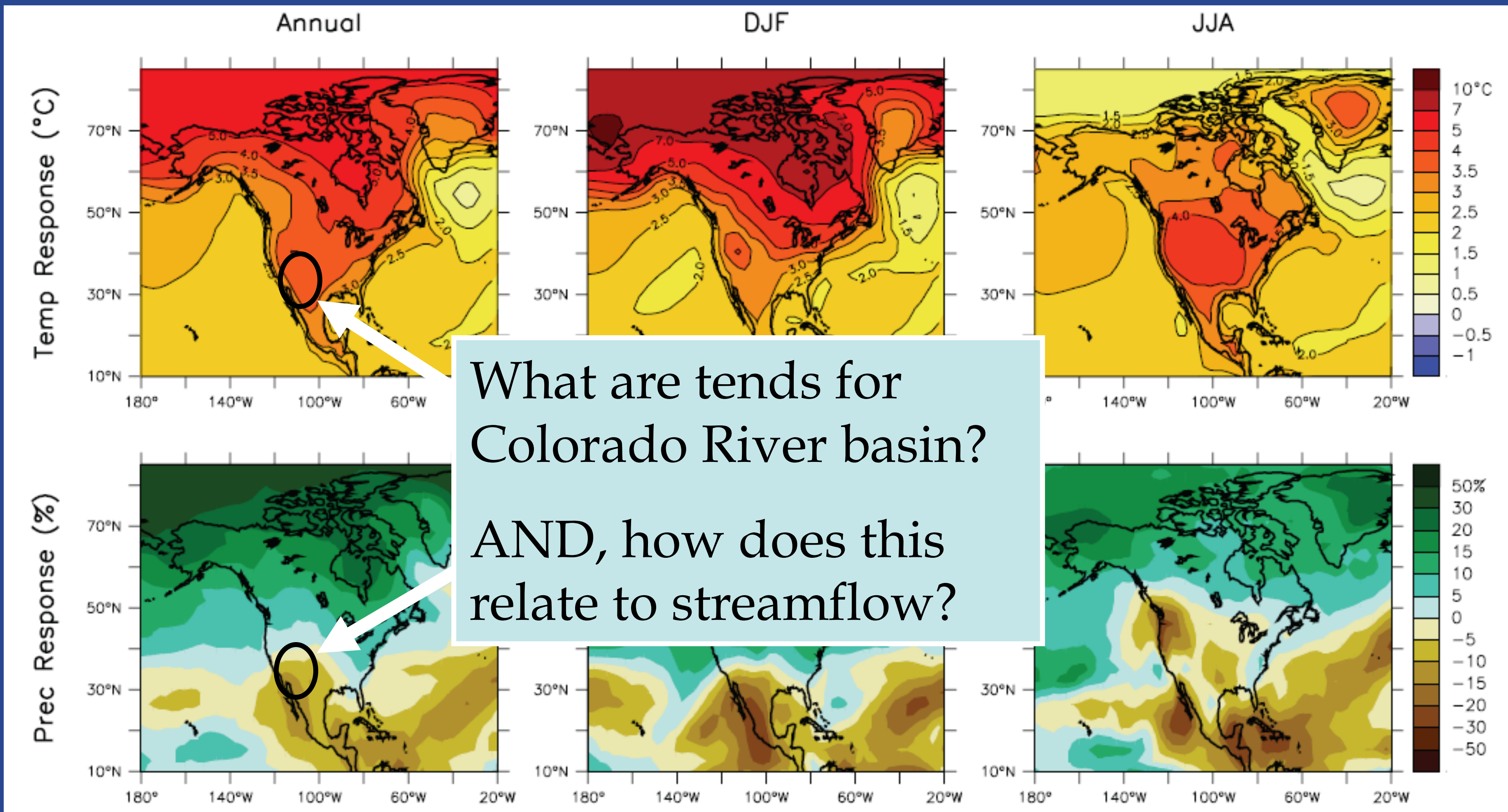
Sensitivity to Spatial Scale: 4km vs 128km runoff simulation



Summary

- ✓ Topography and hydrologic structure is crucial: resolving snow vs. rain and other processes in the Colorado River Basin is crucial. In general, runoff sensitivities calculated directly from GCMs overestimate flow decline due to inflated temperature sensitivity and precipitation elasticity
- ✓ Change in precipitation in the basin by 2050 is still uncertain, based on the spread of CMIP3 projections
- ✓ CMIP3 projections suggest an increase in temperature across the basin of at least 2° C
- ✓ From results so far, we think that we may be able to narrow the projected future Colorado River Flow from a range of +18% to -45% to a likely range of -10% to -20%
- ✓ Communication Matters: Hydrologist, Climatologists and Water Managers speak in different dialects and with different terminology

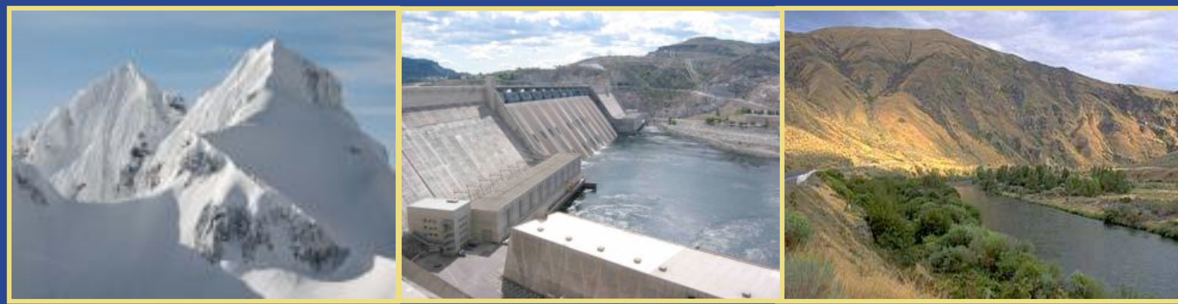
Intergovernmental Panel on Climate Change (IPCC) 2007



