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Climate Change and California Water Resources:
where do we go from here?
Ed Maurer
Civil Engineering
Santa Clara University
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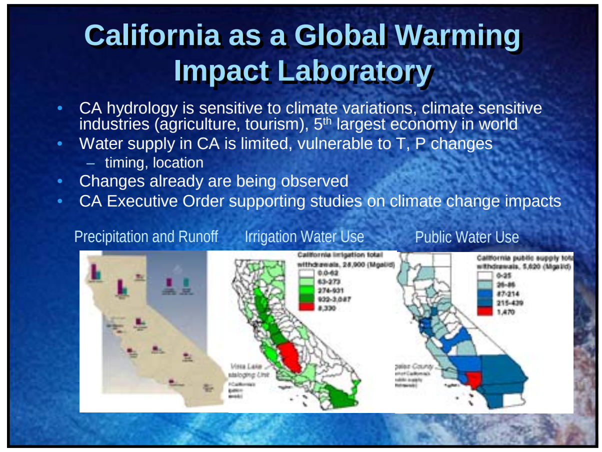
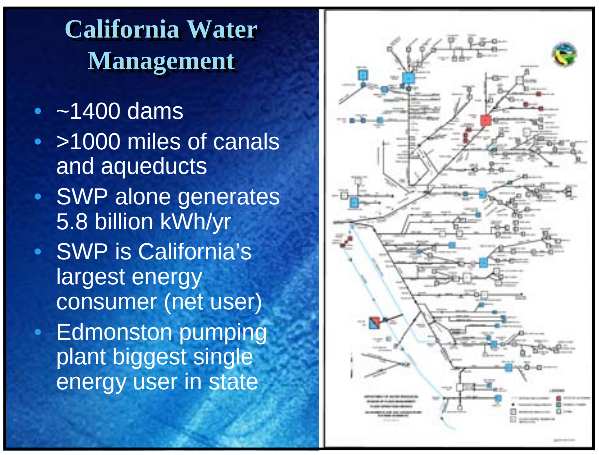
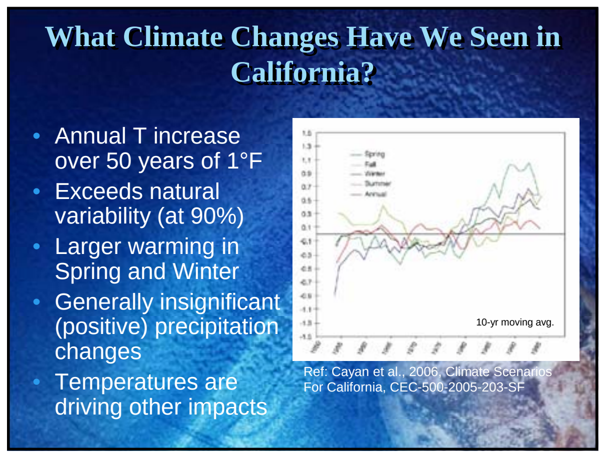
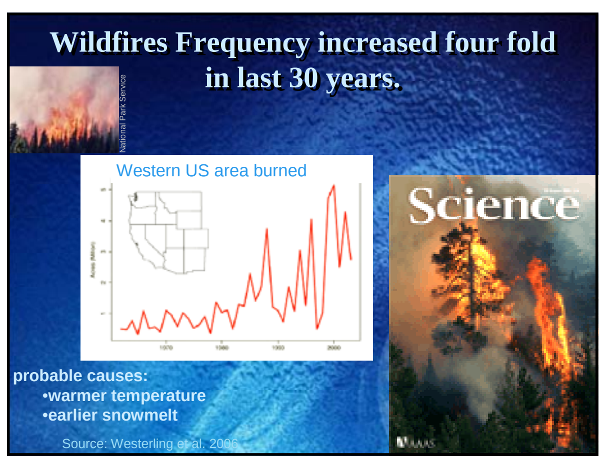
Environmental Engineering and Science Seminar
April 18, 2008


