Climate Change in Colorado

A Synthesis to Support Water Resources Management and Adaptation

A REPORT FOR THE COLORADO WATER CONSERVATION BOARD

Colorado
University of Colorado at Boulder

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COLORADO WATER CONSERVATION BOARD
STATE OF COLORADO
1876
1937

Western Water Assessment

Colorado
University of Colorado at Boulder

Climate Change in Colorado: Overview

State of the science regarding the physical aspects of climate change that are important for evaluating impacts on Colorado's water resources, and developing adaptation strategies out to the mid-21st century

Commissioned by **CWCB**

Supports

- Governor Ritter's **Colorado Climate Action Plan**
- State Water Supply Initiative
- Governor's Conference on Managing Risks of Drought and Climate
- Complements several other efforts

Audience

- Water-related planners, decisionmakers, and policymakers in Colorado

Technical Level

- More technical than "Citizen's Guide", less technical than the IPCC reports
- Jargon minimized; glossary; Fahrenheit units; Published figures/data re-plotted for simplicity and to focus on CO
- Educate about models and their strengths and weaknesses

Western Water Assessment

Climate Change in Colorado: Process

Quick turn-around ~ 4 months.

Colorado-focused studies lacking: we had to extract results, re-do graphics, or perform analysis of existing data for Colorado-specific graphics.

Involvement by a broad panel -- over 350 comments!

Geographic Scope

- Colorado
- Colorado's River Basins
- Western United States

Uncertainty -- "*Likelihood*" has a specific meaning in climate science

- Evaluating the research at the level of saying "X is ***very likely*** to happen" requires a lengthier and more involved process than we could accommodate. We quote "likelihood statements" from other assessments where appropriate.

Climate Change in Colorado: Multiple levels of detail

- Executive Summary
- Key Points
- Technical details in the text
- Sidebars -- Examples of use of climate change information
  - –Aspen
  - –Boulder
  - –Front Range Vulnerability Study

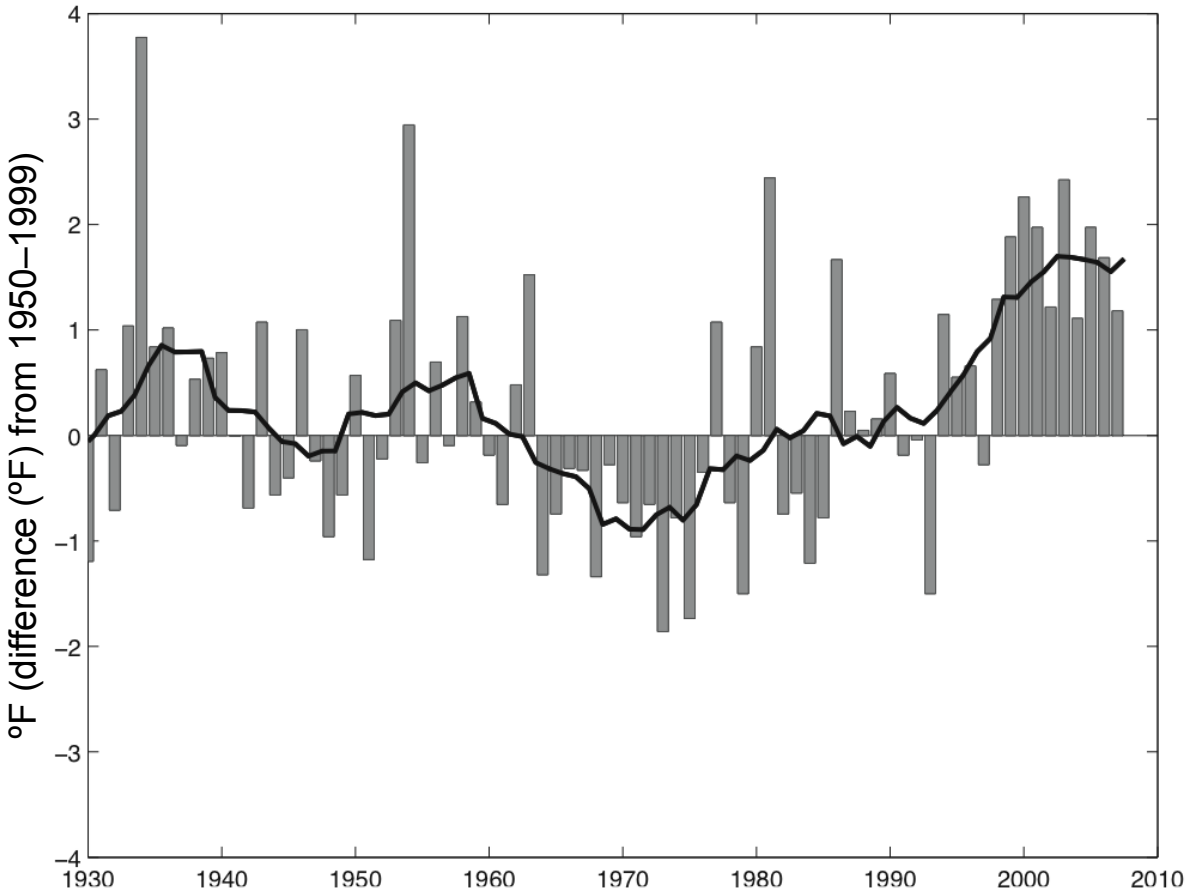
"Cognitive Challenges"

"Cognitively, climate change information is difficult to integrate into water resources management.

- First, within the water resources engineering community, the **stationarity assumption** is a fundamental element of professional training.
- Second, the century **time scales of climate change** exceed typical planning and infrastructure design horizons and are remote from human experience.
- Third, even individuals trying to stay up-to-date can face confusion in conceptually melding **the burgeoning climate change impacts literature**."

CCSP 5.1, Chapter 5, "Decision Support for Water Resources Management", Holly C. Hartmann, lead author.

Observations: Statewide Temperature Trend

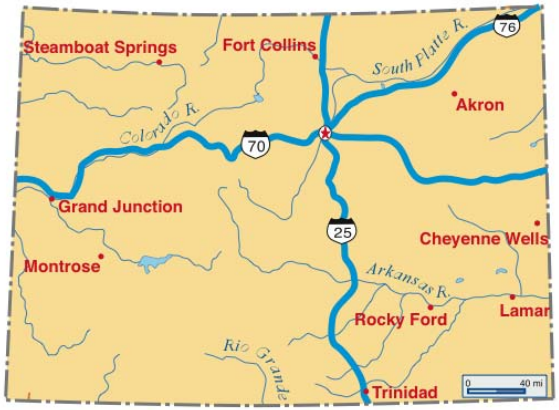


Temperatures in Colorado have increased by about 2ºF during the past 30 years.

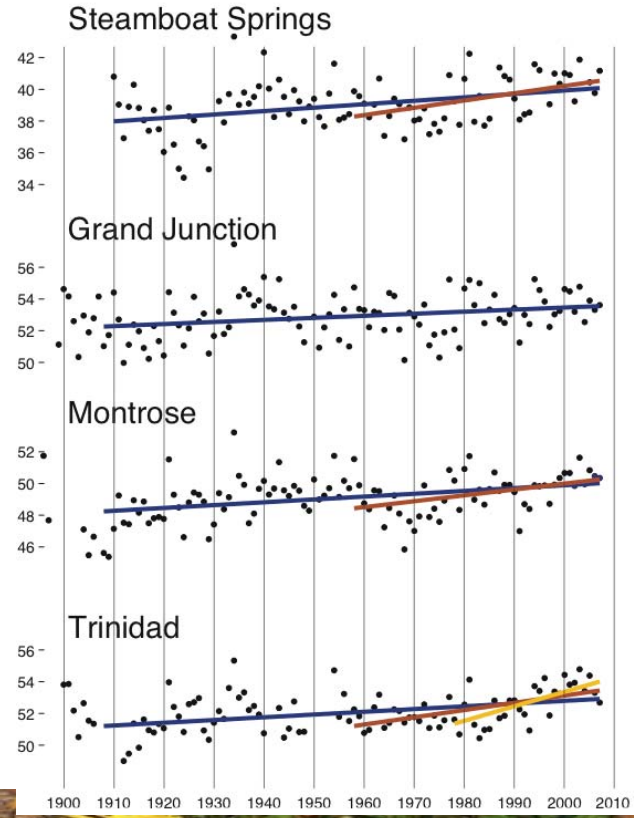
Warm periods in the 1930's and 1950's, cool period during the 1960's- early 1970's

