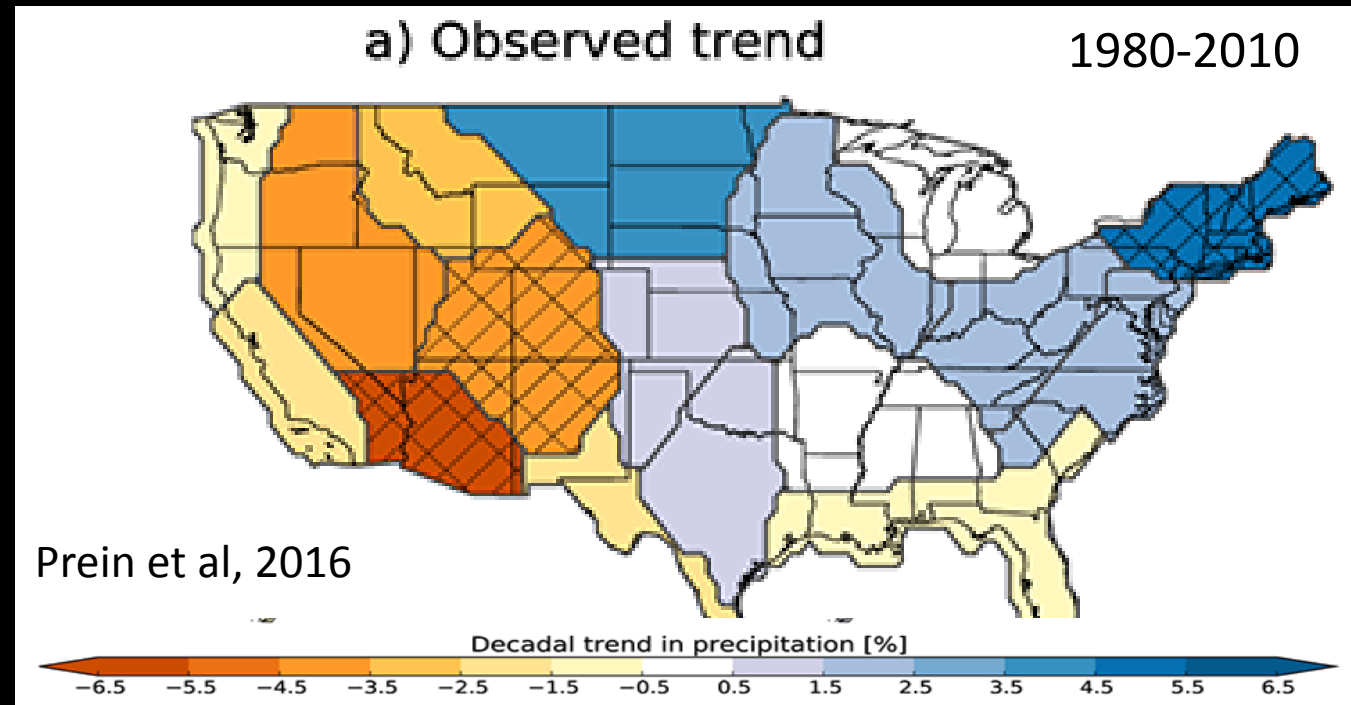


# Impact of Climate and Climate Change on Surface Water Supplies

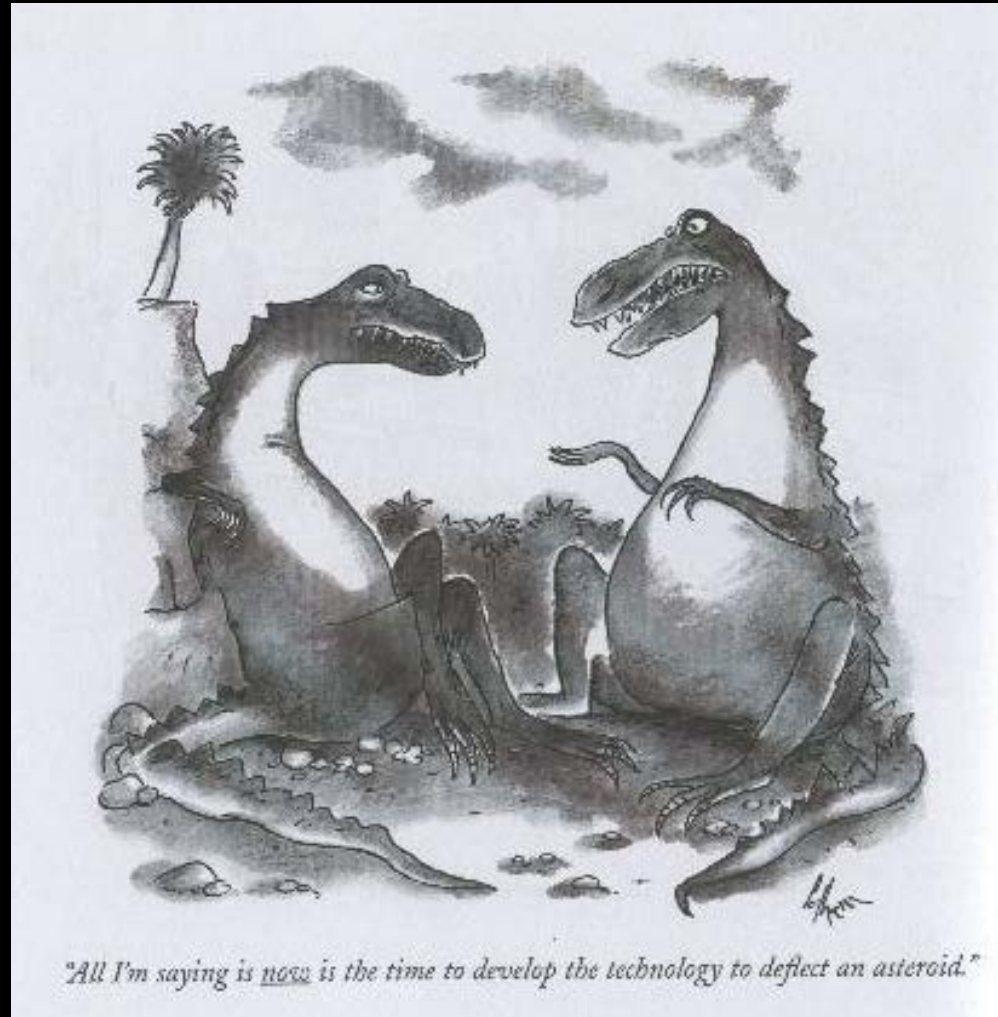
Water In-Service  
UA Cooperative  
Extension  
Phoenix-Tempe AZ  
August 11-12, 2016



Brad Udall  
Colorado State University  
[Bradley.udall@colostate.edu](mailto:Bradley.udall@colostate.edu)  
@bradudall

# \*Outline

- **Climate Change Science**
  - Climate Change is Water Change
- Recent Climatology
- California, Colorado Droughts
  - Temperature Linkage
  - Megadroughts
- Reasons for Optimism
  - Paris
  - US
  - Technology, Economics



# The Effects of Doubling the CO<sub>2</sub> Concentration on the Climate of a General Circulation Model<sup>1</sup>

SYUKURO MANABE AND RICHARD T. WETHERALD

*Geophysical Fluid Dynamics Laboratory/NOAA, Princeton University, Princeton, N.J. 08540*

(Manuscript received 6 June 1974, in revised form 8 August 1974)

## ABSTRACT

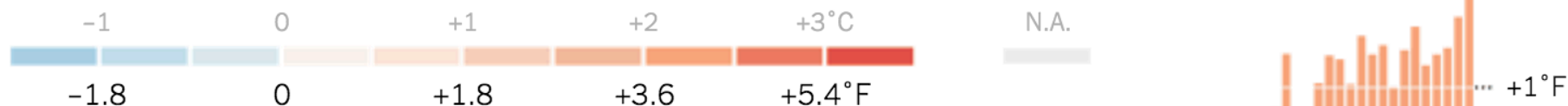
An attempt is made to estimate the temperature changes resulting from doubling the present CO<sub>2</sub> concentration by the use of a simplified three-dimensional general circulation model. This model contains the following simplifications: a limited computational domain, an idealized topography, no heat transport by ocean currents, and fixed cloudiness. Despite these limitations, the results from this computation yield some indication of how the increase of CO<sub>2</sub> concentration may affect the distribution of temperature in the atmosphere. It is shown that the CO<sub>2</sub> increase raises the temperature of the model troposphere, whereas it lowers that of the model stratosphere. The tropospheric warming is somewhat larger than that expected from a radiative-convective equilibrium model. In particular, the increase of surface temperature in higher latitudes is magnified due to the recession of the snow boundary and the thermal stability of the lower troposphere which limits convective heating to the lowest layer. It is also shown that the doubling of carbon dioxide significantly increases the intensity of the hydrologic cycle of the model.

# 2015 Was Hottest Year in Historical Record, Scientists Say

By JUSTIN GILLIS JAN. 20, 2016

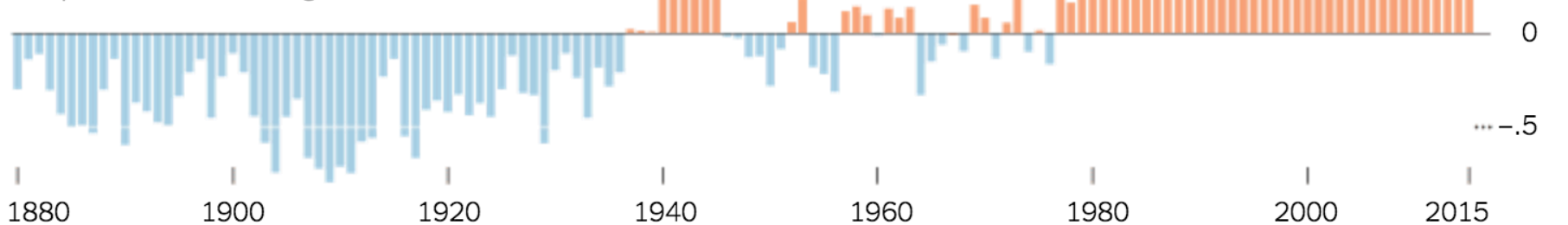
## How far above or below average temperatures were in 2015

Compared with the average from 1901 to 2000



## Average global surface air temperatures

Compared with the average from 1901 to 2000



Source: NASA Goddard Institute for Space Studies

By The New York Times

- Back to Back Records 2014, now 2015
- No 'Pause' or 'Hiatus'
- Accelerating Trend?