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 Water Management
• ~1400 dams
• >1000 miles of canals and aqueducts
• SWP alone generates 5.8 billion kWh/yr
• SWP is California's largest energy consumer (net user)
• Edmonston pumping plant biggest single energy user in state

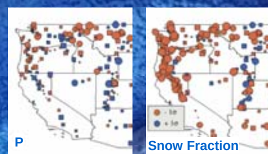

What Climate Changes Have We Seen in California?
• Annual T increase over 50 years of 1°F
• Exceeds natural variability (at 90%)
• Larger warming in Spring and Winter
• Generally insignificant (positive) precipitation changes
• Temperatures are driving other impacts
10-yr moving avg.
Ref: Cayan et al., 2006, Climate Scenarios For California, CEC-500-2005-203-SF


Drought
Droughts have become longer and more intense, and have affected larger areas since the 1970s.
2002: Stressed piñon pines
2004: Massive die-off of piñon pines
Jemez Mountains near Los Alamos
Source: IPCC Climate Change 2007: The Physical Science Basis—Summary for Policymakers.


Wildfires Frequency increased four fold in last 30 years.
National Park Service
Western US area burned
Science
probable causes:
•warmer temperature
•earlier snowmelt
Source: Westerling et al. 2006

More Winter Precipitation Falling as Rain

- Trends in precip and winter snow fall shown
- Reduced snowfall is response to warming during winter wet days (0-3°C)
- Changes of 2nd half of 20th century:
- Red indicates decreasing snow fraction
- About 10% decrease in fraction of winter precip as snow
- Low to moderate elevations (<1500 m) impacted most



Ref: Knowles et al., 2006, J. Climate 19.

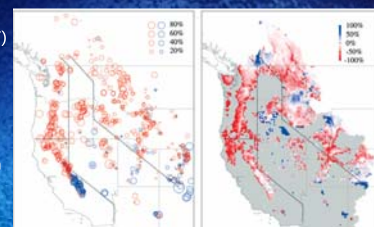
Less snow at end of winter

Decrease in April 1 snowpack (1950-1997)

Changes again most heavily concentrated at low to moderate elevations

In some higher-elevation locations where precipitation has increased (>10%) snow has increased

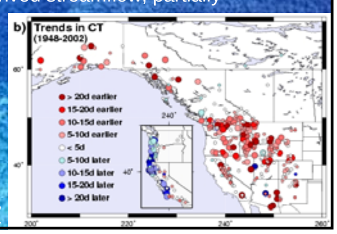
Connected primarily to global warming trends



source: Mote et al, 2005

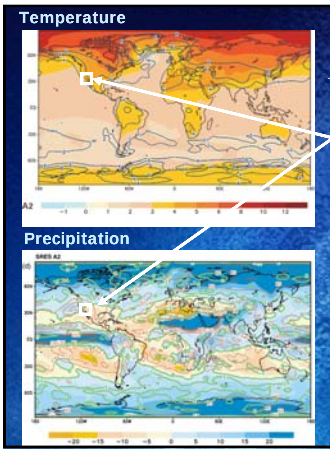
Stream flow is arriving earlier for snow-dominated rivers

- Trends correspond to a timing shift of **1 to 3 weeks** and more over the past ~50 years
- Timing shift dominated by changes in snowmelt-derived streamflow, partially attributed to warming



Ref: Stewart et al., 2005, J. Climate 19.

Looking toward the future: Global Scale

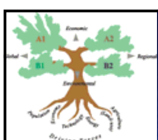


California

Change in Annual Temperature and Precipitation

for 2071-2100 relative to 1961-1990

- Warming is certain; warming related impacts high-confidence
- Precipitation changes harder to discern



What Does the Future Hold?

