Anticipating Future Climate Change Impacts on California mountain hydrology

Photos from USGS

Ed Maurer

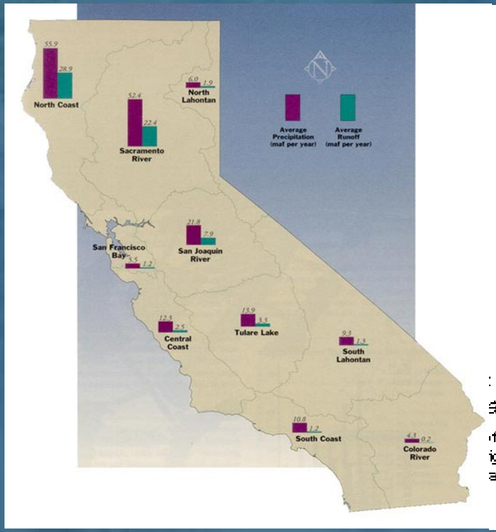
Santa Clara University

California Water and Environmental Modeling Forum
March 1, 2006

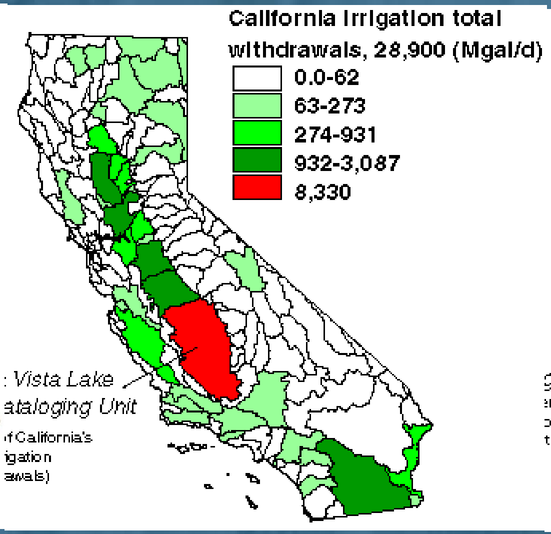
California as a Global Warming Impact Laboratory

- 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

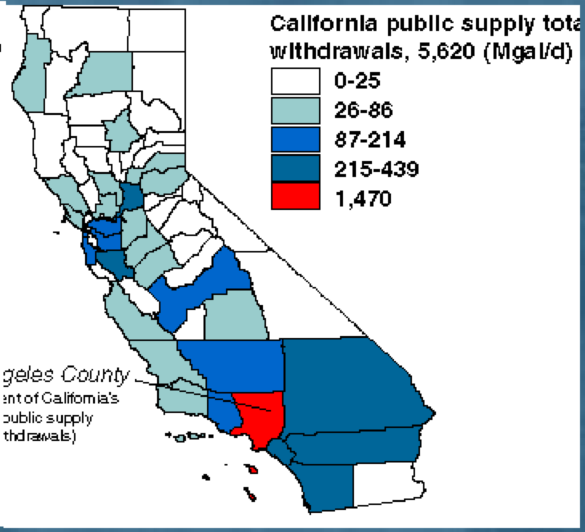
Precipitation and Runoff



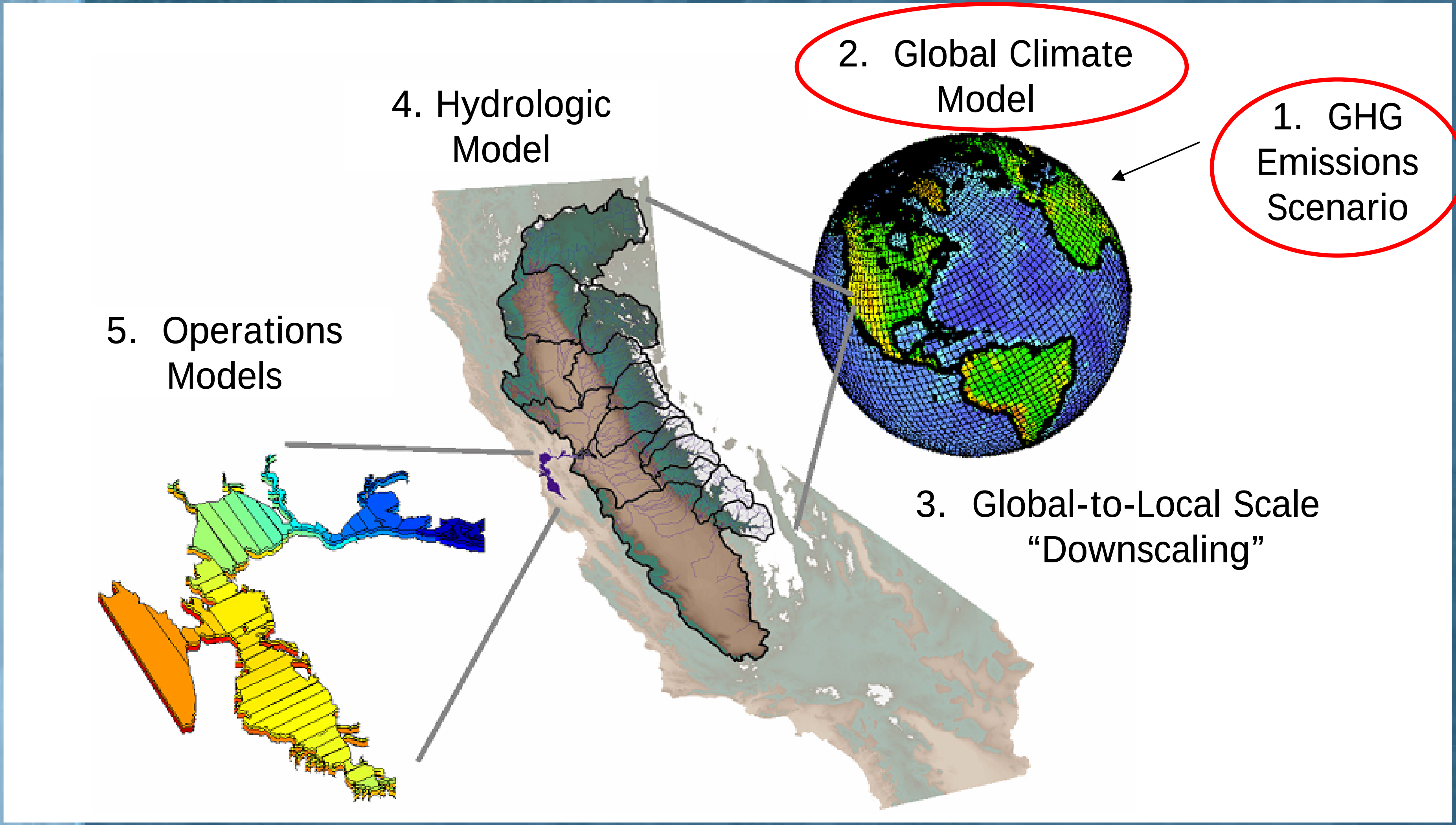
Irrigation Water Use



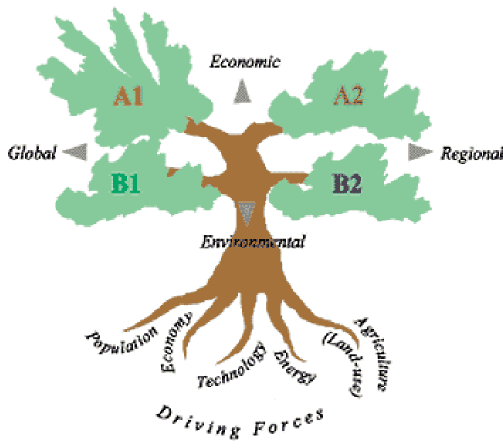
Public Water Use



Cascade of Models (and Uncertainty)