# American Geophysical Union Fall Meeting – San Francisco

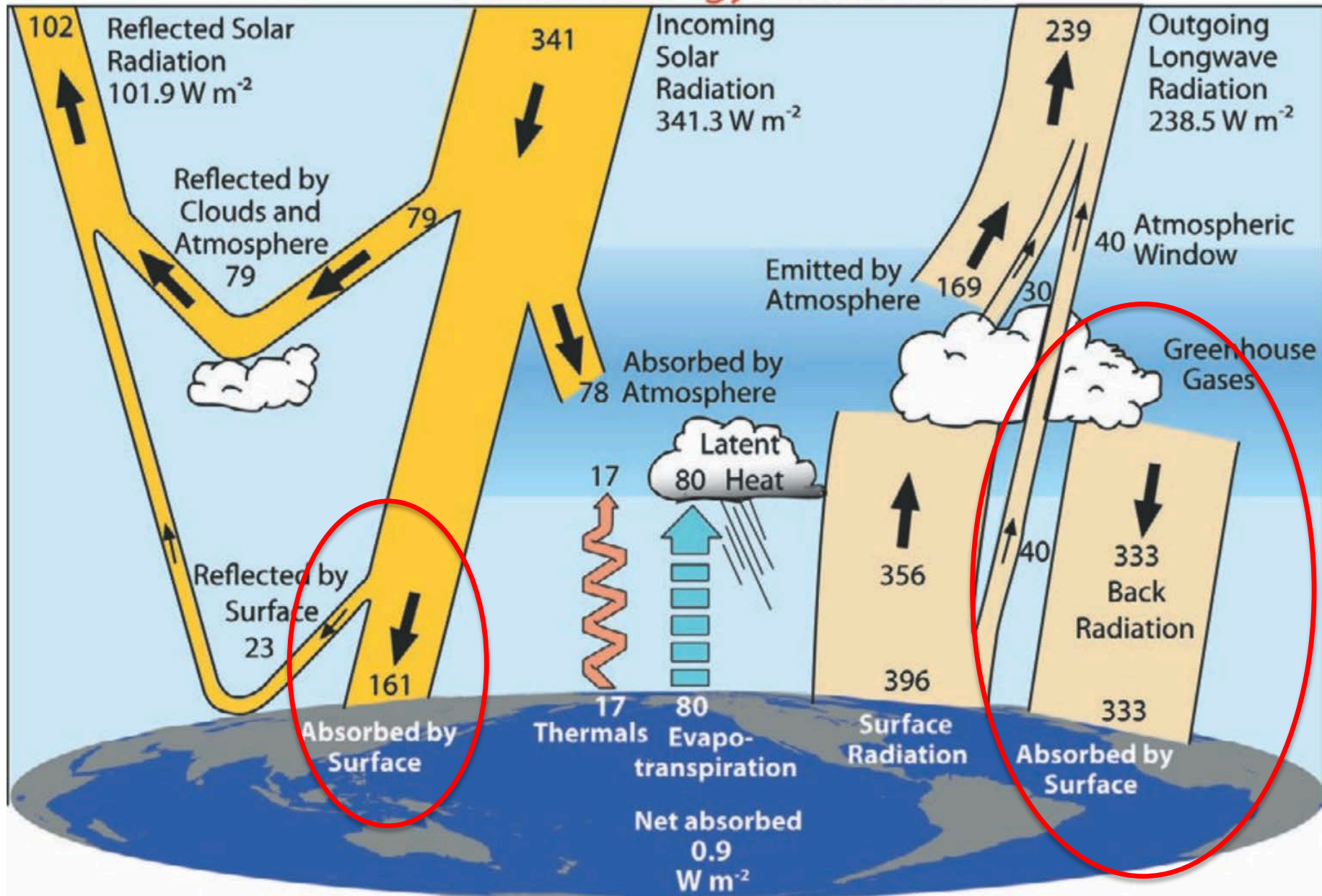
- December every Year
- 24,000 Earth Scientists
- Fully Accepted Science
  - Earth is Warming
  - Humans are the Cause
  - Very Risky to Burn
  - Carbon unabated
  - Water Cycle will be
  - Impacted
- Theory vs “Belief”



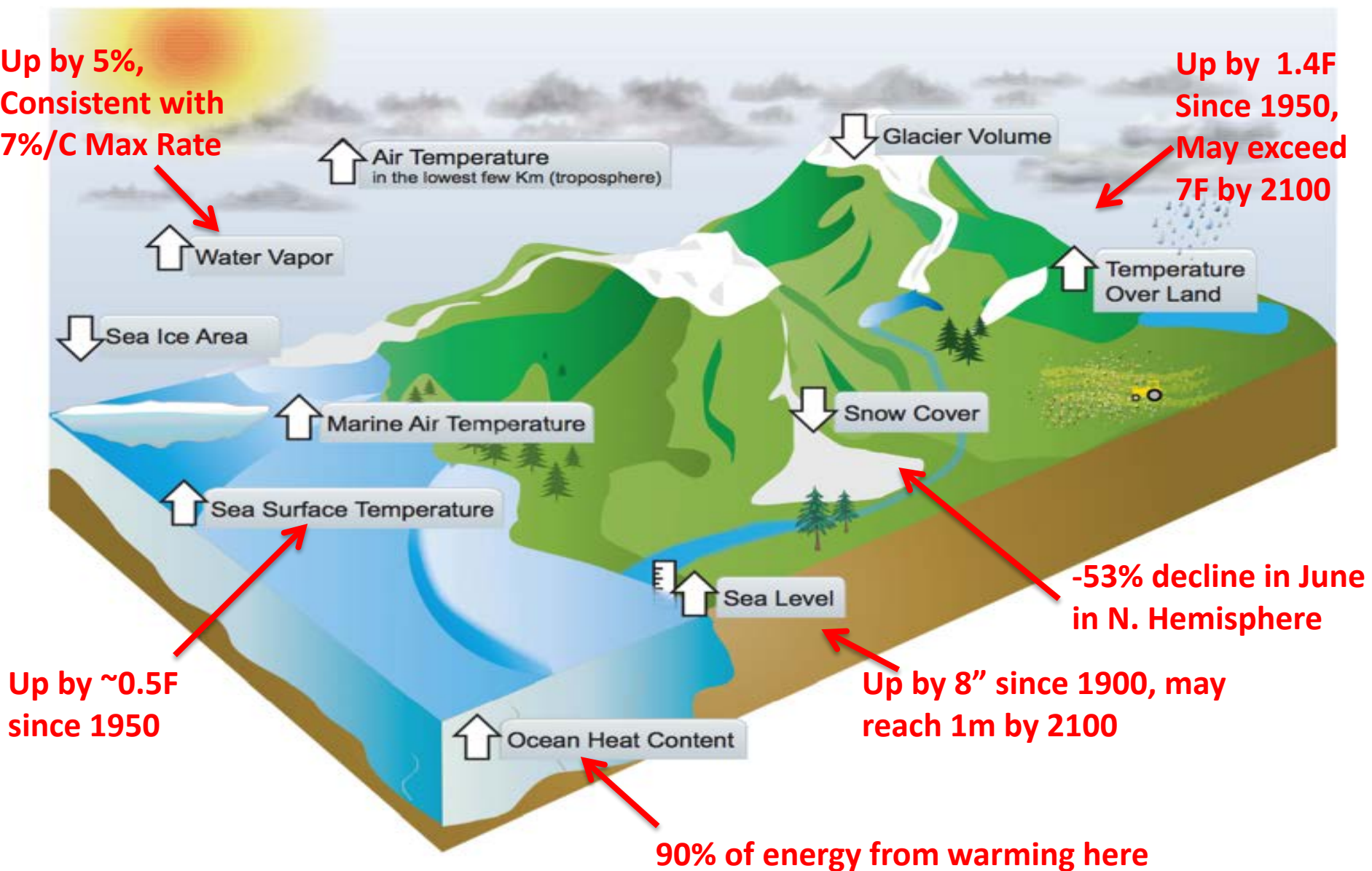
# Climate Change is Water Change

- Heat Drives the Water Cycle –  
1000 km<sup>3</sup> evaporates daily from the oceans
  - The Water Cycle mixes heat from areas of too much to too little
  - As the Atmosphere Warms it Holds More Moisture:  
~5F warming is 20% increase
  - Heating Up the Earth (and uneven heating) results in Water Cycle changes
    - More Evaporation, More Precipitation, More Moisture
    - Changes in weather patterns
    - Wet Wetter, Dry Drier Standard Rule
    - More Intense Floods and Droughts
  - All Kinds of Water Changes Already Noted
    - More rain/less snow, Earlier Runoff, Higher Water Temps, More Intense Rain
- 