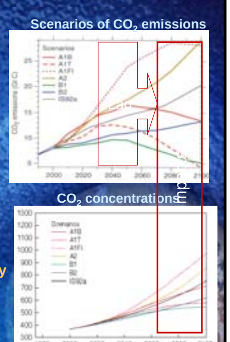
How society changes in the future:

"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**

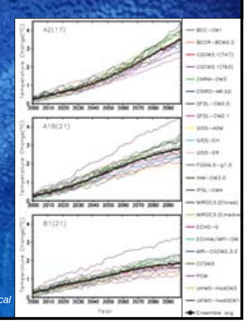


Future Projection with Different Global Climate Models

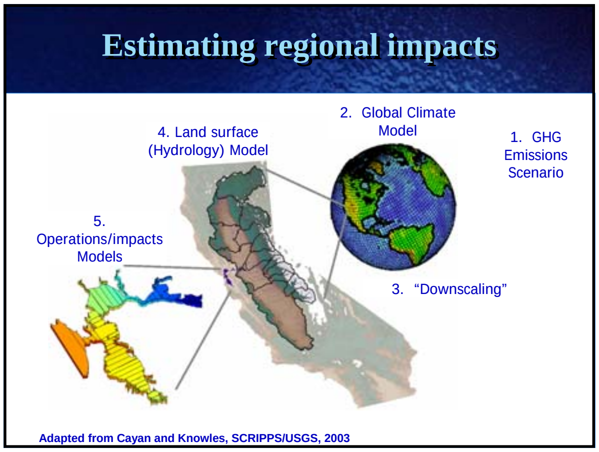
The projected future climate depends on Global Climate Model (or General Circulation Models, GCM) used:

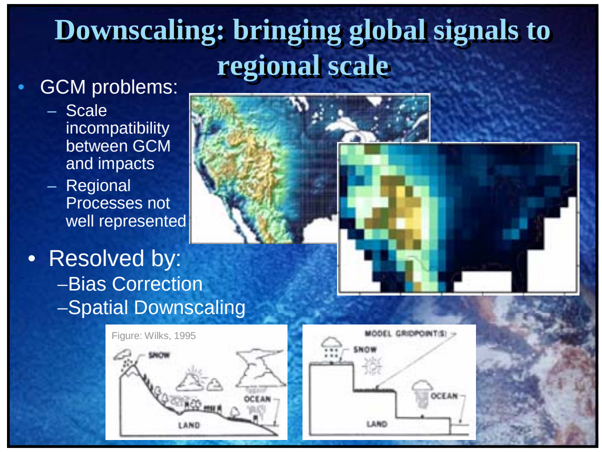
- Varying sensitivity to changes in atmospheric forcing (e.g. CO_2, aerosol concentrations)
- Different parameterization of physical processes (e.g., clouds, precipitation)

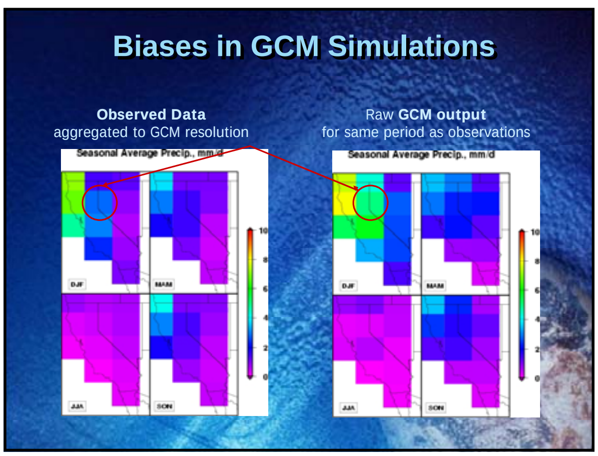
Global mean surface air temperature change of GCMs under same SRES emissions