Adapted from Cayan and Knowles, SCRIPPS/USGS, 2003 by Levi Brekke



Future GHG Emissions

How society changes in the future:

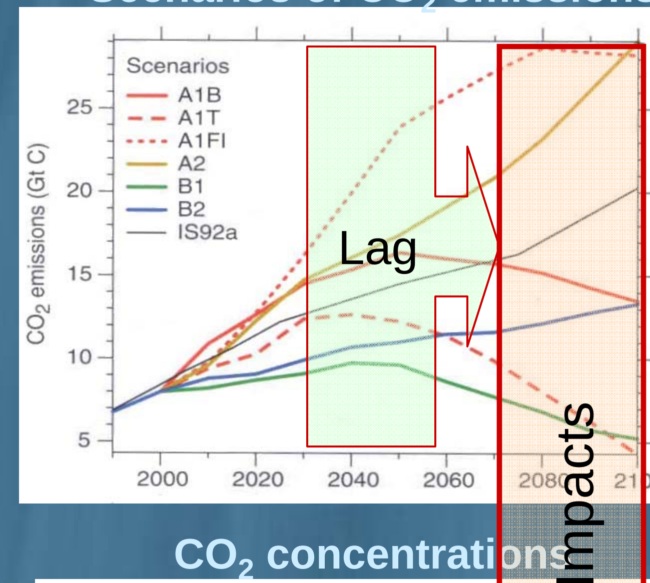
"Scenarios" of greenhouse gas emissions:

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

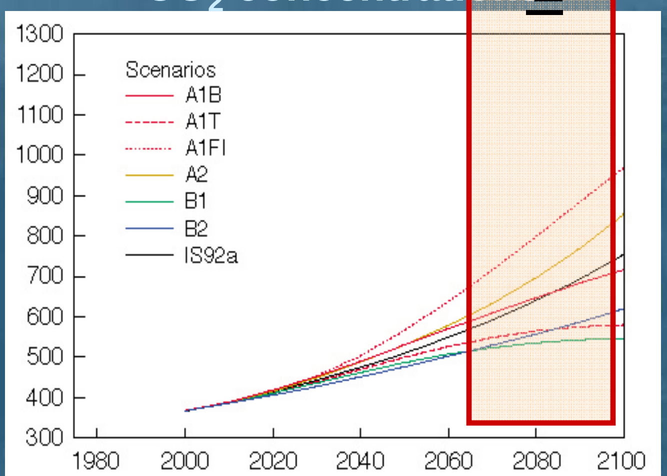
A2: Technological change and economic growth more fragmented, slower, higher population growth – **Less high for 21st century**

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**

Scenarios of CO_2 emissions



CO_2 concentrations

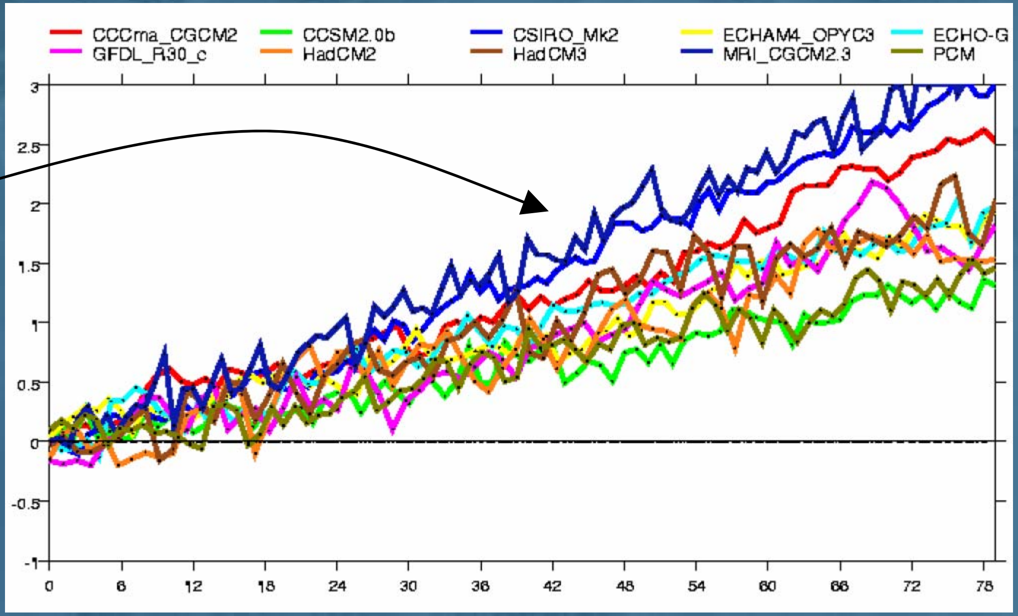


Global Climate Models - Uncertainty

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.