# Global Energy Flows $W m^{-2}$

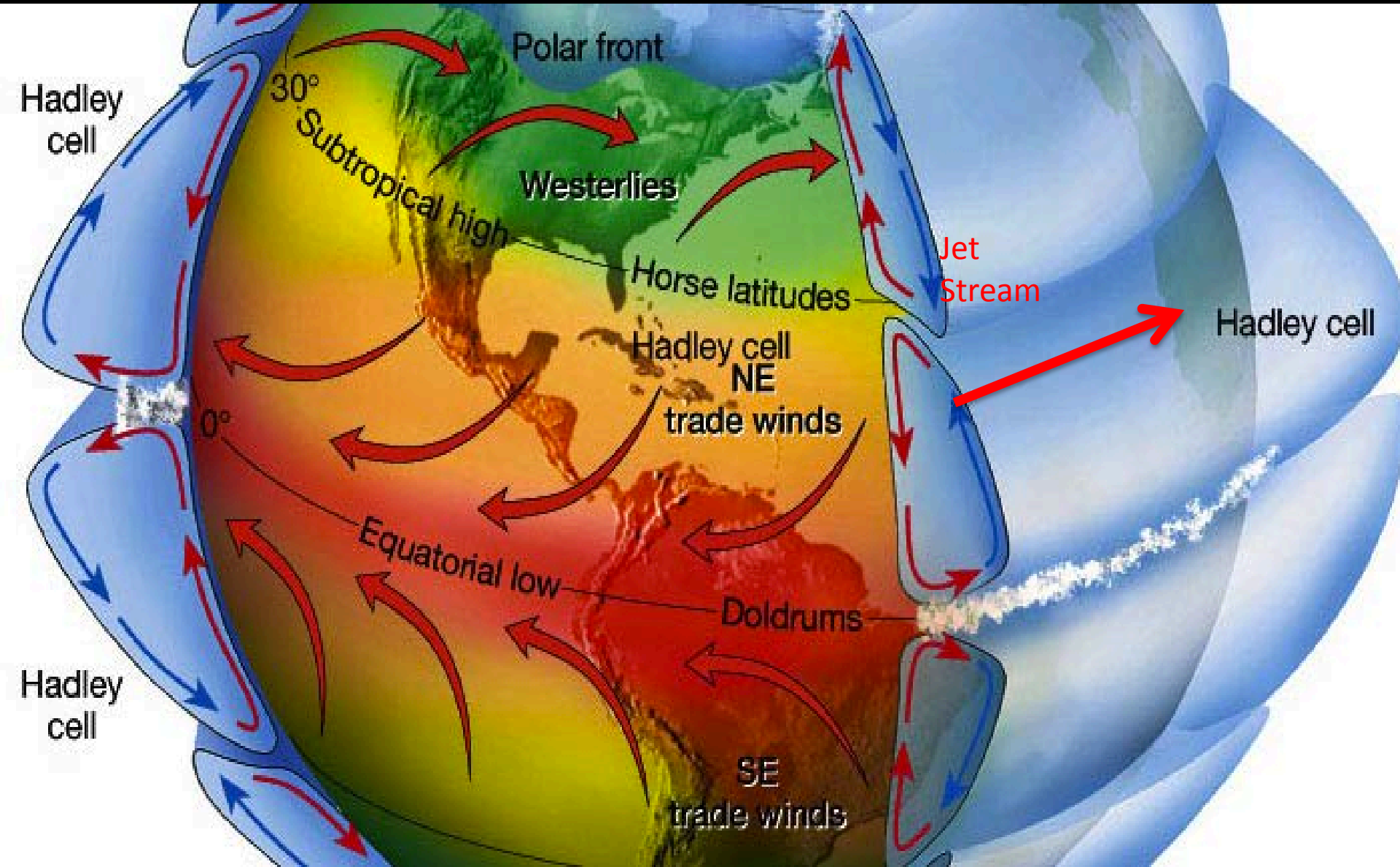


**IPCC: All Kinds of Observations are Consistent with Climate Change Expectations. 7 out of 10 are water cycle related here...**





# Expanding Hadley Cells

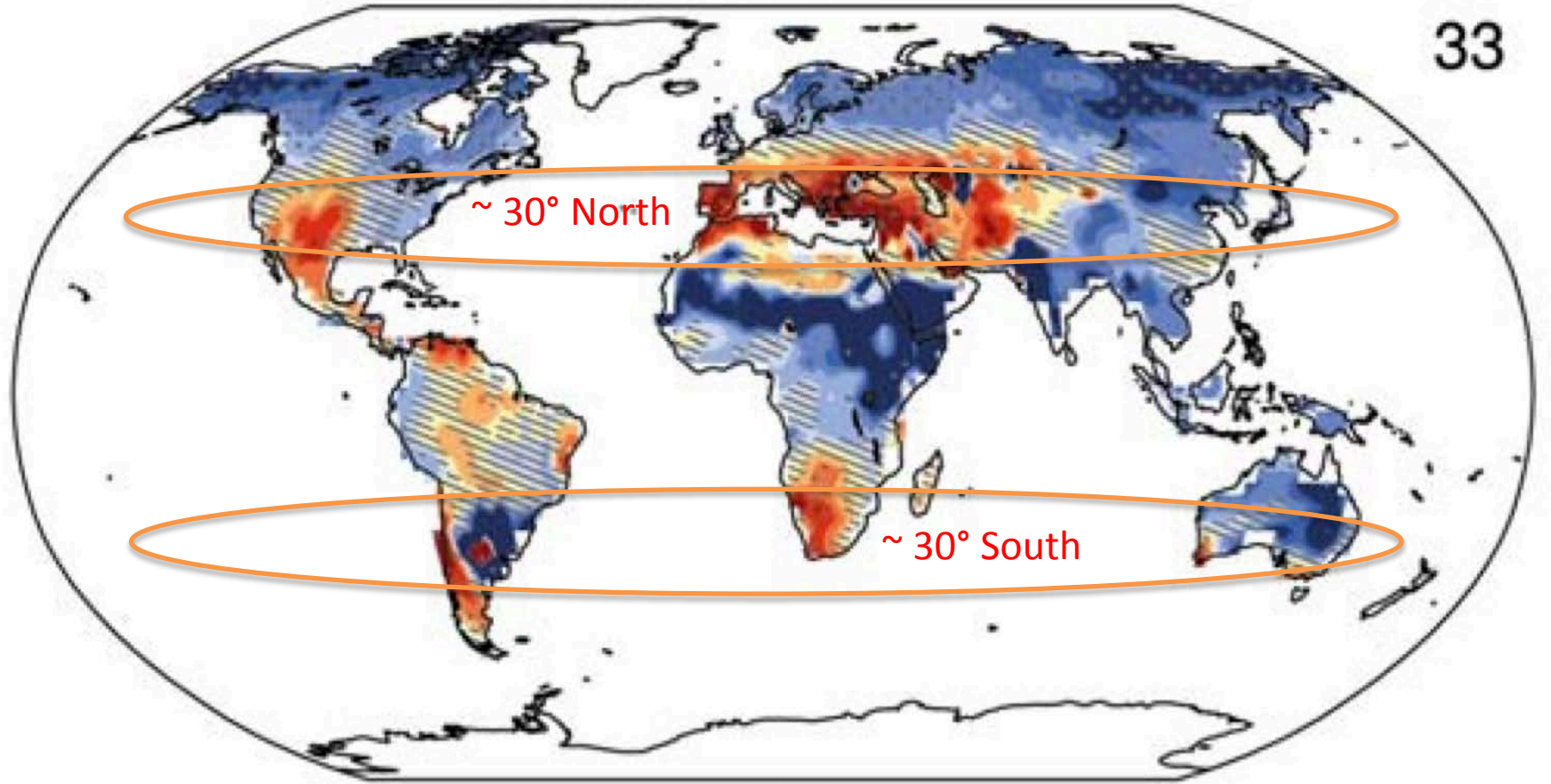


# Projections for 2081 to 2100

Precipitation is not runoff!

## Runoff

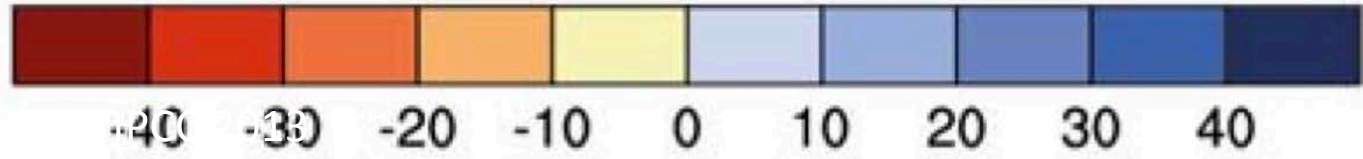
33



~ 30° North

~ 30° South

(%)



CLIMATE CHANGE

## Stationarity Is Dead: Whither Water Management?

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

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

- Water resource planning uses “climate stationarity”  
– climate of the future = the climate of the past
- Less and less true as we move forward
- Both supply and demand are changing
- New water projects have substantial uncertainty

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- Some Strategies



*"All I'm saying is now is the time to develop the technology to deflect an asteroid."*

# California Winter 2014-2015 Drought

- Winter Temperatures
  - Sierra Winter Above 32 F,
  - (1<sup>st</sup> time >32F in 120 years)
- Sierra Precipitation
  - Rain, not Snow
  - Not the driest!
  - (40% to 90% of normal)
- Snowpack
  - Lowest Ever - 5% on April 1
  - (1977 at 25%)
  - 500-Year (?) Return Period
- Drought
  - Worst in 1200 (?) Years
- Water Deliveries
  - Record Low to CVP Contractors

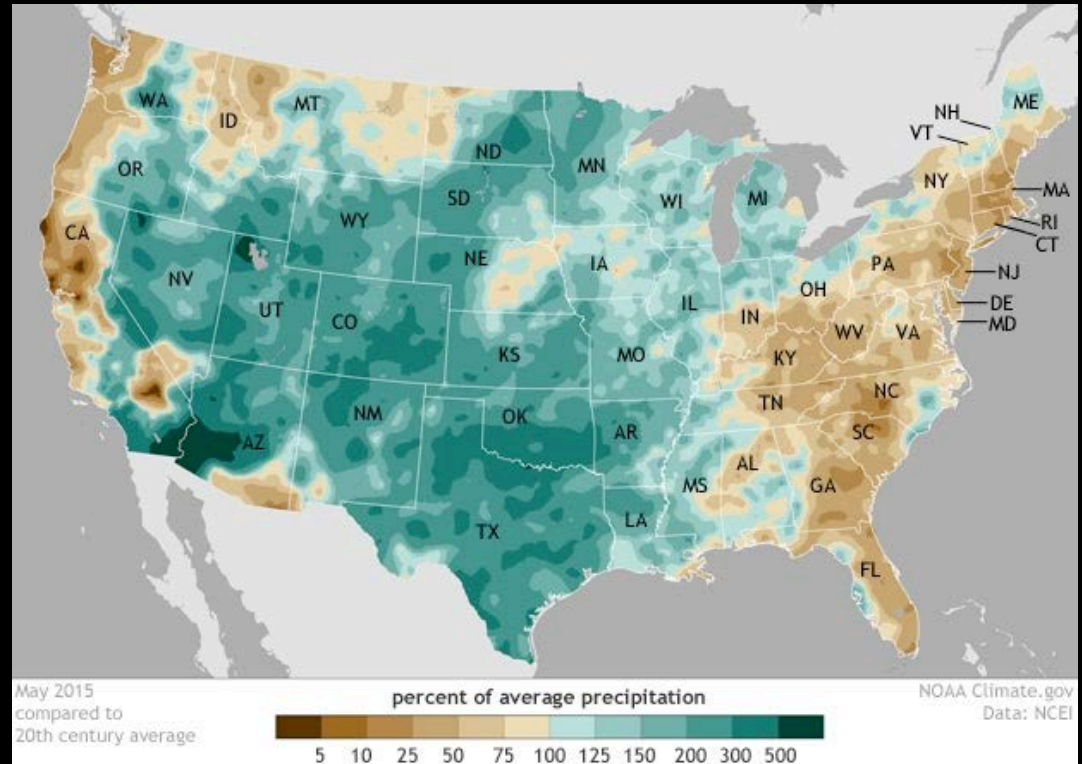


# May 2015 was wettest month ever recorded in U.S.

Friday, June 12, 2015

May 2015 was the country's wettest May since records began 121 years ago.