Consensus Forecasts of Temperature and Precipitation Changes from IPCC AR4 GCMs

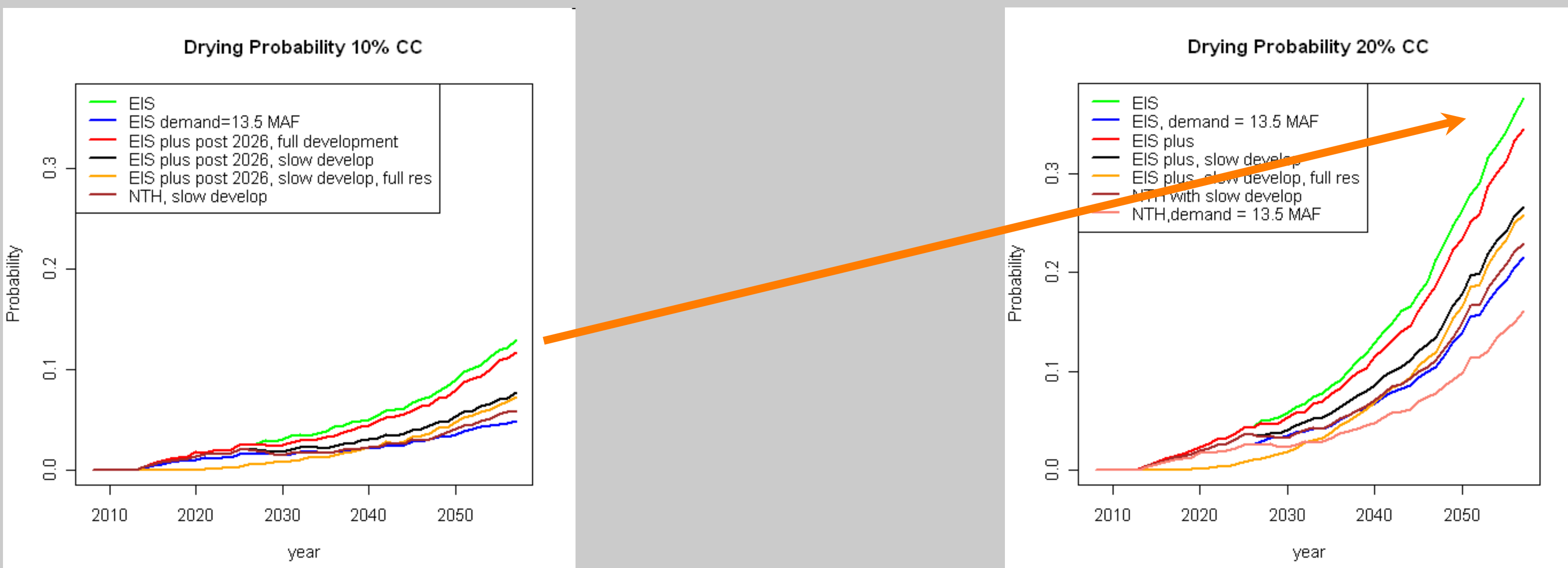
Future work

- Further resolve sensitivity to warming and areas producing the most runoff, and their role in modulating regional scale sensitivities
- Compare results across models: Are sensitivities and precipitation characteristics similar between models?
- Investigate changes in Colorado flow and other measures from an ensemble of climate change?
- Explore further how improved understandings of land-surface interactions and model uncertainty can aid decision-making