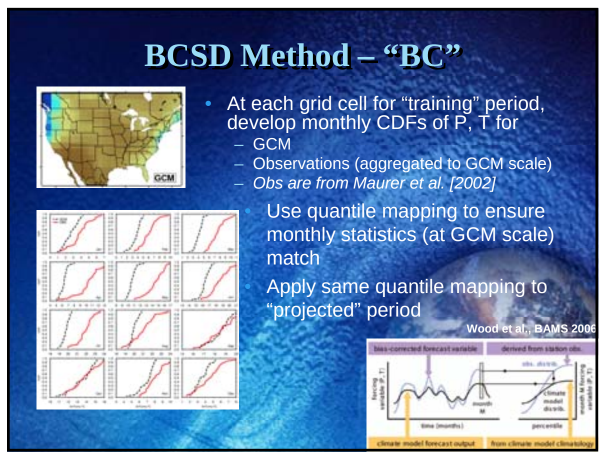


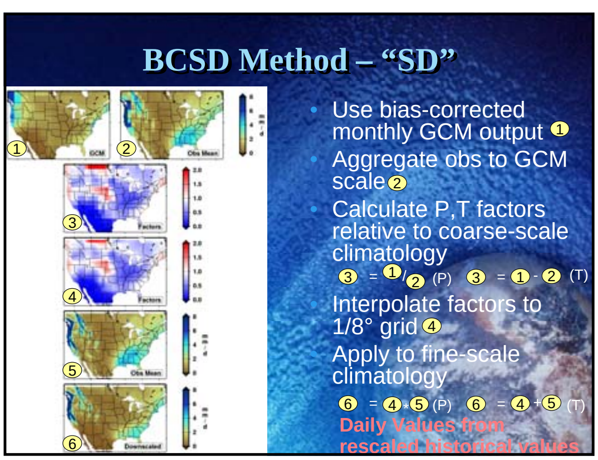
Source: IPCC *Climate Change 2007: The Physical Science Basis*, Chapter 10

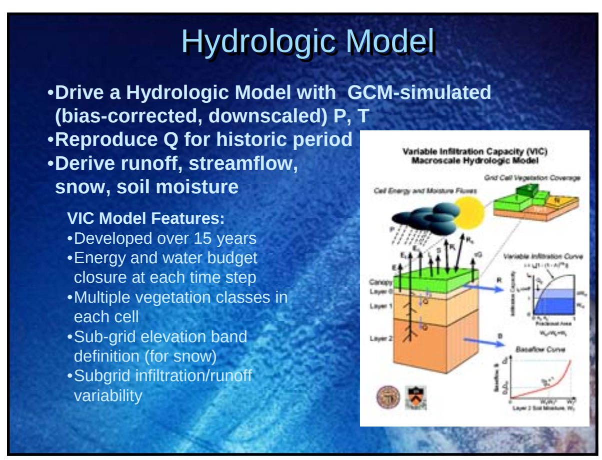

Estimating regional impacts
2. Global Climate Model
4. Land surface (Hydrology) Model
1. GHG Emissions Scenario
5. Operations/impacts Models
3. "Downscaling"
Adapted from Cayan and Knowles, SCRIPPS/USGS, 2003


Downscaling: bringing global signals to regional scale
• GCM problems:
– Scale incompatibility between GCM and impacts
– Regional Processes not well represented
• Resolved by:
–Bias Correction
–Spatial Downscaling
Figure: Wilks, 1995
SNOW
OCEAN
LAND
MODEL GRIDPOINT(S)


Biases in GCM Simulations
Observed Data
aggregated to GCM resolution
Raw GCM output
for same period as observations
Seasonal Average Precip., mm/d
DJF
MAM
JJA
SON

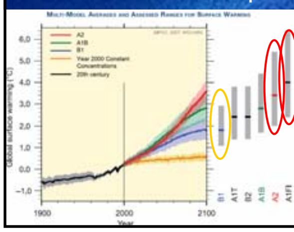

BCSD Method – "BC"
• At each grid cell for "training" period, develop monthly CDFs of P, T for
– GCM
– Observations (aggregated to GCM scale)
– Obs are from Maurer et al. [2002]
Use quantile mapping to ensure monthly statistics (at GCM scale) match
Apply same quantile mapping to "projected" period
Wood et al., BAMS 2006
GCM