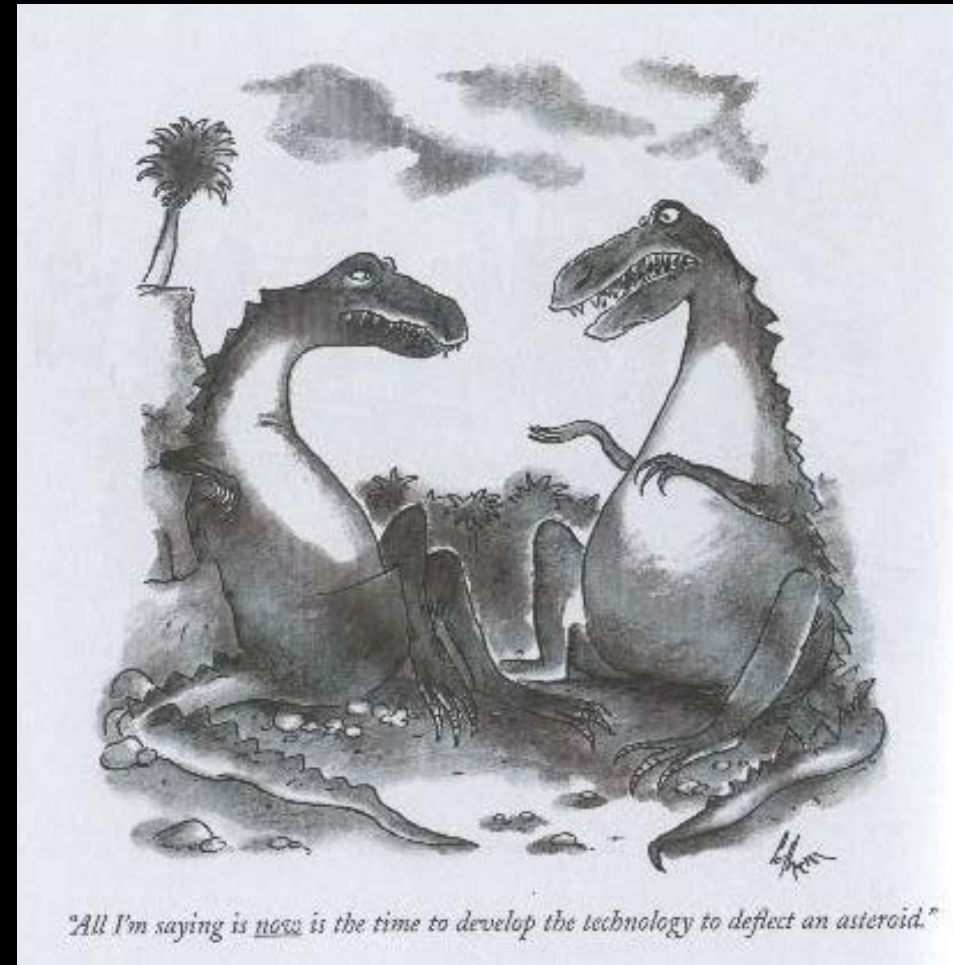
In fact, it was the wettest month ever recorded!



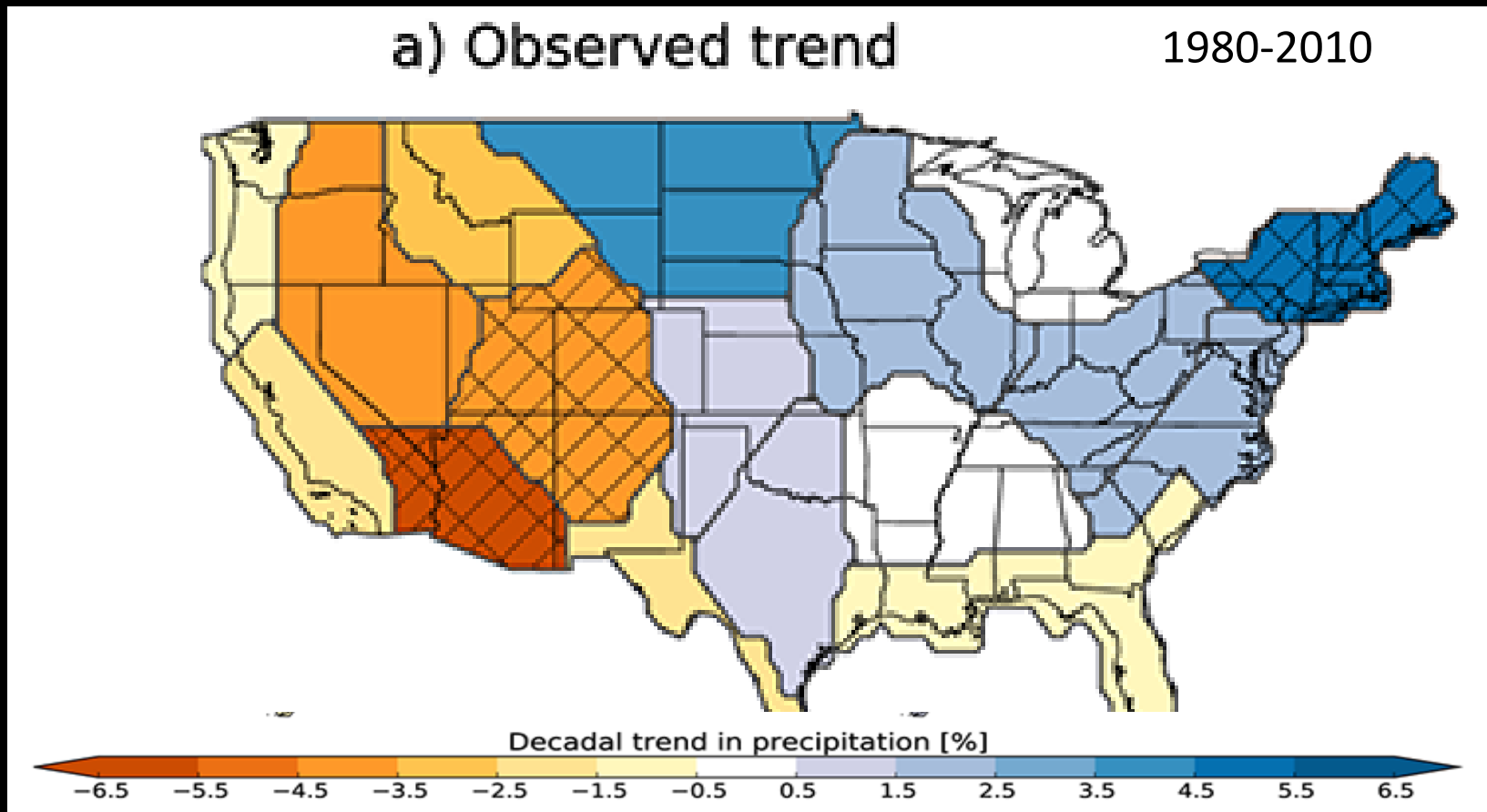
<https://www.climate.gov/news-features/featured-images/may-2015-was-wettest-month-ever-recorded-us>

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# Running dry: The U.S. Southwest's drift into a drier climate state



Weather Patterns that provide winter precipitation are becoming less frequent due to Hadley Cell Expansion. Southwest Precipitation has declined by 25%.

Prein et al, 2016



# Anthropogenic warming has increased drought risk in California

Noah S. Diffenbaugh<sup>a,b,1</sup>, Daniel L. Swain<sup>a</sup>, and Danielle Touma<sup>a</sup>

<sup>a</sup>Department of Environmental Earth System Science and <sup>b</sup>Woods Institute for the Environment, Stanford University, Stanford, CA 94305

Edited by Jane Lubchenco, Oregon State University, Corvallis, OR, and approved January 30, 2015 (received for review November 22, 2014)

- No change in precipitation over last few decades
- But the occurrence of drought has increased in last two decades over previous century
- The probability that precipitation deficits occur with warm temperatures has increased

# Status of the Two Largest Reservoirs in the United States

2000 = Full

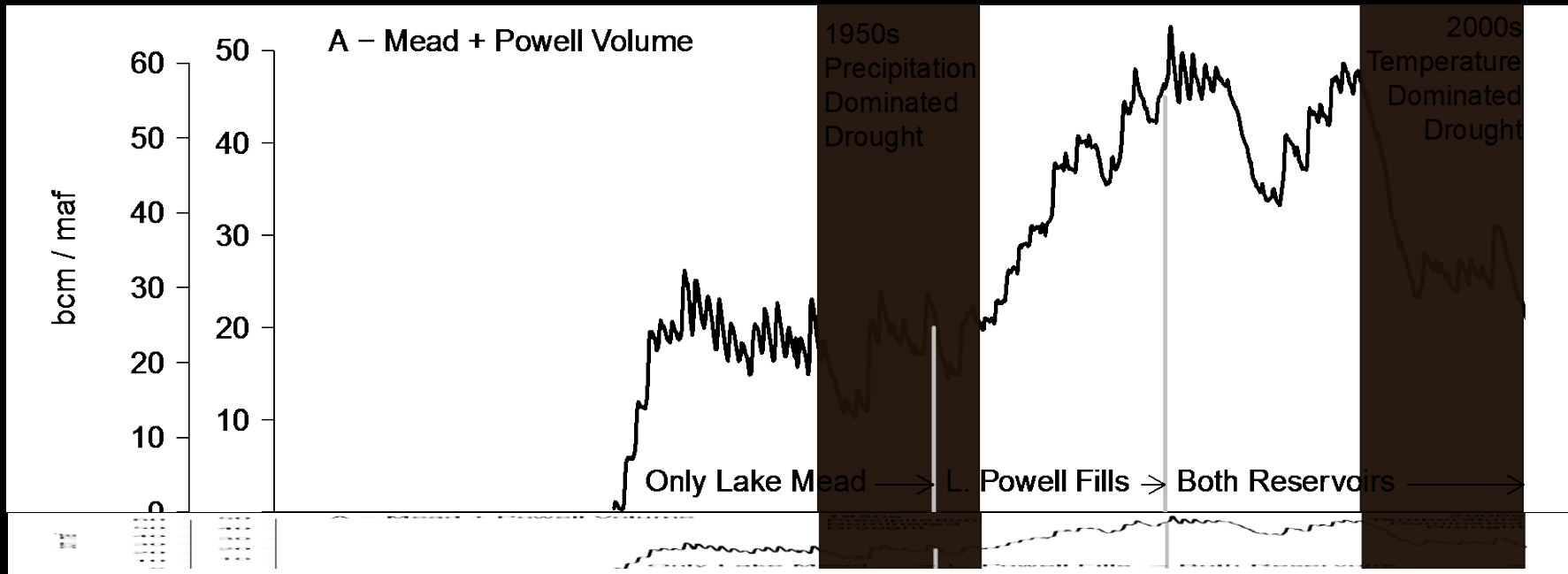
2015 = ~ 40%

Most Serious Drought since records kept

Causes...

