Uncertainty in projected impacts of climate change on water

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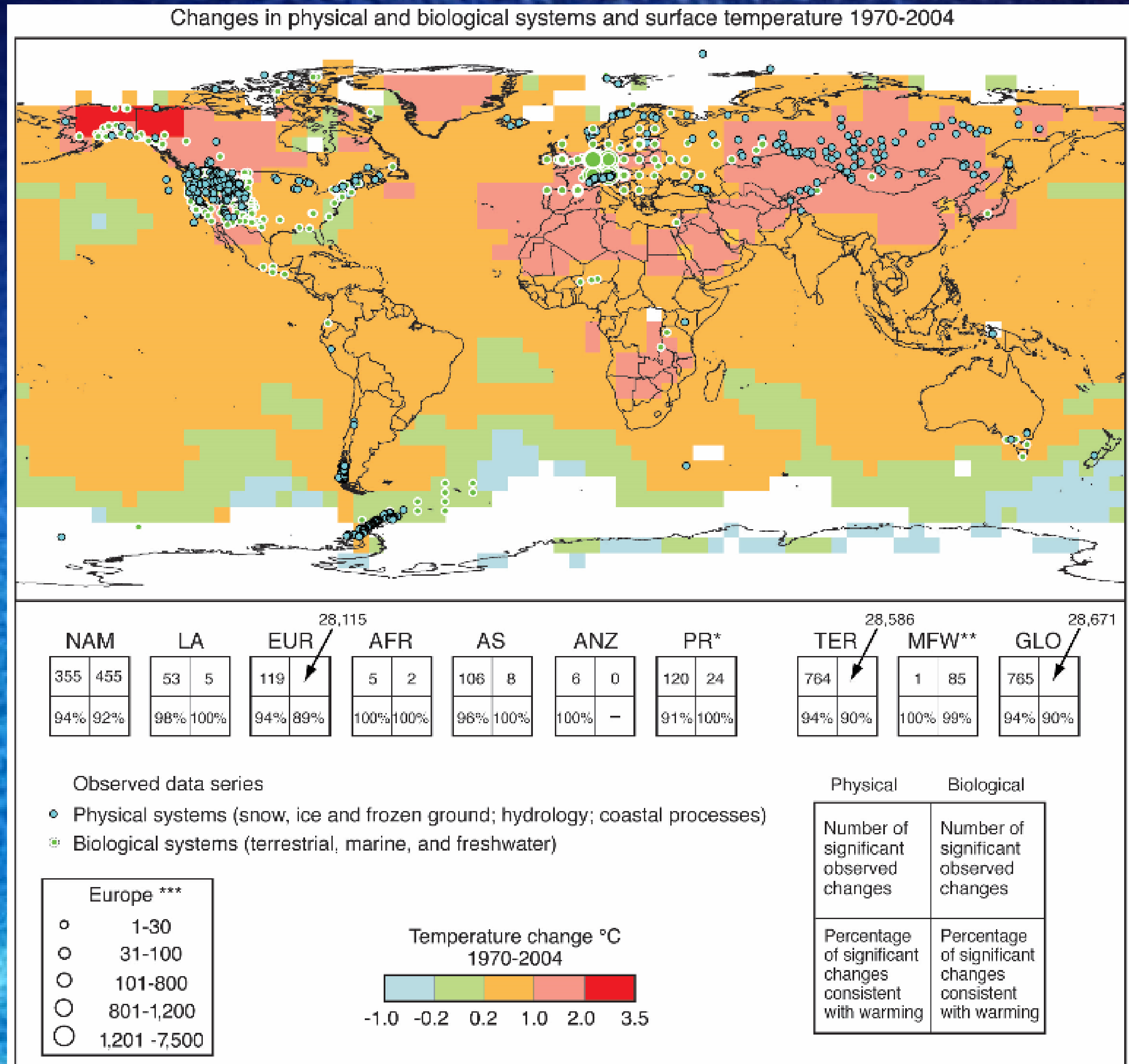
23 abril 2009

Observed Changes: 1970-2004

- High confidence changes in:
  - rainfall intensity
  - extreme temperatures
  - regional drought
  - glacier melt
  - early snowmelt
  - lake warming
- Changes are consistent with observed warming

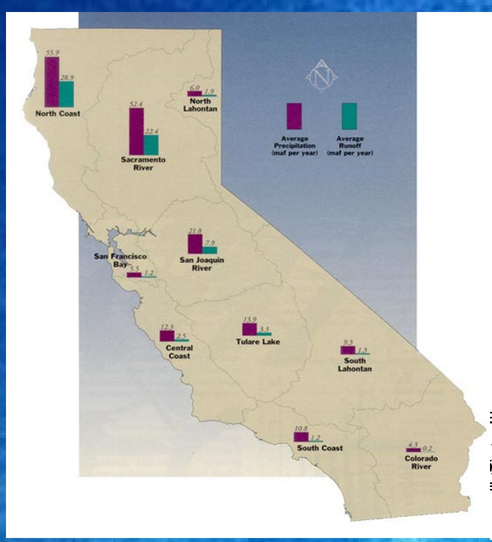


Source: IPCC *Climate Change 2007: Impacts, Adaptation, and Vulnerability* -- Summary for Policymakers.

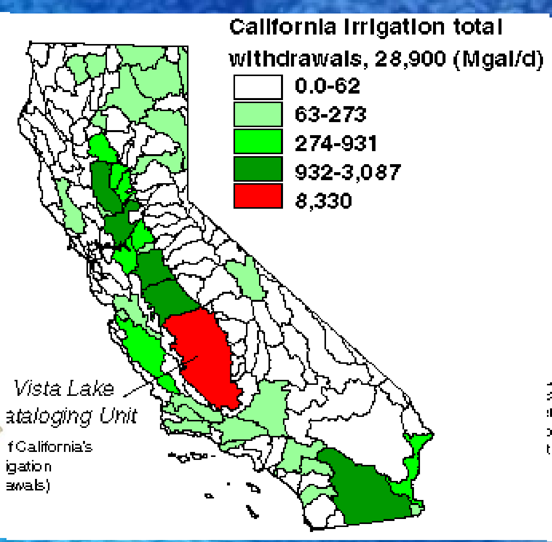
California as a Global Warming Impact Laboratory

- 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

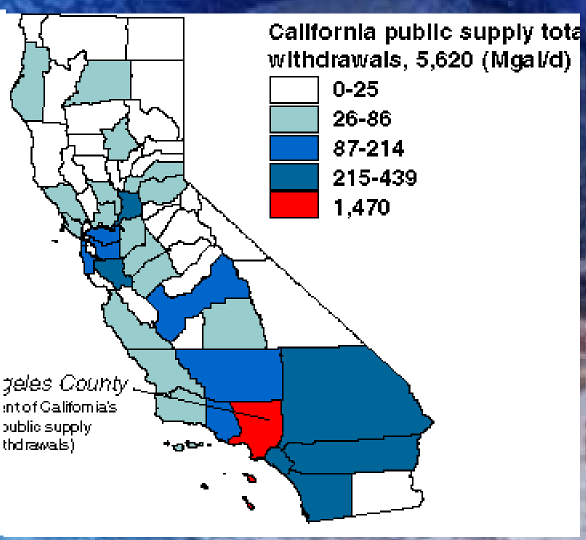
Precipitation and Runoff



Irrigation Water Use

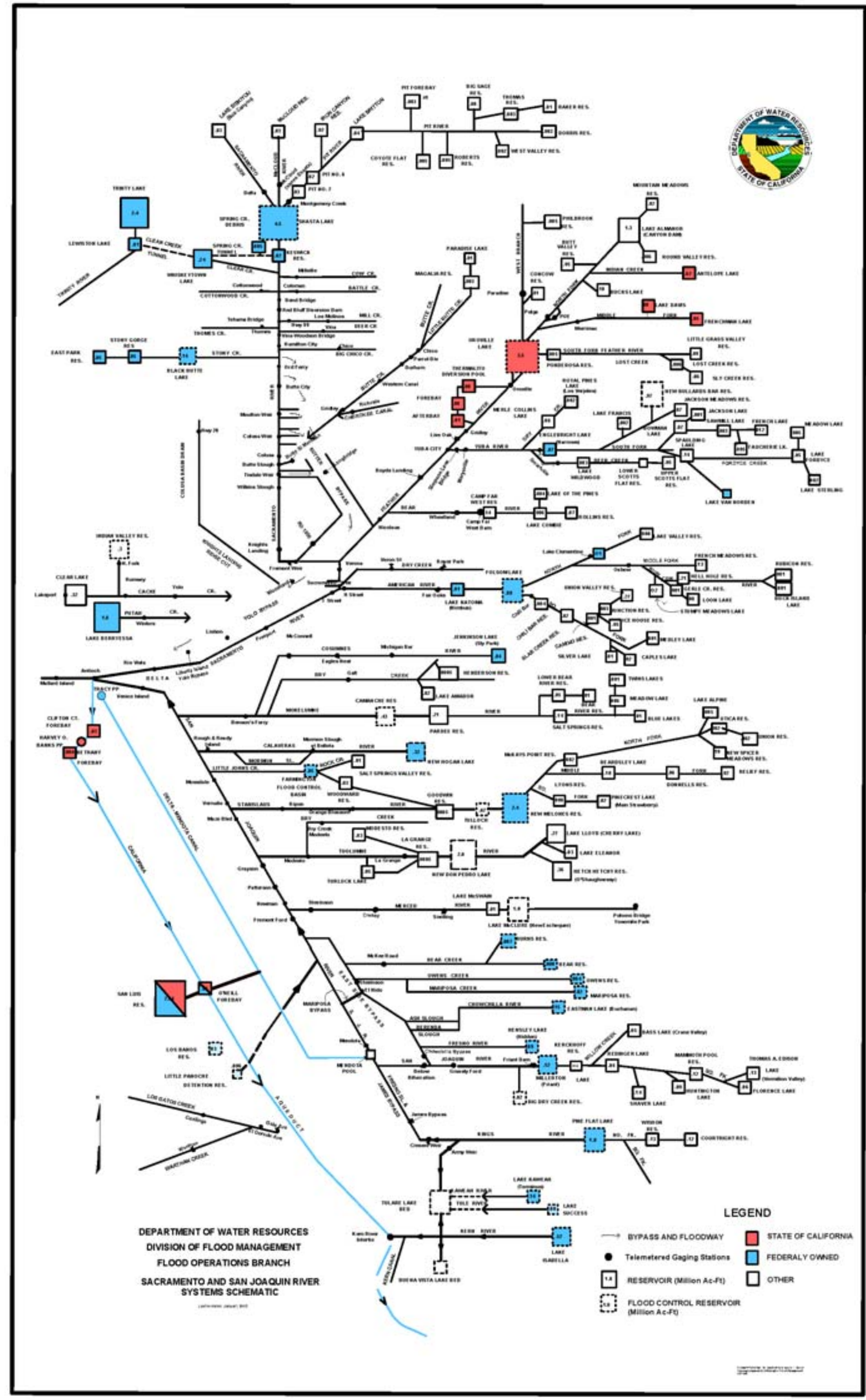


Public Water Use



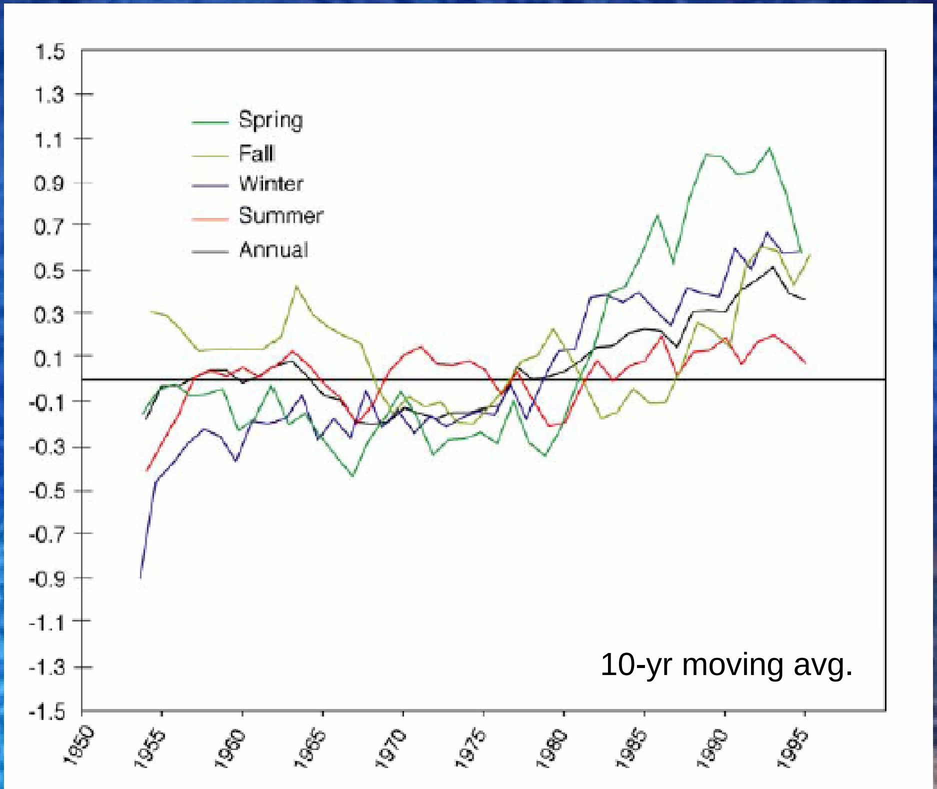
California Water Management

- ~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



Ref: Cayan et al., 2006, Climate Scenarios For California, CEC-500-2005-203-SF

Increasing drought and wildfire

Droughts have become longer and more intense, and have affected larger areas since the 1970s.

