Anticipating Future Climate Change Impacts on California mountain hydrology

1928

2000

Photos from USGS

Ed Maurer

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California as a Global Warming Impact Laboratory

- CA hydrology is sensitive to climate variations, climate sensitive industries (agriculture, tourism), 5th largest economy in world
- Water supply in CA is limited, vulnerable to T, P changes – timing, location
- Changes already are being observed
- CA Executive Order supporting studies on climate change impacts

Precipitation and Runoff

Irrigation Water Use

Public Water Use

California Irrigation total withdrawals, 28,900 (Mgal/d)

- 0.0-62
- 63-273
- 274-931
- 932-3,087
- 3,088
- 8,330

California public supply total withdrawals, 5,620 (Mgal/d)

- 0-25
- 26-86
- 87-214
- 215-439
- 1,470
Cascade of Models (and Uncertainty)

1. GHG Emissions Scenario
   Adapted from Cayan and Knowles, SCRIPPS/USGS, 2003 by Levi Brekke

2. Global Climate Model

3. Global-to-Local Scale "Downscaling"

4. Hydrologic Model

5. Operations Models

Adapted from Cayan and Knowles, SCRIPPS/USGS, 2003 by Levi Brekke
How society changes in the future:

“Scenarios” of greenhouse gas emissions:

**A1fi**: Rapid economic growth and introduction of new, efficient technologies, technology emphasizes fossil fuels – *Highest estimate of IPCC*

**A2**: Technological change and economic growth more fragmented, slower, higher population growth – *Less high for 21st century*

**B1**: Rapid change in economic structures toward service and information, with emphasis on clean, sustainable technology. Reduced material intensity and improved social equity - *Lowest estimate for 21st century*
Global Climate Models - Uncertainty

The projected future climate depends on Global Climate Model (or General Circulation Models, GCM) used:
- Varying sensitivity to changes in atmospheric forcing (e.g. CO$_2$, aerosol concentrations)
- Different parameterization of physical processes (e.g., clouds, precipitation)

Global mean air temperature by 10 GCMs identically forced with CO$_2$ increasing at 1%/year for 80 years

Source: Covey et al.
Comparison of Uncertainties

- Higher $\Delta T$ with A2 than B1
- $T$ varies over a range $\approx 3^\circ C$
- Annual $\Delta P$ less discernable
- $\Delta P$ within $\pm 20$
- Some GCMs sensitive to IC

**AR4 Temperature and Precipitation Anomalies in 2070-2099**

- Temperature: A2 mean = 3.4$^\circ C$, $\sigma$=0.8$^\circ C$; B2 mean = 1.7$^\circ C$, $\sigma$=0.7$^\circ C$
- Precipitation: A2 mean = -1.7%, $\sigma$=12.3%; B2 mean = +1.5%, $\sigma$=10.7%

<table>
<thead>
<tr>
<th>Difference Between B1 and A2 Emissions</th>
<th>Difference between all GCMs</th>
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<tbody>
<tr>
<td>1$^\circ C$</td>
<td>2$^\circ C$</td>
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<tr>
<td>3$^\circ C$</td>
<td>5$^\circ C$</td>
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**B1 Emission Scenario**

**A2 Emission Scenario**

**Figure: K. Hayhoe**
Problems using GCMs for Regional Impact Studies

• The problems:
  – GCM spatial scale incompatible with hydrologic processes
    • roughly 2 – 5 degrees resolution
    • some important processes not captured
  – Though they accurately capture large-scale patterns, GCMs have biases

• Resolved by:
  – Bias Correction
  – Spatial Downscaling

Figure: Wilks, 1995
Biases in GCM Simulations

Observed Data
aggregated to GCM resolution

Raw GCM output
for same period as observations
Bias Correction

- Mean and variance of observed data are reproduced for climatological period
- Temperature trends into future in GCM output are preserved
- Relative changes in mean and variance in future period GCM output are preserved, mapped onto observed variance
Spatial downscaling

1) Performed on bias-corrected output, at each GCM scale grid cell
   - Month-by-month comparison of GCM output with climatological monthly avg.
   - P (scale) and T (shift) factor time series developed
2) Factors interpolated to 1/8° grid cell centers (about 150 km² per grid cell)
3) Interpolated factors applied to monthly observed time series
4) Daily data derived with random resampling
Hydrologic Model