Lake Powell: Drought

Lake Mead: Structural Deficit ("overuse")

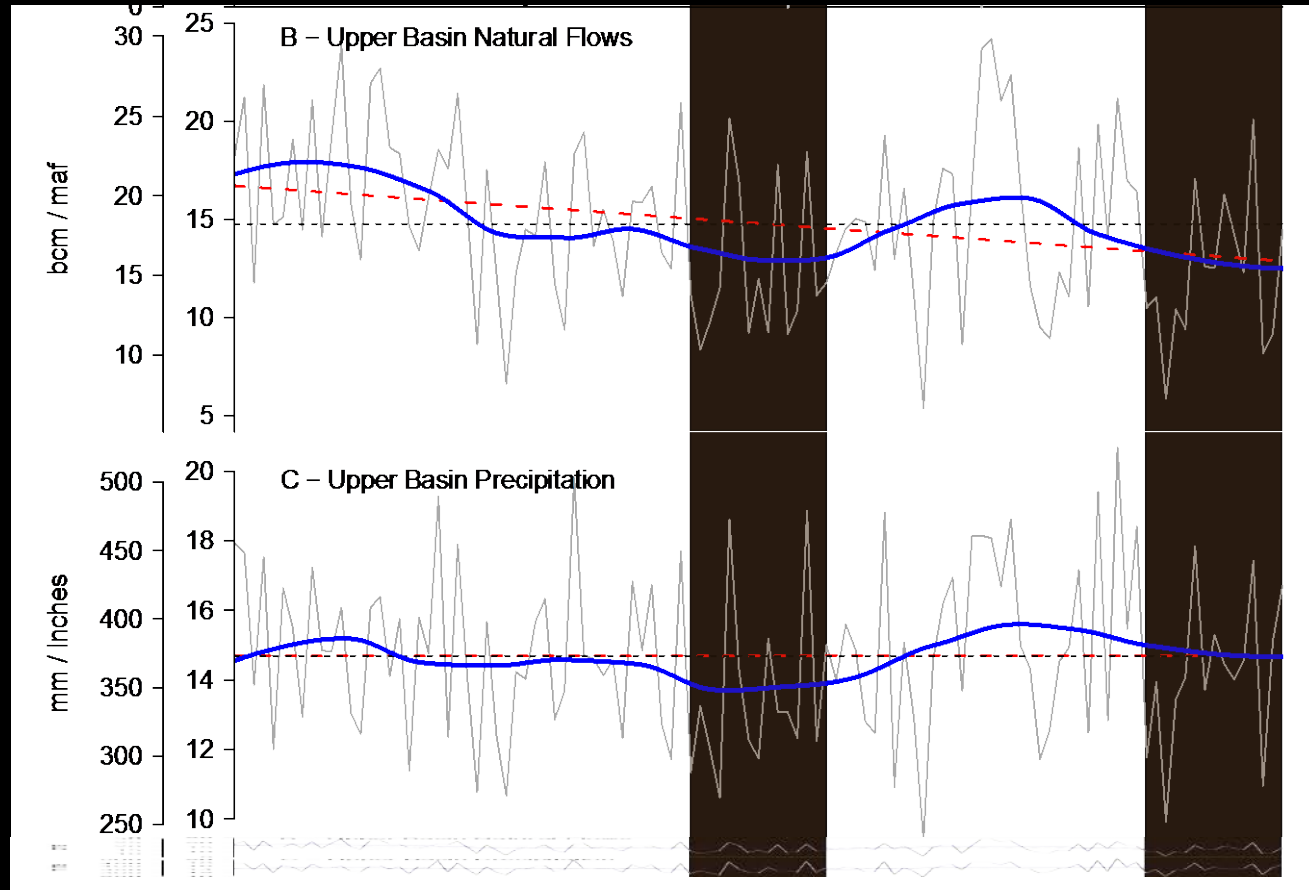


# Two Droughts – Two Different Causes

1953-1967 Drought  
- 18% Flow  
Reduction  
- 6.8% Precipitation

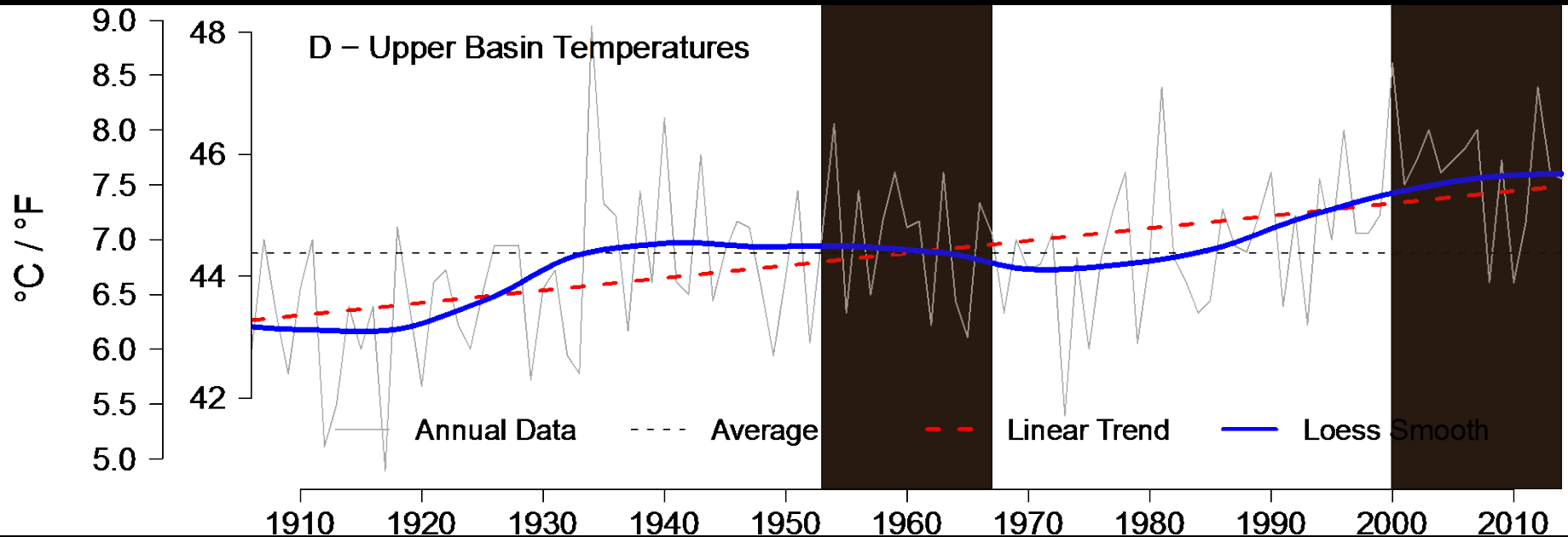
2000-2014 Drought  
- 19% Flow  
Reduction  
- 2.5% Precipitation

Note: 2000 is only 40% of  
the 1950s precip decline



Source: Udall & Overpeck, 2016; flow data from  
Reclamation, PRISM Precipitation

# Temperatures Key to 2000s Decline



2000-14 Temperatures are 1.6°F above 1906-99 Average

Temperature Sensitivity Explains 1/6 to 1/2 of the current runoff reduction

Why? Higher ET, longer snow-free periods

Source: Udall & Overpeck 2016, PRISM Temperatures

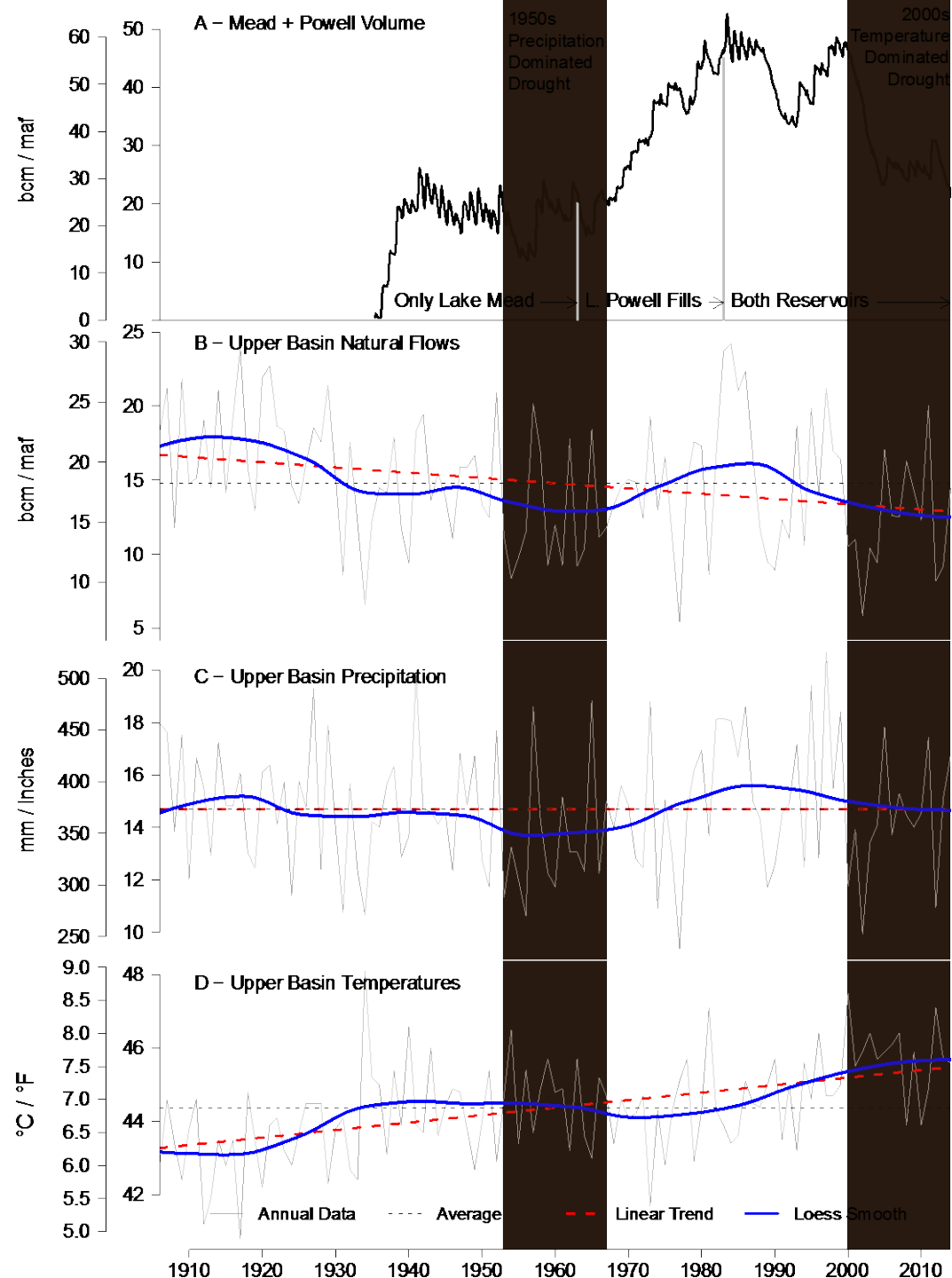
The Complete Picture...