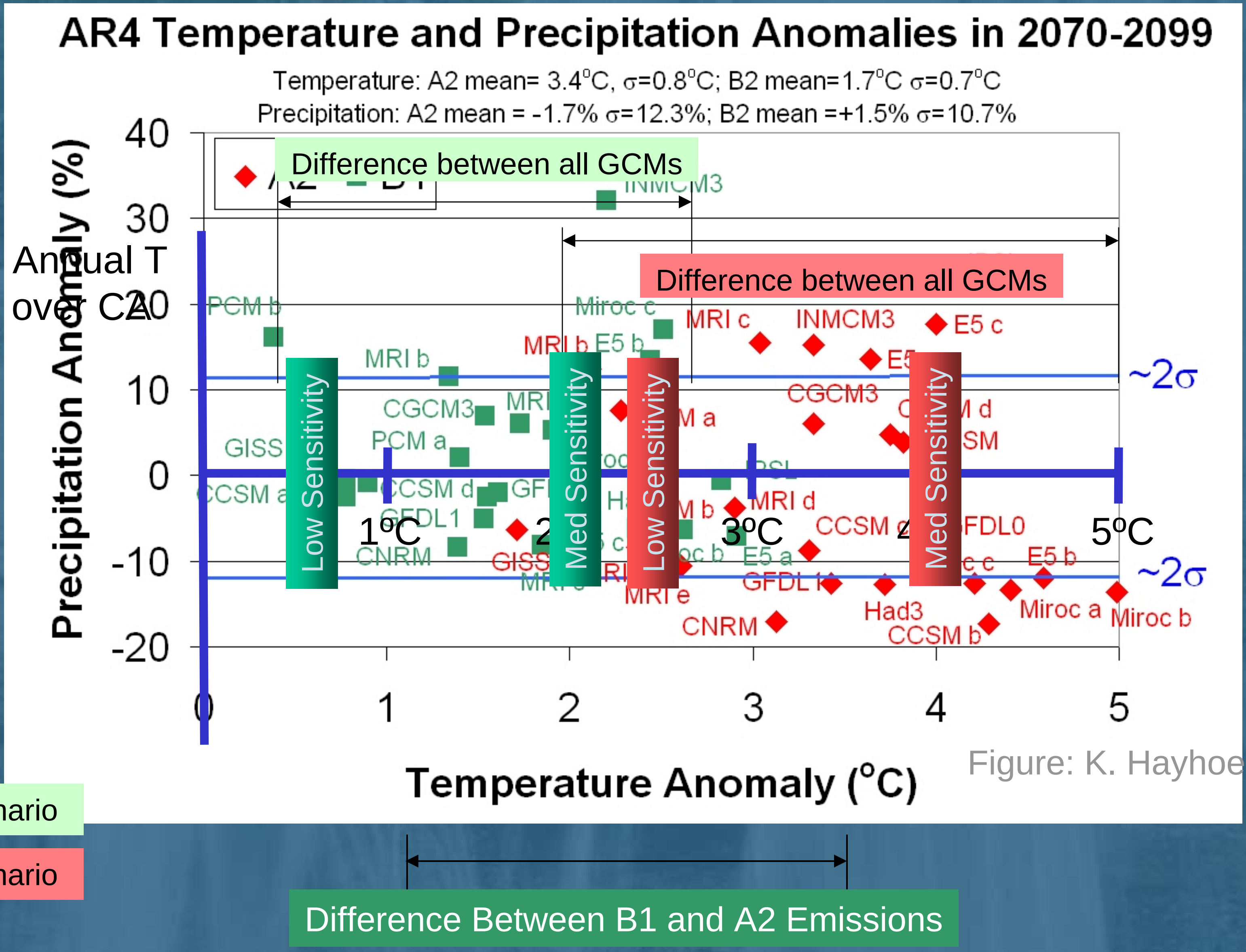
Comparison of Uncertainties

- **Higher ΔT with A2 than B1**
- **T varies over a range ≈ 3°C**

Average Annual T change over CA

- **Annual ΔP less discernable**
- **ΔP within ±20%**

- **Some GCMs sensitive to IC**

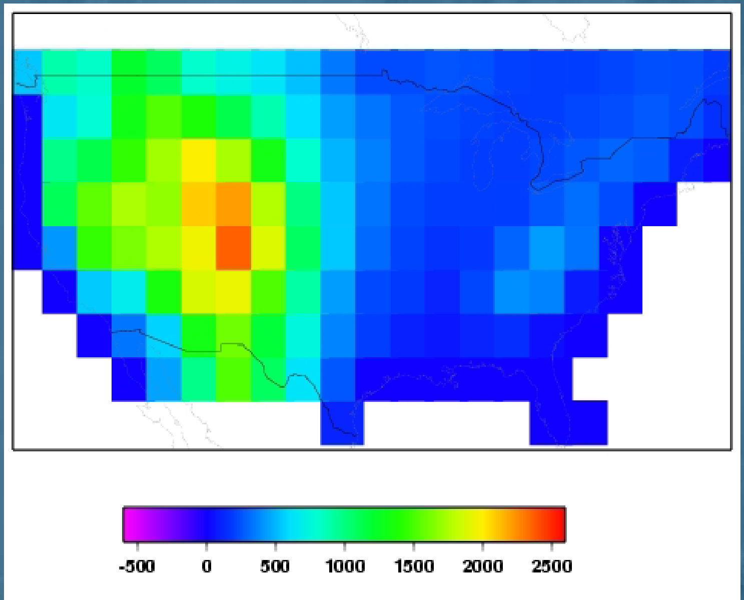


B1 Emission Scenario

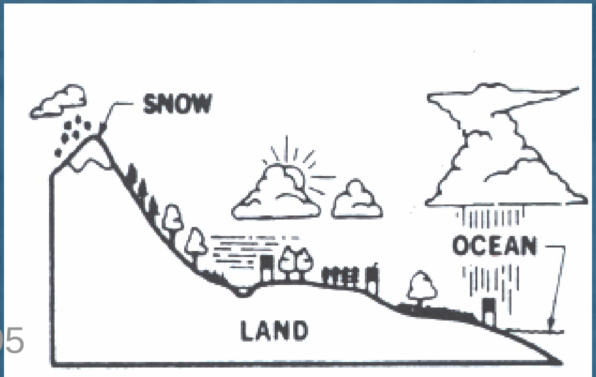
A2 Emission Scenario

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



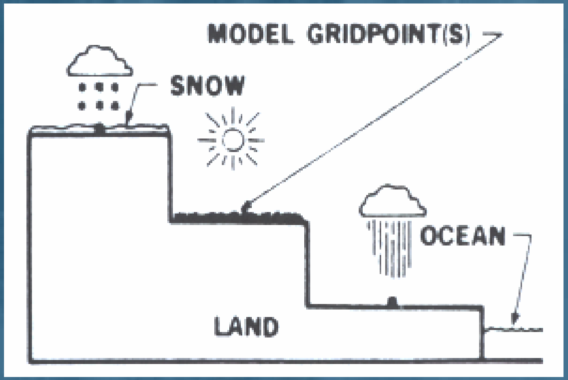
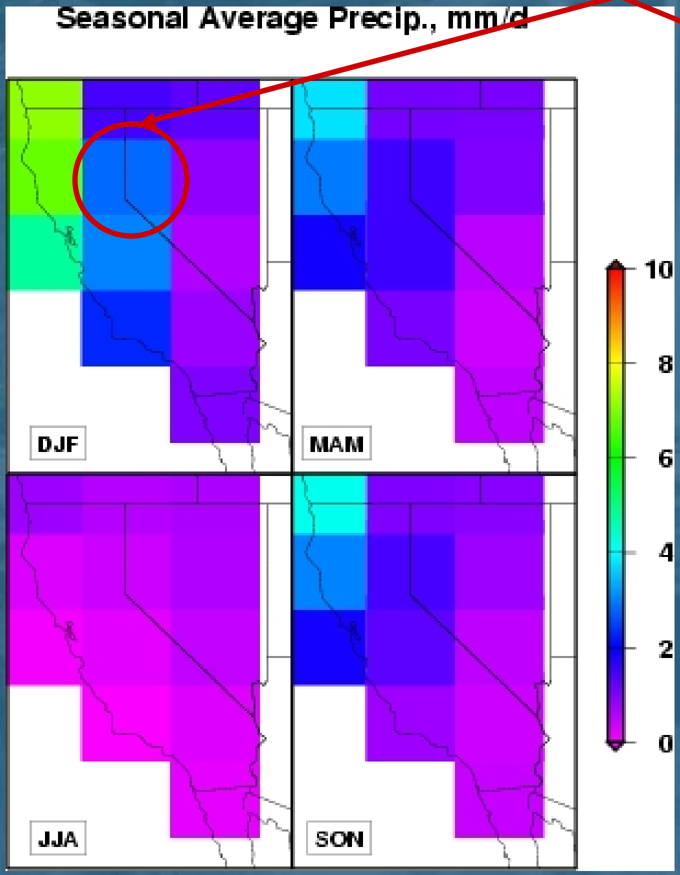