Probable causes of wildfire increases:

- warmer temperature
- earlier snowmelt

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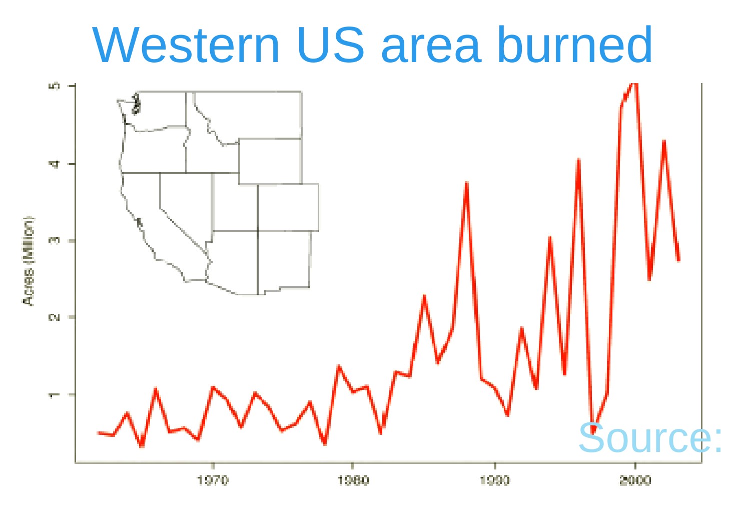
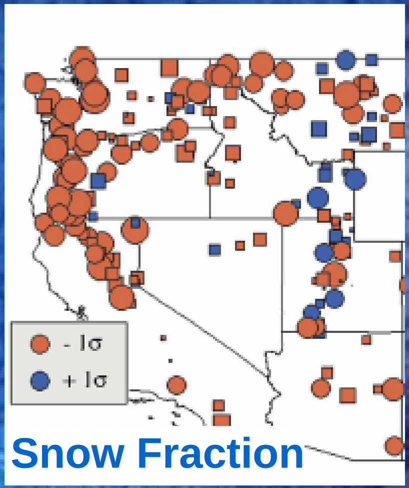


Source:

Sources: IPCC *Climate Change 2007: The Physical Science Basis*—Summary for Policymakers.
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)
- Red indicates decreasing snow fraction
- About 10% decrease in fraction of winter precip as snow
- Low to moderate elevations (<1500 m) impacted most



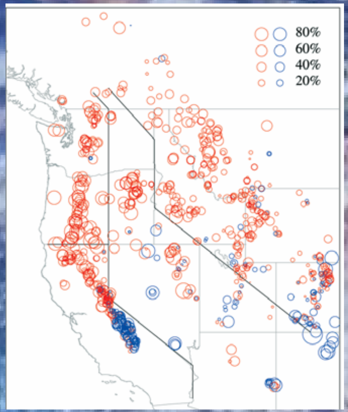
Ref: Knowles et al., 2006, J. Climate 19.

Decrease in April 1 snowpack (1950-1997)

Changes again most heavily concentrated at low to moderate elevations

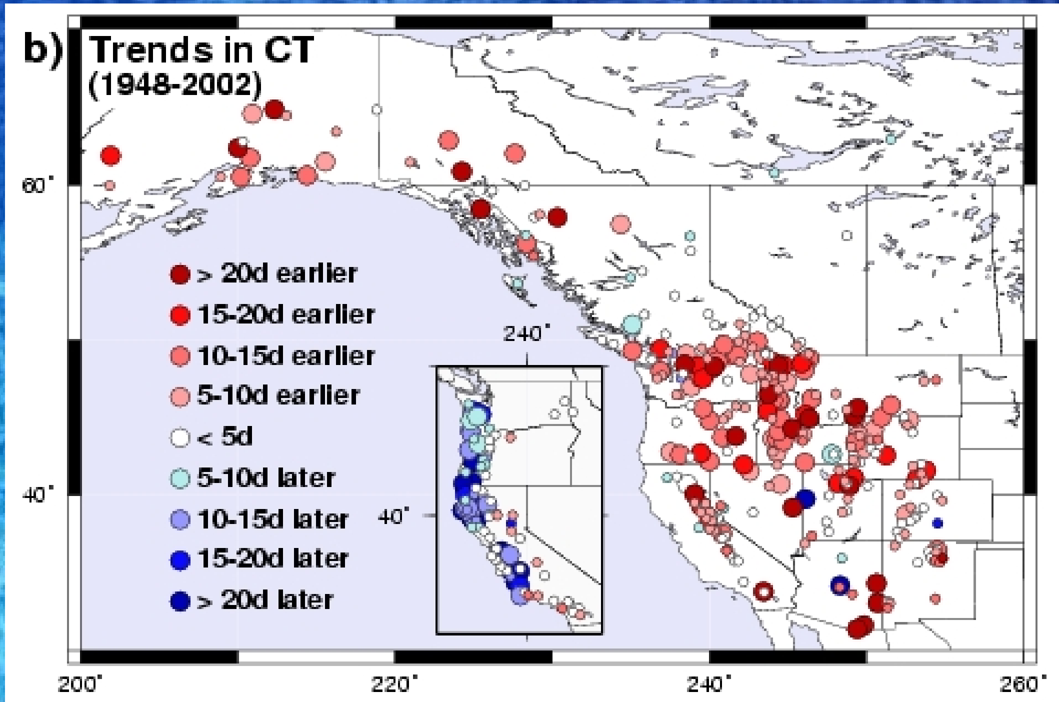
In some higher-elevation locations where precipitation has increased (>10%) snow has increased

Connected primarily to global warming trends



Stream flow is arriving earlier for snow-dominated rivers

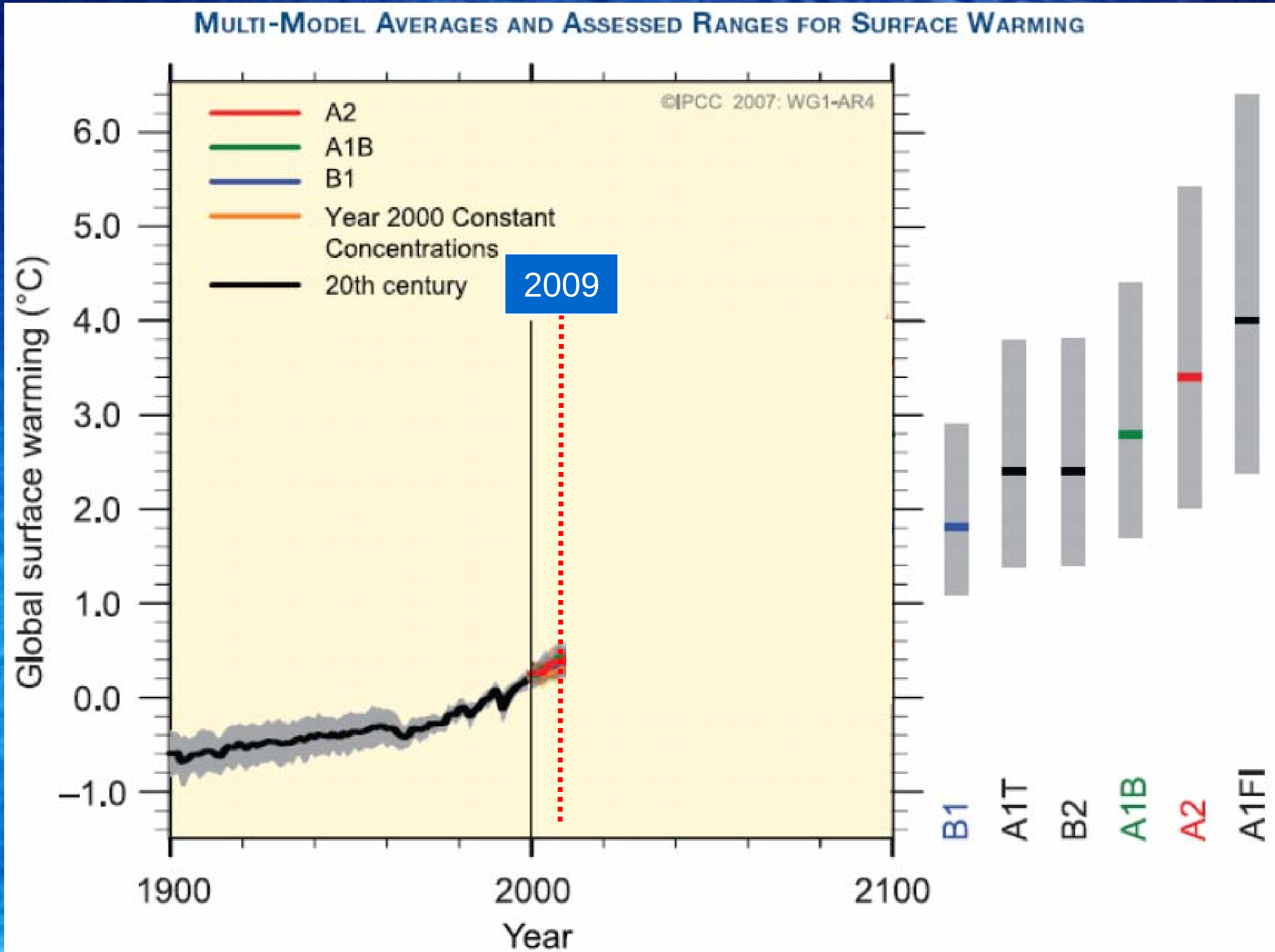
- Trends correspond to a timing shift of **1 to 3 weeks** and more over the past ~50 years
- Timing shift dominated by changes in snowmelt-derived streamflow, partially attributed to warming



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

Where are we now, relative to future warming?

- *Lines are multi-model global averages of warming (relative to 1980–1999)*
- *Shading denotes the ±1 standard deviation*
- *The orange line is for concentrations were held constant at year 2000 values.*
- *Grey bars are "likely range of warming"*

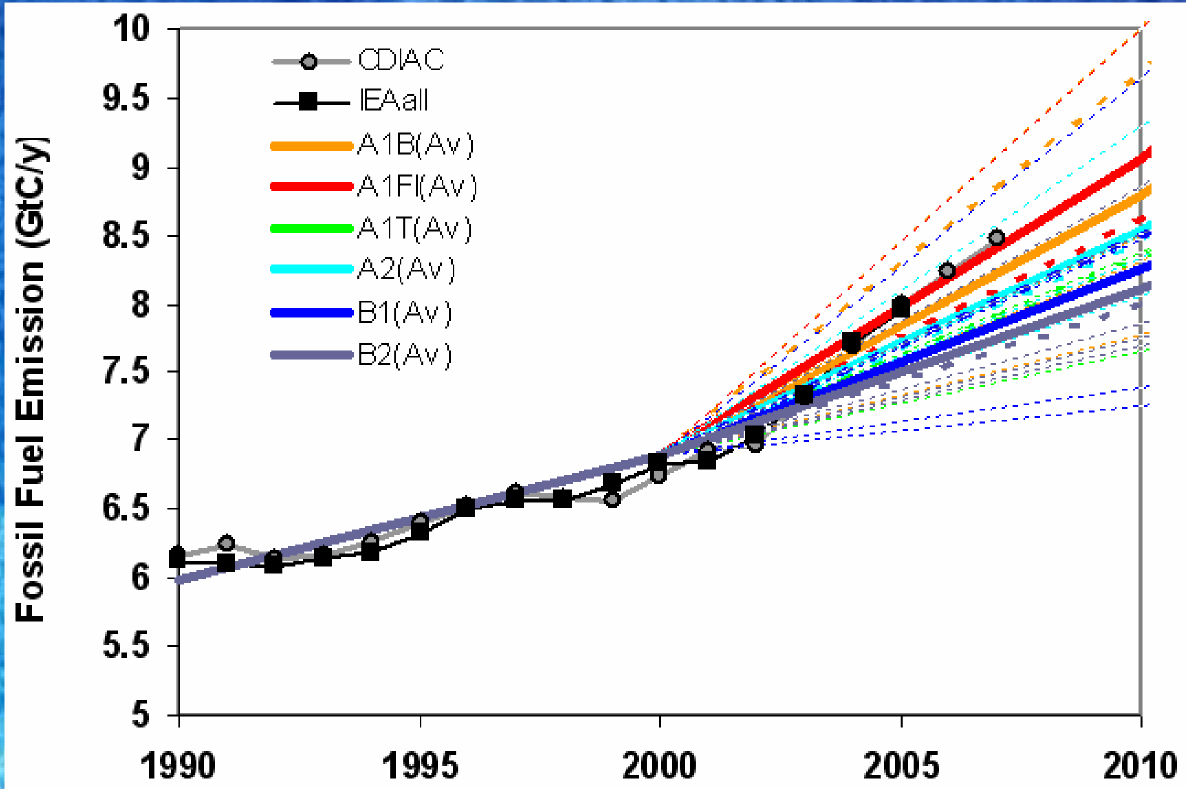


Which pathway are we on?