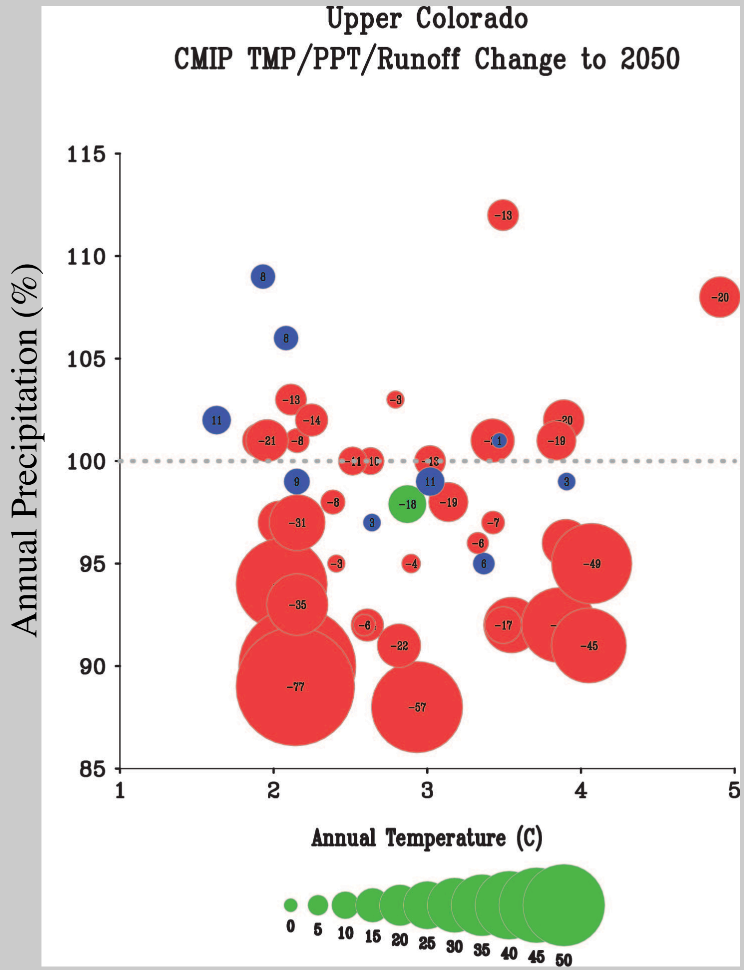


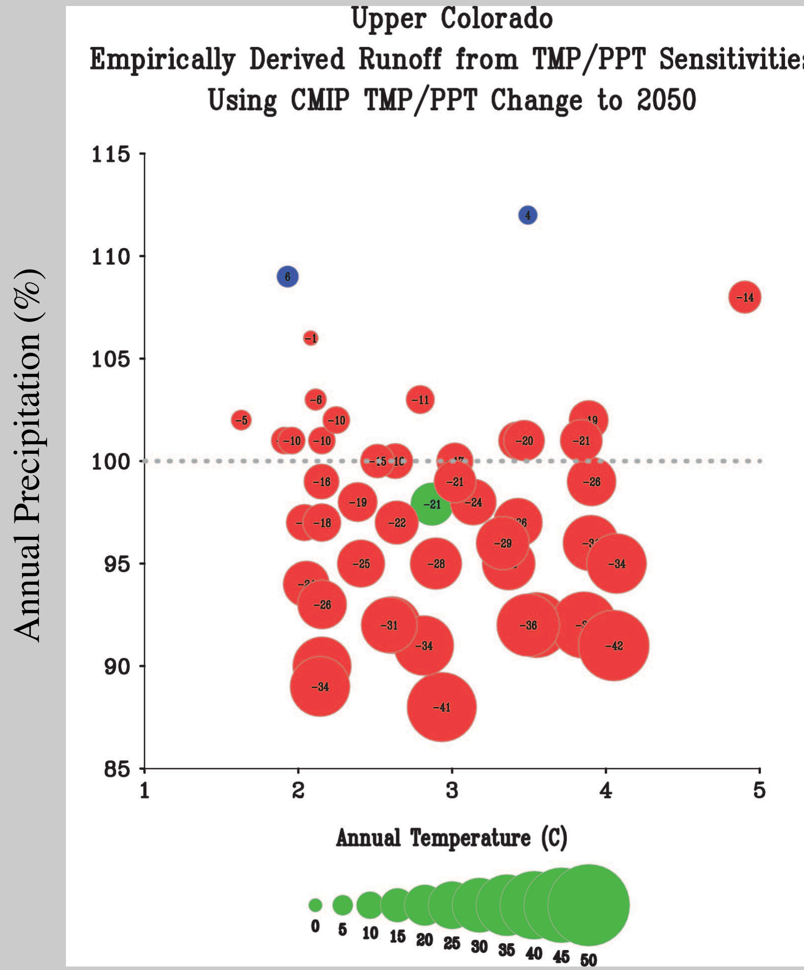
Concluding Thoughts

- The good news is that our work has been able to narrow the projected future Colorado River Flow from a range of +18% to -45% to a likely range of -10% to -20%
- Less good news is that a recent study (Rajagopalan et al, 2009) reveals a significant increase in the risk of reservoir drying with a 20% rather than a 10% projected decrease in Colorado River Flow