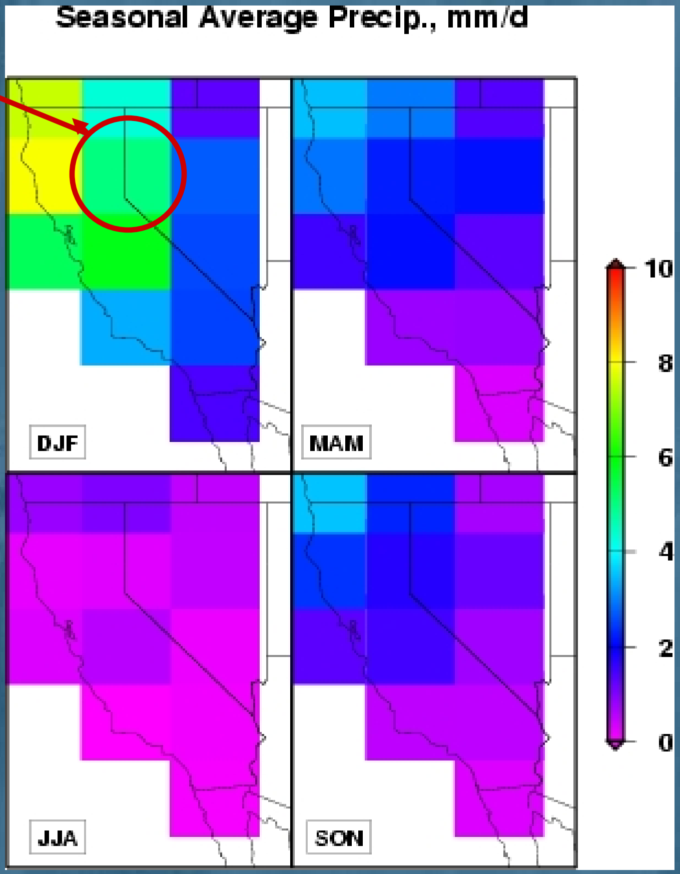
Figure: Wilks, 1995

Biases in GCM Simulations

Observed Data
aggregated to GCM resolution



Raw **GCM output**
for same period as observations

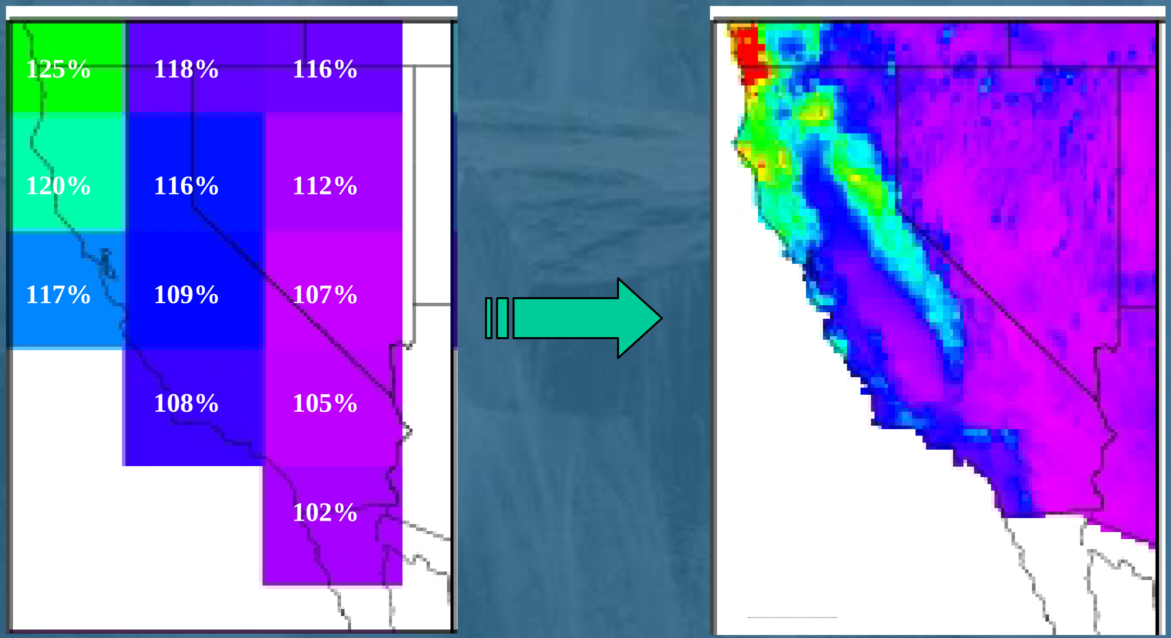


Bias Correction

- 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

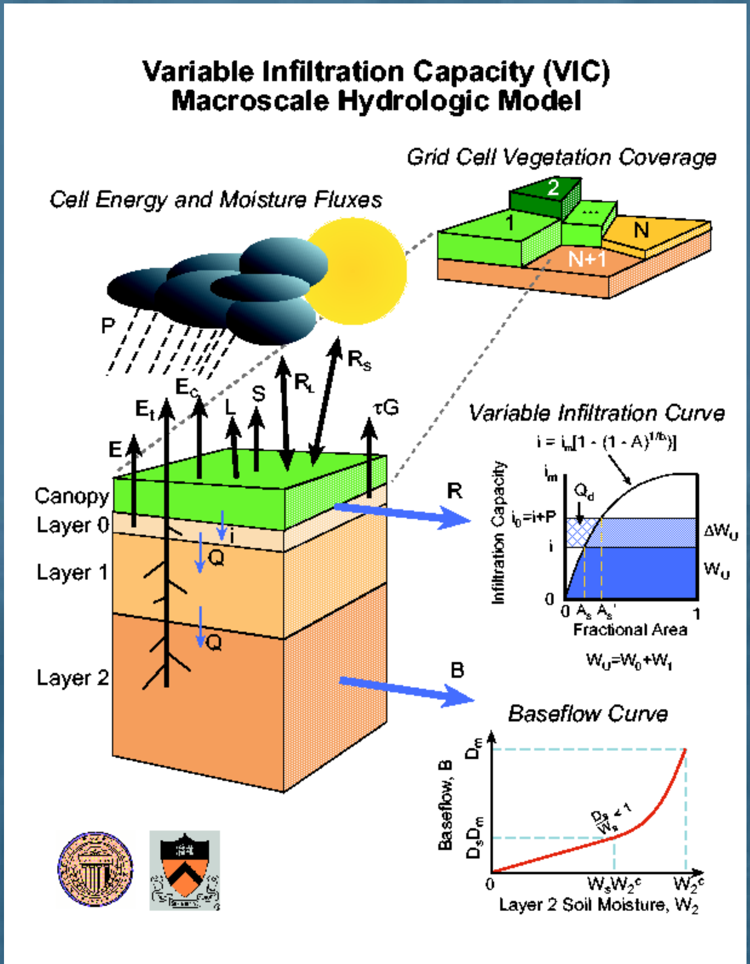
Spatial downscaling

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 km^2 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