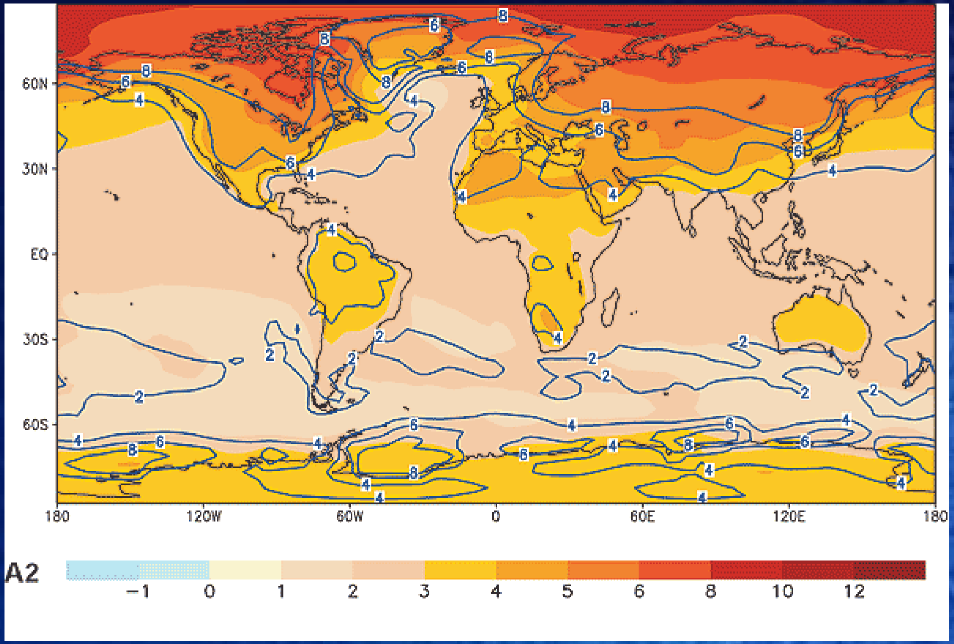
- Current emissions are tracking above the most intense IPCC emission scenario

Raupach et al., PNAS, 2007
Global Carbon Project

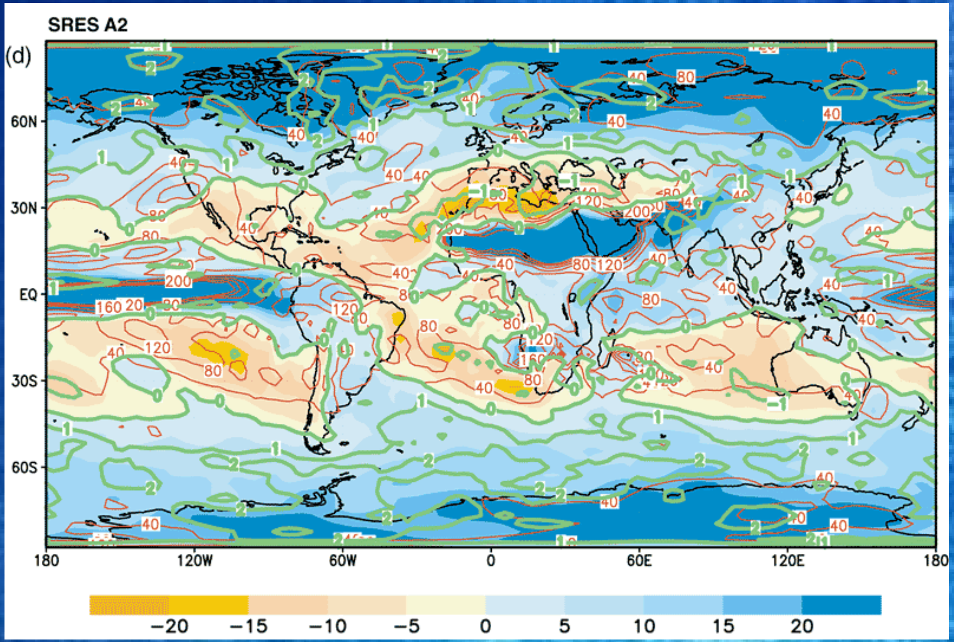
- Scenarios trends are averages across all models available for each scenario class.
- Red dots indicate the revised and updated numbers for 2005 and 2006 respectively.



Temperature



Precipitation



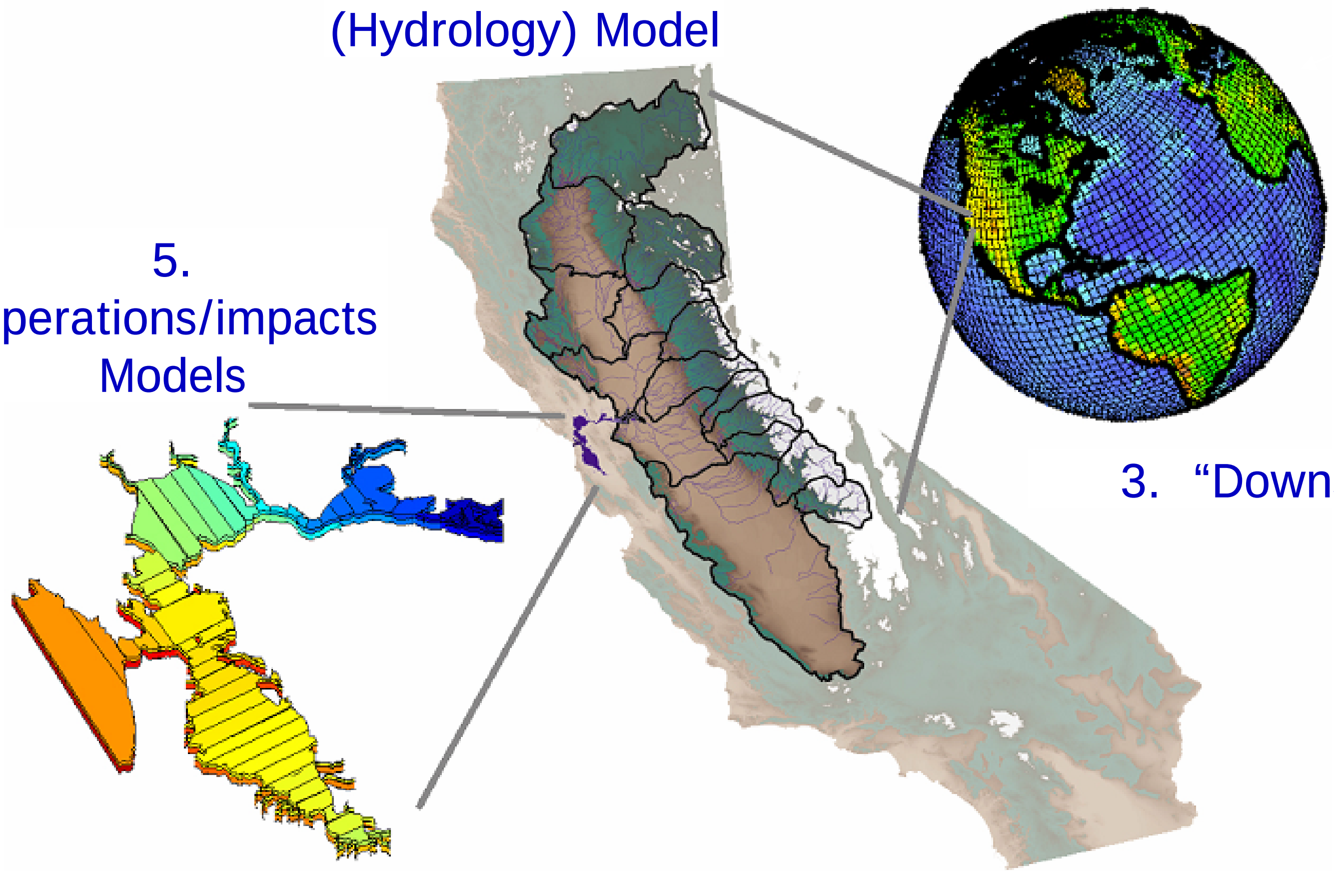
Looking toward the future: Global Scale

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

Estimating regional impacts



Adapted from Cayan and Knowles, SCRIPPS/USGS, 2003

Emissions Uncertainty and Inter-generational Responsibility

How society changes in the future:

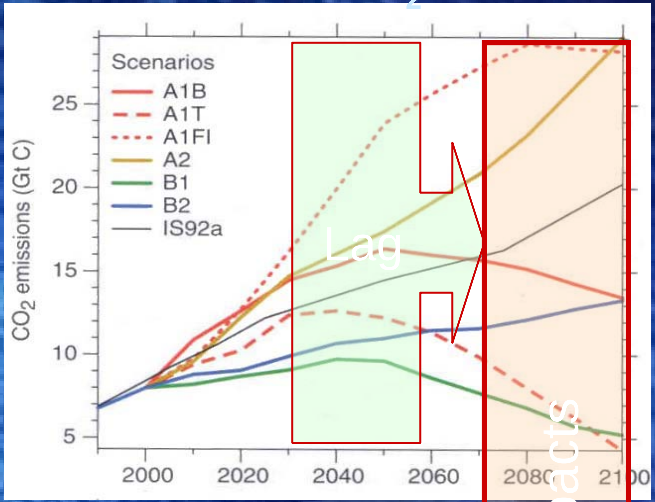
"Scenarios" of greenhouse gas emissions:

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

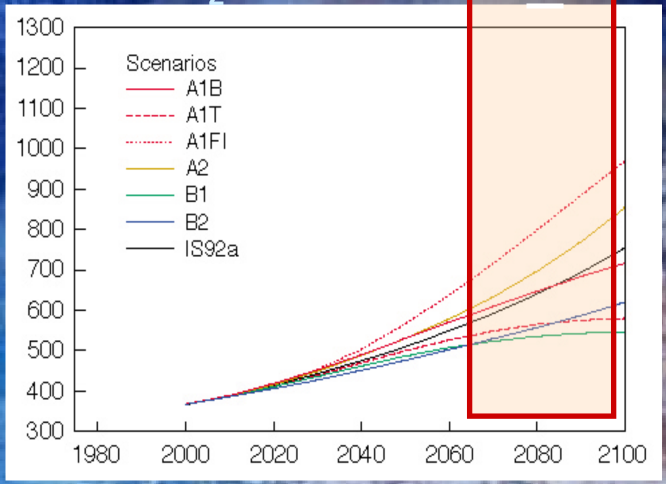
A2: Technological change and economic growth more fragmented, slower, higher population growth – **Less high for 21st century**

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

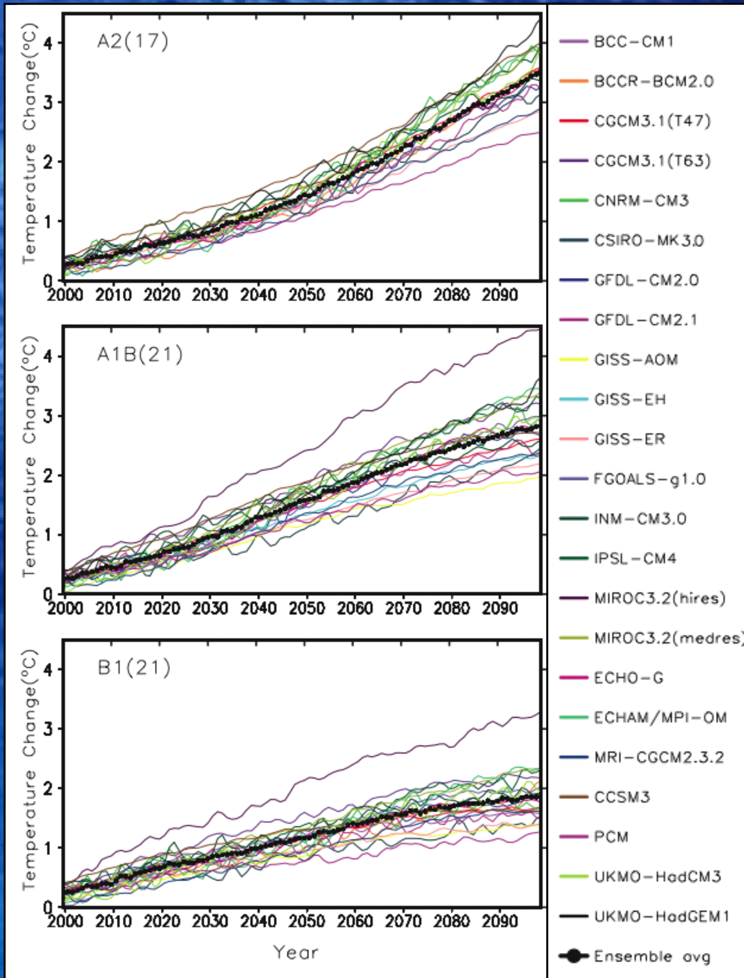


Projecting Impacts with Climate Models

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)