You have to invoke higher temperatures to explain the current drought.

AND....

This does not bode well for the future...

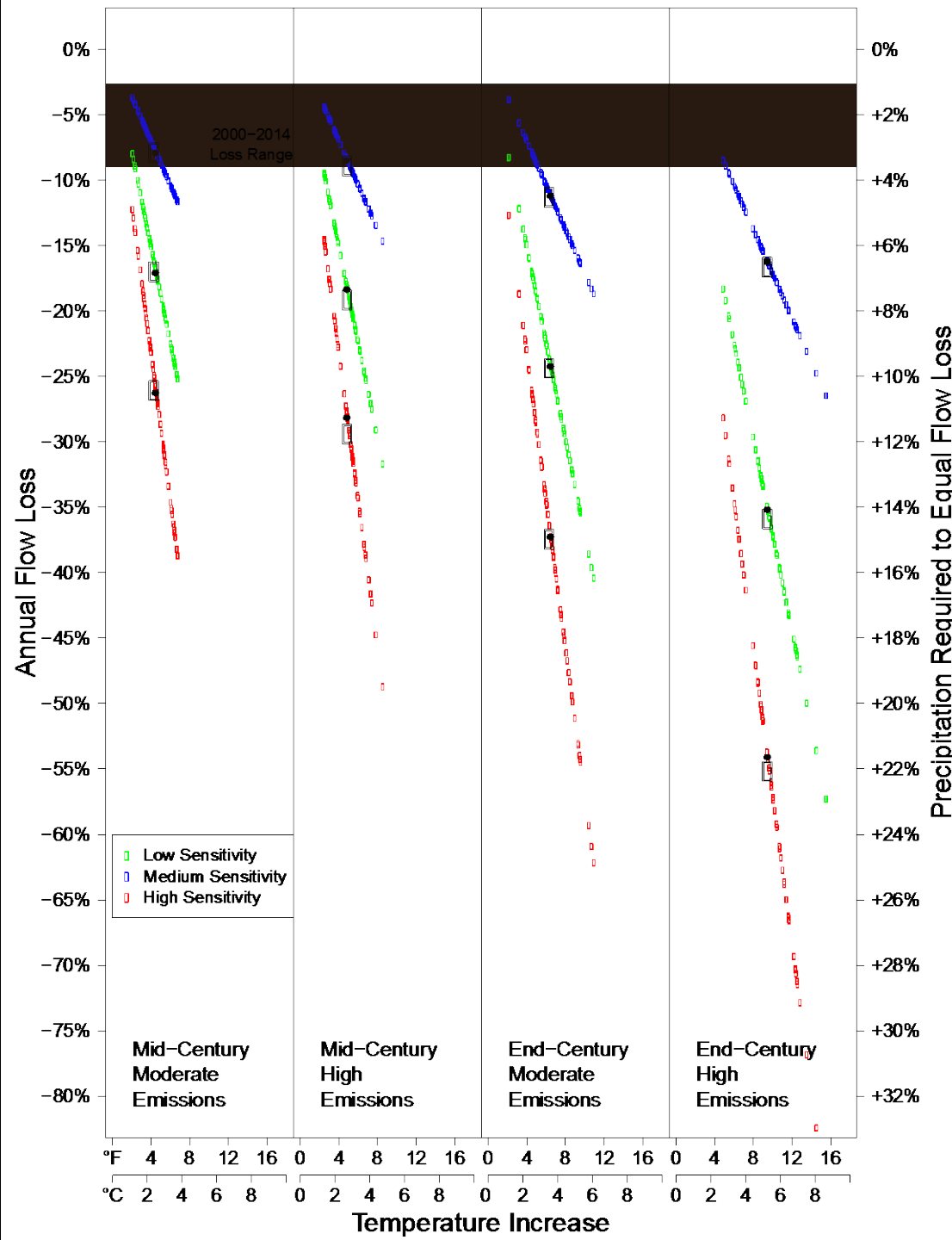
Source: Udall & Overpeck 2016



# Colorado River Future Flow Losses

Climate Change a  
combination of ...

- 1. For-Sure Temperature  
Rise -> Flow Losses
- 2. Not-Sure Precipitation  
Change -> Flow Gains?

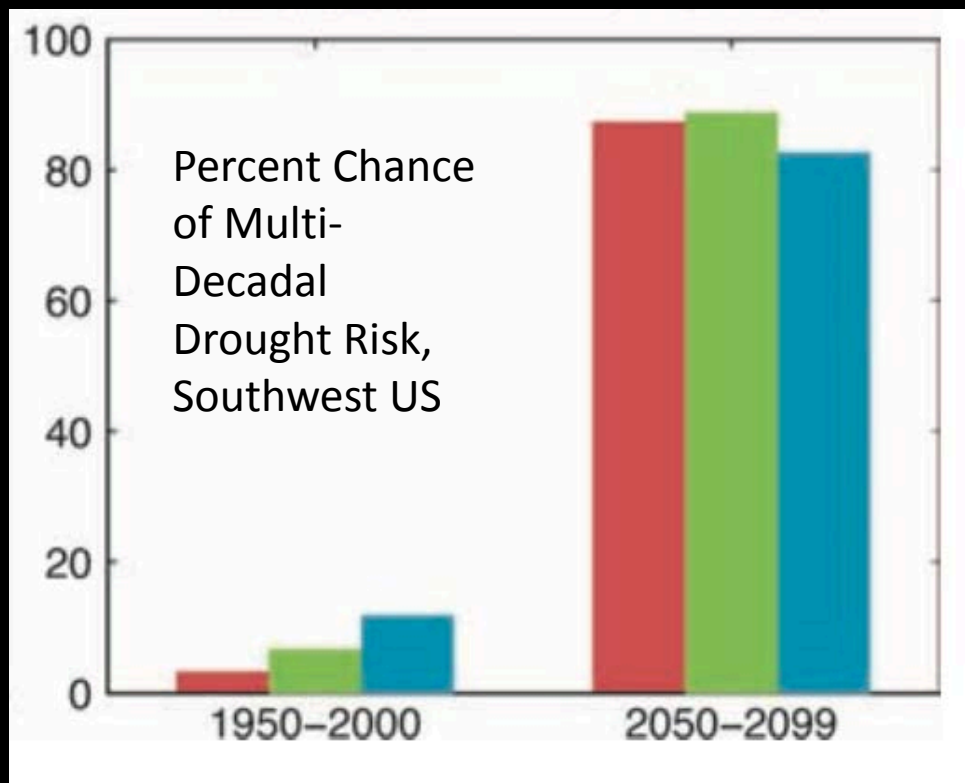


# Unprecedented 21st century drought risk in the American Southwest and Central Plains

Benjamin I. Cook,<sup>1,2\*</sup> Toby R. Ault,<sup>3</sup> Jason E. Smerdon<sup>2</sup>

In both Central Plains and Southwest, Multi-decadal Drought Risk\* exceeds 80% in 21<sup>st</sup> Century

\* Defined as Drought lasting 35 or more years

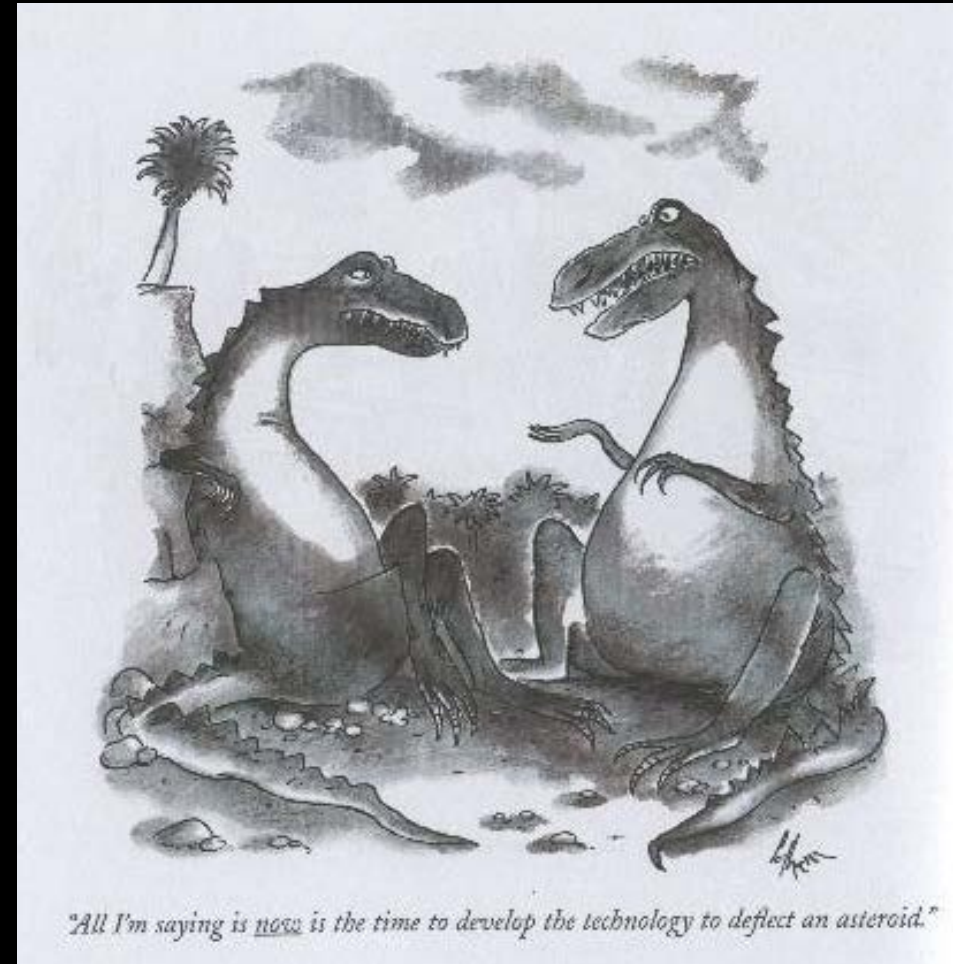


- Increasing influence of air temperature on upper Colorado River streamflow
  - Woodhouse et al, 2016
- Understanding Uncertainties in Future Colorado River Streamflow
  - Vano, et al, 2014
- Projections of declining surface-water availability for the southwestern United States
  - Seager et al, 2012
- The Unusual Nature of Recent Snowpack Declines in the North American Cordillera
  - Pederson, et al, 2011
- Future dryness in the southwest US and the hydrology of the early 21st century drought
  - Cayan, et al, 2010
- Dry Times Ahead
  - Overpeck and Udall, 2010
- Model Projections of an Imminent Transition to a More Arid Climate in Southwestern North America
  - Seager et al, 2009
- Water supply risk on the Colorado River: Can management mitigate?
  - Rajagopalan et al, 2009
- When Will Lake Mead Go Dry?
  - Barnett and Pierce, 2008
- Attribution of Declining Western U.S. Snowpack to Human Effects
  - Pierce, et al, 2008
- Warming may create substantial water supply shortages in the Colorado River basin
  - McCabe and Wolock, 2007



