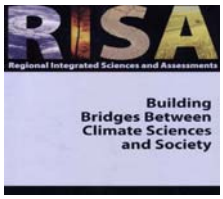
Reconciling Projections of Colorado River Flows

-- A joint effort of NOAA RISAs and partners --

Three RISAs in Co. Basin



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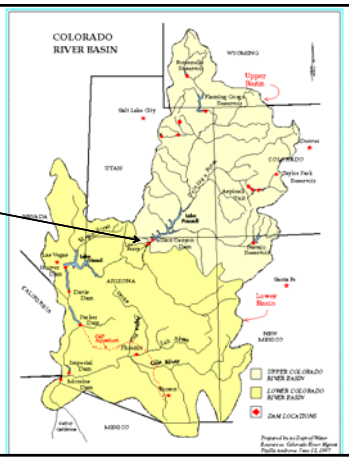
RISAs – Regional Integrated Sciences and Assessment Projects

- Nick Graham, Dan Cayan - California Applications Project (CAP)
- Dennis Lettenmaier, Andy Wood – Climate Impacts Group (CIG)
- Robin Webb, Marty Hoerling, **Brad Udall** – Western Water Assessment (WWA)
- Jonathan Overpeck, **Holly Hartmann** – Climate Assessment for the Southwest (CLIMAS)

… and a large supporting cast…

- **Kelly Redmond**, Western Regional Climate Center –
- **Chris Milly**, Mike Dettinger - USGS
- Kevin Werner – NWS Western Region Headquarters
- Tom Pagano – USDA-NRCS National Water and Climate Center
- Eric Wood - Princeton
- Kosta Georgakakos - Hydrologic Research Center
- Hugo Hidalgo – Scripps Institute for Oceanography

Lee's Ferry



The 2000s Southwest Drought

Water Year	Inflow to Powell (% of Average)	Powell and Mead % Capacity
1999	109%	95%
2000	62%	86%
2001	59%	78%
2002	25%	63%
2003	52%	55%
2004	51%	46%
2005	105%	54%
2006	72%	51%
2007	~50%	49%
Average 1999-2006	67%	66%

Table 1. Nine recent years of estimated natural flows for the Upper Colorado River Basin and storage/% capacity in Lake Mead and Lake Powell. (Courtesy of T. Fulp, USBR)

USGS Fact Sheet 2004-3062 (2004)

Figure 2. Replicate photographs of Lake Powell at the confluence with the Dirty Devil River (entering from left). A. June 29, 2002. B. December 23, 2003. (Photographs by John C. Dohrenwend)

A Big Question

Is the current Southwest drought a once-or-twice-a-century drought like those of the past 500 years …

Or…

a harbinger of things to come - a different type of drought that we have not observed before ?

Efforts to Determine Southwestern Drought Prospects Under Climate Change

• Early Studies - Scenarios
– Stockton and Boggess, 1979
– Revelle and Waggoner, 1983

• Mid Studies, First GCM Use
– Nash and Gleick, 1991, 1993
– McCabe and Wolock, 1999 (NAST)
– IPCC, 2001

• More Recent Studies
– Christensen et al., 2004
– Milly et al.,2005, "Global Patterns of trends in runoff"
– Christensen and Lettenmaier, 2007
– Hoerling and Eischeid, 2007, "Past Peak Water?"
– Seager et al, 2007, "Imminent Transition to more arid.."
– IPCC, 2007 (Regional Assessments)

Hydrologic Cycle Changes in a Warmer World

Extra Energy Means enhanced hydrologic cycle
– Higher temps increase atmosphere moisture holding capacity
– Higher temps imply globally increased evaporation
– Precipitation must increase globally (but not necessarily regionally)
– More intense precipitation - Floods
– More intense drying - Drought
  • Mid-continental summertime drying
  • Increased evaporation will increase water demand
– More rain, less snow
– Earlier spring runoff

IPCC 2007 Southwest North America Regional Findings

- Annual mean warming likely to exceed global mean
- Western NA warming likely between 2C and 7C at 2100
- In Southwest greatest warming in summer
- Precipitation likely to decrease in Southwest
- Snow season length and depth very likely to decrease

From: Brad Udall

Recent Studies of Mid-century Climate Change Impacts on Colorado River flows (Lee's Ferry)

Recent Studies	Projected Flow Reductions
Christensen et al., 2004	~18%
Christensen and Lettenmaier, 2007	~-6%
Milly et al., 2005	10 to 25%
Hoerling and Eischeid, 2007	~45%
Seager et al., 2007	"an imminent transition to a more arid climate"