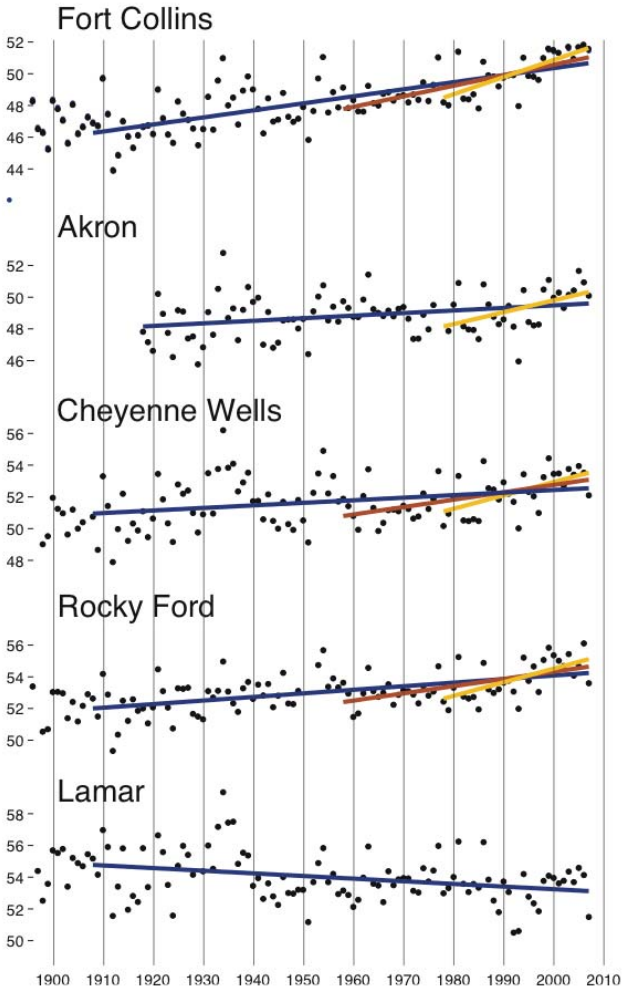
Data: National Climatic Data Center
Graphics: CO Climate Report, 2008

Observations: Temperature



Source: CO Climate Report, 2008





Of 27 temperature trends computed :

- 19 are increasing
- 1 is decreasing
- 7 were not significant

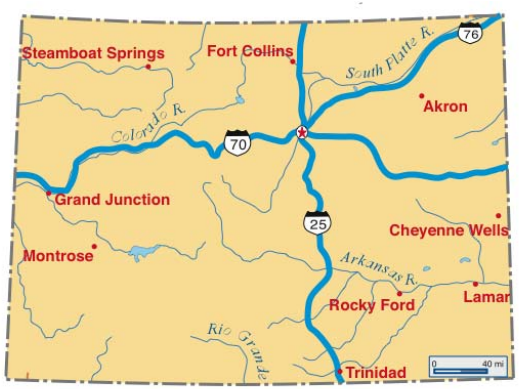
A trend at a single station is not definitive because of local effects. Look at the big picture!

30 year trend

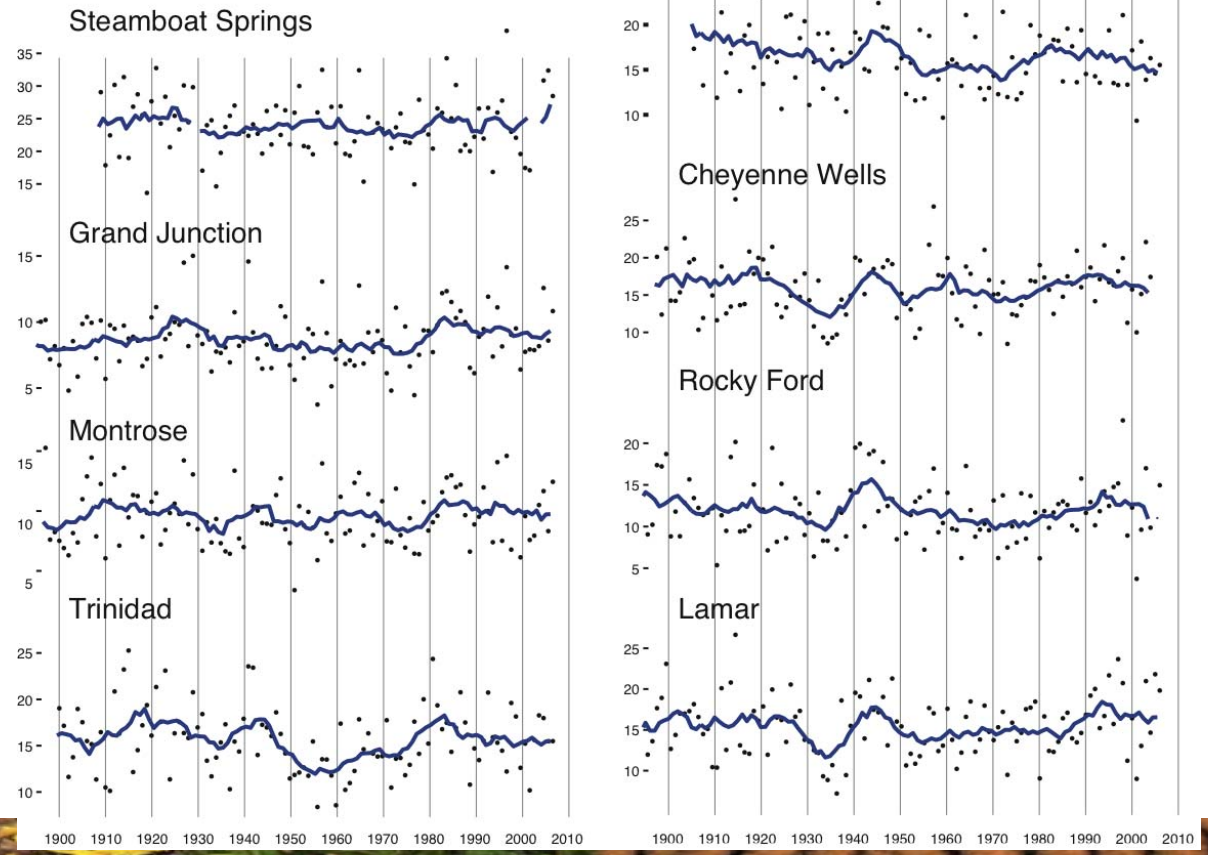
50 year trend

100 year trend

Observations: Precipitation

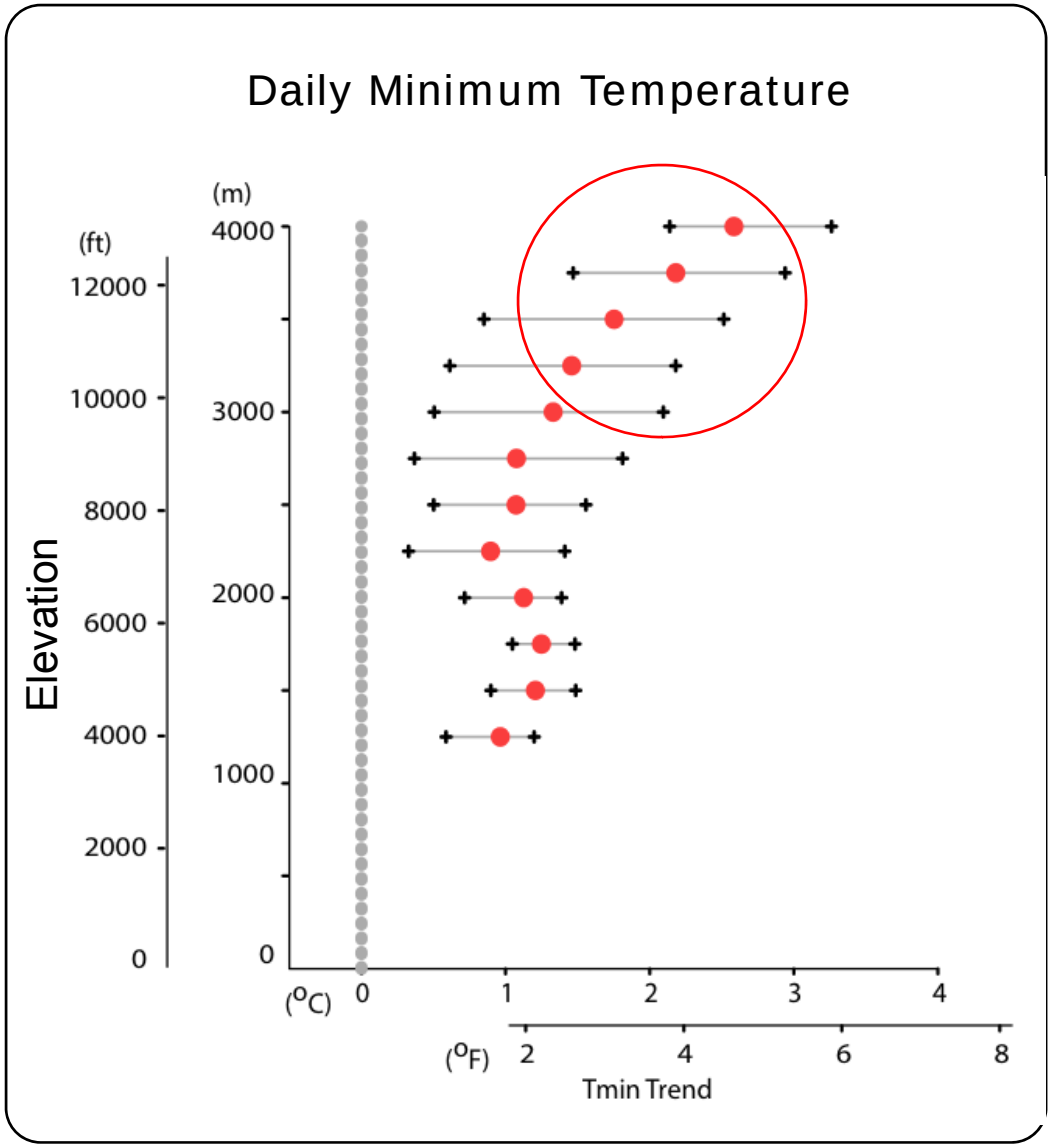


Source: CO Climate Report, 2008



In all parts of Colorado, no consistent long-term trends in annual precipitation is detected.