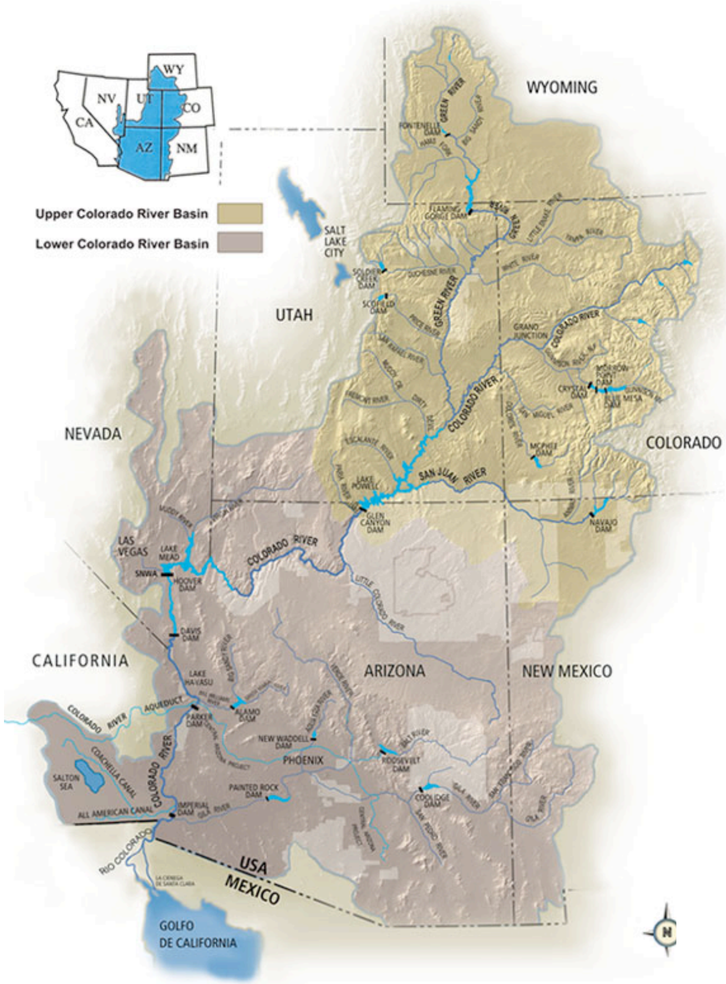


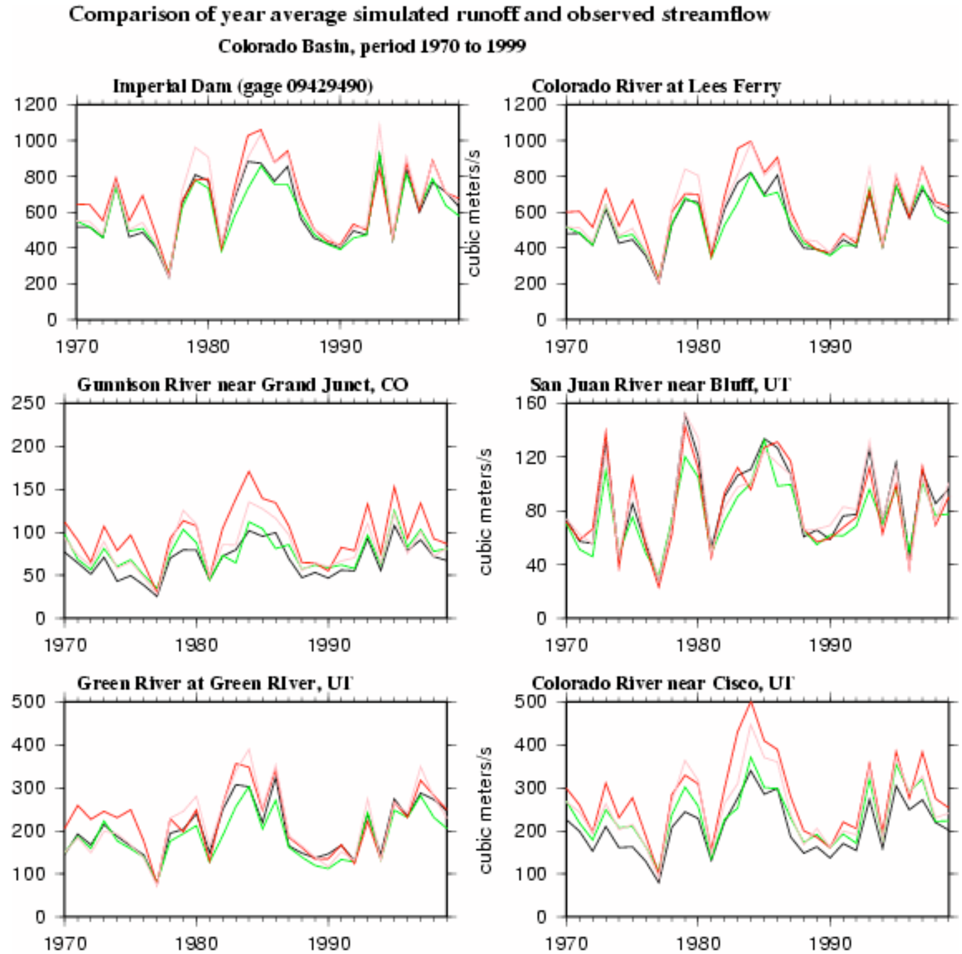
CMIP3 Runoff at 2050 calculated directly and using estimated sensitivity (10%) & elasticity (2%)





Historic climate forcings





Naturalized flow — PRISM

Wood and Lettemaier — Maurer et al.

Methodology

Climate Forcings	Land-surface Hydrologic Models	Measures
Historic	Variable Infiltration Capacity (VIC)	temp sensitivity $= \dfrac{\dfrac{Q_{ref+0.1} - Q_{ref}}{Q_{ref}}}{0.1 \text{ deg C}}$
Delta changes	Noah LSM	precip elasticity $= \dfrac{\dfrac{Q_{ref-1\%} - Q_{ref}}{Q_{ref}}}{1\%}$
GCM scenarios	Sacramento (SAC)	with time, spatially…
Regional climate models	Catchment LSM	
	Community Land Model	
	SAC operational	
	2-Layer Soil Water Balance	
	possibly others…	