BCSD Method – "SD"
• Use bias-corrected monthly GCM output 1
• Aggregate obs to GCM scale 2
• Calculate P,T factors relative to coarse-scale climatology
3 = 1/2 (P) 3 = 1 - 2 (T)
• Interpolate factors to 1/8° grid 4
• Apply to fine-scale climatology
6 = 4 · 5 (P) 6 = 4 + 5 (T)
Daily Values from rescaled historical values
GCM
Obs Mean
Factors
Downscaled


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 15 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
Variable Infiltration Capacity (VIC) Macroscale Hydrologic Model

"Bookend" Studies to Cope With Uncertainties

- Brackets range of uncertainty
- Useful where impacts models are complex



AOGCM	Equilibrium climate sensitivity (°C)
1: BCC-CM1	n.a.
2: BCCR-BCM2.0	n.a.
3: CCSM3	2.7
4: CGCM3.1(T47)	3.4
5: CGCM3.1(T63)	3.4
6: CNRM-CM3	n.a.
7: CSIRO-MK3.0	3.1
8: ECHAM5/MPI-OM	3.4
9: ECHO-G	3.2
10: FGOALS-g1.0	2.3
11: GFDL-CM2.0	2.9
12: GFDL-CM2.1	3.4
13: GISS-AOM	n.a.
14: GISS-EH	2.7
15: GISS-ER	2.7
16: INM-CM3.0	2.1
17: IPSL-CM4	4.4
18: MIROC3.2(hires)	4.3
19: MIROC3.2(medres)	4.0
20: MRI-CGCM2.3.2	3.2
21: PCM	2.1
22: UKMO-HadCM3	3.3
23: UKMO-HadGEM1	4.4

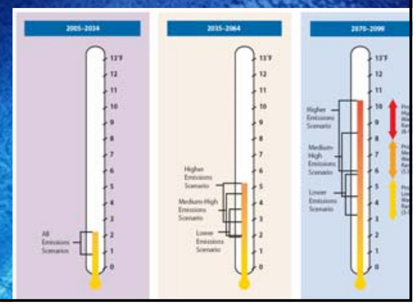
Bracketing Future Warming for California

CA average annual temperatures for 3 30-year periods

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

Summer temperatures increases (end of 21st century) vary widely:
Lower: 3.5-9 °F
Higher: 8.5-18 °F

Ref: Luers et al., 2006, CEC-500-2006-077



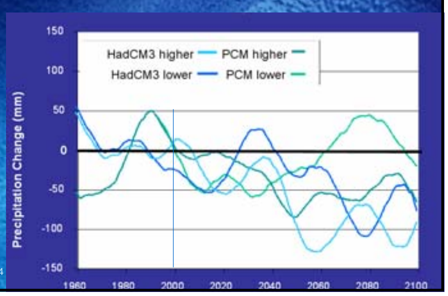
Bracketing Future California Precipitation

Statewide Winter Average

Winter precipitation accounts for most of annual total

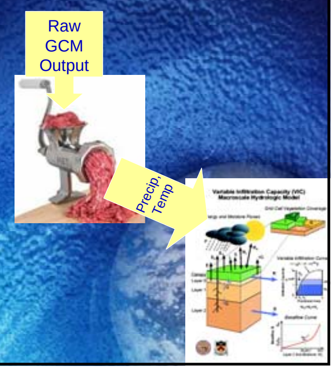
High interannual variability – less confidence in precipitation-induced changes than temperature driven impacts.

Ref: Hayhoe et al., 2004



Generating Regional Hydrologic Impacts

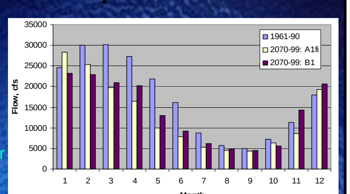
- BCSD downscaling of GCM Precip and Temp
- Use to drive VIC model
- Obtain runoff, streamflow, snow