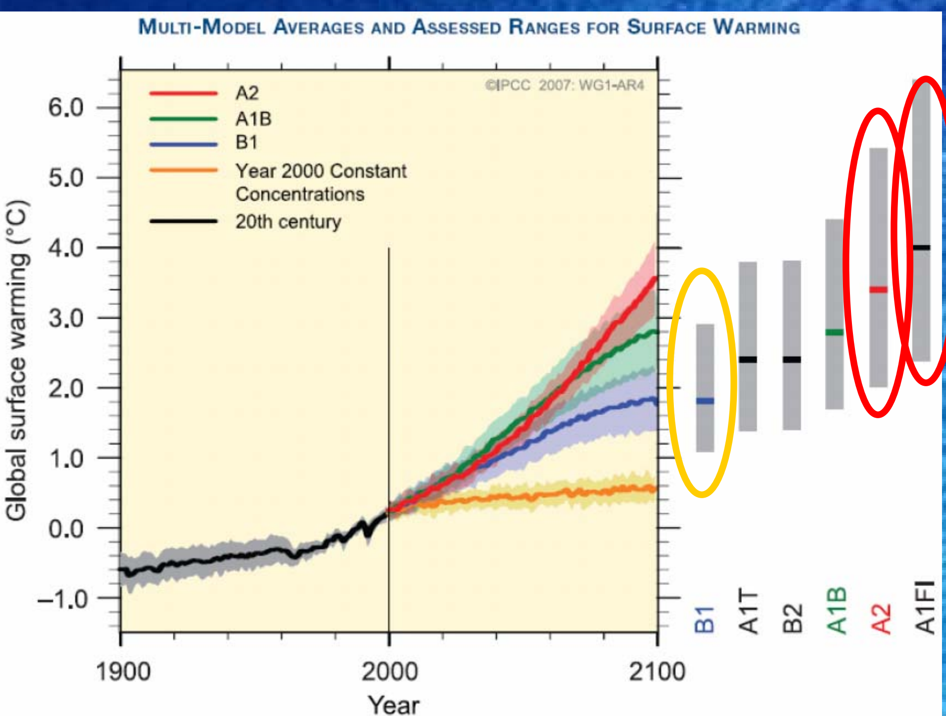
Global mean surface air temperature change of GCMs under same SRES emissions



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

"Bookend" Studies to Cope With Uncertainties

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

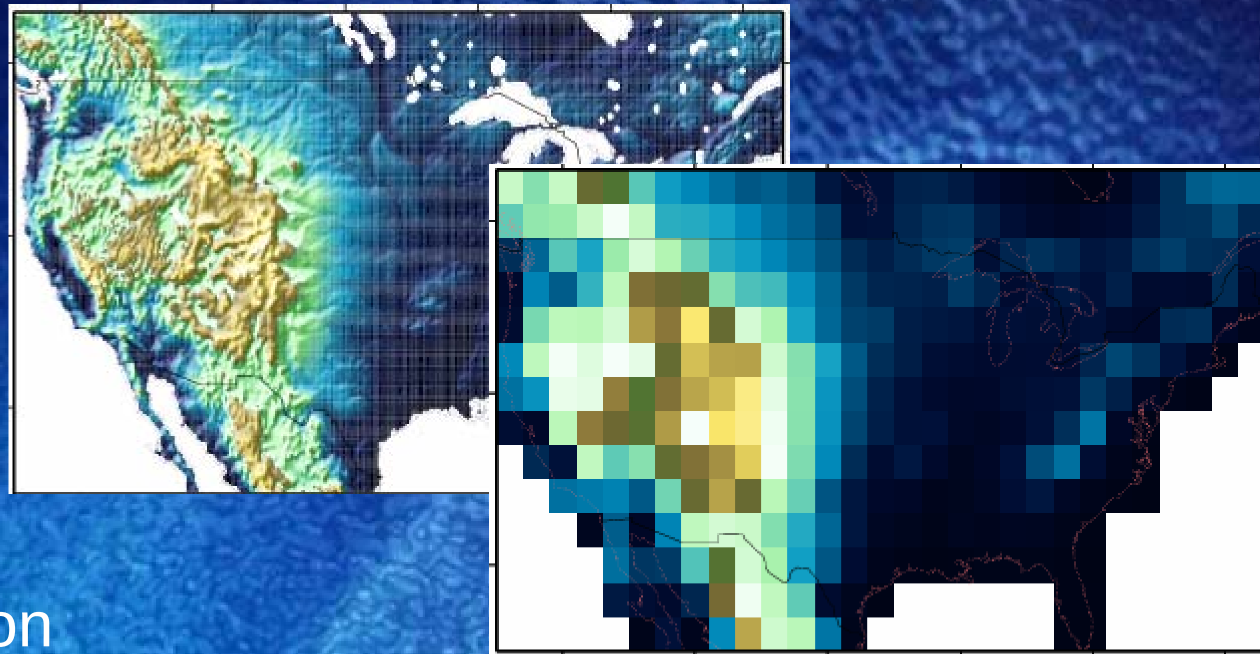


Multiple global estimates quantify uncertainty

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

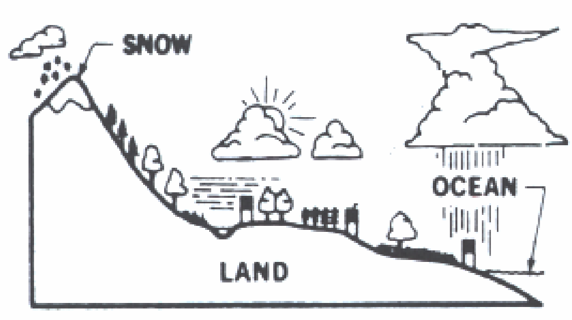
Downscaling: bringing global signals to regional scale

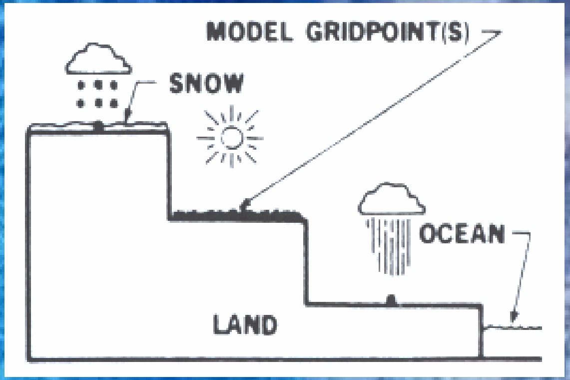
- GCM problems:
  - Scale incompatibility between GCM and impacts
  - Regional Processes not well represented



- Resolved by:
  - Bias Correction
  - Spatial Downscaling

Figure: Wilks, 1995





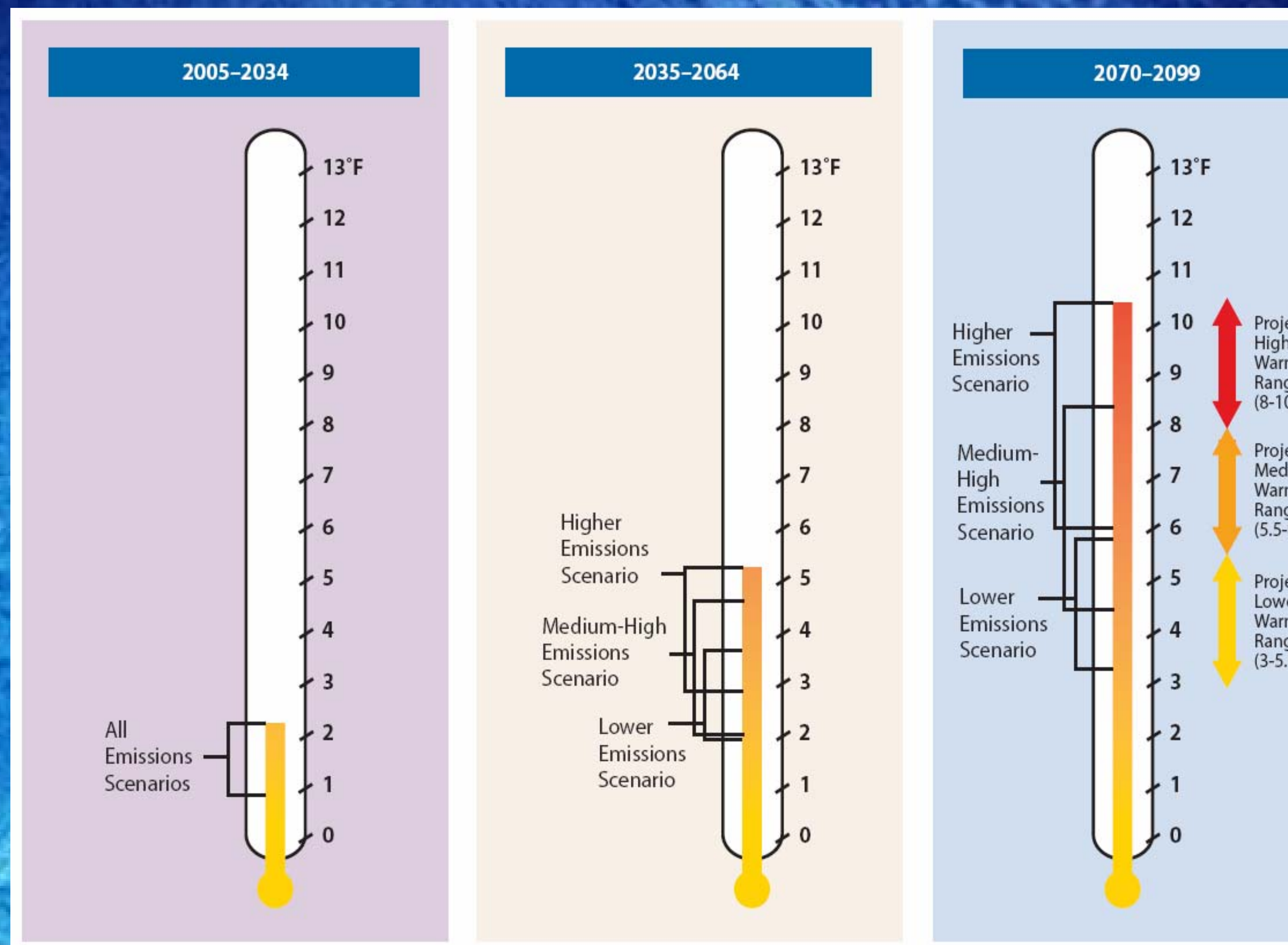
Bracketing Future Warming for California

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



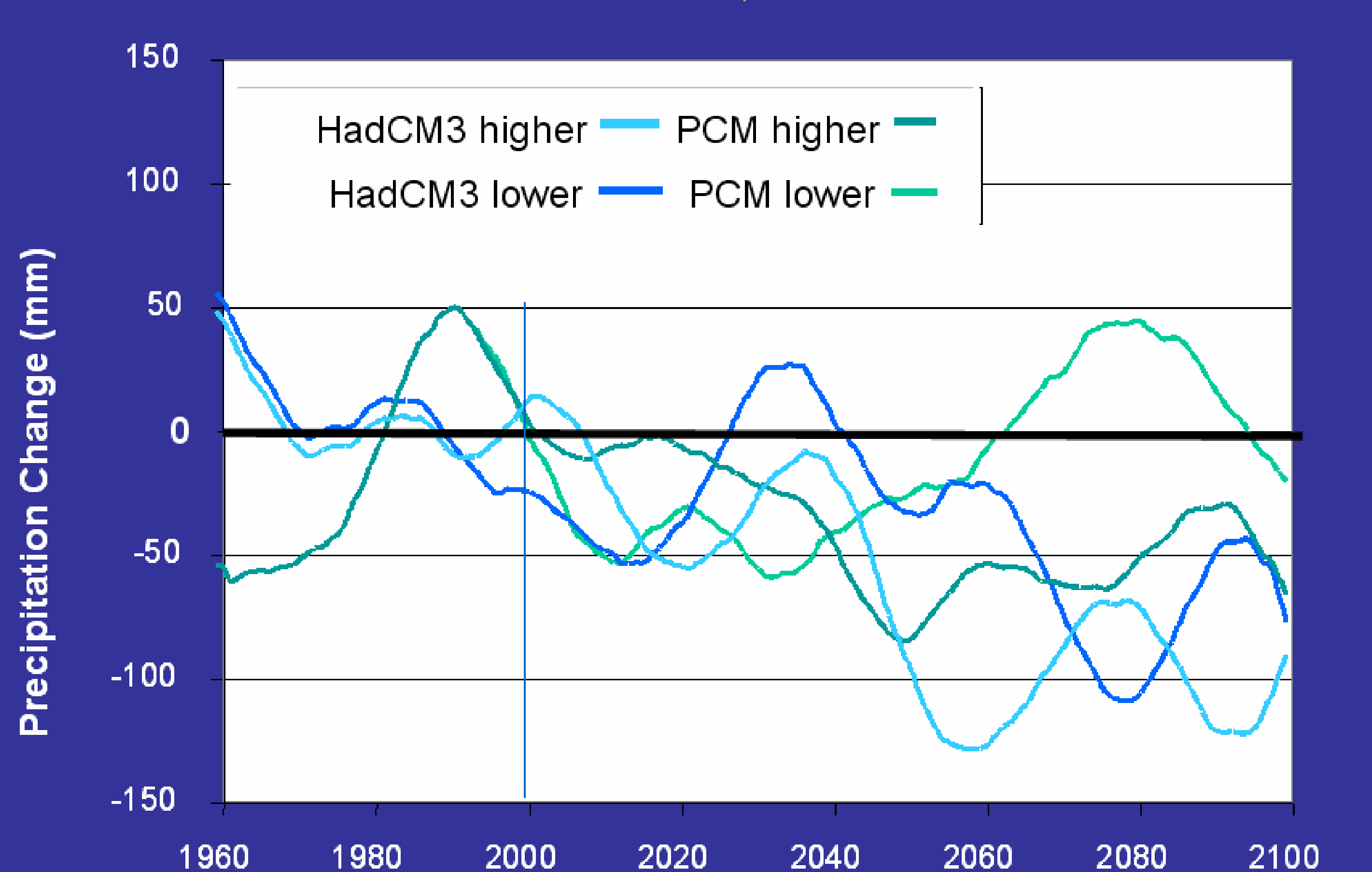
Bracketing Future California Precipitation