Observations: Temperature and Elevation (1979–2006)



Temperatures have increased more at high elevations.

Warmer Spring temperatures have lead to earlier runoff.

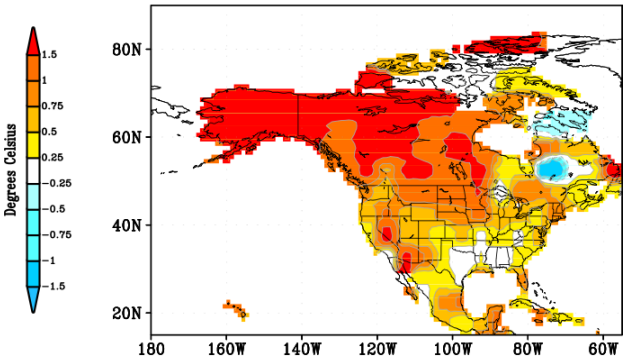
However…

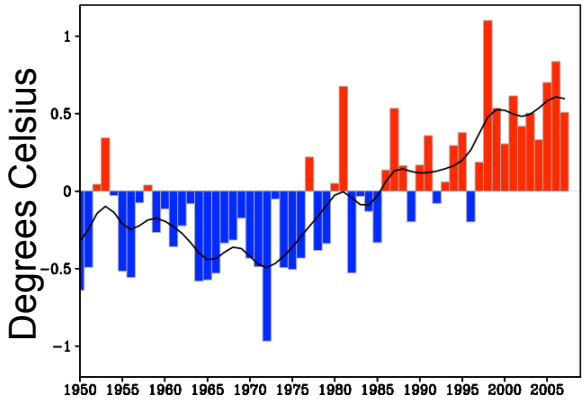
- Changes in the proportion of precipitation falling as rain rather than snow are small.
- No significant widespread change in Colorado's total snowpack
- Temperatures at high elevation remain below freezing in the Winter
- Almost no meteorological data from the alpine zone

Source: Diaz and Eischeid, 2007

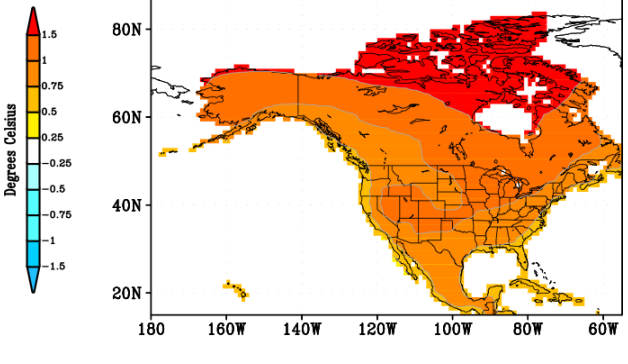
Attribution: Observed v. Modeled Temperature (1950–2007)

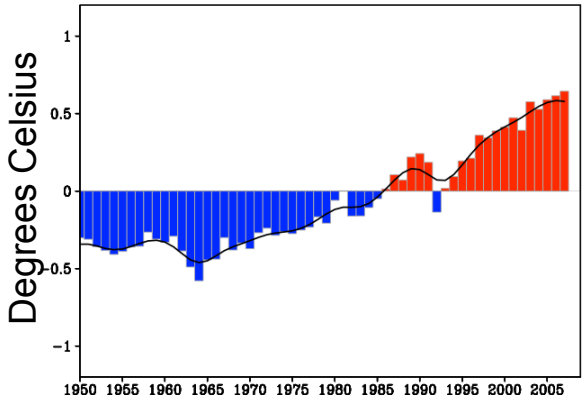
Observed





Modeled



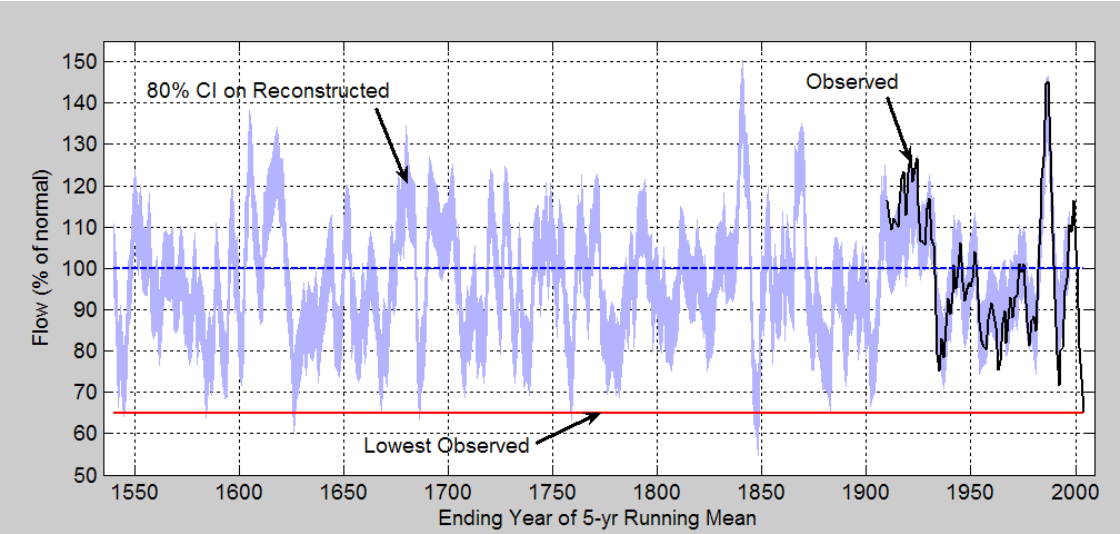


Attribution of observed temperature changes to greenhouse gas emissions more difficult at smaller spatial scales because climate variability is larger at these scales.

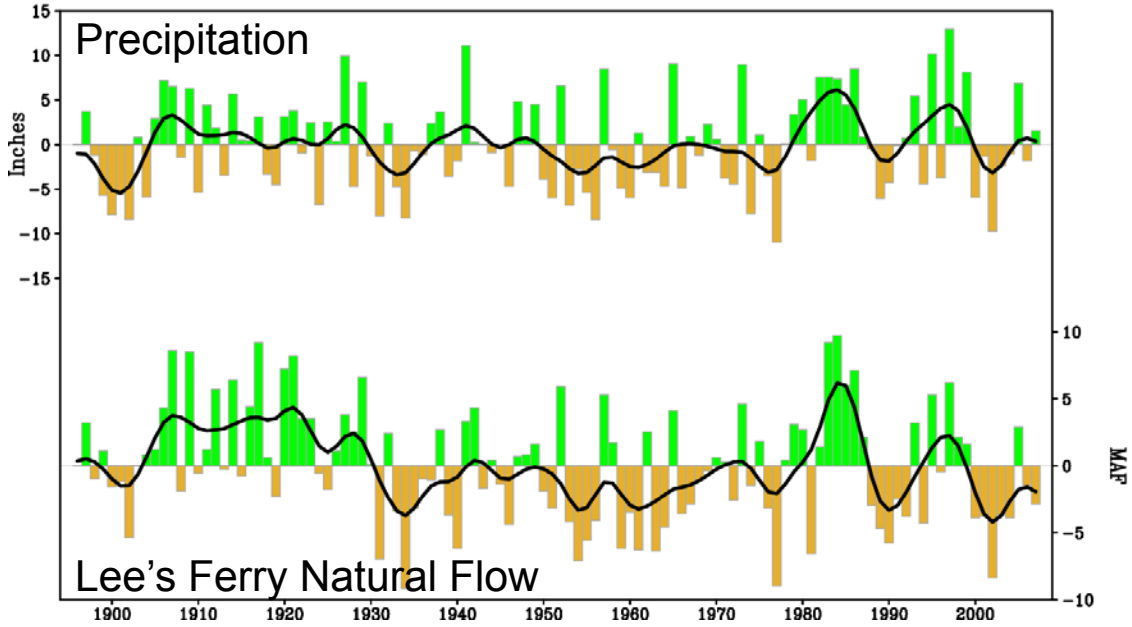
- The accumulation of greenhouse gases in the atmosphere is *very likely* the cause of most of the increase in global average temperature (IPCC).
- In North America, "human-induced warming has *likely* caused much of the average temperature increase over the past 50 years" (CCSP 3.3).
- Climate models show a 1F warming in the West in the last 30 years in response to greenhouse gas emissions.

Source: CO Climate Report, 2008

Precipitation and River Flow in the Upper Colorado Basin



The paleoclimate record shows longer and more severe droughts than in the historical record.



Historical droughts/low flows can be attributed mainly to changes in precipitation

Nevertheless, there is an indication that recent warming has increased the severity of drought in the southwest United States.