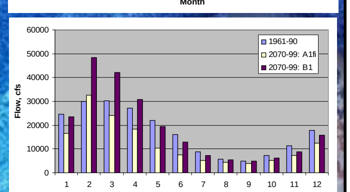


Bracketing Streamflow Impacts: North CA

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





Water Delivery Reliability

- Reduction in SWP deliveries, esp under high emissions (*Vicuna et al., 2007*)

Surface water deliveries, TAF				
	hadcm3		pcm	
	sresb1	sresa1fi	sresb1	sresa1fi
2020-2049	3105 (-1%)	2895 (-8%)	2691 (-14%)	2623 (-17%)
2070-2099	2505 (-20%)	2283 (-27%)	3188 (+1%)	2320 (-26%)

- Rising salinity (+20% on avg) at San Joaquin R. at Vernalis affects Delta water quality and reservoir management
- This is due just to timing of streamflow: without sea level rise, extreme storms, levee failures.
- Temperature-related impacts (like timing) have lower uncertainty than precipitation-related

Bracketing Impacts on California Snow

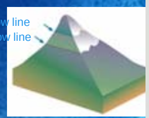
End of Century:

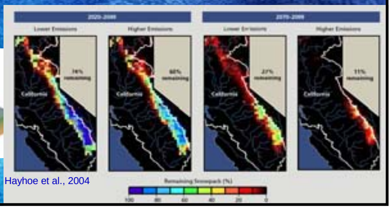
29–73% loss for the lower emissions scenario
(3-7 MAF)

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

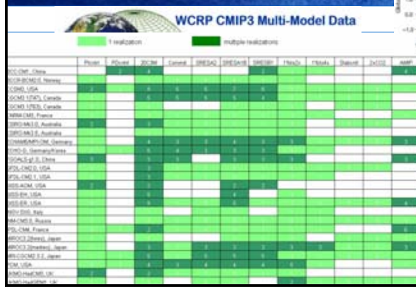


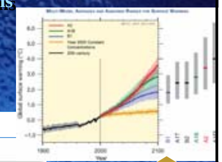


Hayhoe et al., 2004

GCM Simulations:
models and emissions

- 20th century through 2100 and beyond
- >20 GCMs
- Multiple Future Emissions Scenarios

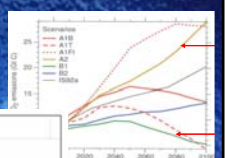




Multiple global estimates quantify uncertainty

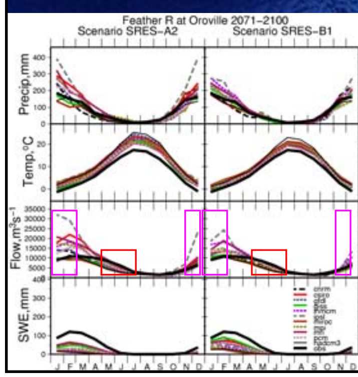
Comparing Impacts to Variability

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



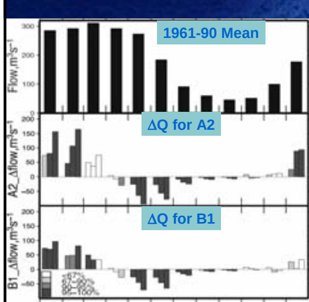
Feather R.

Multi-Model Ensemble Projections for Feather River



- •Increase Dec-Feb Flows
  - +77% for A2
  - +55% for B1
- •Decrease May-Jul
  - -30% for A2
  - -21% for B1

Feather River at Oroville Dam



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

Only May-August are differences in flow (A2 vs. B1) statistically different at >70%

Projected CT Shifts at reservoir inflows - from 22 GCM runs

Projected Changes in Timing Relative to 1961-1990 (from Maurer, 2007)