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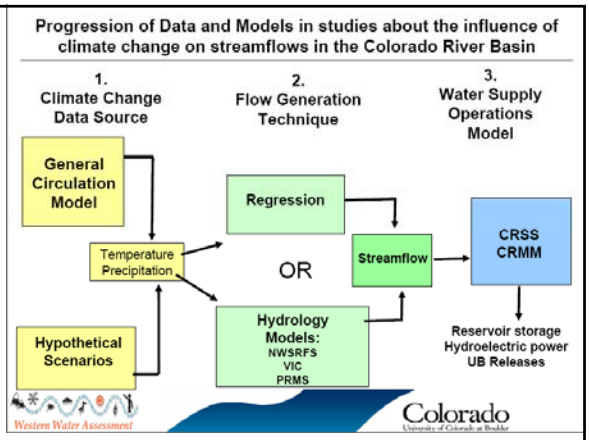
Skeptical Response: These are so different, we can't trust any of them…

Alternative Response: None of these studies show increasing flows. Any decrease is a source of concern.

Joint Response: We need to resolve these differences!

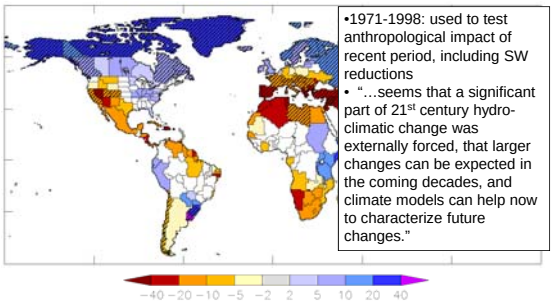
Do the differences reflect climate uncertainty or... Do they result from different methods and models?



From: Brad Udall

Model-Projected Changes in Annual Runoff, 2041-2060

Percent change relative to **1900-1970 baseline**. Any color indicates that >66% of models agree on sign of change; diagonal hatching indicates >90% agreement.



•1971-1998: used to test anthropological impact of recent period, including SW reductions
• "…seems that a significant part of 21st century hydro-climatic change was externally forced, that larger changes can be expected in the coming decades, and climate models can help now to characterize future changes."

(After Milly, P.C.D., K.A. Dunne, A.V. Vecchia, Global pattern of trends in streamflow and water availability in a changing climate, *Nature*, **438**, 347-350, 2005.)

From: Chris Milly

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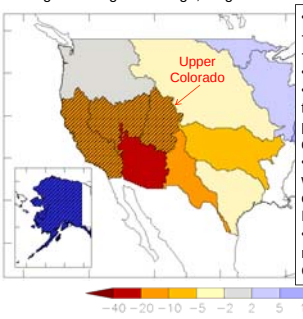
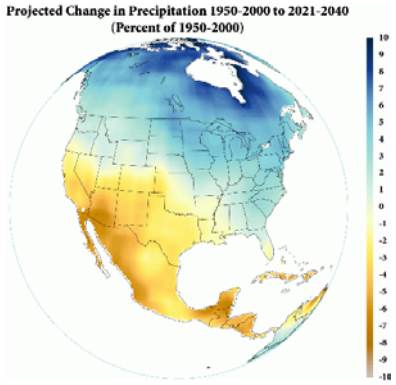


•10 to 20% Less Runoff
- **A1B emissions**
- **12 GCMs**
• > 90% of Models Agree
• Decreases in runoff due to temperature increases, perhaps small precipitation declines
• Dryness consistent with worldwide poleward movement of deserts from ~30 N/S Latitude
• Warning: GCMs have relatively crude hydrologic Cycle: P-E, regression routing

(After Milly, P.C.D., K.A. Dunne, A.V. Vecchia, Global pattern of trends in streamflow and water availability in a changing climate, *Nature*, **438**, 347-350, 2005.)

From: Chris Milly

Seager et al, 2007

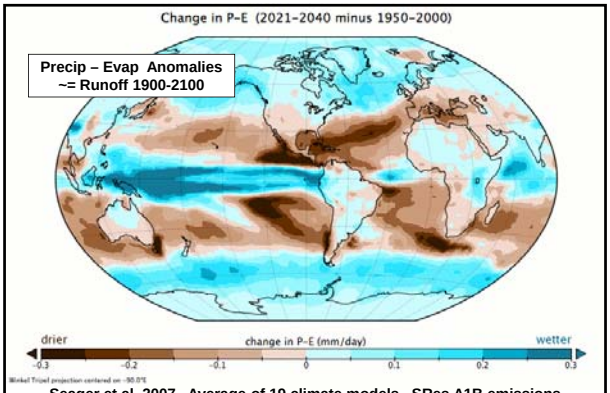


-Average of 19 climate models.
- SRes A1B emissions scenario
- Periods of reference