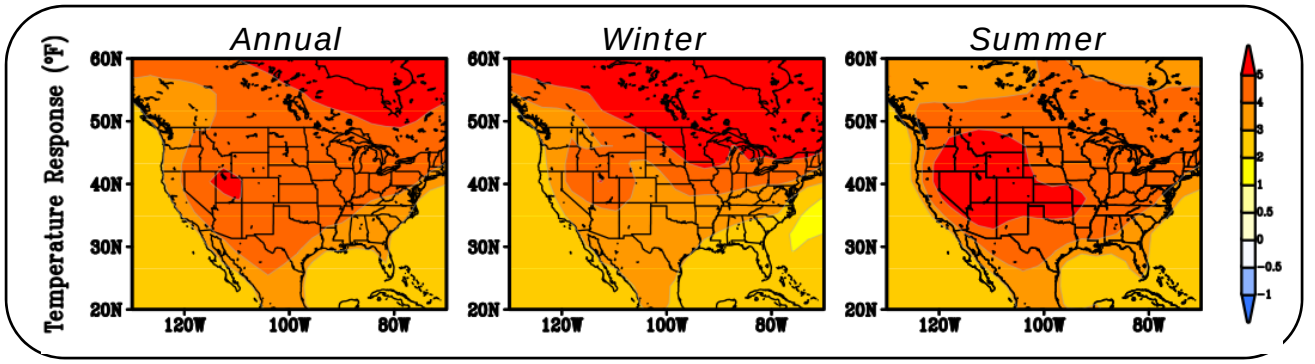
Will future droughts be qualitatively different because of projected warming?

Source: CO Climate Report, 2008

Projected Temperature & Precipitation Changes in 2050

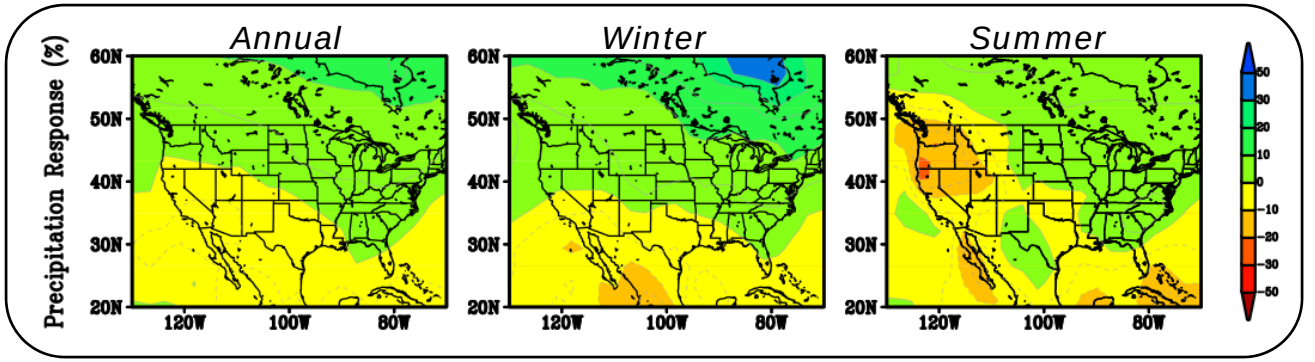
Temperature

Colorado: range
+4°F Annual [2.5-5.5]
+3°F Winter [2-5]
+5°F Summer [3-7]



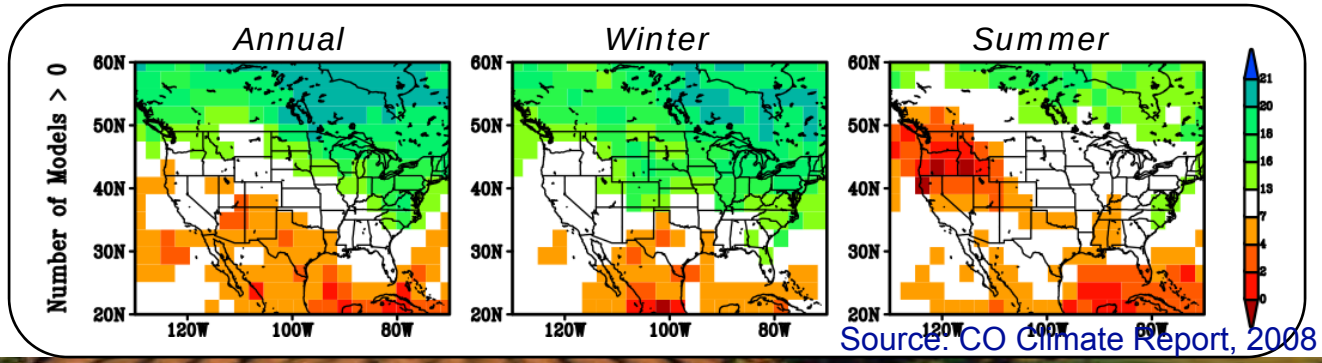
Precipitation

Colorado is in a zone of small precipitation changes



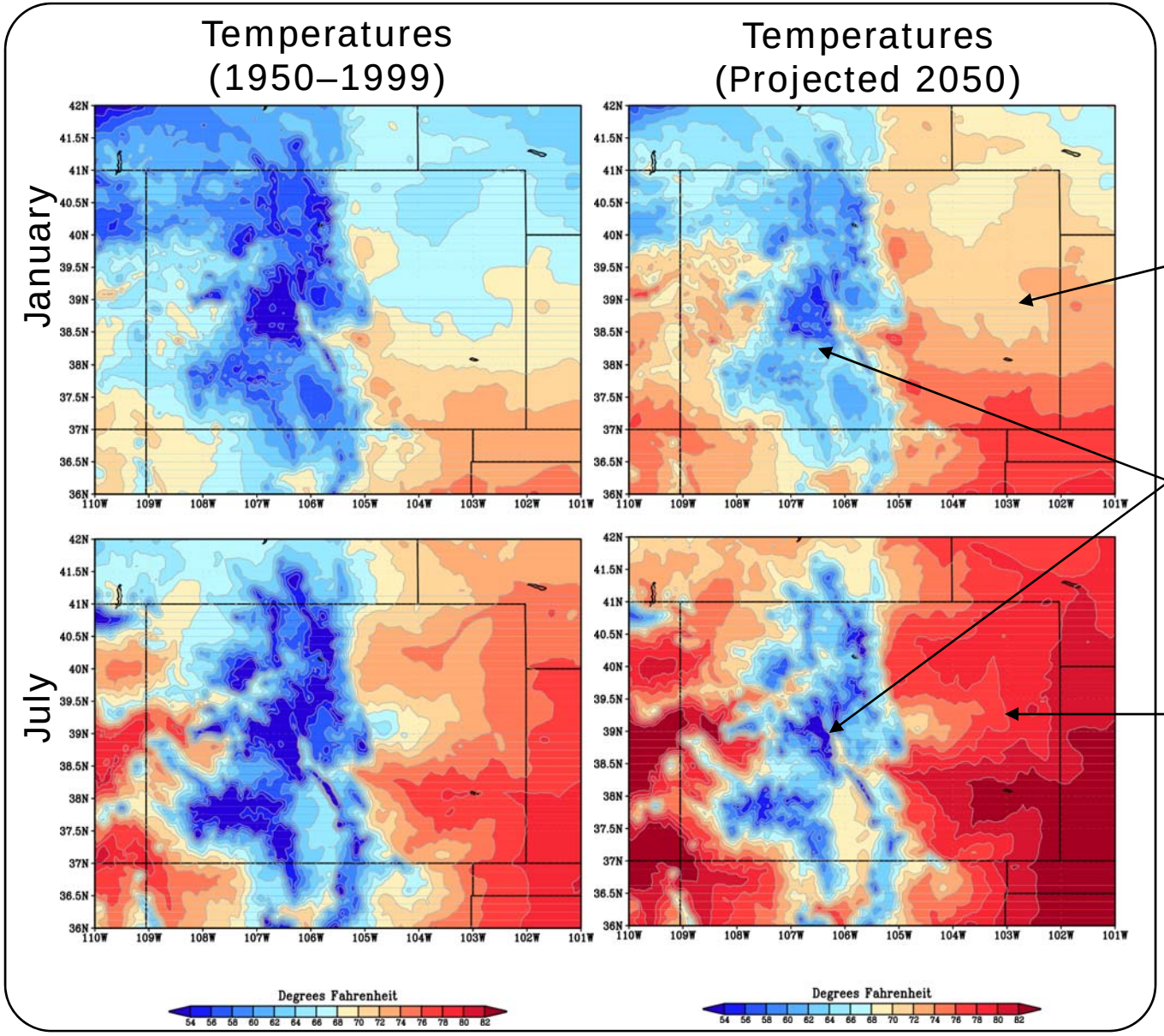
Model Agreement for Precipitation

Colorado is in a region of weak model agreement



Source: CO Climate Report, 2008

Projections: Temperature



What would the projected changes mean for Colorado's varied climate?