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# Paris, France 195 Nations December 12, 2015



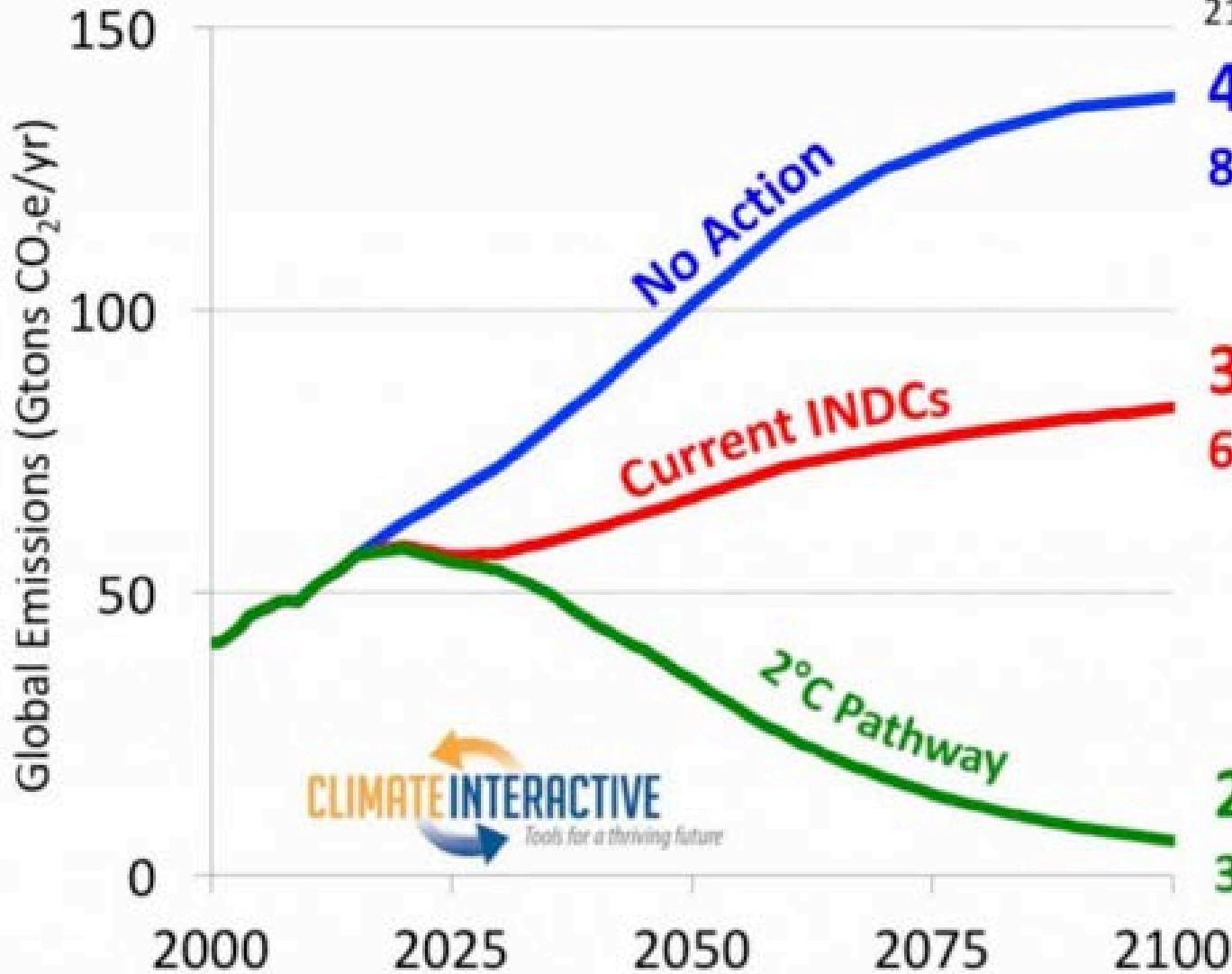
# Global Greenhouse Gas Emissions

Estimated  
2100 temp:

**4.5°C**  
**8.1°F**

**3.5°C**  
**6.3°F**

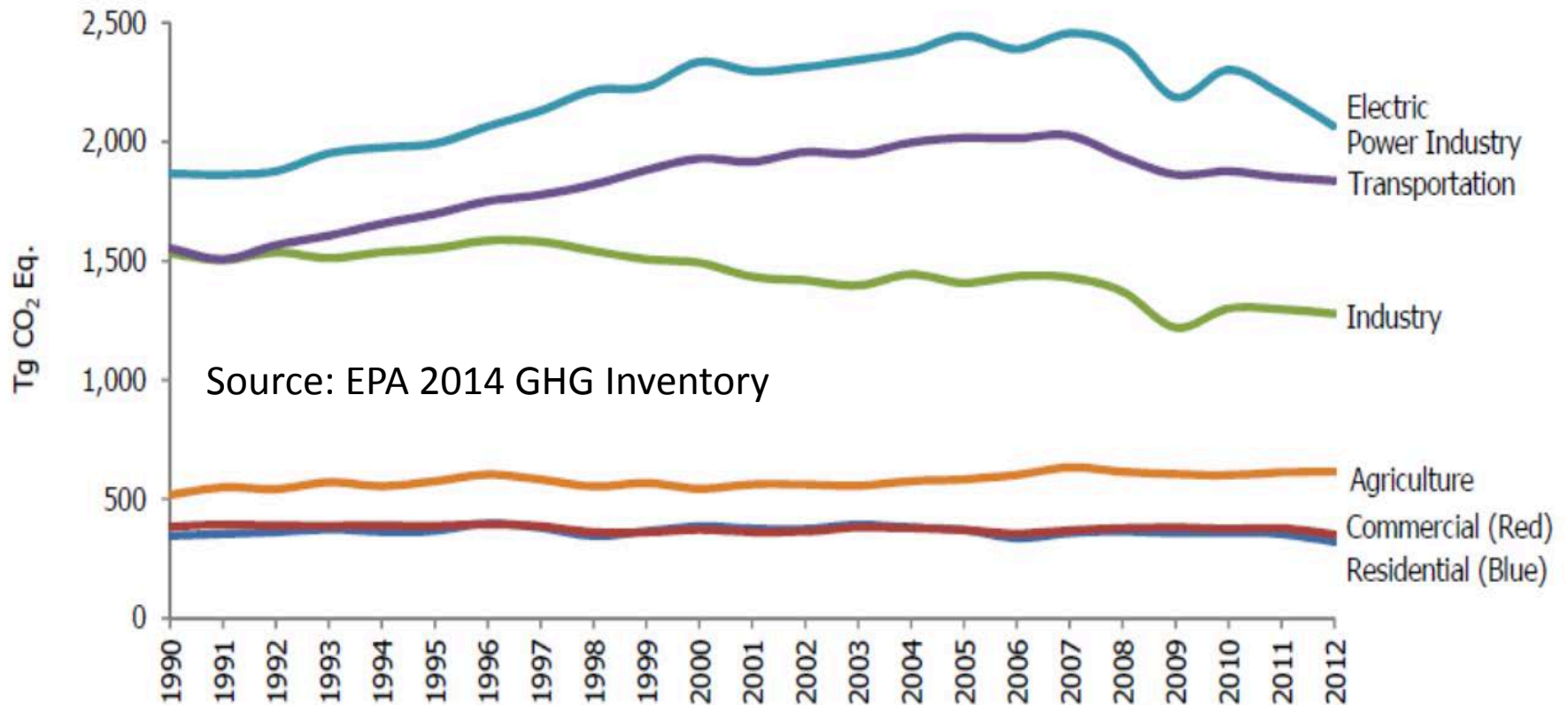
**2.0°C**  
**3.6°F**



# US Emissions Peaked 2007

## Emissions by Sector

Figure ES-13: Emissions Allocated to Economic Sectors



# Conclusions

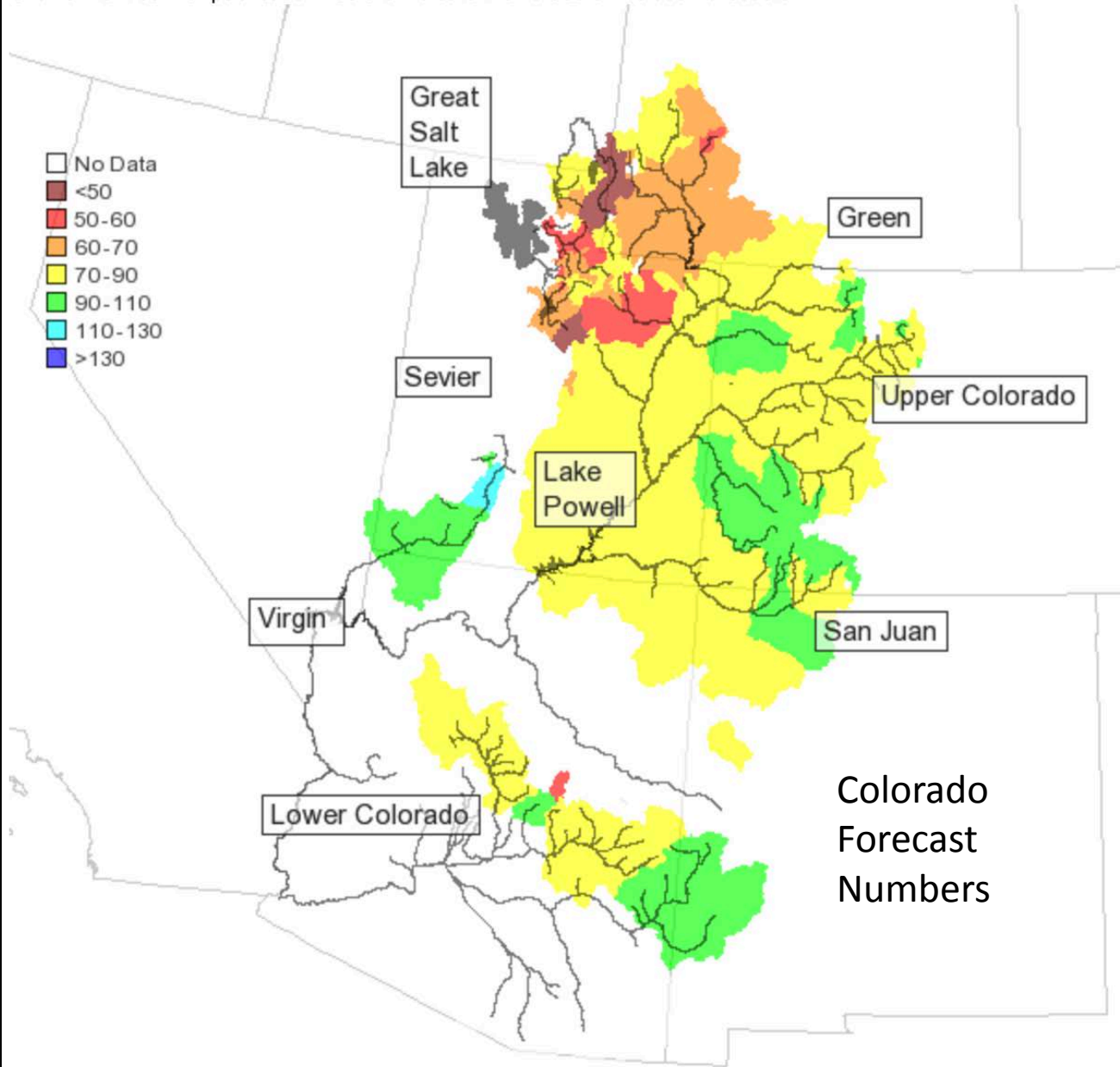
- Climate Change Defining Issue of 21<sup>st</sup> Century
  - Water at the heart of impacts
  - We can “legislate” away drought
    - Have technical/economic capacity to banish climate change...but maybe not political will
  - Solutions at hand, but need to pursue with all possible haste
- Many Water Solutions Possible
  - But nothing is easy...