Statewide Winter Average

Winter precipitation accounts for most of annual total

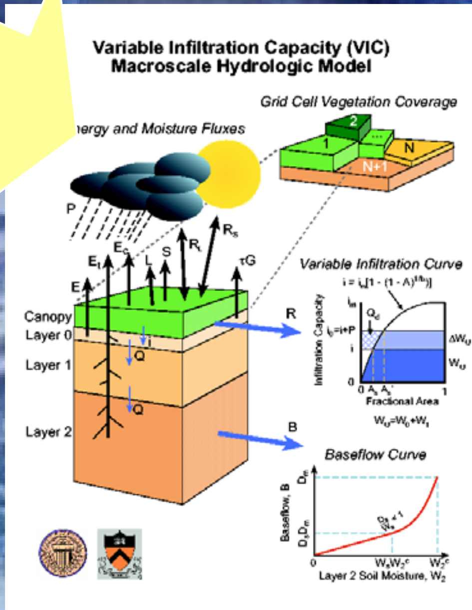
High interannual variability – less confidence in precipitation-induced changes than temperature driven impacts.

Ref: Hayhoe et al., 2004



Generating Regional Hydrologic Impacts

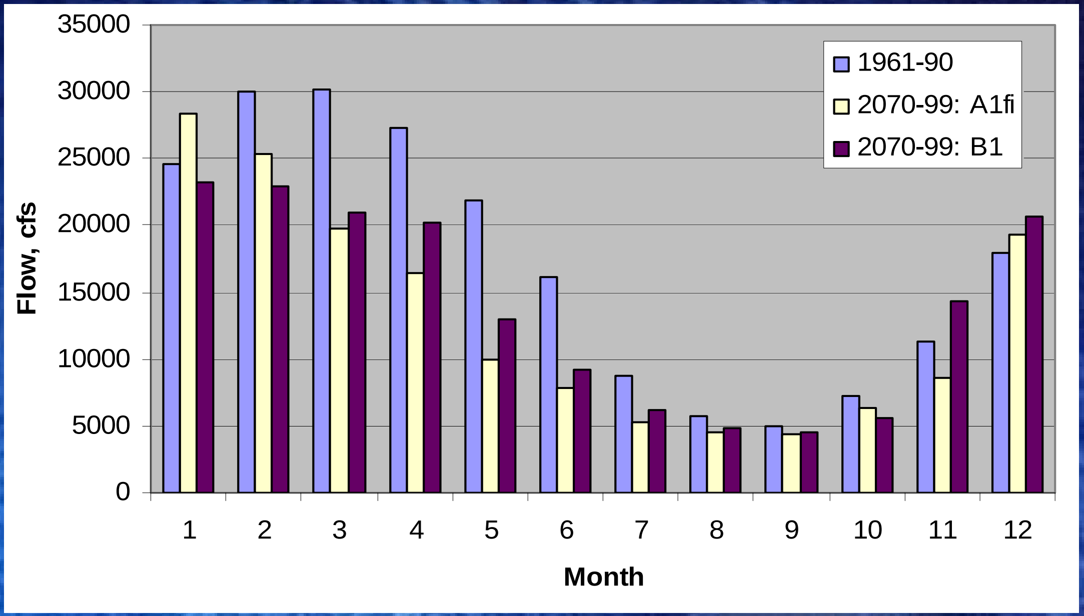
- BCSD downscaling of GCM Precip and Temp
- Use to drive VIC model
- Obtain runoff, streamflow, snow



Bracketing Streamflow Impacts: North CA

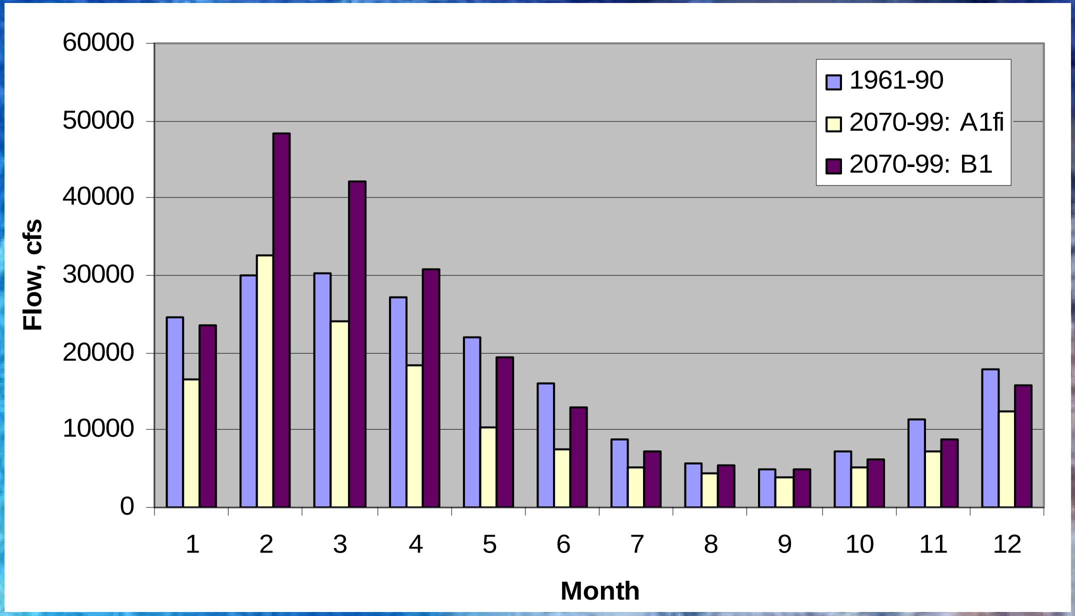
HadCM3 shows:

- 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

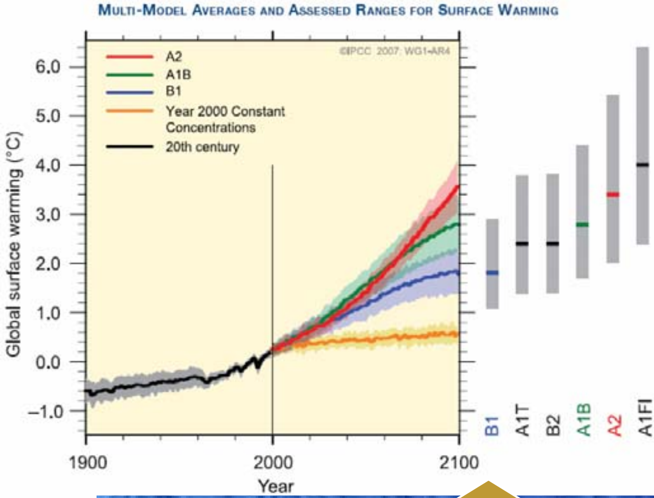
- Reduction in SWP deliveries, esp under high emissions (*Vicuna et al., 2007*)

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

GCM Simulations:
models and emissions

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



Multiple global estimates quantify uncertainty

WCRP CMIP3 Multi-Model Data

1 realization — multiple realizations

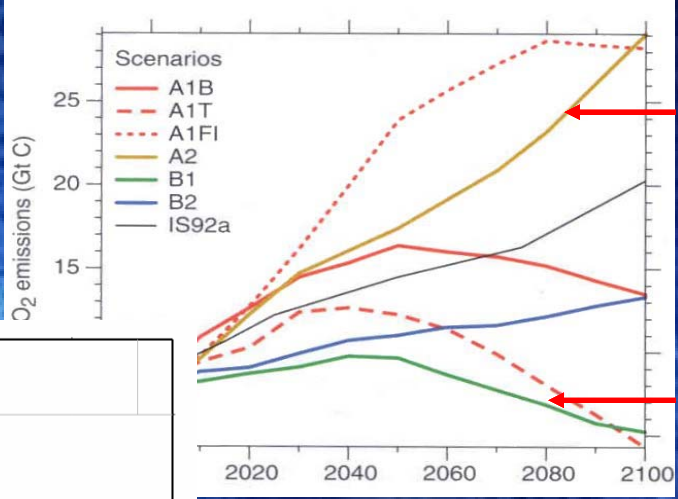
	PIcntrl	PDcntrl	20C3M	Commit	SRESA2	SRESA1B	SRESB1	1%to2x	1%to4x	Slabcntl	2xCO2	AMIP
BCC-CM1, China		2	4				2	1	1			4
BCCR-BCM2.0, Norway	1		1	1	1	1	1	1				
CCSM3, USA	2	1	9	5	5	7	8	1	1	1	1	1
CGCM3.1(T47), Canada	1		5	5	5	5	4	1	1	1	1	
CGCM3.1(T63), Canada	1		1			1	1	1		1	1	
CNRM-CM3, France	1		1	1	1	1	1	1	1			1
CSIRO-Mk3.0, Australia	2		3	1	1	1	1	1		1	1	
CSIRO-Mk3.5, Australia	1		1	1	1	1	1	1				
ECHAM5/MPI-OM, Germany	1		4	3	3	4	3	3	1	1	1	3
ECHO-G, Germany/Korea	1	1	5	4	3	3	3	1	1			
FGOALS-g1.0, China	3		3	3		3	3	3				3
GFDL-CM2.0, USA	1		3	1	1	1	1	1	1	1	1	
GFDL-CM2.1, USA	1		3	1	1	1	1	1	1			
GISS-AOM, USA	2		2			2	2					
GISS-EH, USA	1		5			4		1				
GISS-ER, USA	1		9	1	1	5	1	1	1	1	1	4
INGV-SXG, Italy	1		1		1	1		1	1			
INM-CM3.0, Russia	1		1	1	1	1	1	1	1	1	1	1
IPSL-CM4, France	1	1	2	1	1	1	1	1	1			6
MIROC3.2(hires), Japan	1		1			1	1	1		1	1	1
MIROC3.2(medres), Japan	1		3	1	3	3	3	3	3	1	1	3
MRI-CGCM2.3.2, Japan	1	1	5	1	5	5	5	1	1	1	1	1
PCM, USA	1	1	4	3	4	4	4	5	1			1
UKMO-HadCM3, UK	2		2	1	1	1	1	1				
UKMO-HadGEM1, UK	1		1		1	1		2	1	1	1	1

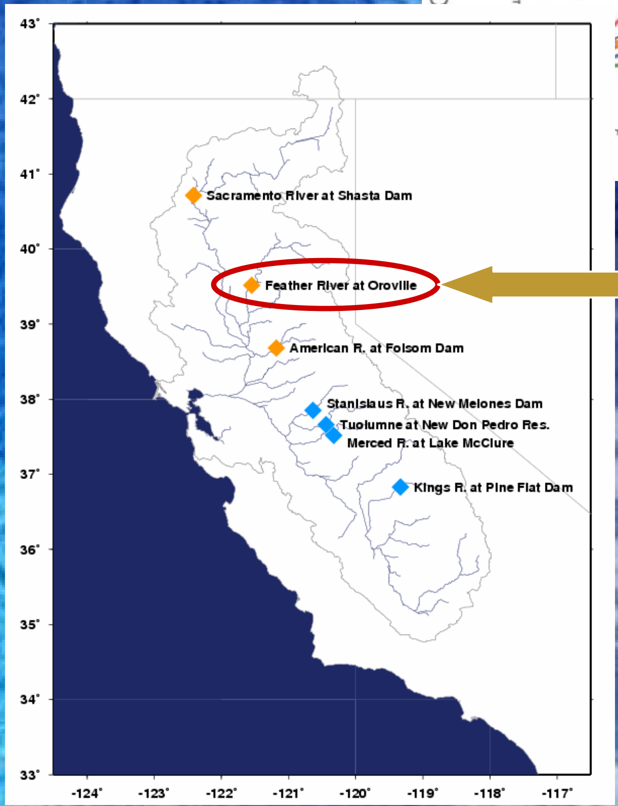
Comparing Impacts to Variability

- 11 GCMs, most recent generation (IPCC AR4)
- 2 Emissions scenarios for each GCM:

  -A2
  -B1

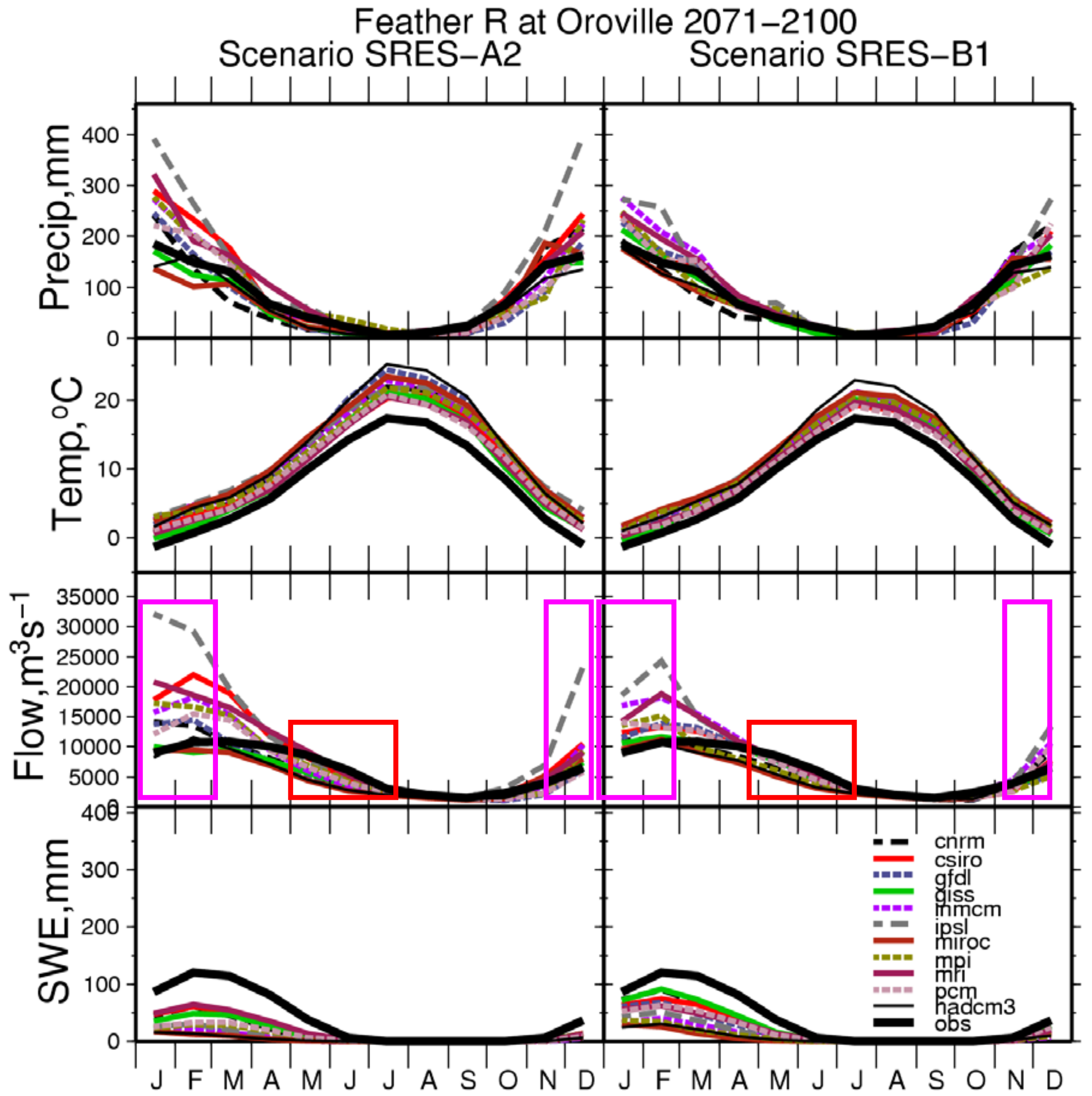
- Same bias correction, downscaling, hydrologic modeling





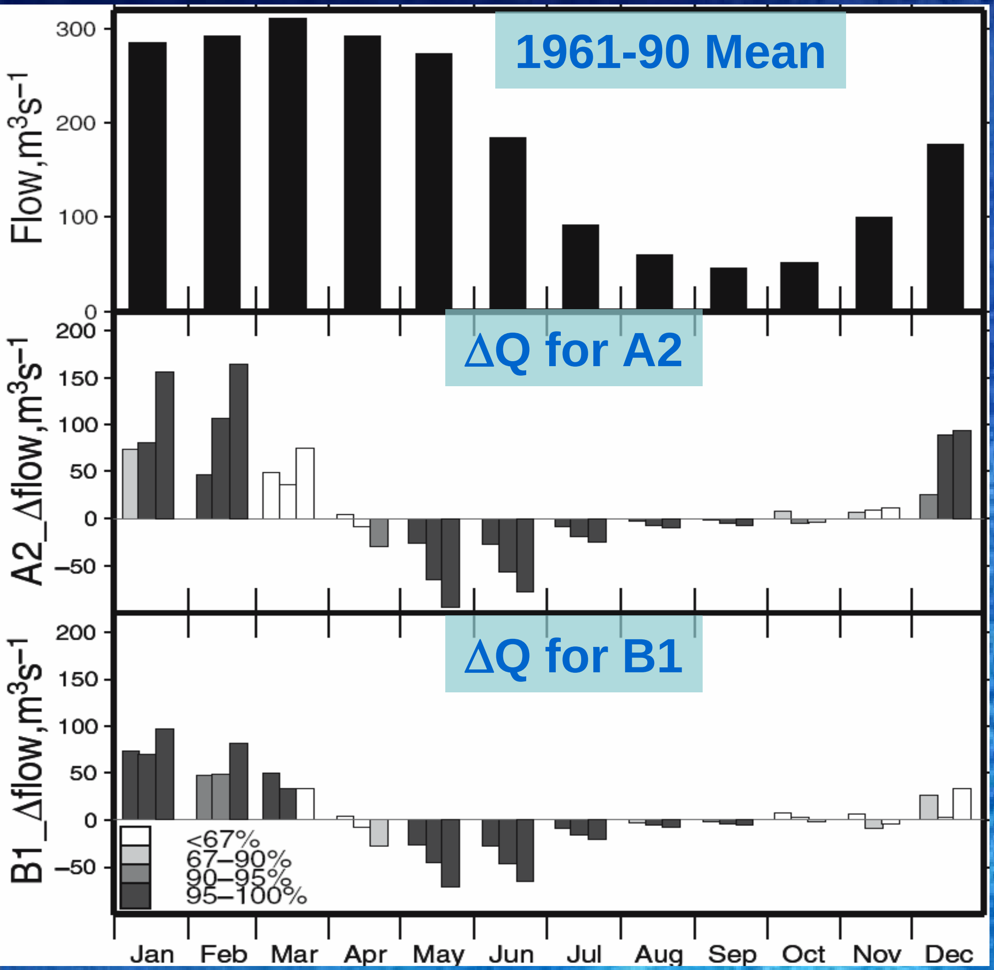
Feather R.

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



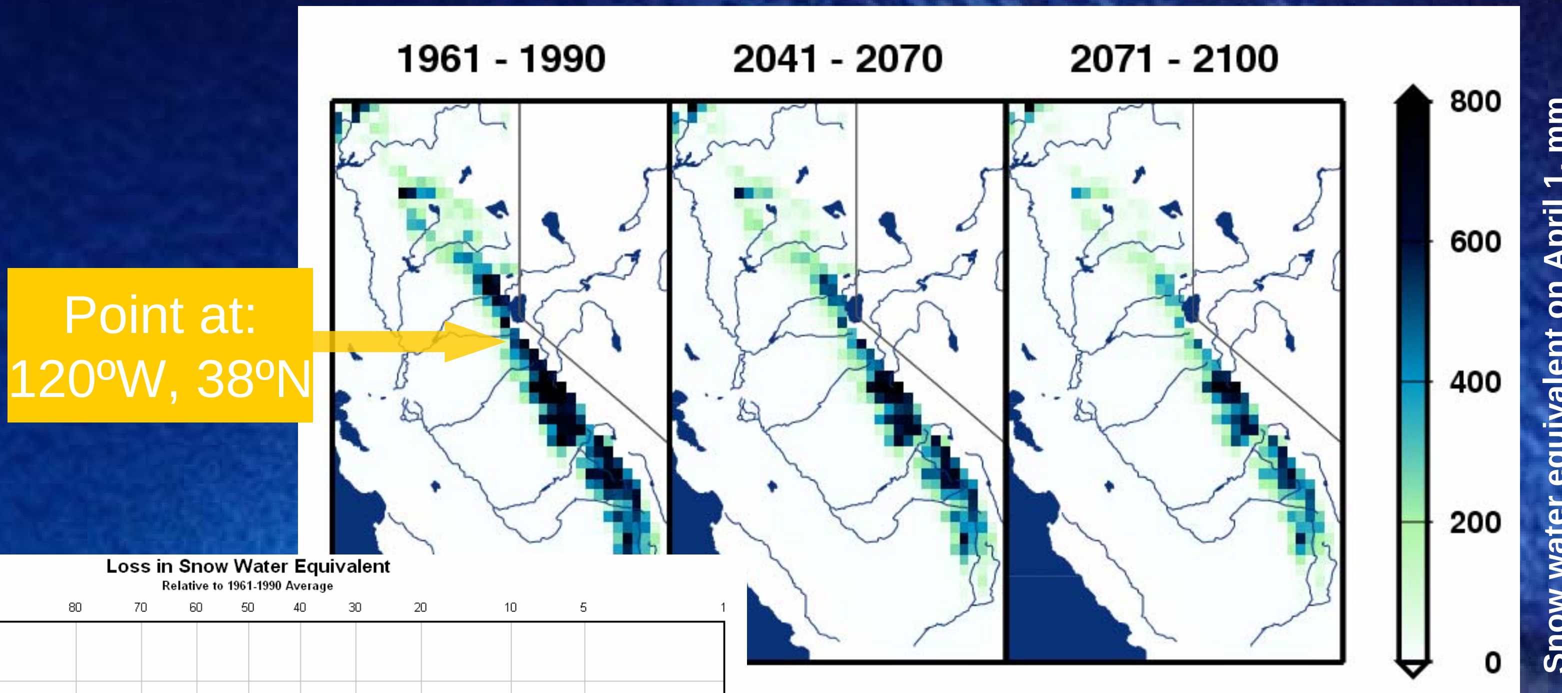
All increases in winter and decreases in spring-early summer flows are high confidence (>95%)

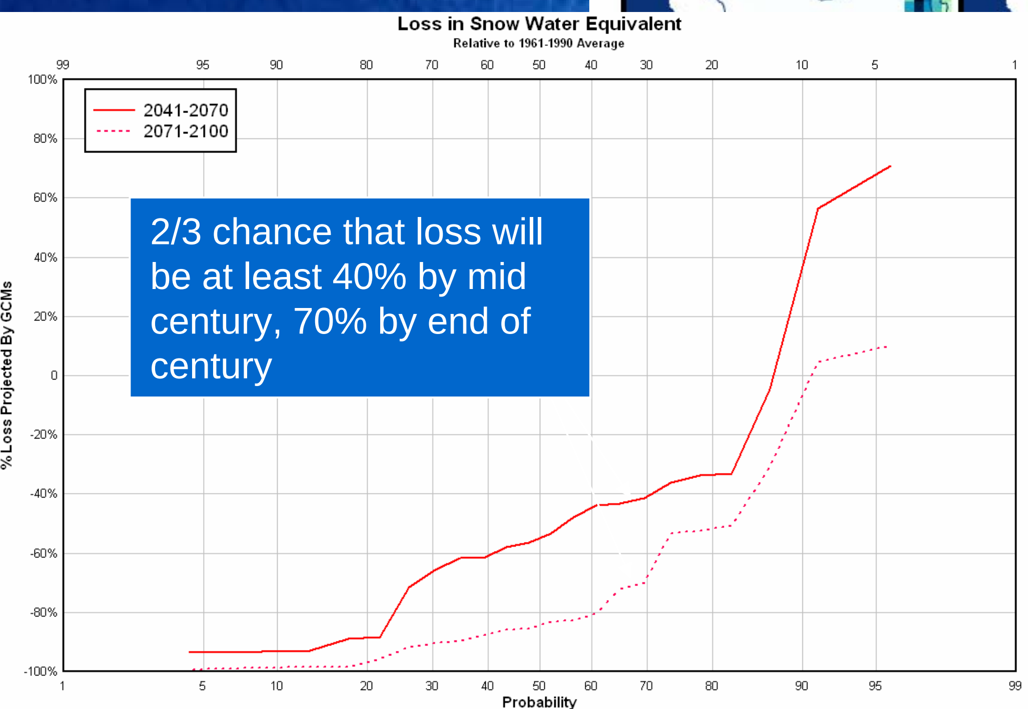
Only May-August are differences in flow (A2 vs. B1) statistically different at >70%