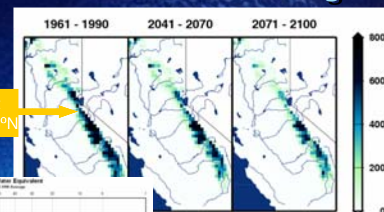
Basin	ΔCT under Mid-High Emissions (A2), days			ΔCT under Low Emissions (B1), days		
	Early 21st Century	Mid 21st Century	End of 21st Century	Early 21st Century	Mid 21st Century	End of 21st Century
Feather R.	**-14**	**-18**	**-23**	**-10**	**-11**	**-17**
American R.	**-19**	**-23**	**-31**	**-17**	**-20**	**-26**
Tuolumne R.	**-9**	**-20**	**-33**	**-10**	**-14**	**-23**
Kings R.	**-9**	**-21**	**-36**	**-8**	**-16**	**-24**

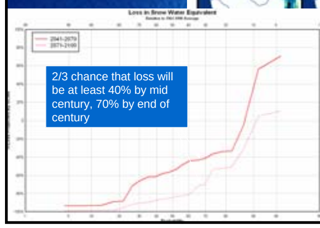
- ΔCT at major inflow points to CA water system: Oroville, Folsom, New Don Pedro, Pine Flat
- Mean of GCMs shows no annual P change
- Small shift in P from spring to winter
- CT shift mostly due to T increases
- All shifts exceed 99% confidence as being different from zero

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

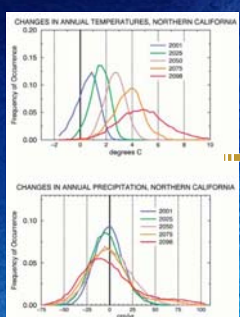
Impact Probabilities for Planning



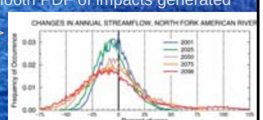


- Combine many future scenarios, models, since we don't know which path we'll follow (22 futures here)
- Choose appropriate level of risk

Statistical Resampling/Smoothing



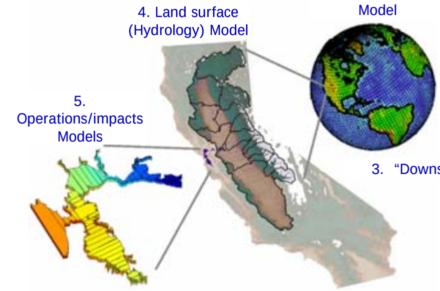
- Mid-range emissions (A2, B2, IS92a) scenarios, 6 GCMs combined.
- Projections resampled and run through hydrology simulation 20,000 times
- smooth PDF of impacts generated



Source: Dettinger MD, 2005

Problem: 20,000 VIC simulations would take >10 years of CPU time!

Revisiting Uncertainty Sources

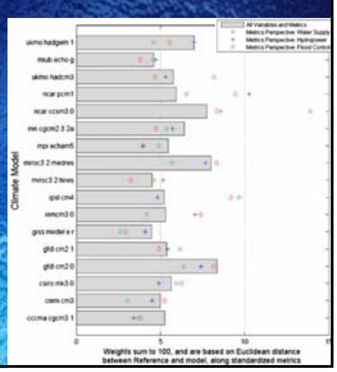


Adapted from Cayan and Knowles, SCRIPPS/USGS, 2003

Can we just select “best” GCMs?

Relative GCM weights

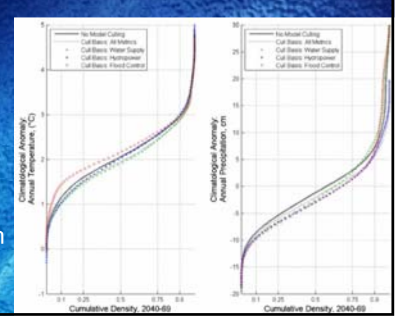
- hydropower
  - teleconnections, interannual variab.
- water supply
  - long-term means, droughts
- flood control
  - extremes, skewness, seasonality
- Even with overlaps, weights vary



Source: Brekke et al., 2008

Weighting Futures using best GCMs

- GCMs with best metrics retained for categories
- Subtle differences in central tendencies
- More consistent difference to ΔP probabilities than ΔT



Source: Brekke et al., 2008

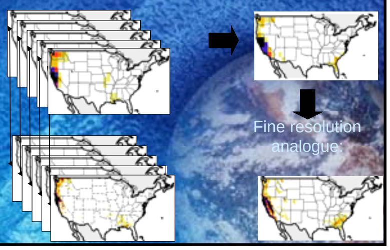
Does Downscaling Method Matter?

