Reconciling Projections of Colorado River Flows
-- A joint effort of NOAA RISAs and partners --

Three RISAs in Co. Basin

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 – NVS 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

The 2000s Southwest Drought

<table>
<thead>
<tr>
<th>Water Year</th>
<th>Inflow to Powell</th>
<th>Powell and Mead</th>
</tr>
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<tbody>
<tr>
<td>1999</td>
<td>108%</td>
<td>50%</td>
</tr>
<tr>
<td>2000</td>
<td>117%</td>
<td>50%</td>
</tr>
<tr>
<td>2001</td>
<td>84%</td>
<td>50%</td>
</tr>
<tr>
<td>2002</td>
<td>39%</td>
<td>60%</td>
</tr>
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<td>2003</td>
<td>52%</td>
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<td>85%</td>
<td>60%</td>
</tr>
<tr>
<td>2005</td>
<td>16%</td>
<td>74%</td>
</tr>
<tr>
<td>2006</td>
<td>78%</td>
<td>64%</td>
</tr>
<tr>
<td>Average 1999-2006</td>
<td>67%</td>
<td>66%</td>
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Table 1. Nine recent years of estimated annual flows for the Upper Colorado River Basin and associated volumes in Lake Mead and Lake Powell. (Courtesy of T. Hidalgo, USGS)

Lee's Ferry
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 Biggess, 1979
  – Revelle and Waggoner, 1983

• Mid Studies, First GCM Use
  – 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 2°C and 7°C at 2100
- In Southwest greatest warming in summer
- Precipitation likely to decrease in Southwest
- Snow season length and depth very likely to decrease

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

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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: Chris Milly

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.”

From: Brad Udall
Seager et al., 2007

Projected Changes in Precipitation 1950-2000 to 2050-2100
(Average of 19 climate models, SRES A1B emissions scenario, Periods of reference)

Figure by Gabriel Vecchi
www.ldeo.columbia.edu/res/ocp/drought/science.shtml

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

Drought ca. 2050 vs Notorious Recent Historical Droughts

Precip - Evap Anomalies ~ Runoff 1900-2100

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

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 Elscheid
NOAA ESRL, Climate Diagnostics Center
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 1895-2005 Lee Ferry annual streamflow (left, blue) derived from the AHA simulations of PDSI (middle) using the downsampling formula that relates observed Lee Ferry flow to observed PDSI during the 20th Century. The dark red area denotes the 40-yr average, and the cloud describes the 10th-90th range of individual simulations. The right panel summarizes the probability distribution function of PDSI averaged over the Upper Colorado River basin for individual years of observations 1895-2005 (black), for the 40-model ensemble, and for the 40-model projections of average PDSI during 2006-2095 (orange) and 2036-2065 (red). Note that the models produce a realistic range of PDSI magnitudes 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..
11-Model Consensus
2 Scenarios (B1, A2)
Colorado River Basin
By Month
3 Future Periods:
2010-2039
2040-2069
2070-2099
Reference: 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.)

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

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

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)
Q ~ Qo + Qp dp + Qt 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 & Eischeid
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)

<table>
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<tr>
<th>Energy Limited</th>
<th>Water Limited</th>
<th>Arid</th>
</tr>
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<tbody>
<tr>
<td>AET = PET</td>
<td>PET = P</td>
<td>AET = 0.20 * PET</td>
</tr>
<tr>
<td>Energy Limited</td>
<td>Water Limited</td>
<td>Arid</td>
</tr>
<tr>
<td>1.00</td>
<td>0.63</td>
<td>0.20</td>
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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 +3°C 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