Figure by Gabriel Vecchi

www.ldeo.columbia.edu/res/div/ocp/drought/science.shtml

R.Seager, M.Ting, I.Held, Y.Kushnir, J.Lu, G.Vecchi, H.-P. Huang, N.Harnik, A.Leetmaa, N.-C.Lau, C.Li, J.Velez, N.Naik, 2007. Model Projections of an Imminent Transition to a More Arid Climate in Southwestern North America. *Science*, DOI: 10.1126/science.1139601



Seager et al, 2007. Average of 19 climate models. SRes A1B emissions scenario. Figure by Naomi Naik. www.ldeo.columbia.edu/res/ocp/drought/science.shtml

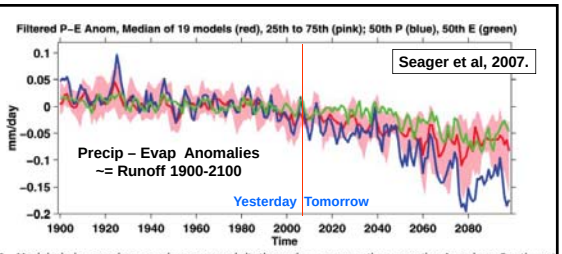
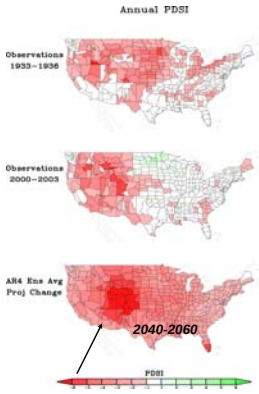


Fig. 1. Modeled changes in annual mean precipitation minus evaporation over the American Southwest (125°W to 95°W and 25°N to 40°N, land areas only), averaged over ensemble members for each of the 19 models. The historical period used known and estimated climate forcings, and the projections used the SResA1B emissions scenario. The median (red line) and 25th and 75th percentiles (pink shading) of the $P - E$ distribution among the 19 models are shown, as are the ensemble medians of P (blue line) and E (green line) for the period common to all models (1900–2098). Anomalies (Anom) for each model are relative to that model's climatology from 1950–2000. Results have been 6-year low-pass Butterworth-filtered to emphasize low-frequency variability that is of most consequence for water resources. The model ensemble mean $P - E$ in this region is around 0.3 mm/day.

- Climate models project drying in SW US
- Likely that this is already occurring
- Recent drought may become normal

Drought ca. 2050 vs Notorious Recent Historical Droughts



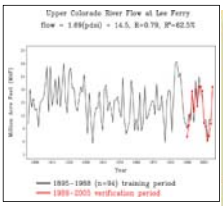
PDSI = Palmer Drought Severity Index

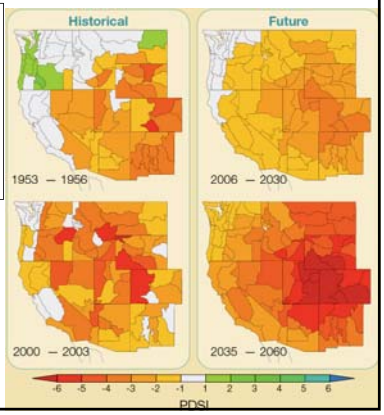
- Seasonal Index
- f(Precipitation)
- f(Temperature)

- 18 models IPCC AR4
- 'BAU' scenario – not consistent with IPCC terminology

Courtesy Marty Hoerling, Jon Eischeid NOAA ESRL Climate Diagnostics Center

Drought ca. 2050 vs Recent Notorious Droughts





Lee's ferry flows (MAF) = 14.5 + 1.68*PDSI

-Explains 63% variance over 1895-1989
- 85% over 1990-2005

Big impact: temperature increasing atmospheric demand for water

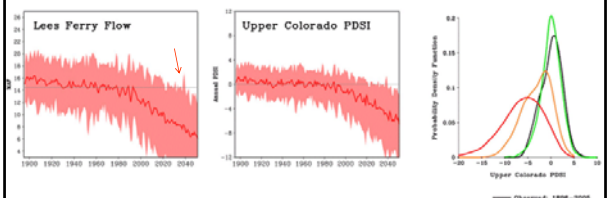
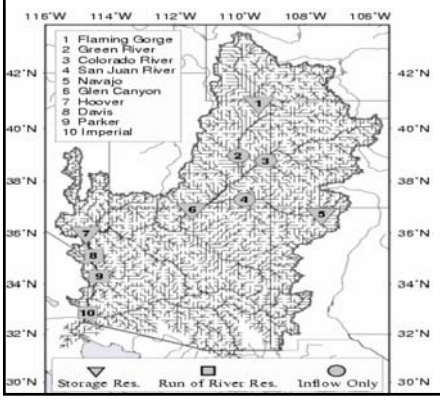