- Compared BCSD (monthly) downscaling with EOF-based Constructed Analogues
- Downscaled NCEP-NCAR Reanalysis for 1950-1999
- Monthly skill in reproducing Reanalysis P and T is high for both

Library of previously observed anomaly patterns:

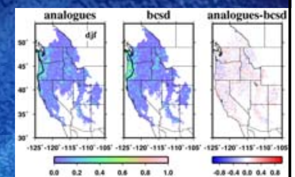
Coarse resolution analogue:

Fine resolution analogue:



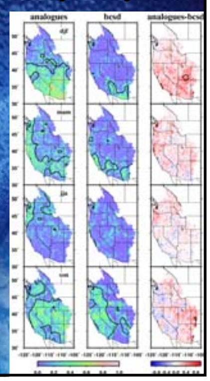
Daily Skill: Dry Extremes

- 20th percentile winter P
- r2 values shown
- 90% confidence line
- Low skill for both methods
  - Daily large-scale data cannot counter lack of skill, poor relationship between scales
- No statistical difference for CA, BCSD
- Similar results for wet extremes
- Difficulty downscaling dry extremes



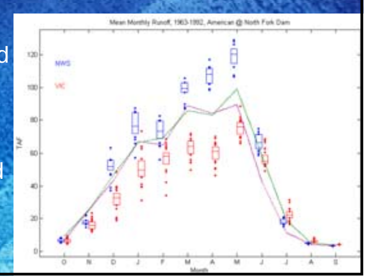
Daily Skill: Consecutive Dry Days

- Seasonal max consecutive dry days
- Winter: CA has higher skill
  - some differences are statistically significant
- Difference in other seasons minor & insignificant
- Max consecutive wet days has similar results
- At annual level differences are also negligible



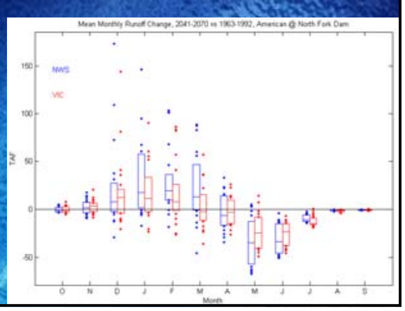
Does choice of hydrologic model matter?

- NWS-SacSMA model
- VIC model
- Each forced with identical modeled historical climate
- Models have different performance and bias for historic period



Comparison of hydrology models

- VIC and SacSMA forced with perturbed historical climate
- Projected changes are not statistically distinguishable



Summary

- GCM/emission uncertainties can be captured probabilistically for use in planning
- Probabilities of impacts (and whether to use 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)
- Selection of GCMs based on past skill can result in small changes to probabilities – "completeness" of ensemble more important
- Downscaling method less important
- Hydrology model also less important

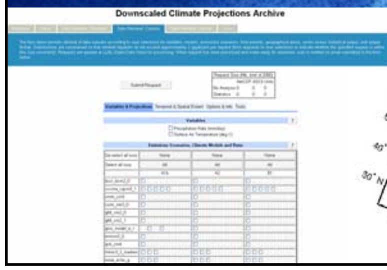
What's Next?

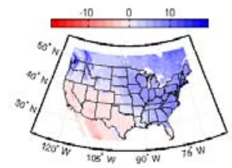
- Expand uncertainty assessment to include dynamic models and statistical downscaling (esp. for extremes)
- Global assessments
- Facilitate regional assessments of interest to water managers

Facilitating Regional Impacts

using multi-model ensembles to capture uncertainty

- PCMDI CMIP3 archive of global projections
- New archive of 112 downscaled GCM runs
- gdo4.ucllnl.org/downscaled_cmip3_projections





Thanks!