Natural Flow at Lee Ferry, AZ

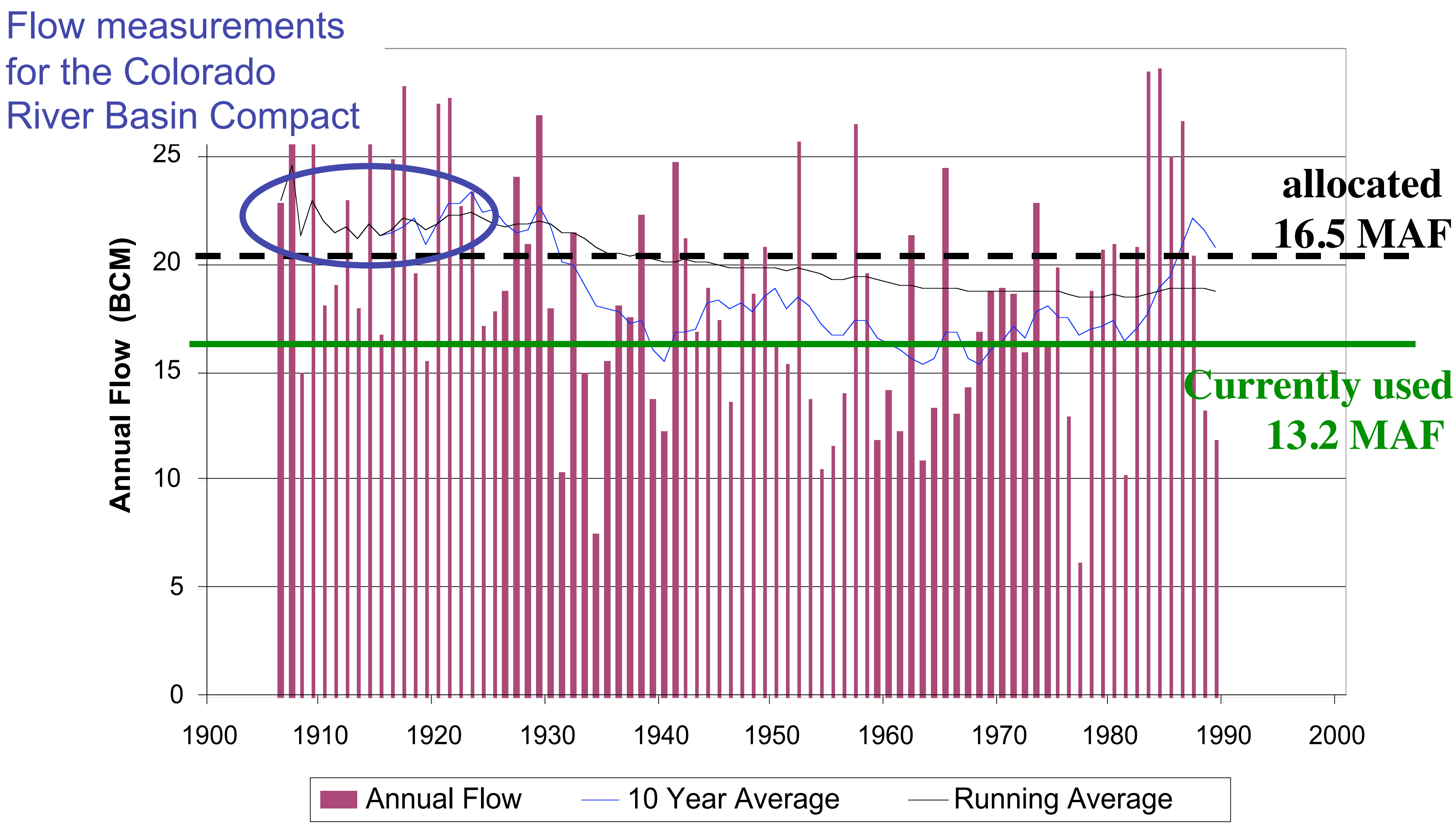
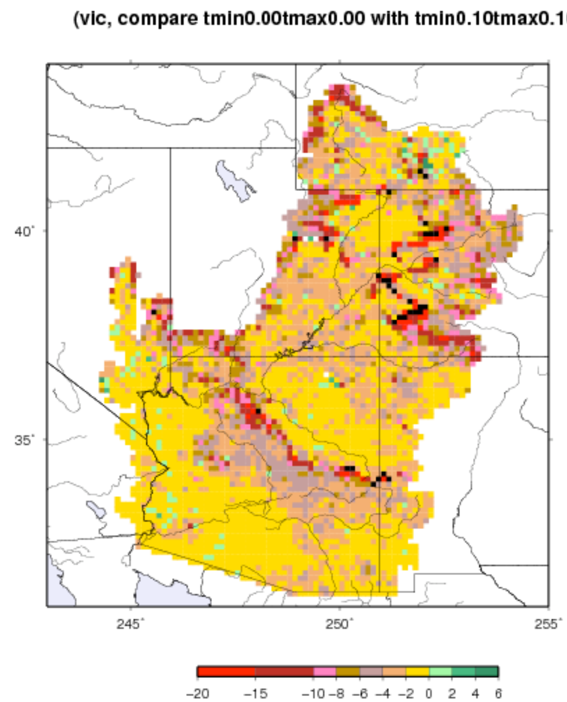
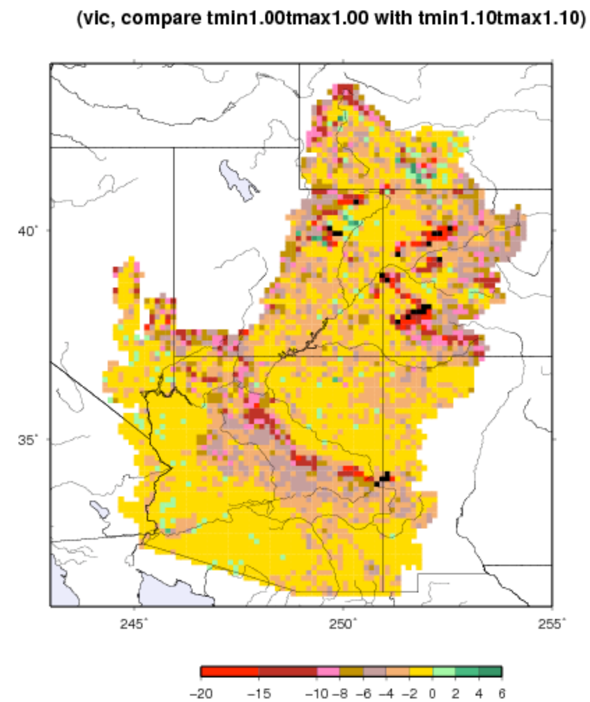
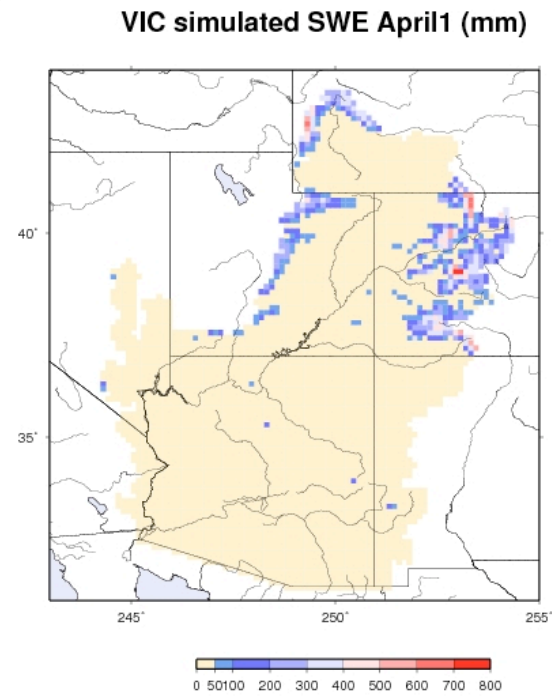