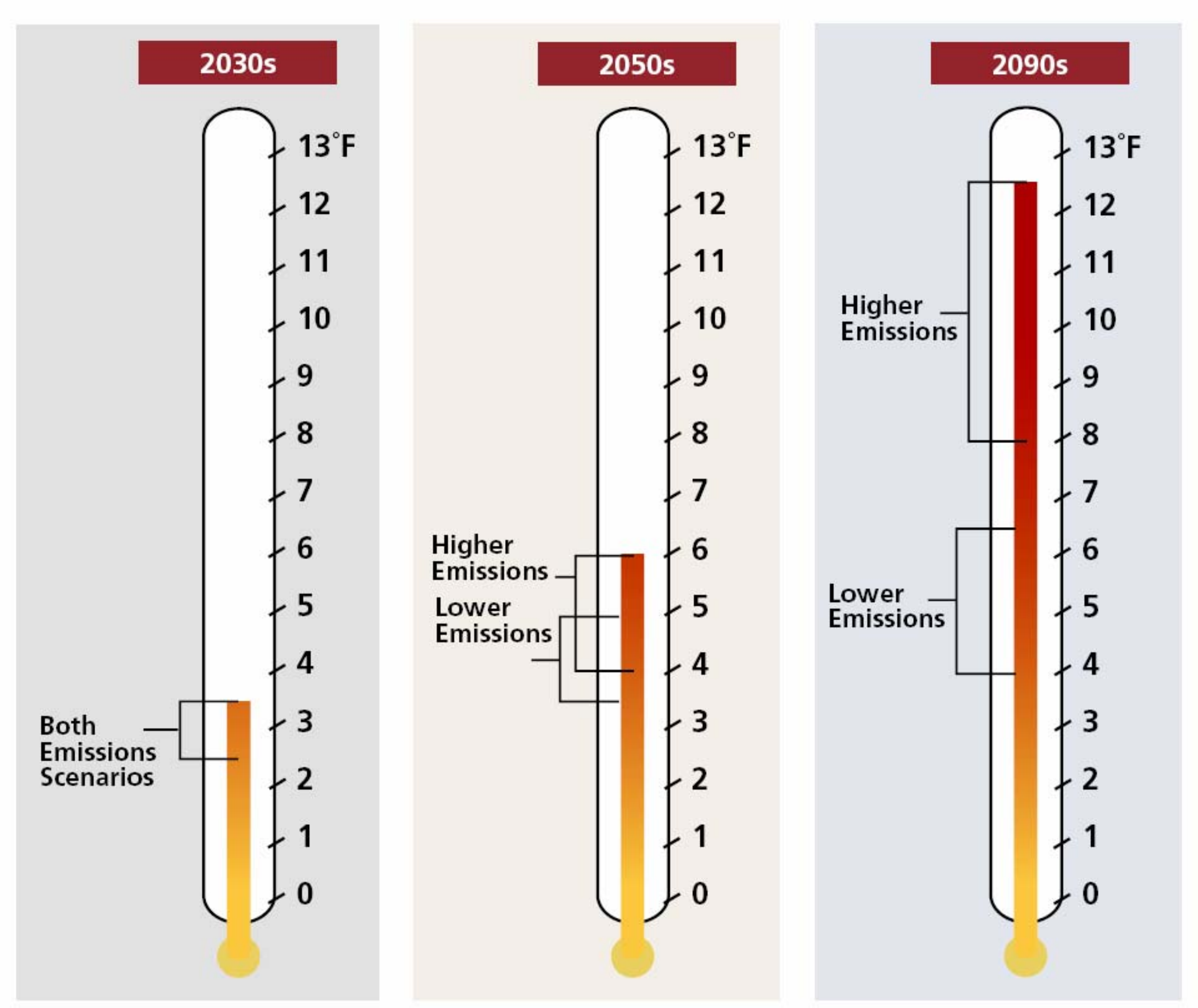
PCM – National Center for Atmospheric Research/Dept. of Energy Parallel Climate Model

Distinguishing Characteristics of both models:

- Both are Coupled Atmosphere-Ocean-Land
- Neither uses flux adjustments
- Model estimates of global annual mean temperature lie within 1ºC 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)



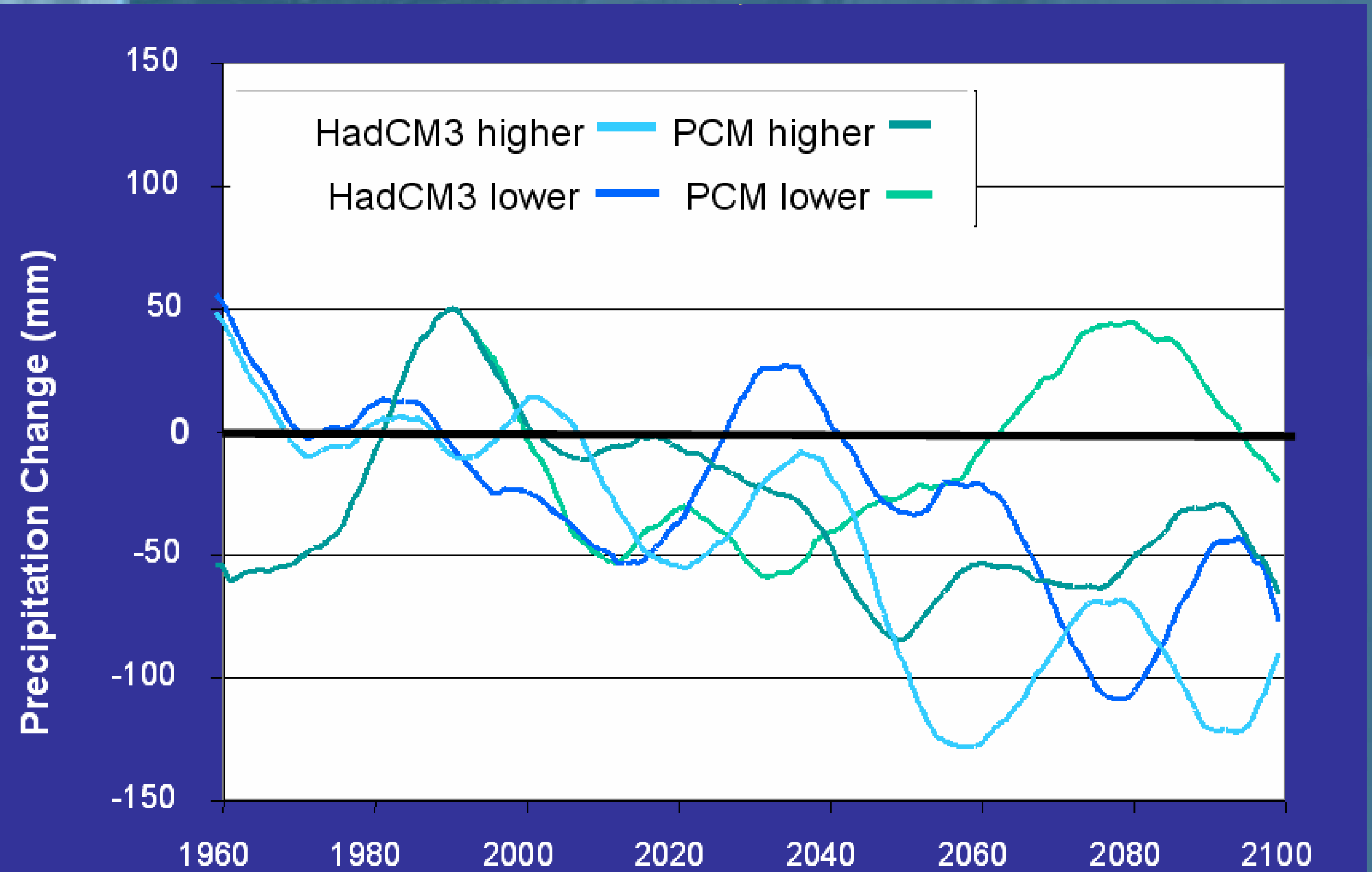
CA average annual temperatures for 3 10-year periods