• Drive a Hydrologic Model with GCM-simulated (bias-corrected, downscaled) P, T
• Reproduce Q for historic period
• Derive runoff, streamflow, snow, soil moisture

VIC Model Features:
• Developed over 10 years
• Energy and water budget closure at each time step
• Multiple vegetation classes in each cell
• Sub-grid elevation band definition (for snow)
• Subgrid infiltration/runoff variability
Bracketing Projected Futures

2 Recent GCMs Used by Hayhoe et al., 1994:

**HadCM3** – UK Meteorological Office Hadley Centre

**PCM** – National Center for Atmospheric Research/Dept. of Energy Parallel Climate Model

Distinguishing Characteristics of both models:
- Both are Coupled Atmosphere-Ocean-Land
- Neither uses flux adjustments
- Model estimates of global annual mean temperature lie within 1°C of observed averages
- Both are state-of-the-art and well-tested, participating in international comparisons

HadCM3 is considered "Medium Sensitivity"
PCM generally "Low Sensitivity"
Different Warming with Different Emissions (B1 vs. A1fi)

CA average annual temperatures for 3 10-year periods

Amount of warming depends on our emissions of heat-trapping gases.

2090-2099 summer temperature increases vary widely:
Lower: 3.5-9 °F
Higher: 8.5-18 °F
Winter precipitation accounts for most of annual total.

High interannual variability – less confidence in precipitation-induced changes than temperature driven impacts.
End-of Century Streamflow: North CA

**HadCM3** shows:
- Annual flow drops 20-24%
- April-July flow drops 34-47%
- Shift in center of hydrograph 23-32 days earlier
- Smaller changes with lower emissions B1

**PCM** shows:
- Annual flow +9% to -29%
- April-July flow drops 6-45%
- Shift in center of hydrograph 3-11 days earlier
- Difference between emissions pathways more pronounced than for HadCM3
Diminishing Sierra Snowpack
% Remaining, Relative to 1961-1990

29–73% loss for the lower emissions scenario (3-7 MAF)
73–89% for higher emissions (7-9 MAF – 2 Lake Shastas)
Dramatic losses under both scenarios
Almost all snow gone by April 1 north of Yosemite under higher emissions
Impacts vary by elevation
Utility of “Bookend” Study

- A large range of futures is bracketed, providing rough “bounds” on uncertainty
- Can identify impacts/sectors at risk
  - Hydrologic impacts substantial under any future
- Compare temperature and precipitation impacts
  - Temperature related impacts diverge greatly under different emissions scenarios (snow melt, streamflow timing, heat waves,…)
  - Precipitation confounds some impacts

Can uncertainty be quantified, and not just bounded?
Comparing Impacts to Variability

• 11 GCMs, most recent generation (IPCC AR4)
• 2 Emissions scenarios for each GCM:
  - A2
  - B1
• Same bias correction, downscaling, hydrologic modeling

Mean Elev = 1550 m
Feather River Flow Changes

All increases in winter and decreases in spring-early summer flows are high confidence (>95%)

End of Century Changes

- Increase Dec-Feb Flows
  - +55% for A2
  - +33% for B1

- Decrease May-Jul
  - -32% for A2
  - -29% for B1
Anticipating an Uncertain Future

- Many long-term impacts are significant, models agree in some respects.
- Differences between scenarios in next 50 years is small relative to other uncertainties.
- Combine GCMs and emissions scenarios into “ensemble” of futures.
- Allows planning with risk analysis.
Impacts on Snow with Combined A2, B1 Ensemble

Mean Impact of all 22 simulations:
- 2041-2070: 74% remaining
- 2071-2100: 55% remaining

How to include uncertainty in planning?

Cell at: 120°W, 38°N
One point: April 1 Snow Loss
All Simulations (B1 and A2)

CDFs for cell at 120°W, 38°N

Is an empirical CDF/PDF the best planning tool?

Do 22 simulations capture range of variability?

2/3 chance that loss will be at least 40% by mid century, 70% by end of century
Conclusions

• GCM/emission uncertainties can be captured probabilistically for use in planning

• Definition of probabilities of impacts (bookend vs. ensembles) depends on:
  – variables to which impacts are sensitive (T-dependent vs. P-dependent)
  – computational demands of impacts models (how many potential futures are useful)