Figure adapted from Christensen and Lettenmaier, 2007

Temperature Sensitivity





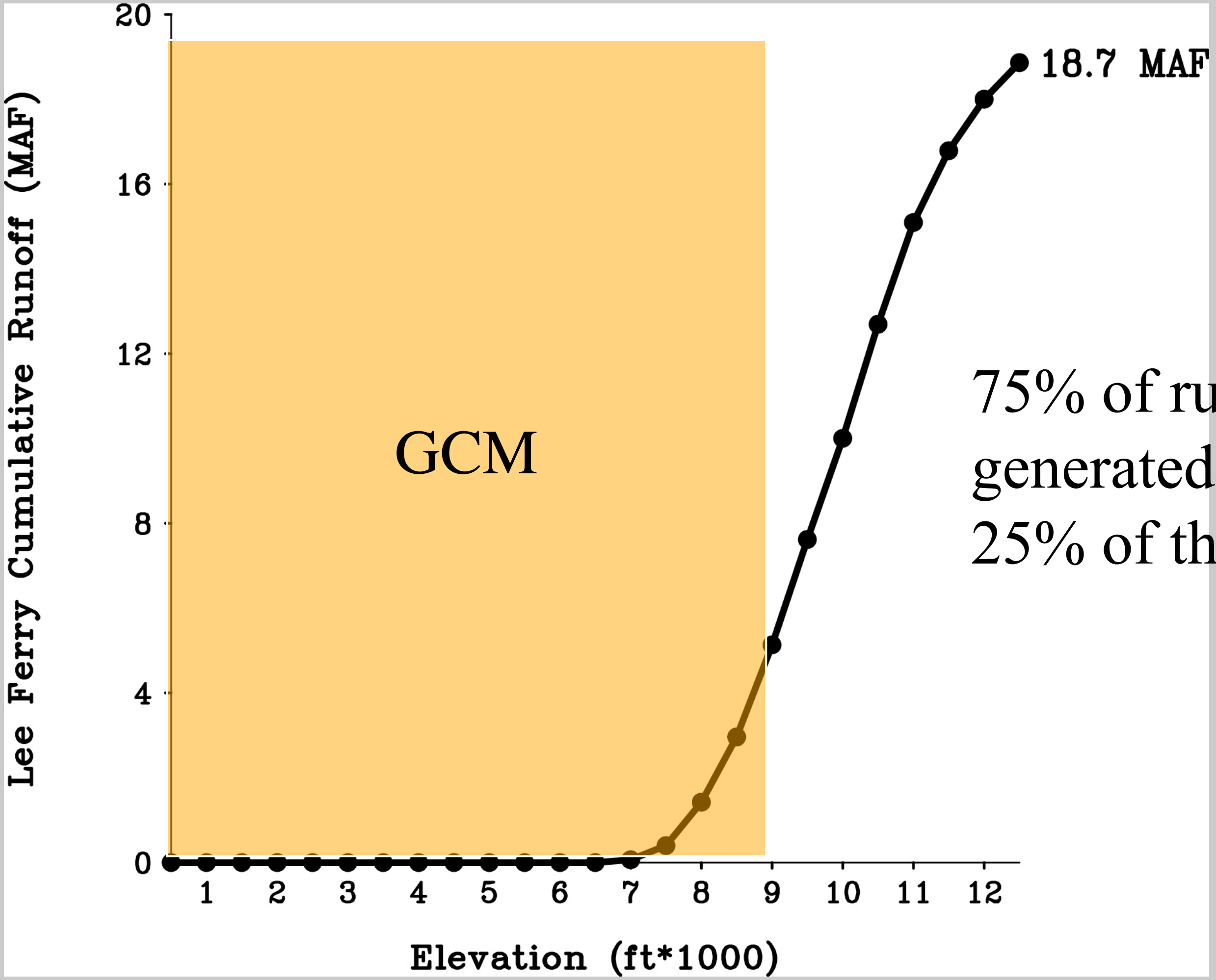


$$\text{temp sensitivity} = \frac{\dfrac{Q_{0.1\ \text{deg C}} - Q_{\text{historic}}}{Q_{\text{historic}}}}{0.1\ \text{deg C}}$$

$$\text{temp sensitivity} = \frac{\dfrac{Q_{1.1\ \text{deg C}} - Q_{1\ \text{deg C}}}{Q_{1\ \text{deg C}}}}{0.1\ \text{deg C}}$$

Preliminary results suggest most sensitive areas along marginal snow zone.

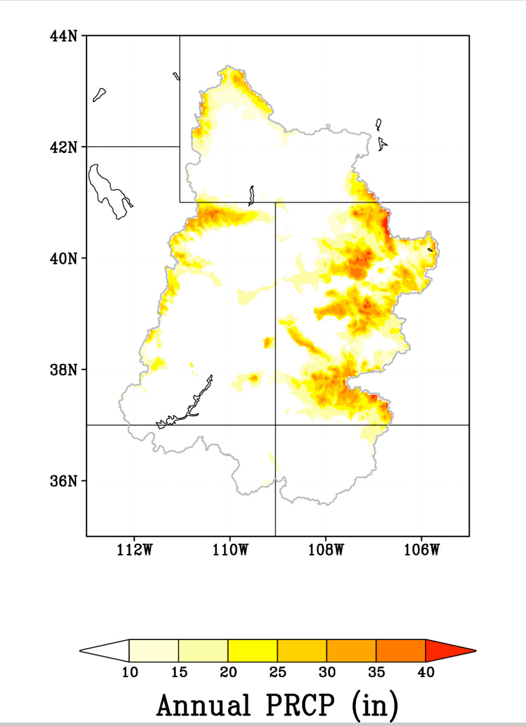
Cumulative Runoff as a function of Elevation