Plate B. The 1895-2050 Lees Ferry annual streamflow (left, maf) derived from the AR4 simulations of PDSI (middle) using the downscaling formula that relates observed Lees Ferry flow to observed PDSI during the 20th Century. The dark red curve denotes the 42-run average, and the cloud describes the 10%-90% range of individual simulations. The right panel summarizes the probability distribution function of PDSI averaged over the Upper Colorado Drainage Basin for individual years of observations 1895-2005 (black), for the 42-models for 1895-2005 (green), and for the 42-model projections of the average PDSI during 2006-2030 (orange) and 2035-2060 (red). Note that the models produce a realistic range of PDSI drought events during the 20th Century, and for the future they produce surface moisture conditions that denote progressive aridification and severe drought conditions.

Marty Hoerling and Jon Eischeid, Past Peak Water in the Southwest, SW Hydrology, 2007..

Colorado River Basin



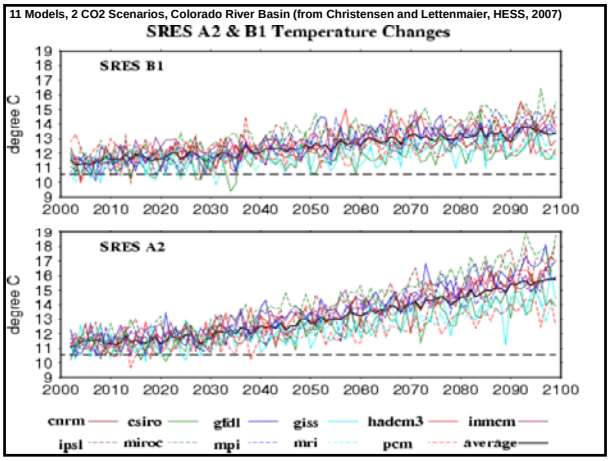
Christensen and Lettenmaier , 2007

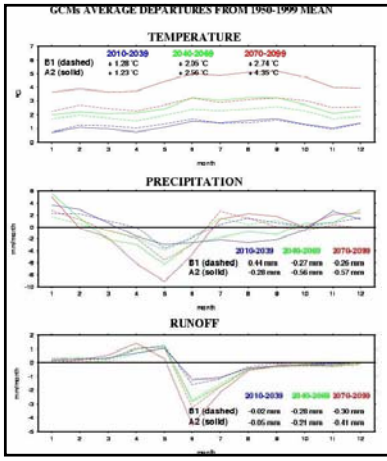
Hydrology and Earth System Sciences – online journal

Variable Infiltration Capacity (VIC model)

CRSS – Operational Co R management system

11 Models, 2 CO2 Scenarios, Colorado River Basin (from Christensen and Lettenmaier, HESS, 2007)





11-Model Consensus
2 Scenarios (B1, A2)

Colorado River Basin

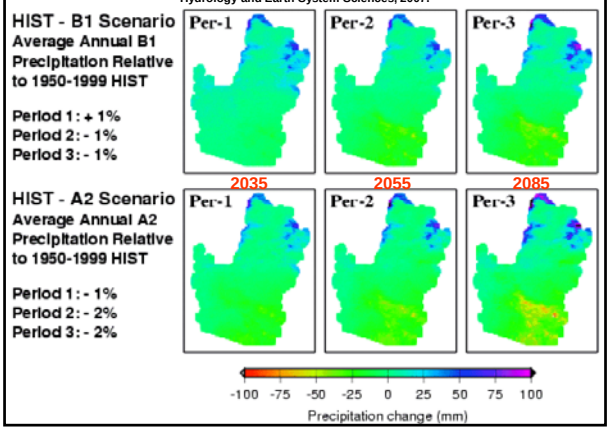
By Month

3 Future Periods:
2010-2039
2040-2069
2070-2099

Referecence: 1950-99

From Christensen and Lettenmaier, Hydrology and Earth System Sciences, 2007

Distribution of Annual Precipitation Change from Recent Historical (Christensen and Lettenmaier, Hydrology and Earth System Sciences, 2007.



Comparison: Christensen et al. (2004) and Christensen & Lettenmaier (2007)

Methodologies essentially the same.