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 Projections

Statewide Average



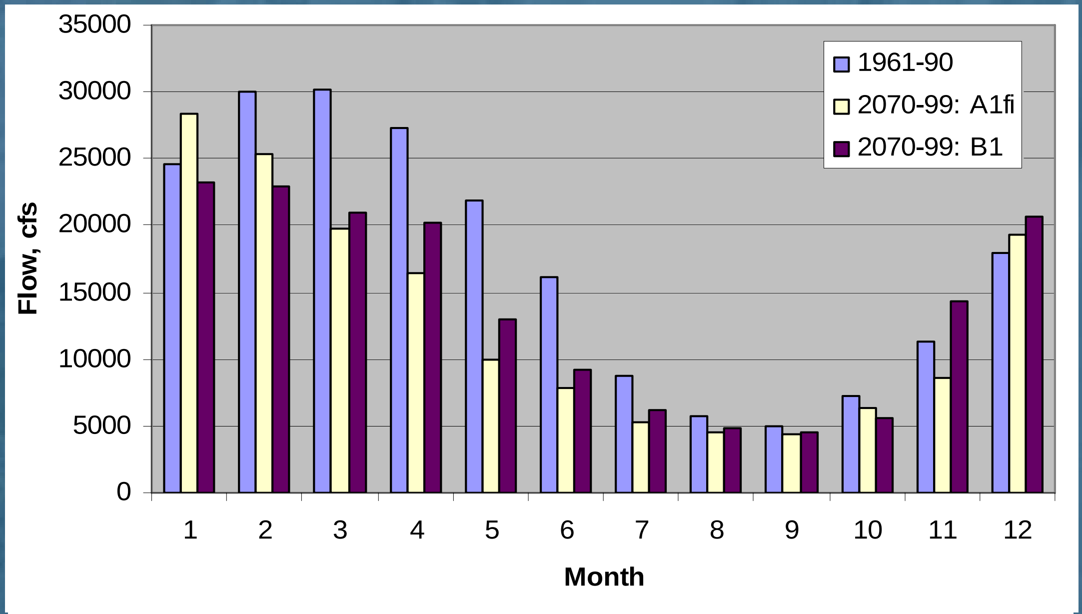
Winter precipitation accounts for most of annual total

High interannual variability – less confidence in precipitation-induced changes than temperature driven impacts.

End-of-Century Streamflow: North CA

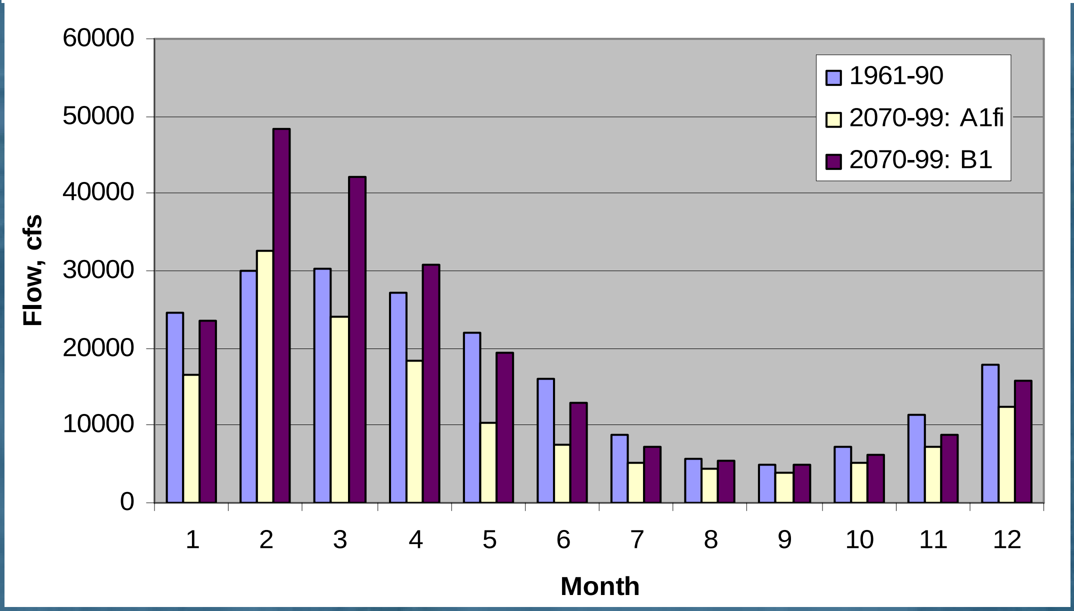
HadCM3 shows:

- 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

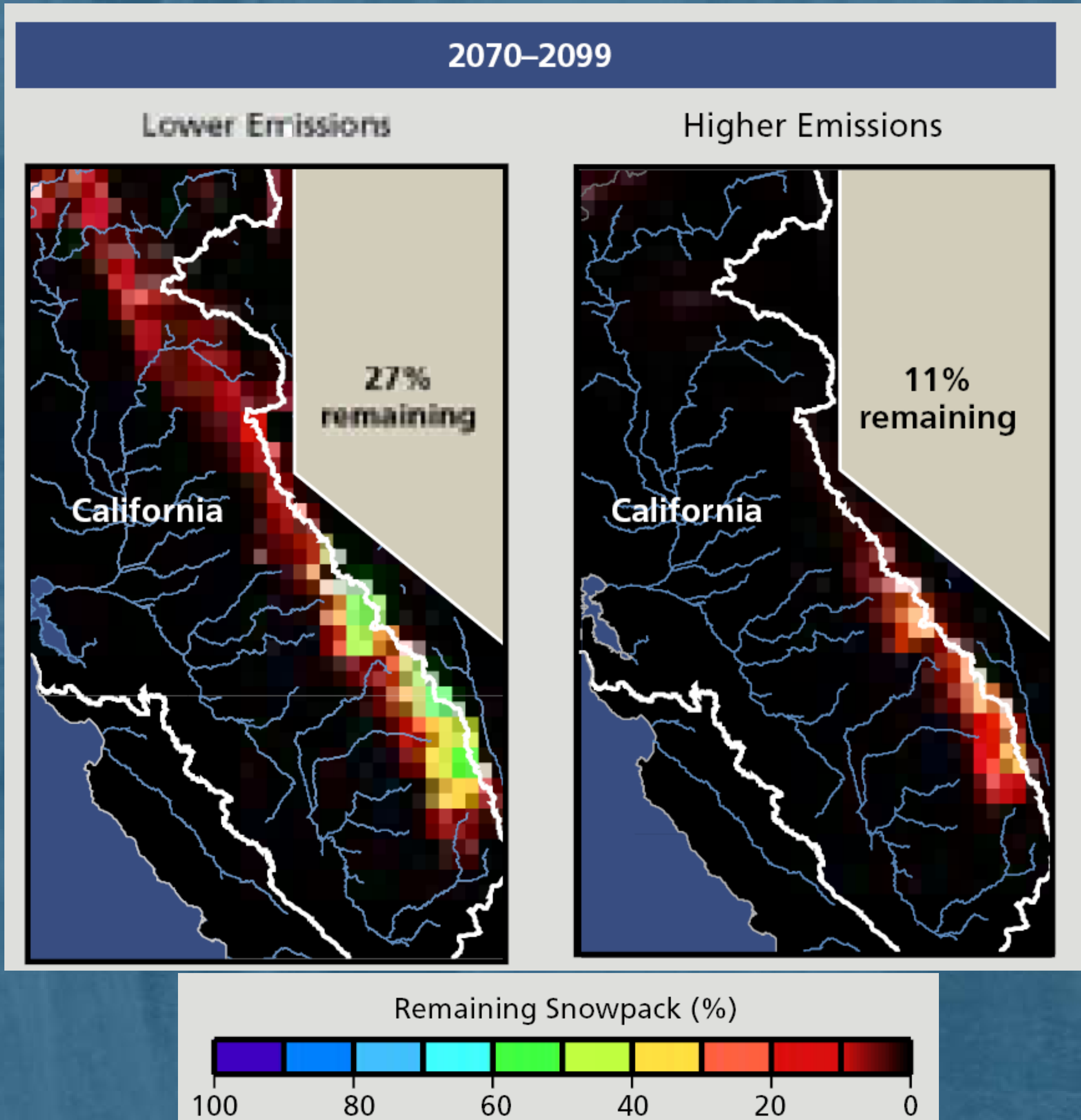
29–73% loss for the lower emissions scenario (3-7 MAF)