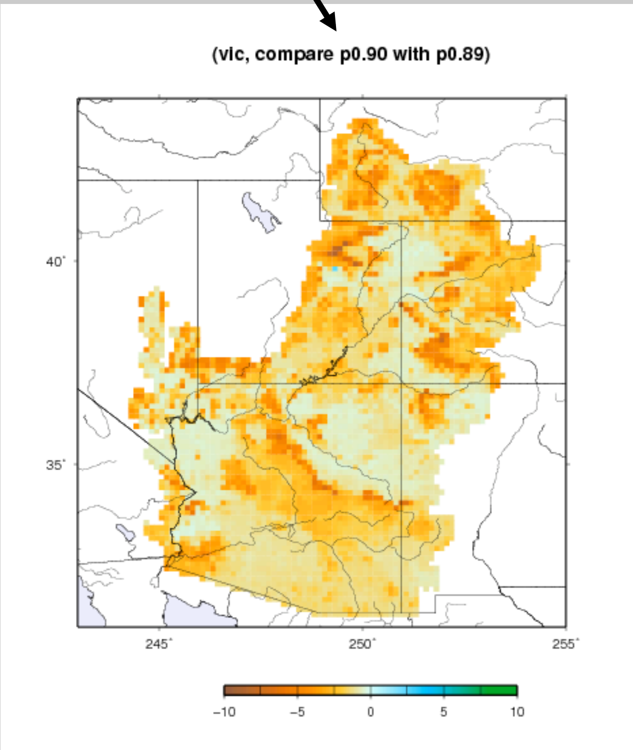


75% of runoff is generated from about 25% of the area

Precipitation Elasticity for Colorado River Flows at Lees Ferry

VIC	2.4%
2-Layer Model	2.0%





Thank you

Questions?? Ideas??

Reconciling Colorado Flow Projections *http://wwa.colorado.edu/current_projects/CO_River/rcn_strmflw_corvr.html*

Julie Vano
jvano@u.washington.edu

Research Objectives

1) Why are there such large discrepancies in projected Colorado River flow changes?

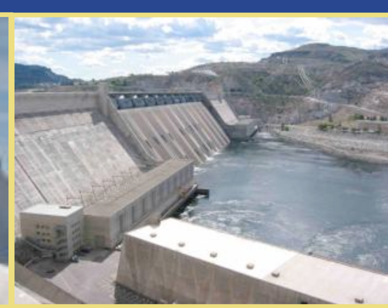
2) How sensitive is runoff to changes in temperature, changes in precipitation, or changes in both temperature and precipitation?

5) What are the underlying mechanisms for these changes (e.g. soil moisture, ET)? In the context of hydrologic sensitivities to (global) climate change, does the land surface hydrology matter, or does it just passively respond to changes in atmospheric circulation?

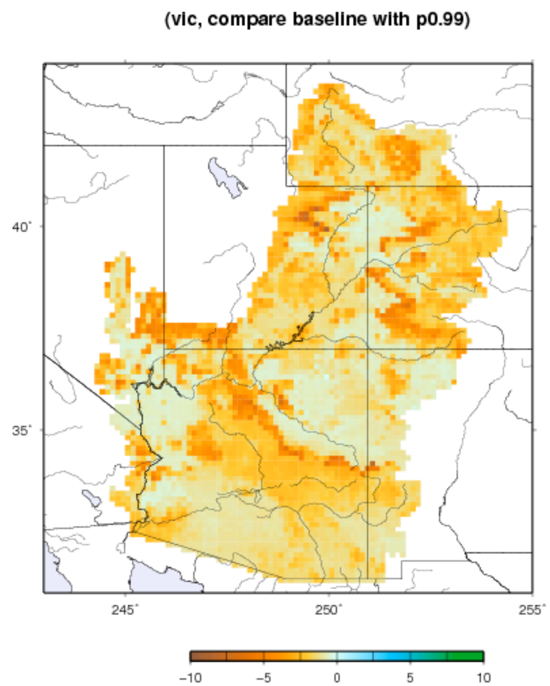
4) What are meaningful measures for water managers and policymakers that incorporate uncertainties in future climate change projections?