C&L 2007 updates Christensen et al. (2004) using 11 IPCC AR4 models (A2, B1 emissions scenarios) rather than Parallel Climate Model (PCM)

Smaller flow reductions relative to Christensen et al. 2004 attributed to:

- **Smaller precipitation reductions (in multi-model mean) in AR4 ensembles relative to 2004 PCM ensembles**
- **Shift in precipitation in 2004 PCM model runs from winter to summer**
- **Shift (in ensemble mean) in AR4 ensemble precipitation from summer to winter**

Intercomparison Hypotheses – so far…

Christensen & Lettenmaier vs Milly et al
a. Differences stem from climate models, time periods, scenarios
Milly et al gets -14 pct vs -6 pct for C&L when he uses the C&L models
b. C&L preprocessing of precipitation inputs to the model
Milly et al get -5 pct Precip, L&C get +2 pct, these parallel -14 and -6

Hoerling & Eischeid vs Milly et al
Q = Q (PDSI)
O ~ Oo + Op dP + Ot dT (because PDSI is f (P,T))
Hypothesis
Large H&E sensitivity to T is an artifact of equating spatial and temporal sensitivities of change in T to change in radiation

Hoerling & Eishcheid
Used PRISM 4 km P and PET
All of the strong correlation of P with annual LF flow comes from >9000 ft
Key open issues
1. **Runoff sensitivity to high elevation warming**
2. **Runoff sensitivity to low elevation warming**
3. **Runoff sensitivity to change in annual precipitation**
4. **Runoff sensitivity to change in annual distribution of precip (seasonality)**

Intercomparison Bottom Line (so far)

The model results agree more when application details agree more… Differences largely reduced.

But … their agreement is based on different processes!

1. Dominated by atmospheric forcing (precipitation, temperature)
2. Dominated by land processes

New Hypotheses – Mike Dettinger

Western streamflow responses to warming will be determined almost equally by both meteorological **and** land-surface (e.g., snowpack) responses

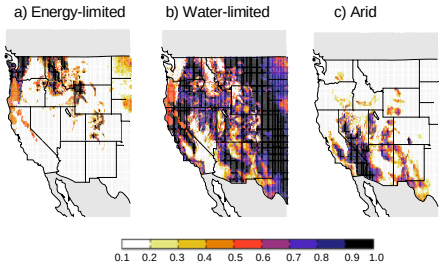
Changes in snowmelt timing can modify water-budget responses to warming, by shifting water availability from seasons of high (and higher) PET into earlier seasons characterized by the same (or less) PET as in historical hydrographs

PDSI does not capture this effect, treats ΔT and ΔP changes interchangeably, and therefore can overestimate drying associated with warming.

GCM-derived runoff and ET downplay snow feedbacks to the point where they also overestimate drying associated with warming.

Concept of Evaporation Efficiency: Ratio AET/PET

Historical frequencies (1960-1999)



Hugo Hidalgo, Dan Cayan, Mike Dettinger

AET = PET	PET = P	AET = 0.20 * PET	AET = 0
Energy Limited	Water Limited	Arid	
1.00	0.63	0.20	0.00

Recommendations – Mike Dettinger

• Snowmelt change **must** play a role in models used to project warming-induced drying and warming-induced ΔE. So, beware of GCM-based P-E for US West.

• To get the processes right, probably necessary to work at spatial resolutions on order of 10 km ***to get reasonable elevations and "concentrations" of precipitation.***

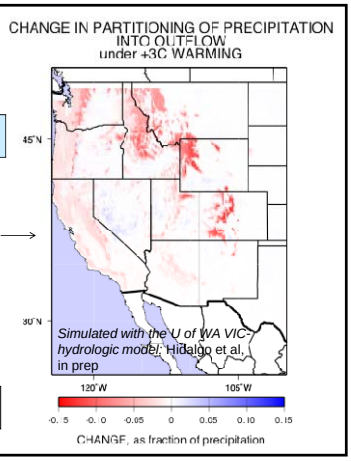
• A really critical but dubious part of existing hydro models is the linkage between snowmelt timing and ΔPET ***(this connection determines whether snow-buffering of runoff change is large or small, positive or negative)***

• Colorado River Basin **may** respond to warming differently from Sierra & Columbia Basins

A Looming Issue??

Sensitivity of runoff and recharge to climate warming.

SIMULATED CHANGES IN RUNOFF+RECHARGE under a uniform +3ºC warming →



Mike Dettinger, Sam Earman, Hugo Hidalgo, Dan Cayan

Project Plans

Intercomparison with identical data (1970-1999 for calibration, 2000-2006 for modeling), calibration frequency, etc.

Additional meetings with decision makers – Spring 2008

Assessment of utility of intercomparison for decision makers

Explore approaches for communicating projection uncertainty