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



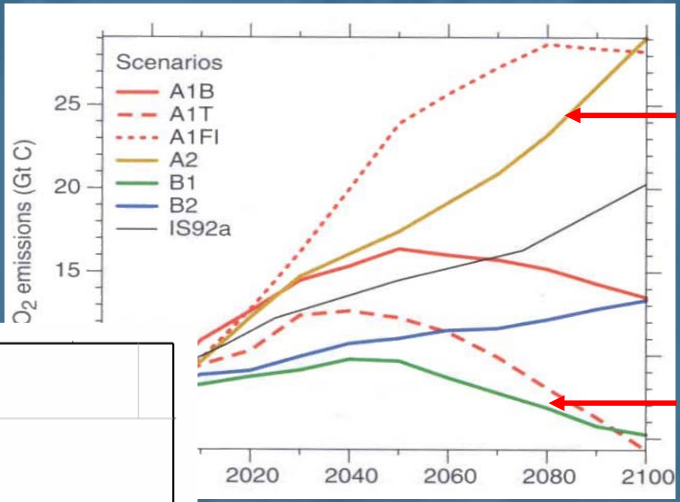
Utility of “Bookend” Study

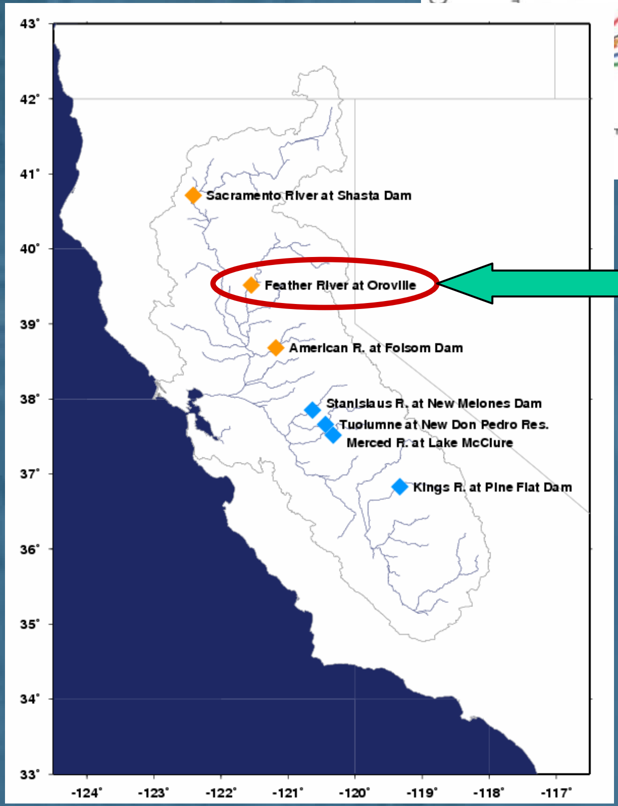
- A large range of futures is bracketed, providing rough “bounds” on uncertainty
- Can identify impacts/sectors at risk
  - Hydrologic impacts substantial under any future
- Compare temperature and precipitation impacts
  - Temperature related impacts diverge greatly under different emissions scenarios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

Can uncertainty be quantified, and not just bounded?

Comparing Impacts to Variability

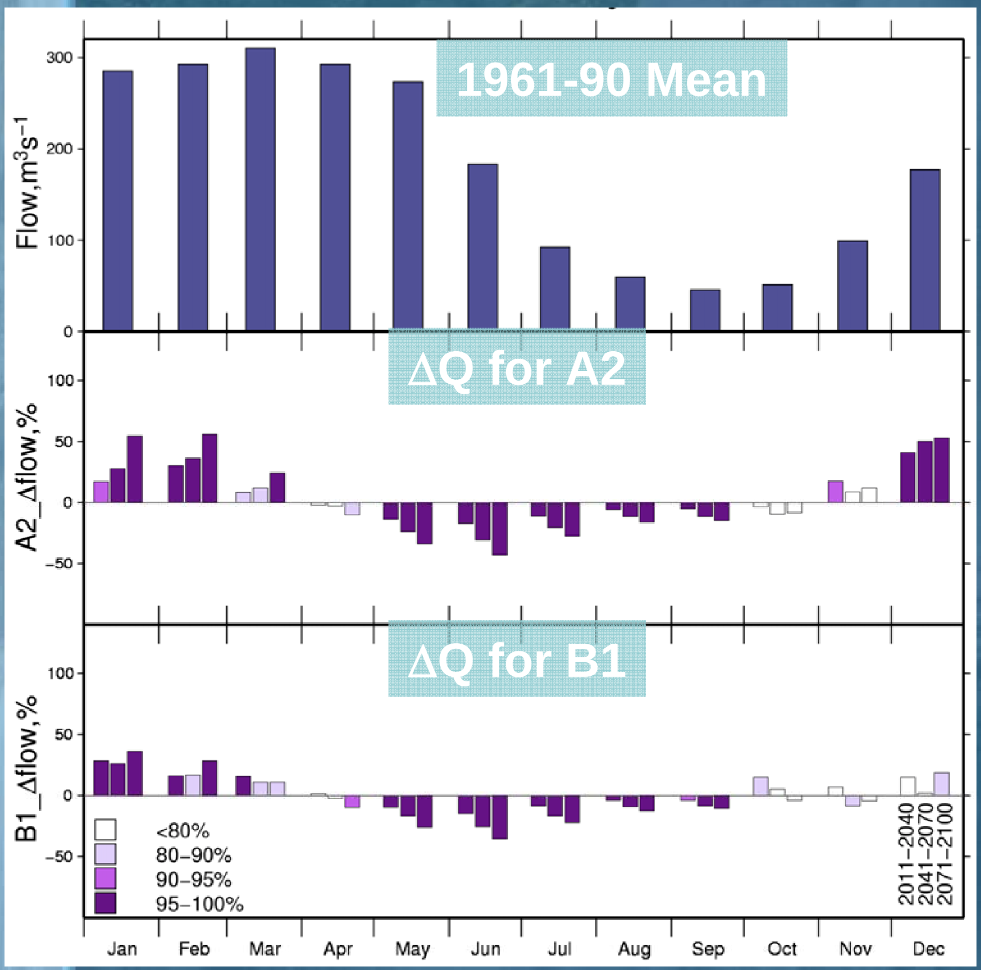
- 11 GCMs, most recent generation (IPCC AR4)
- 2 Emissions scenarios for each GCM:
  - -A2
  - -B1
- Same bias correction, downscaling, hydrologic modeling