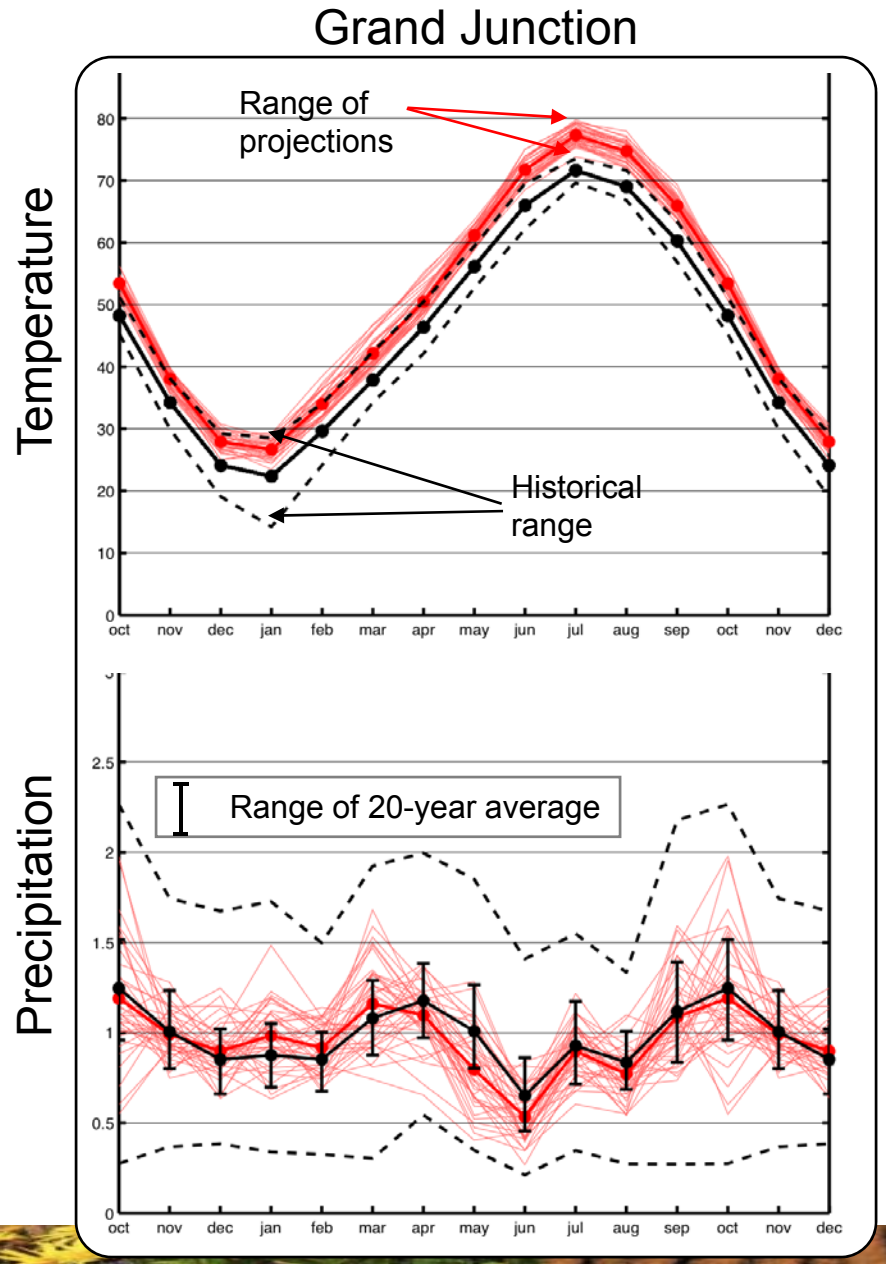
Winter temperatures shift northward on the plains

Temperatures creep upwards in the mountains in all seasons

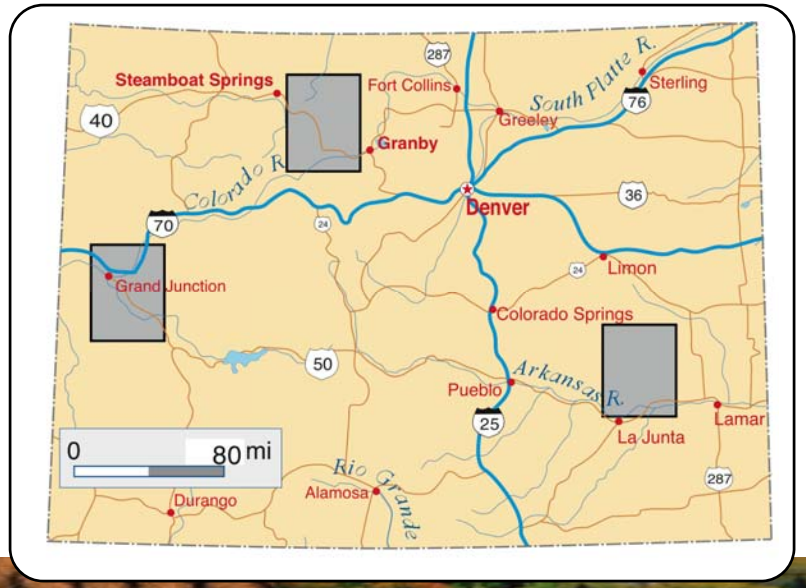
Summer temperatures shift westward on the plains bringing the temperatures of the Kansas border to the Front Range.

Source: CO Climate Report, 2008

Projections: Temperature & Precipitation

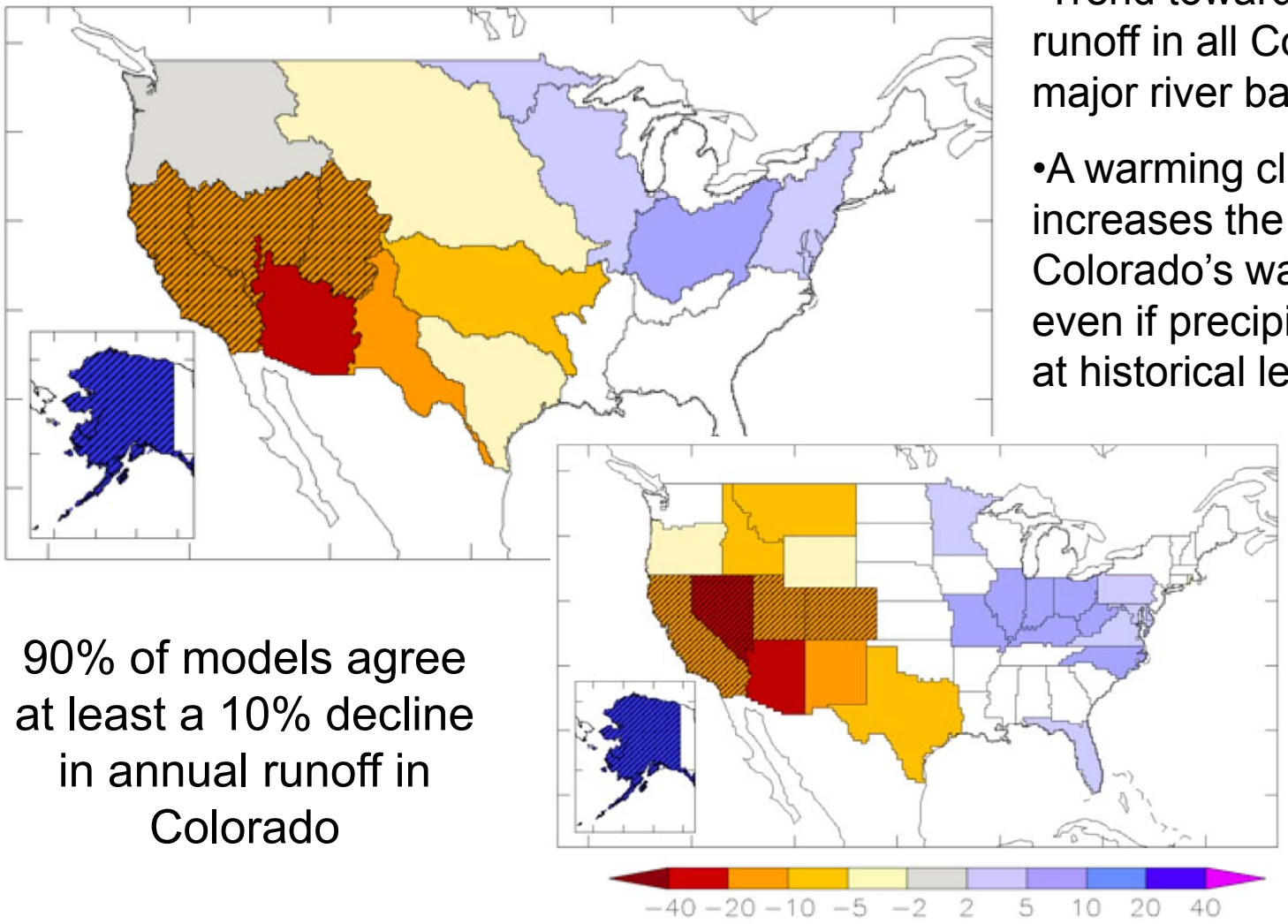


- Summers warm more than winters
- Average summer temperatures similar to the hottest months in the past fifty years.
- Heat waves; fewer cold winters
- Projected precipitation trends small compared to the variability.