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

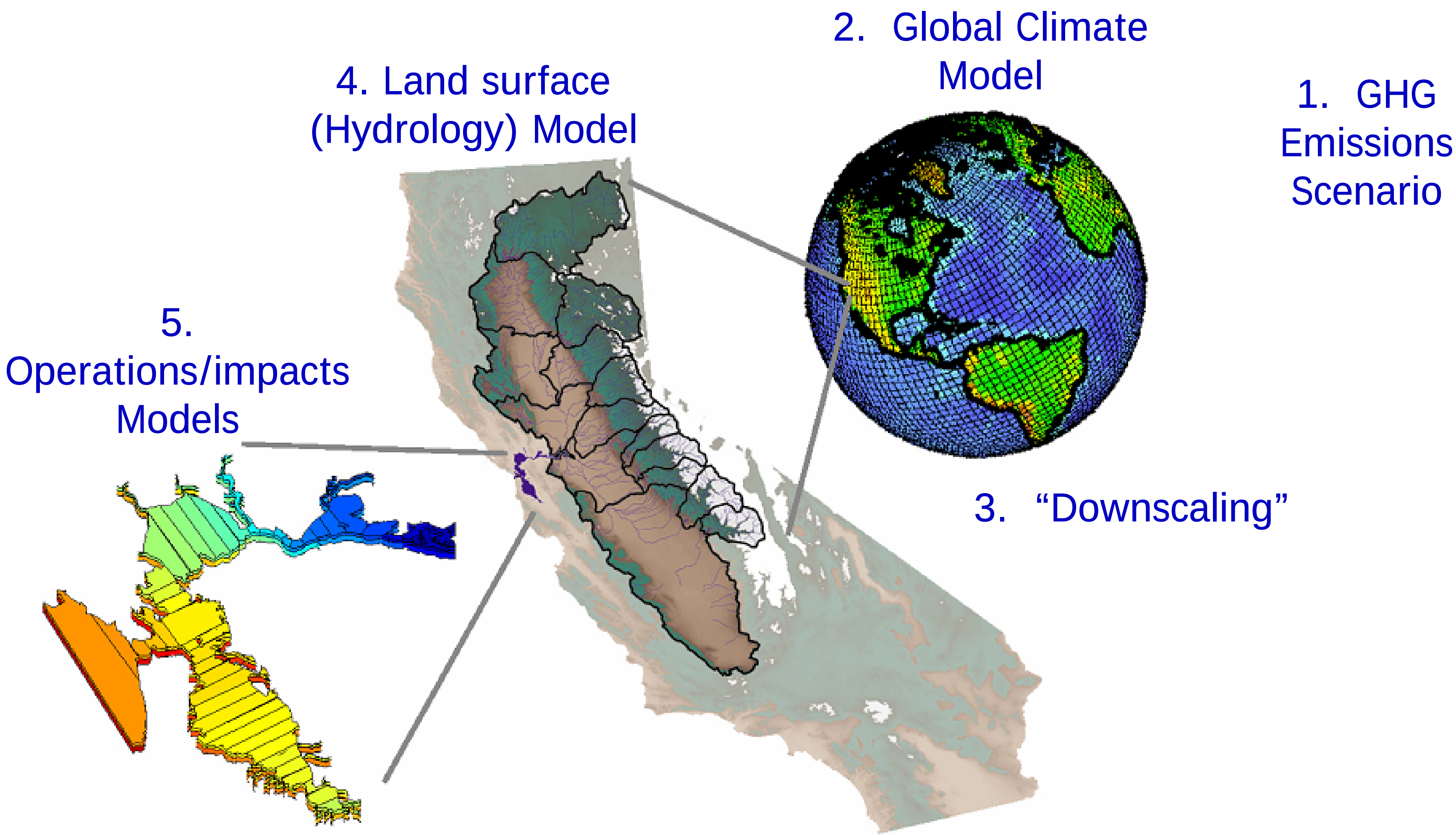
Impact Probabilities for Planning





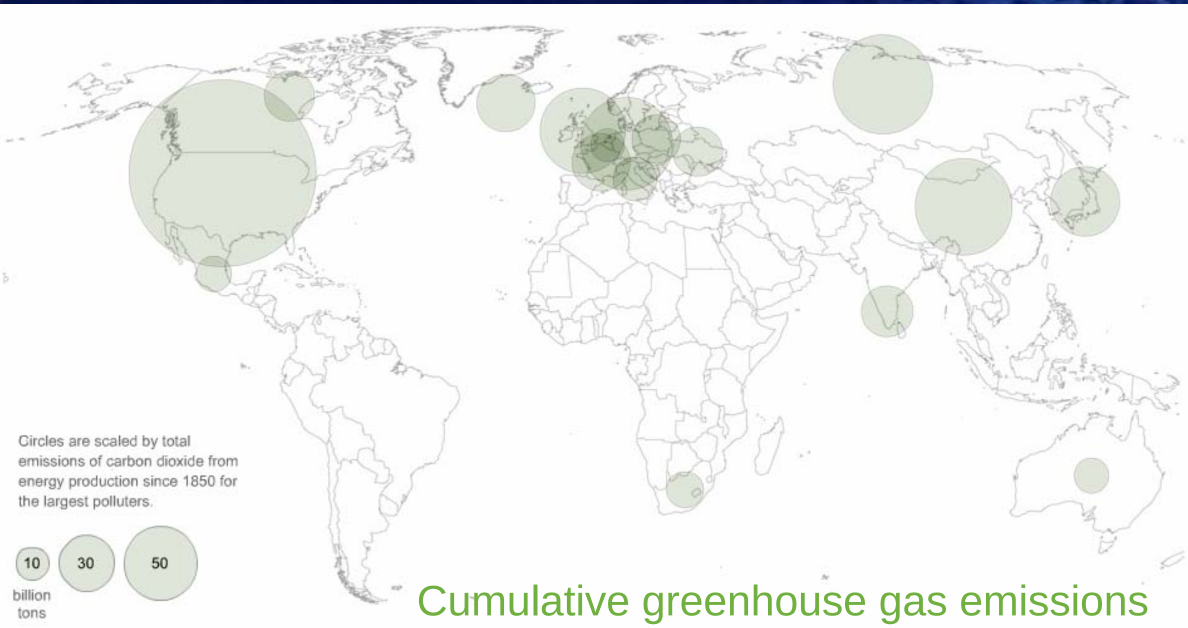
- Combine many future scenarios, models, since we don't know which path we'll follow (22 futures here)
- Choose appropriate level of risk

Revisiting Uncertainty Sources



Adapted from Cayan and Knowles, SCRIPPS/USGS, 2003

Expanding beyond California



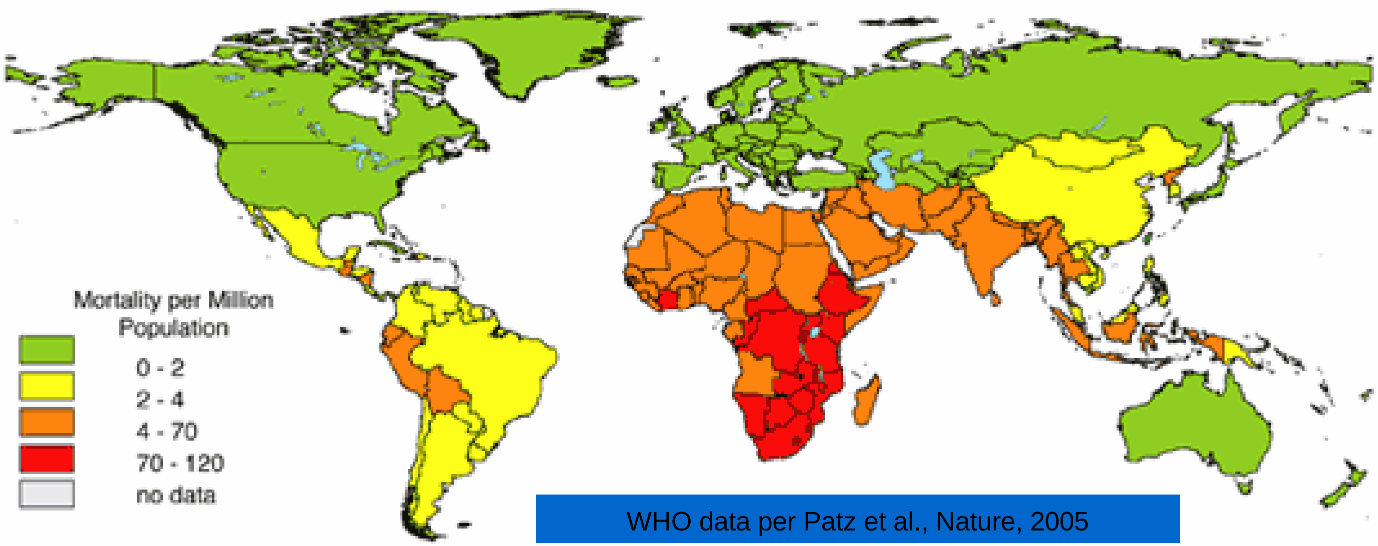
Cumulative greenhouse gas emissions

Sources: World Resources Institute; Intergovernmental Panel on Climate Change Working
Shishmaref Erosion and Relocation Coalition; Monsanto; Thames Estuary 2100; BAST; B
peer-reviewed scientific papers

Changes in health outcomes, including:

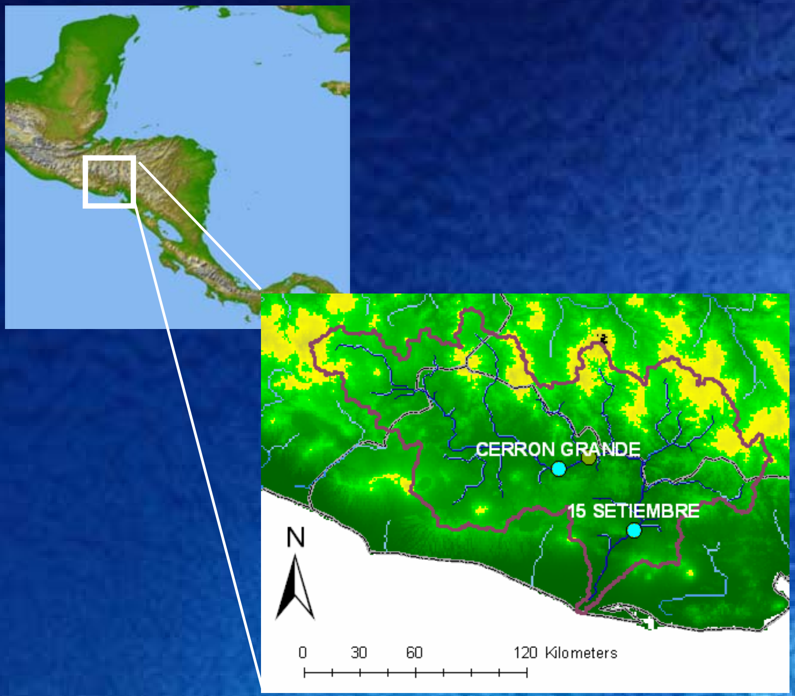
- cardiovascular diseases
- diarrhea
- malaria
- inland and coastal
- flooding
- malnutrition

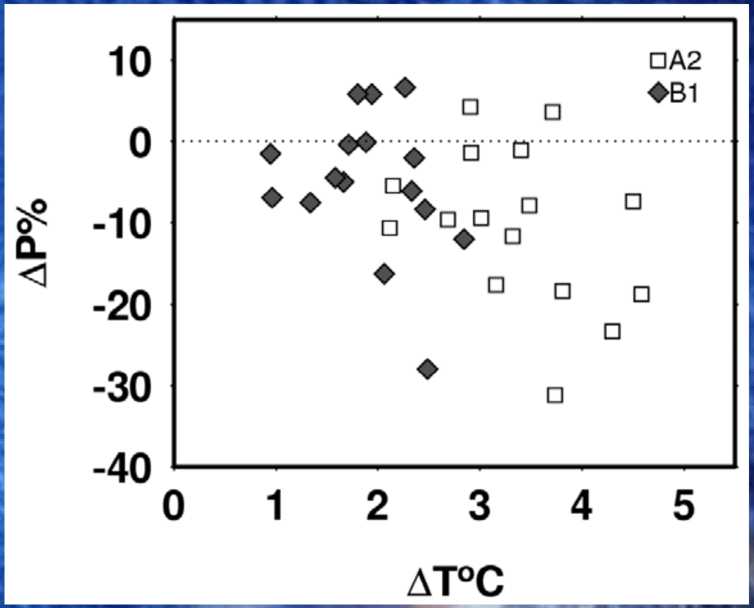
Estimated Deaths Attributed to Climate Change in the Year 2000, by Subregion*