Mean Elev = 1550 m

Feather River Flow Changes



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

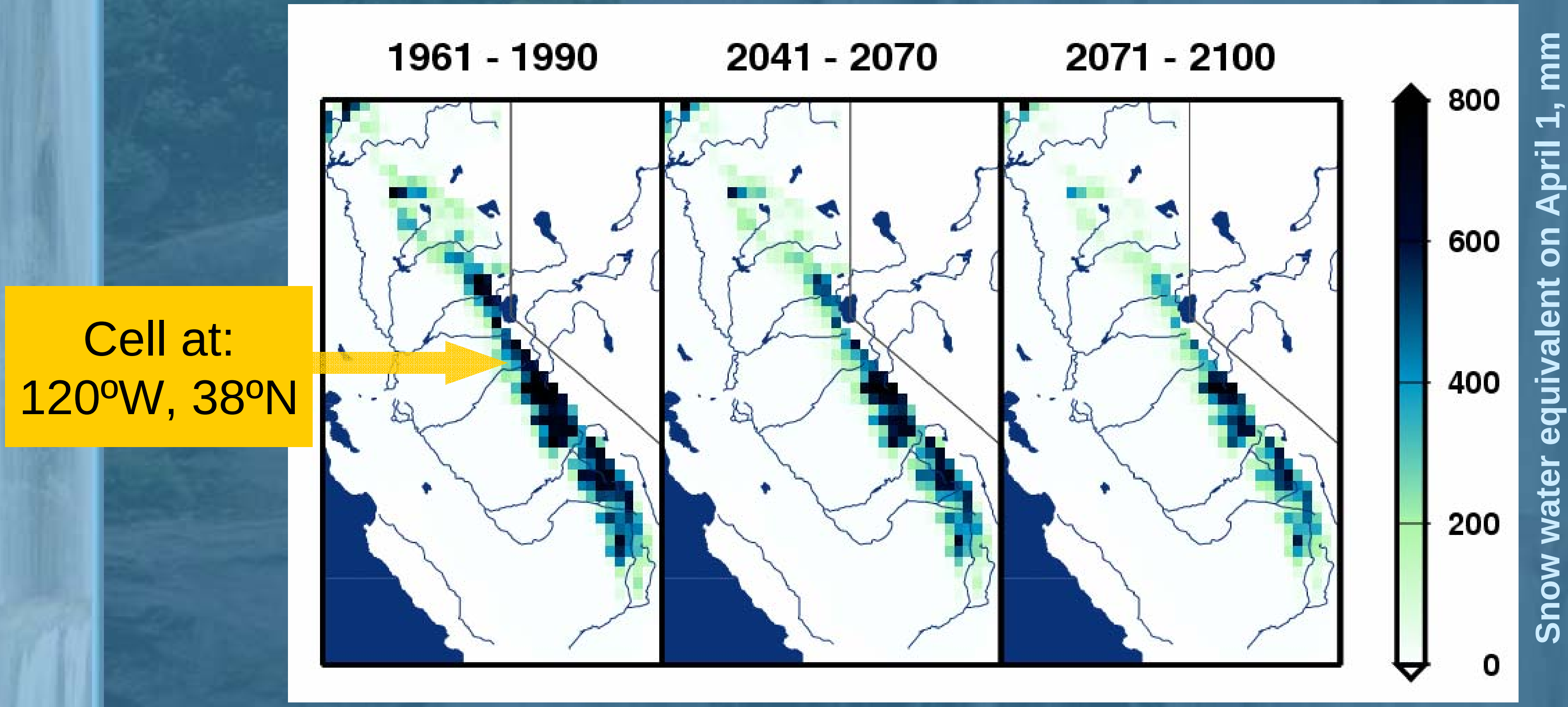
End of Century Changes

- 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

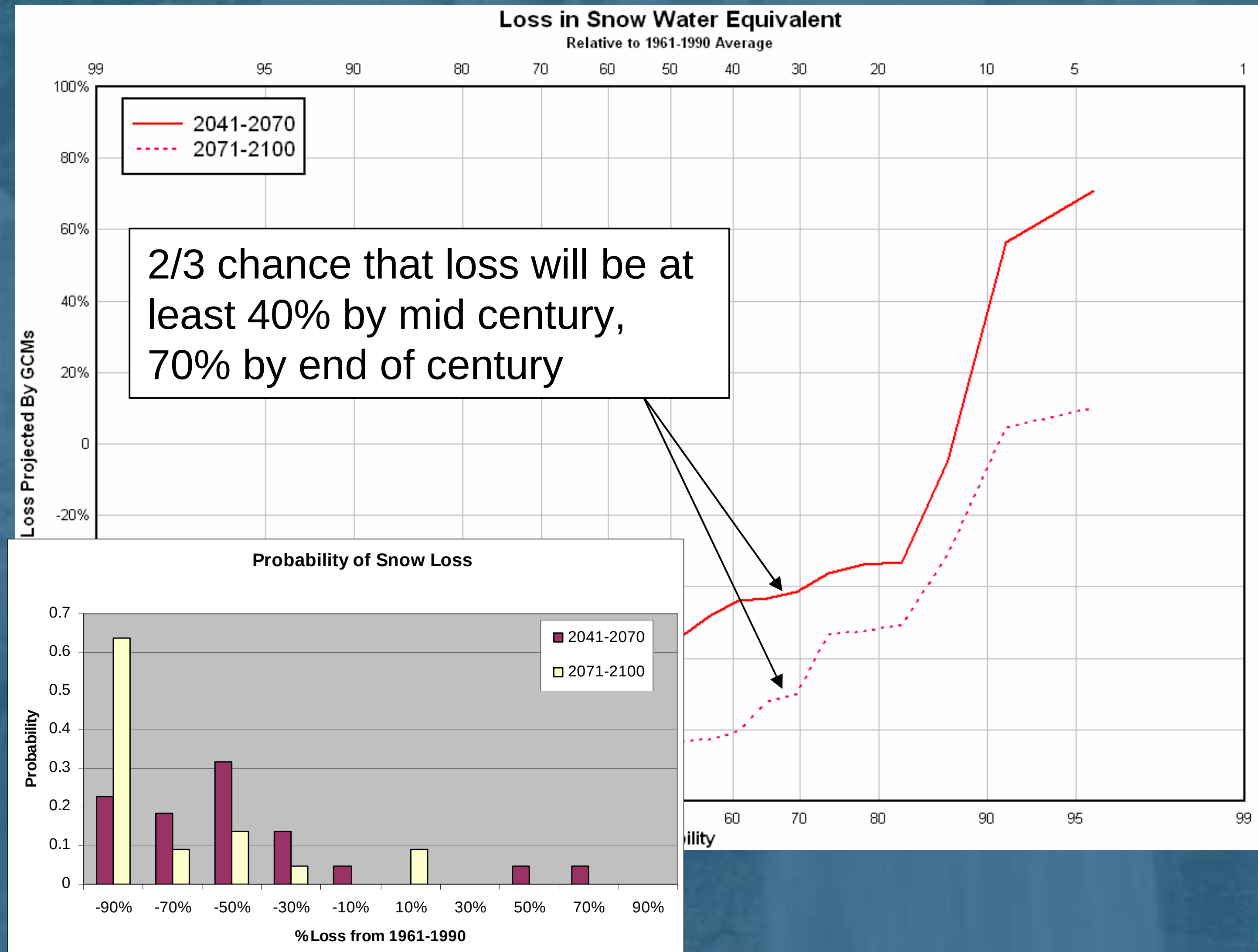
How to include uncertainty in planning?

One point: April 1 Snow Loss All Simulations (B1 and A2)

CDFs for cell at 120ºW, 38ºN

Is an empirical CDF/PDF the best planning tool?

Do 22 simulations capture range of variability?



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)