Source: CO Climate Report, 2008

Projections: Changes in Annual Runoff

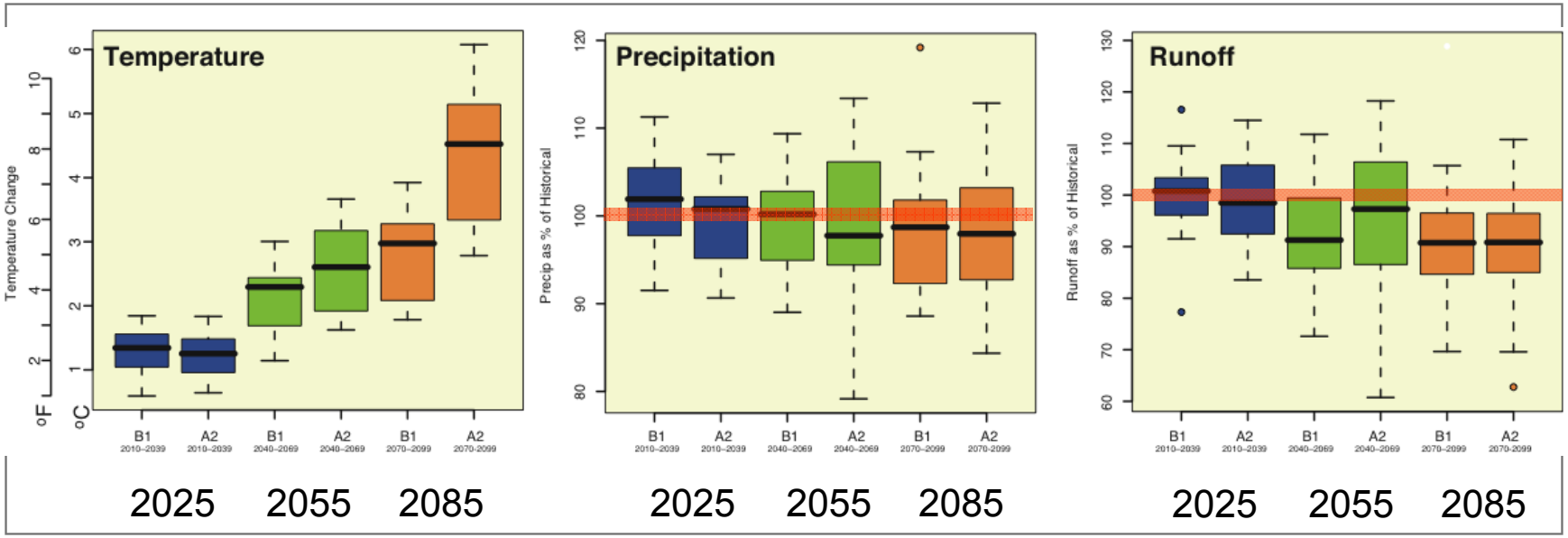


- Trend toward reduced runoff in all Colorado's major river basins
- A warming climate increases the risk to Colorado's water supply even if precipitation remains at historical levels.

90% of models agree at least a 10% decline in annual runoff in Colorado

Source: Milly et al. 2005

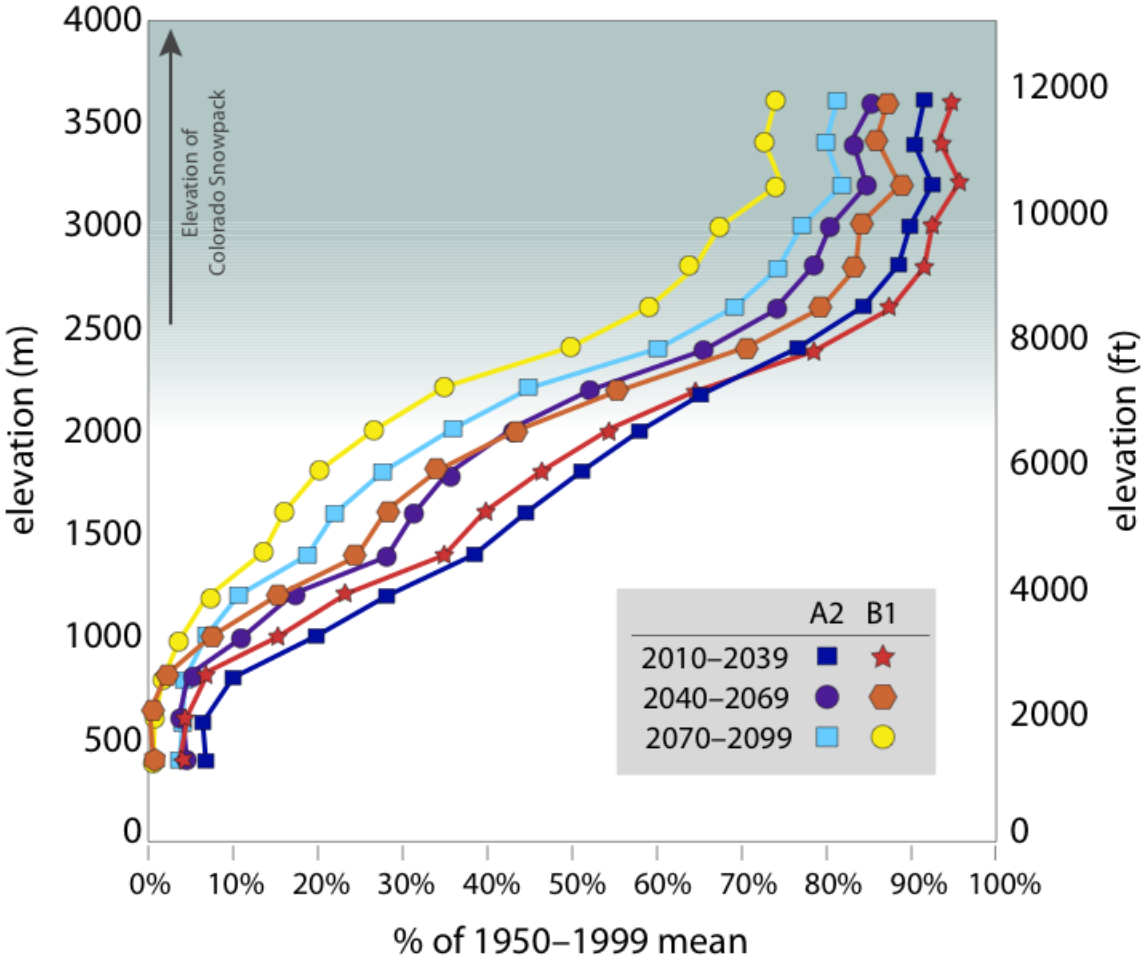
Projections: Upper Colorado River Basin



- Range of projections for the Colorado River (multi-model average): -6% to -20%
- Range of projections for a single 20-year period within a single study can be large due to different climate model drivers and natural variability.
- A warming climate increases the risk to Colorado's water supply even if precipitation remains at historical levels.

Data: Christensen and Lettenmeier, 2007
Graphics: Climate Change in CO, 2008

Projections: Colorado River Basin Snowpack

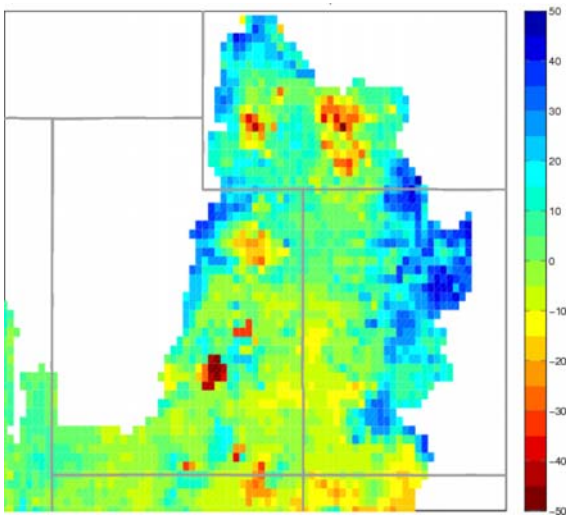


Projected declines in Colorado's snowpack are not as severe as elsewhere in the West at lower elevations.

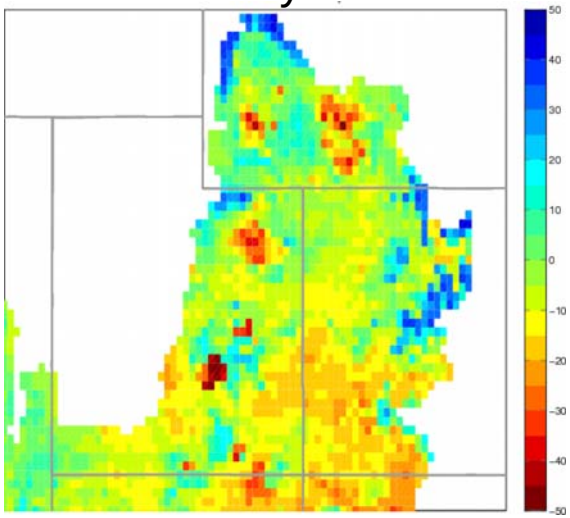
Data: Christensen and Lettenmeier, 2007
Graphics: Climate Change in CO, 2008