WHO data per Patz et al., Nature, 2005

Changes for the Rio Lempa basin

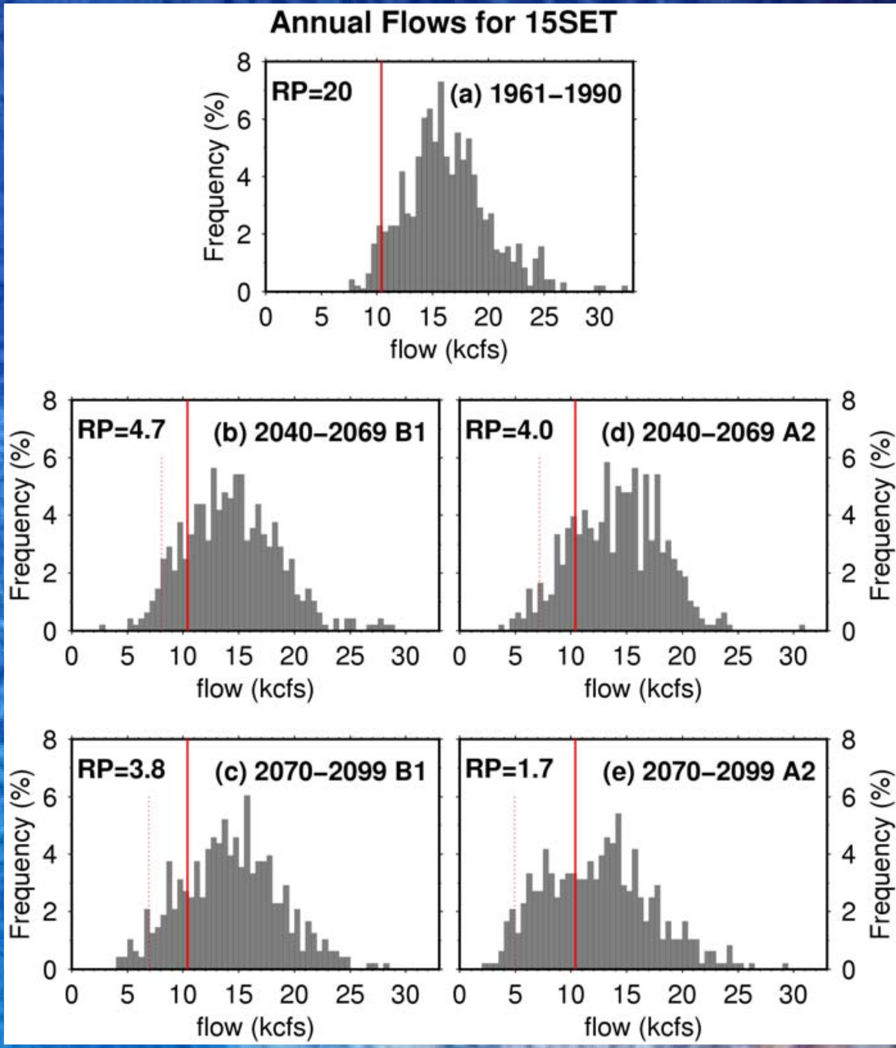




- Warming for A2 significantly higher than B1
- Only 5 of the 32 GCMs show wetter futures
- GCMs under warmer A2 are drier than B1.

Changes to Inflows at 15 Setiembre

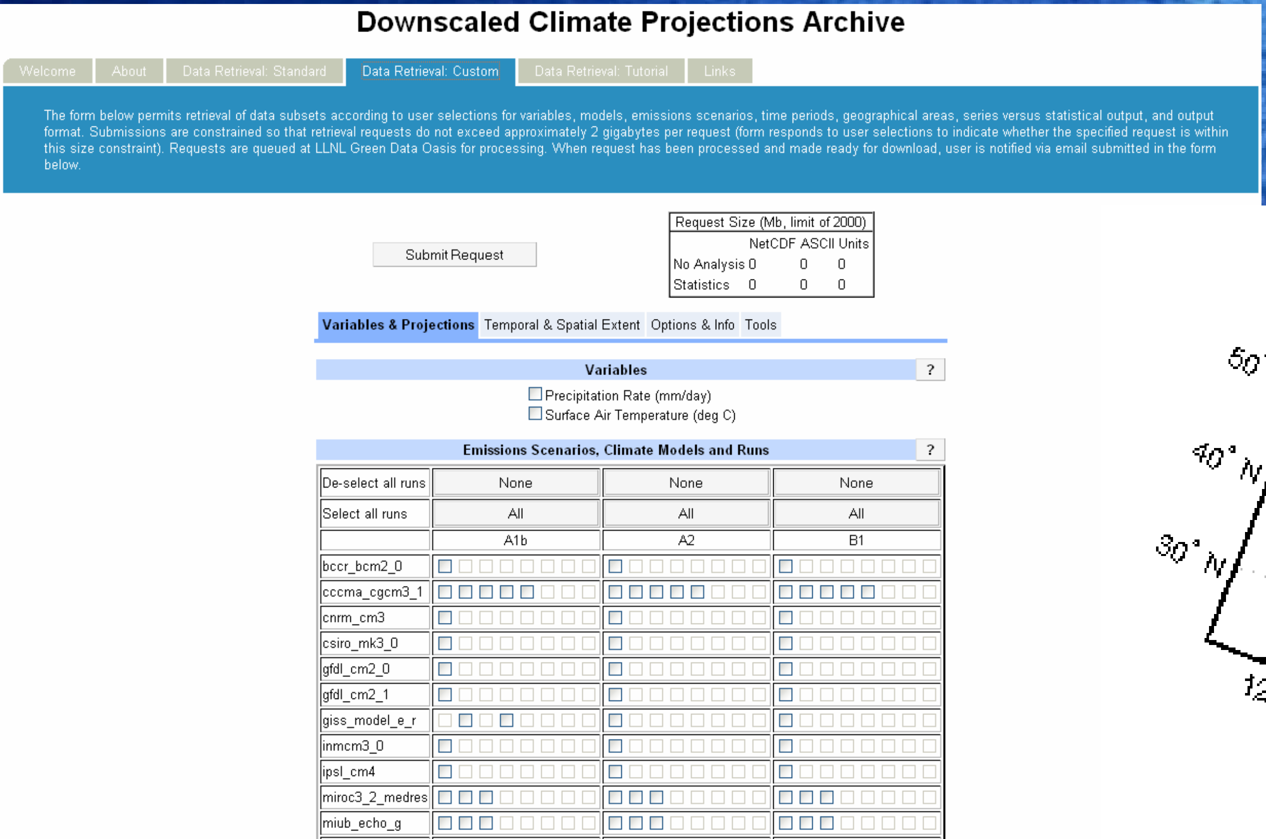
- Inflows to the major reservoirs will decline by 13-24%
- Greatest drops in reservoir inflow July-August, 21 to 41%.
- Drop in firm hydropower generation capability may range from 33% to 53% near the end of the 21st century.
- 20-year return low flow, a measure of firm hydropower production capacity, drops 33% (B1) to 53% (A2) by 2070-2099



Sharing Data for 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



Downscaled Climate Projections Archive

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The form below permits retrieval of data subsets according to user selections for variables, models, emissions scenarios, time periods, geographical areas, series versus statistical output, and output format. Submissions are constrained so that retrieval requests do not exceed approximately 2 gigabytes per request (form responds to user selections to indicate whether the specified request is within this size constraint). Requests are queued at LLNL Green Data Oasis for processing. When request has been processed and made ready for download, user is notified via email submitted in the form below.

Submit Request

Request Size (Mb, limit of 2000)	NetCDF	ASCII	Units
No Analysis	0	0	0
Statistics	0	0	0

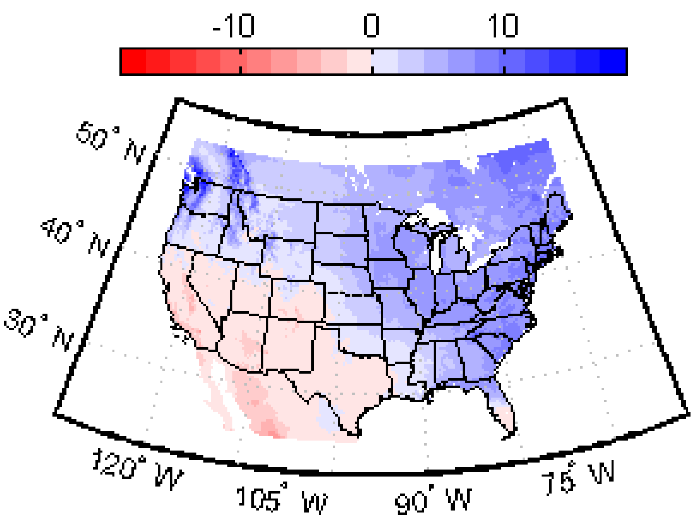
Variables & Projections | Temporal & Spatial Extent | Options & Info | Tools

Variables ?

- Precipitation Rate (mm/day)
- Surface Air Temperature (deg C)

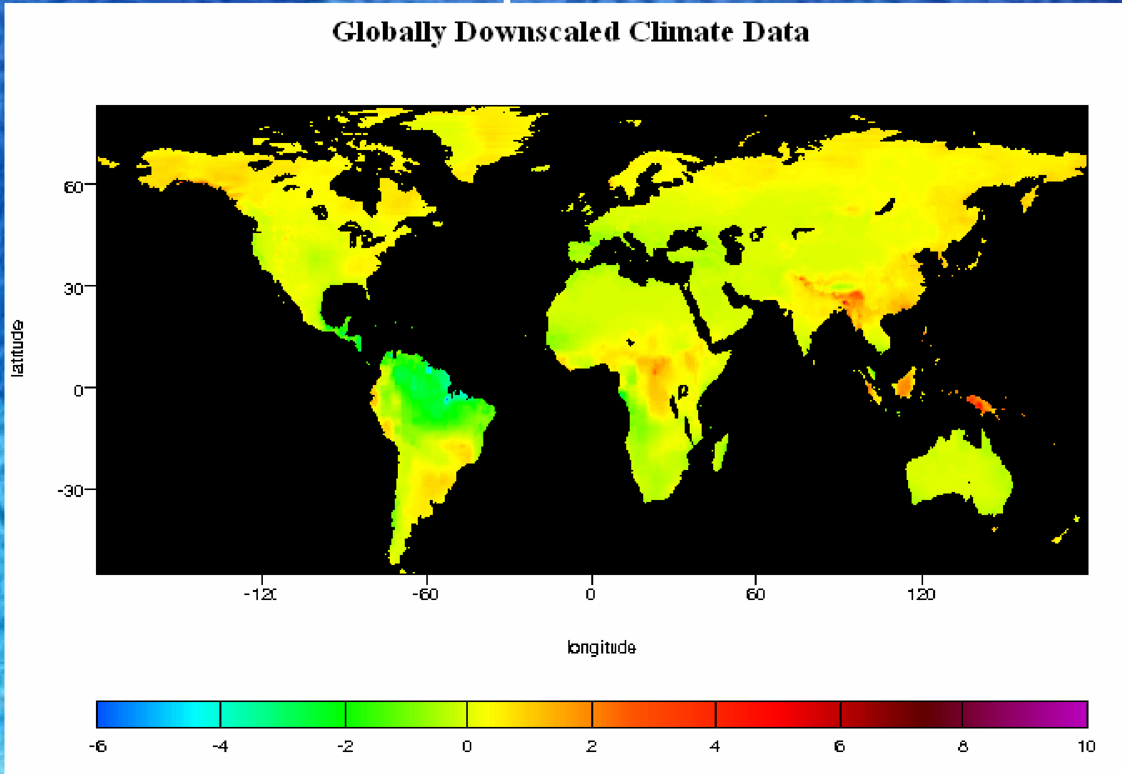
Emissions Scenarios, Climate Models and Runs ?

De-select all runs	None	None	None
Select all runs	All	All	All
	A1b	A2	B1
bccr_bcm2_0			
cccma_cgcm3_1			
cnrm_cm3			
csiro_mk3_0			
gfdl_cm2_0			
gfdl_cm2_1			
giss_model_e_r			
inmcm3_0			
ipsl_cm4			
miroc3_2_medres			
miub_echo_g			



Multi-model ensembles for global studies

- ½ - degree (~50km) downscaled GCM data available for 48 GCM runs through 2099.
- http://www.engr.scu.edu/~emaurer/global_data
- Interactive interface under development



Thanks!