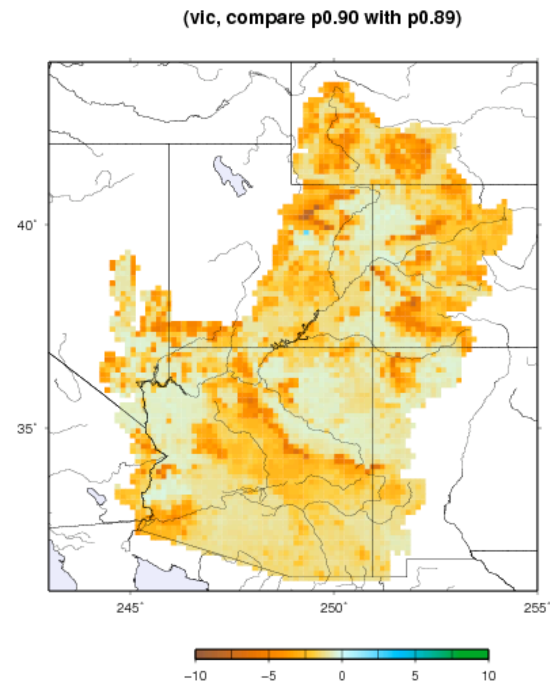
Concluding thoughts

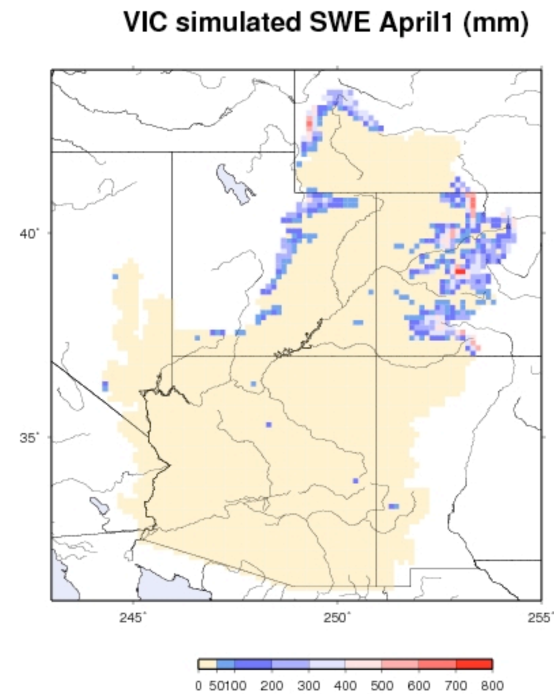
- Temperature sensitivities decrease with increasing temperature, although overall magnitude is larger
- Magnitude of precipitation elasticities become more negative with a 10% decline in precip
- Sensitivities appear to be at marginal snow zone
- Trends most notable at sub-basin level, spatial patterns matters
- Preliminary results, more coming soon…


Preliminary precip elasticities







$$\text{precip elasticity} = \frac{\dfrac{Q_{99\%} - Q_{historic}}{Q_{historic}}}{1\%}$$

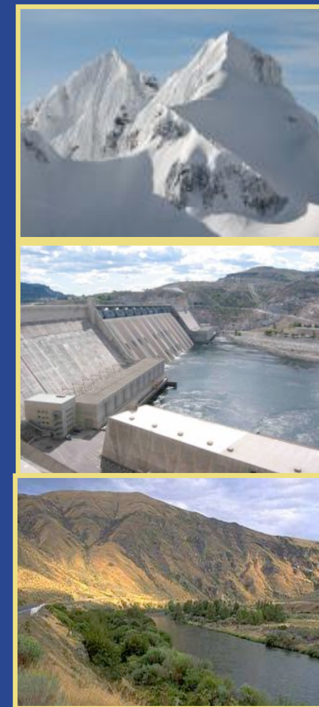
$$\text{precip elasticity} = \frac{\dfrac{Q_{89\%} - Q_{90\%}}{Q_{90\%}}}{1\%}$$

Reconciling Projections of Colorado River Stream Flow Over the Next Century

Julie Vano
Dept of Civil and Environmental Engineering, Univ of Washington

Dennis Lettenmaier
Dept of Civil and Environmental Engineering, Univ of Washington

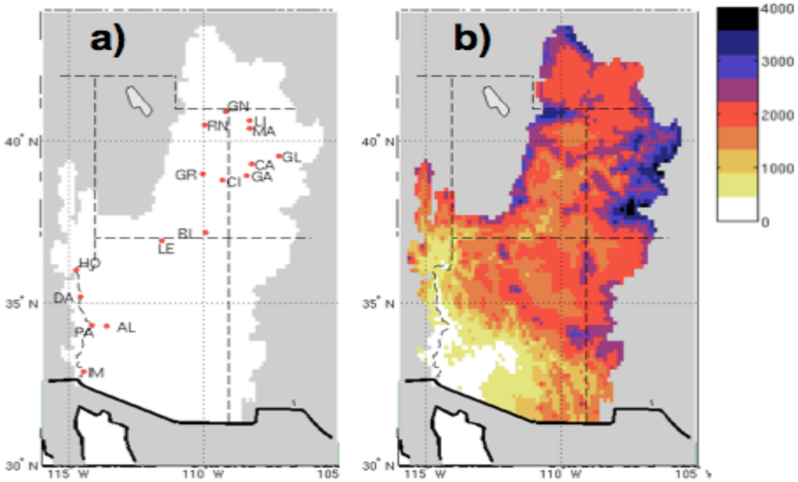
Tapash Das
SCRIPPS Institution of Oceanography, Univ of California - San Diego



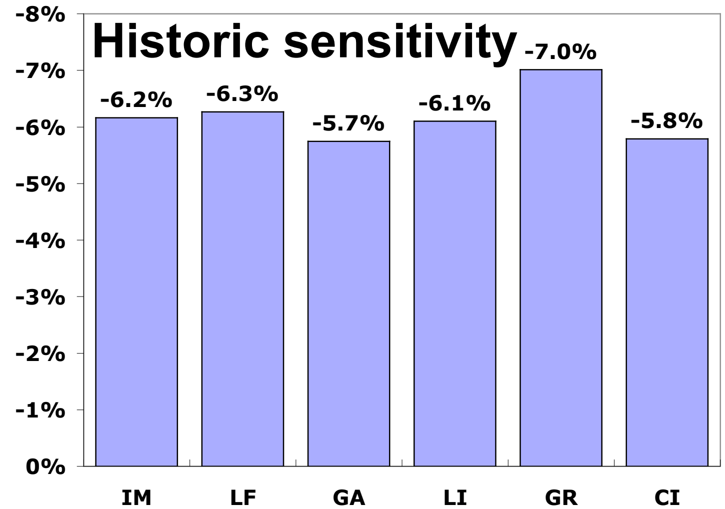
November 10, 2009
American Water Resources Assoc National Conference, Seattle, WA

Climate science in the public interest

Spatial Patterns of Sensitivity by Sub-basin



a) Locations of Colorado River main stem stations and tributaries b) Elevations, in meters



<u>Station Key:</u>
GA: Gunnison River near Grand Junction
CI: Colorado River near Cisco
GR: Green River at Green River
LI: Snake River near Lilly, CO
LE or LF: Colorado River at Lees Ferry
IM: Colorado River below Imperial Dam

Green River by Greendale is most sensitive, Snake River undergoes largest change in sensitivities (from historic to 3 deg C)