Projections: Colorado River Basin Soil Moisture 2050

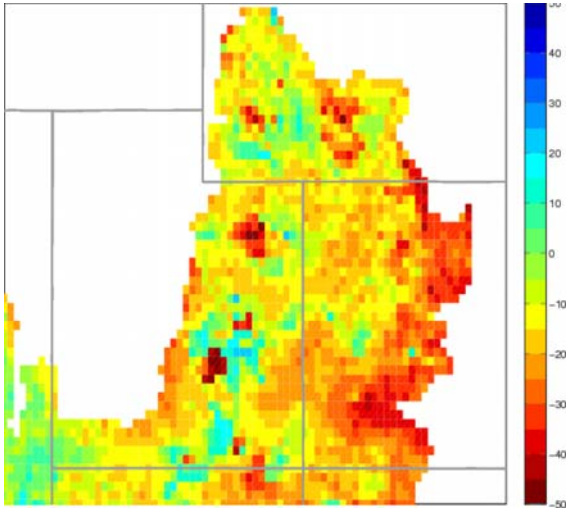
April



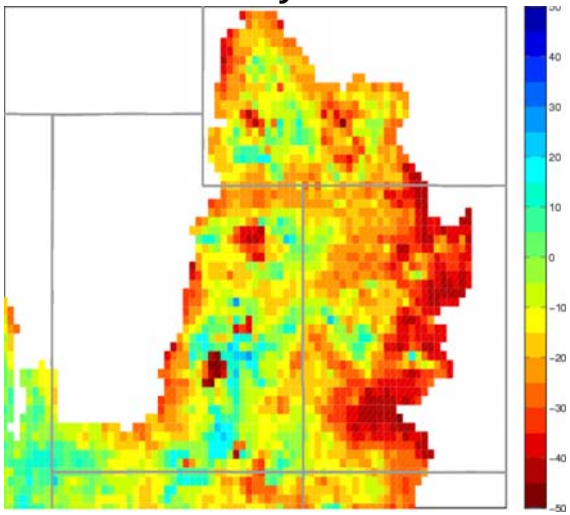
May



June



July

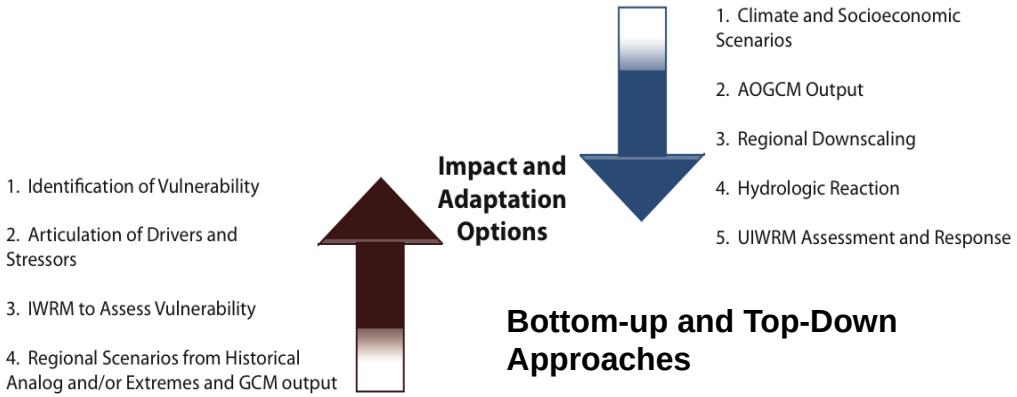


Earlier snowmelt leads to wetter conditions in April, and much drier conditions by summer.

Source: CO Climate Report, 2008
Data: Dennis Lettenmaier, UW

Integrating Climate Information into Water Resources Planning and Management

- Report *leads into* uses of climate in drought mitigation and adaptation planning
  - The assessment of specific sensitivities and vulnerabilities of water supply and ecosystem impacts is beyond the scope of this report
- Description of vulnerability analysis and Integrated Resource Planning (IRP)
  - Potential uses of the information in this report in assessment of climate risks and vulnerabilities and in integrated resource planning and adaptation.
- Aspen and Boulder studies provide examples of how climate change information has been considered in water-related resource planning
- Two projects are in progress use climate projections to explore possible water supply scenarios to which managers may need to adapt:
  - CWCB-funded Joint Front Range Climate Change Vulnerability Study and Colorado River Water Availability Study



Challenging Times for Water Managers!

Issues	Observed and/or Projected Change
Water demands for agriculture and outdoor watering	Increasing temperatures raise evapotranspiration by plants, lower soil moisture, alter growing seasons, and thus increase water demand.
Water supply infrastructure	Changes in snowpack, streamflow timing, and hydrograph evolution may affect reservoir operations including flood control and storage. Changes in the timing and magnitude of runoff may affect functioning of diversion, storage, and conveyance structures.
Legal water systems	Earlier runoff may complicate prior appropriation systems and interstate water compacts, affecting which rights holders receive water and operations plans for reservoirs.
Water quality	Although other factors have a large impact, Nwater quality is sensitive both to increased water temperatures and changes in patterns of precipitationÓ(CCSP SAP 4.3, p. 149). For example, changes in the timing and hydrograph may affect sediment load and pollution, impacting human health.
Energy demand and operating costs	Warmer air temperatures may place higher demands on hydropower reservoirs for peaking power. Warmer lake and stream temperatures may affect water use by cooling power plants and in other industries.
Mountain habitats	Increasing temperature and soil moisture changes may shift mountain habitats toward higher elevation.
Interplay among forests, hydrology, wildfires, and pests	Changes in air, water, and soil temperatures may affect the relationships between forests, surface and ground water, wildfire, and insect pests. Water-stressed trees, for example, may be more vulnerable to pests.
Riparian habitats and fisheries	Stream temperatures are expected to increase as the climate warms, which could have direct and indirect effects on aquatic ecosystems (CCSP SAP 4.3), including the spread of in-stream non-native species and diseases to higher elevations, and the potential for non-native plant species to invade riparian areas. Changes in streamflow intensity and timing may also affect riparian ecosystems.
Water- and snow-based recreation	Changes in reservoir storage affect lake and river recreation activities; changes in streamflow intensity and timing will continue to affect rafting directly and trout fishing indirectly. Changes in the character and timing of snowpack and the ratio of snowfall to rainfall will continue to influence winter recreational activities and tourism.
Groundwater resources	Changes in long-term precipitation and soil moisture can affect groundwater recharge rates; coupled with demand issues, this may mean greater pressures on groundwater resources.

What's coming down the road?

- US Climate Change Science Program (CCSP) assessments. Some chapters still to be released. 1.3 (Attribution) and 4.3 (paleoclimate, with more discussion of drought).
- Reconciling Colorado River Flows
- NARCCAP (Regional Climate Modeling Intercomparison)
- Colorado Headwaters Project (NCAR)
- IPCC Fifth Assessment Report (anticipated 2012)-- modeling studies are getting under way

The Synthesis

Even in the absence of precipitation changes, temperature increases alone, combined with related changes in evaporation and soil moisture suggest a decline and seasonal shift in runoff for most of Colorado's river basins by the mid-21st century.

“A synthesis of findings in this report suggests a reduction in total water availability by the mid-21st century.”

Where do we go from here?

•Climate change impacts/vulnerability studies. Take the "scientific basis" that is synthesized in this report, and continue to the level of impacts.

•Fill gaps in the science and keep up with (and participate in) ongoing scientific research.

- •Colorado-specific studies
- •Colorado river projections
- •Modeling issues: regional and local processes
- •Better understanding of precipitation uncertainty

•Invest in your own climate science capacity and expertise.

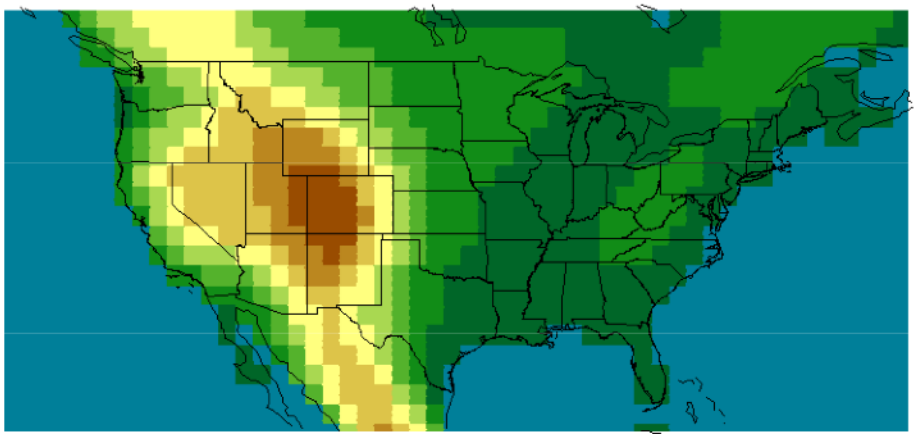
"A continuing dialogue among climate scientists, water resources managers, planners, and policymakers, of which this report is a part, will ensure that the robust scientific findings benefit society."

Colorado
University of Colorado at Boulder

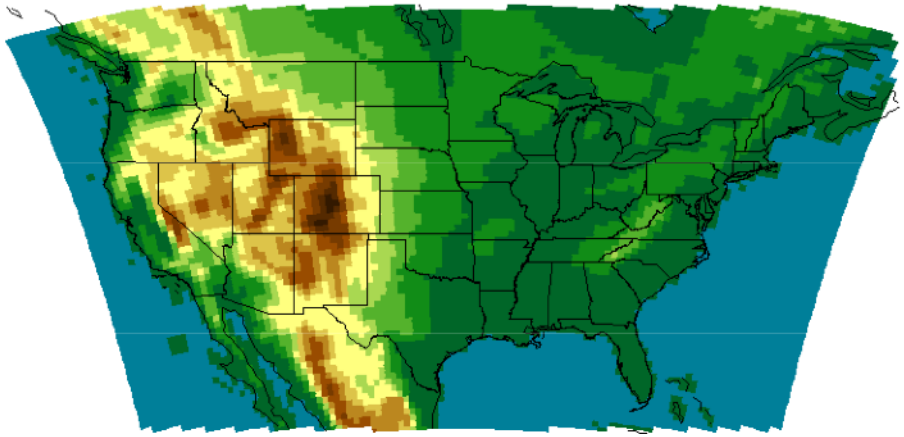
Supplementary Slides

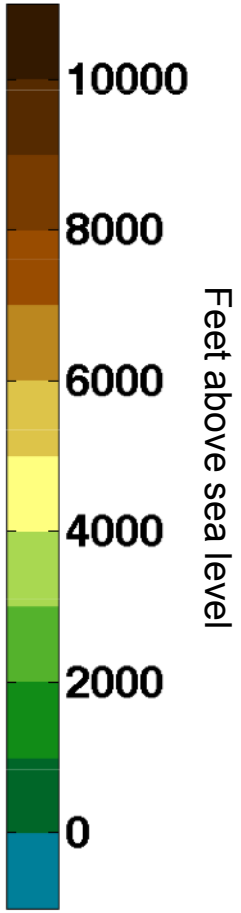
Elevation on Global and Regional Climate Model Grids

NCAR Community Climate System Model



WRF Regional Climate Model





Source: CO Climate Report, 2008

CWCB Goals

Report on the state of the science regarding the physical aspects of climate change that are important for evaluating impacts on Colorado's water resources, and developing adaptation strategies out to the mid-21st century

Science to support:

- Governor Ritter's Climate Change Action Plan
- State Water Supply Initiative
- Governor's Conference on Managing Risks of Drought and Climate, Oct 8-10, 2008
- Complements several other efforts

Audience

- water-related planners, decisionmakers, and policymakers in Colorado

Geographic Scope

- Beyond the state's borders, because of Colorado's role as a headwaters for supply in the West

Technical Level

- More technical than "Citizen's Guide", less technical than the IPCC reports
- Jargon minimized; glossary; Fahrenheit units; published figures/data re-plotted for simplicity and to focus on CO
- Educate about models and their strengths and weaknesses

Key Implications

A synthesis of findings in this report suggests a reduction in total water availability by the mid-21st century

- 21st century climate may pose new challenges to water managers that are unlike those experienced in the 20th century.
- Lengthy droughts and wet periods were more common from about 800 to 1900 in the West Previous centuries had more
- Even in the absence of climate change new understanding of past hydrology warrants a renewed focus on drought planning.
- Water supply systems are facing complex stresses, including increasing demands from a growing population and potential energy development.
- These challenges are magnified by the need to consider climate change. Therefore, there is an emerging need for vulnerability assessments, for adaptation planning, and for bringing climate change information into ongoing integrated resource planning.

Key unresolved issues

The "jury is still out" on these unresolved topics

- Insufficient data, research in progress or yet to be done
- In other cases, research is in progress, but the results may not be as robust as needed.
- These uncertainties limit projections for water supply

- **Modeling issues**
  - Regional and local processes and their role in Colorado's climate must be better modeled
  - Precipitation projections and related phenomena are key uncertainties
  - Finer spatial resolution to better represent Colorado's mountainous terrain and precipitation processes

- **Colorado-specific studies**
  - Relatively little work on the Arkansas, Rio Grande, Platte River basins

- **Understanding causes of drought**
  - Issues include runoff efficiency, effects of increased temperatures, uncertainty in precipitation projections, and the causes of the 2000s drought

- **Hydrologic projections for the Colorado River**
  - Large range among projections of river flows; a study is underway to reconcile these studies

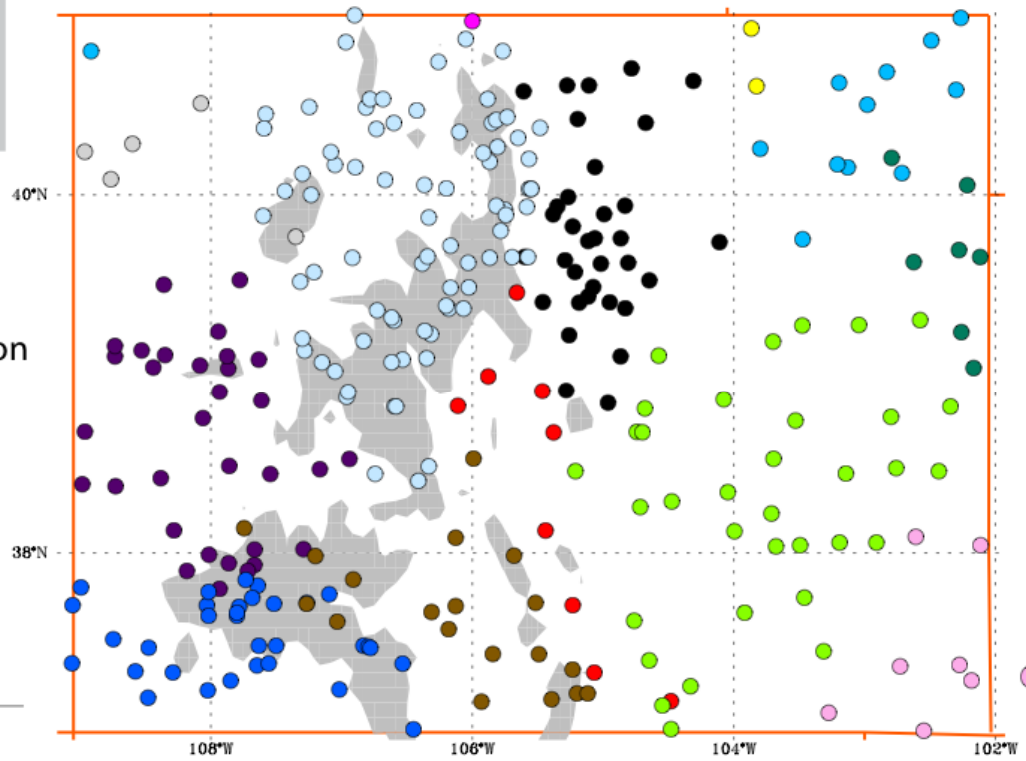
Report Findings

Major concepts

- A snapshot of the state of science at a key point in Colorado's history
- Climate in Colorado is highly variable compared to other states
- The mountains and elevation make Colorado's climate unique compared with other Western states
- Temperatures have been increasing in Colorado and will continue to rise
- Uncertainty in precipitation projections
- Even in the absence of precipitation changes, temperature increases alone combined related changes in evaporation and soil moisture, all recent hydrologic projections show a decline in runoff for most of Colorado's river basins by the mid-21st century

A synthesis of findings in this report suggests a reduction in total water availability by the mid-21st century

Observations: Regional Temperature Trends



Division	North Central Mountains	North Front Range	Northeast
1932–2006 75-year trend (°F)	0.8	0.0	0.3
1957–2006 50-year trend (°F)	2.6	1.5	0.5
1977–2006 30-year trend (°F)	1.6	2.5	1.8

Division	Grand Junction & Gunnison	Arkansas Valley
1932–2006 75-year trend (°F)	-0.1	0.7
1957–2006 50-year trend (°F)	1.6	2.0
1977–2006 30-year trend (°F)	1.2	1.8

Division	Southwest	Lower Arkansas Valley
1932–2006 75-year trend (°F)	-0.3	-1.3
1957–2006 50-year trend (°F)	0.2	0.5
1977–2006 30-year trend (°F)	2.0	-0.1

Division	San Luis Valley	Southern Front Range
1932–2006 75-year trend (°F)	na	na
1957–2006 50-year trend (°F)	1.9	0.7
1977–2006 30-year trend (°F)	2.4	1.1

Source: CO Climate Report, 2008

Larger Context: Timescales of Climate Change

The future of Colorado's climate beyond 2050 depends on the greenhouse gas emissions path that the world follows. As the world warms, feedbacks in the climate system may further increase global greenhouse gas concentrations. Warming in Colorado may trigger changes in land cover that would alter regional climate. The possibility has been raised of large, potentially irreversible changes in the climate system particularly if global average temperatures increase more than a few degrees (e.g., Hanson et al. 2007).

"Stationarity is Dead"

POLICYFORUM

CLIMATE CHANGE

Stationarity Is Dead: Whither Water Management?

Climate change undermines a basic assumption that historically has facilitated management of water supplies, demands, and risks.

P. C. D. Milly,[1]* Julio Betancourt,[2] Malin Falkenmark,[3] Robert M. Hirsch,[4] Zbigniew W. Kundzewicz,[5] Dennis P. Lettenmaier,[6] Ronald J. Stouffer[7]

"Recent developments [in climate projections] have led us to the opinion that the time has come to move beyond the wait-and-see approach."

"Rapid flow of such climate-change information from the scientific realm to water managers will be critical for planning, because the information base is likely to change rapidly as climate science advances during the coming decades. Optimal use of available climate information will require extensive training of (both current and future) hydrologists, engineers, and managers in nonstationarity and uncertainty."

Joe Barsugli is a Research Scientist at the Cooperative Institute for Research in the Environmental Sciences (CIRES) at the University of Colorado, Boulder. He received his Ph.D. in Atmospheric Sciences from the University of Washington in Seattle on the theory of atmosphere-ocean interactions. His specialty is "climate dynamics", which is the study of the changing weather and climates of the past, present and future with an emphasis on the role of atmospheric and oceanic fluid motions -- winds and currents -- often using global climate models. His research has ranged from the role of sea-ice during the last Ice Age, to the effects of El Nino on individual storms, to the impacts of Tropcial ocean "hot spots" in climate change. In the last two years working with the NOAA/CU Western Water Assessment he has been studying the use of weather forecasts in reservoir operations on the Colorado River, and the use of climate change projections to inform water resources planning in the West. He is one of the lead authors of "Climate Change in Colorado: A Synthesis to support Water Resources Management and Adaptation."