*"Perhaps you'd like a second opinion?"*

# Water Supply Outlook, March 1, 2016

Click on text box for publication. Colors indicate the values of residual forecasts.



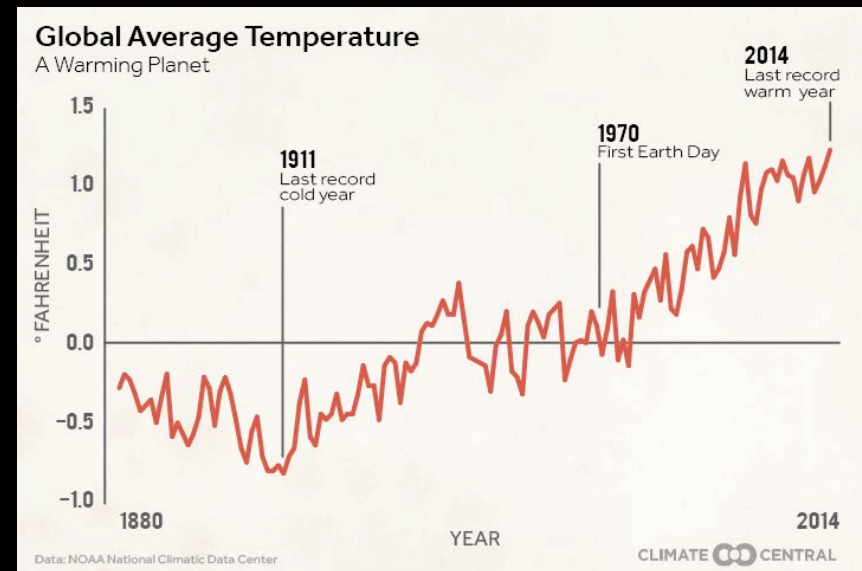
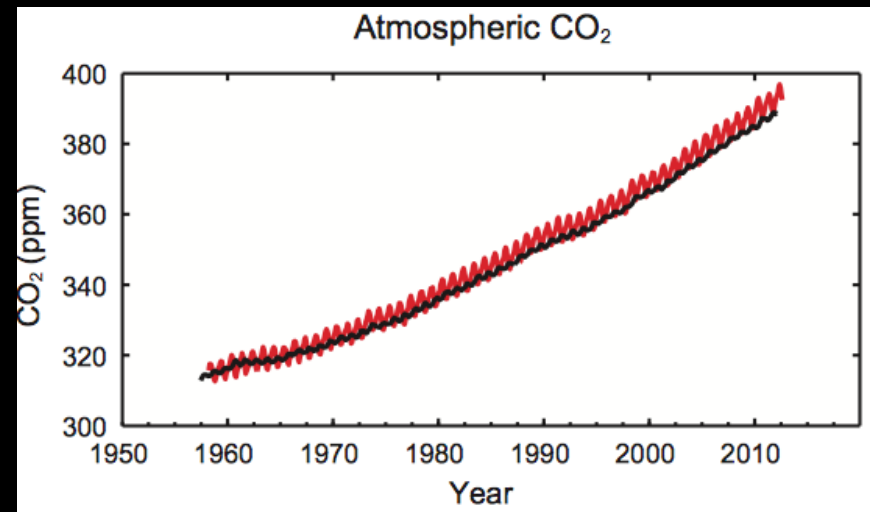
Colorado River  
Runoff  
Projections,  
March 1, 2016

3/16/16 Lake  
Powell Forecast  
was 73% of  
Average

Wet May – 94%  
of normal

Colorado  
Forecast  
Numbers

- Earth is about 60F warmer than it should be
- Very Small Concentrations of Greenhouse Gasses (GHGs) are the cause. CO<sub>2</sub> is most important one.
- Earth's Temperatures have fluctuated widely over its 4.5B year history But NOT during human ascendency of last 2k years
- Humans are adding enormous amounts of GHGs to the atmosphere every day and it is increasing over time. On a path to double CO<sub>2</sub> by 2050
- Planet is now 1.8 F warmer due to GHG emissions. No other plausible explanation for the warming
- Total Warming will be related to GHG concentrations, not emissions



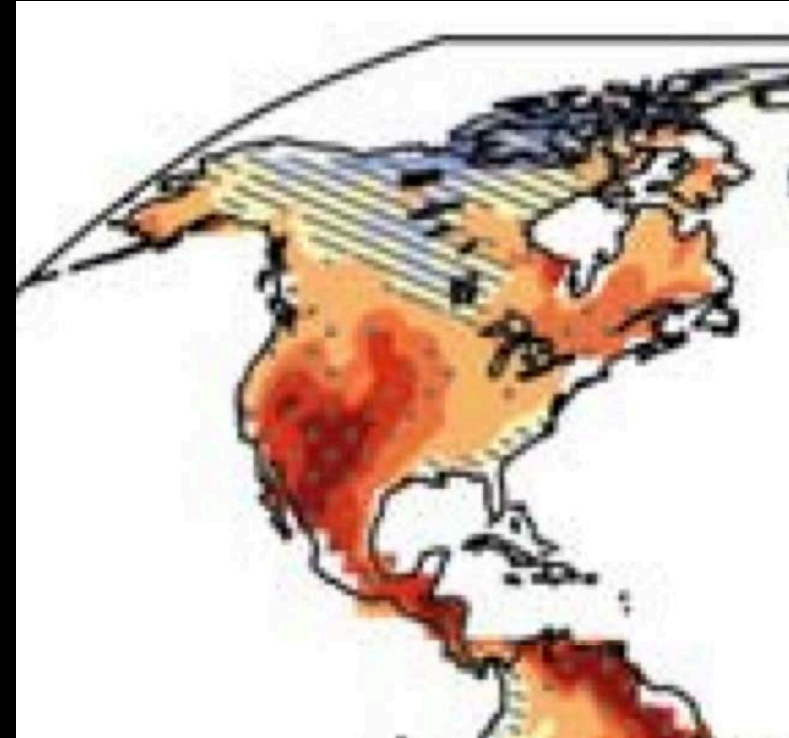
# \* Climate Change Basics



# Projected Drying in U.S. Southwest

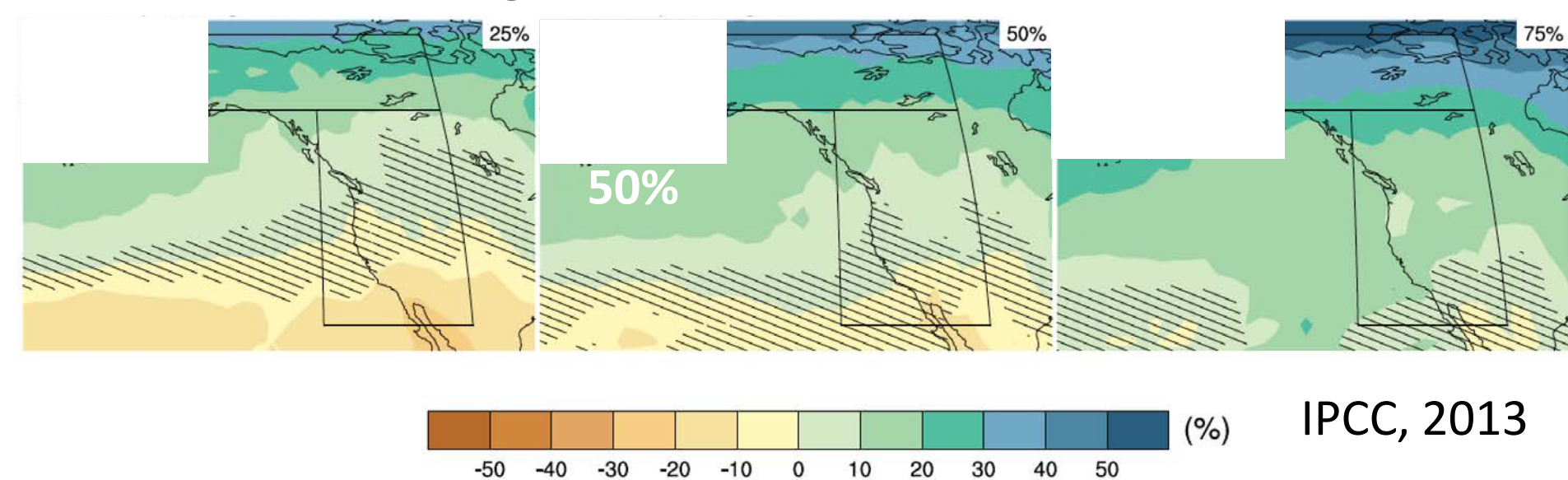
- “Regional to global-scale projections of soil moisture and drought remain relatively uncertain compared to other aspects of the water cycle. Nonetheless, drying in the Mediterranean, **southwestern U.S.** and south African regions are consistent with projected changes in Hadley circulation, so drying in these regions as global temperatures increase is likely for several degrees of warming under the RCP8.5 scenario.”

Soil Moisture @2100



# Latest Climate Model Projections (Ensemble average of 39 global models)

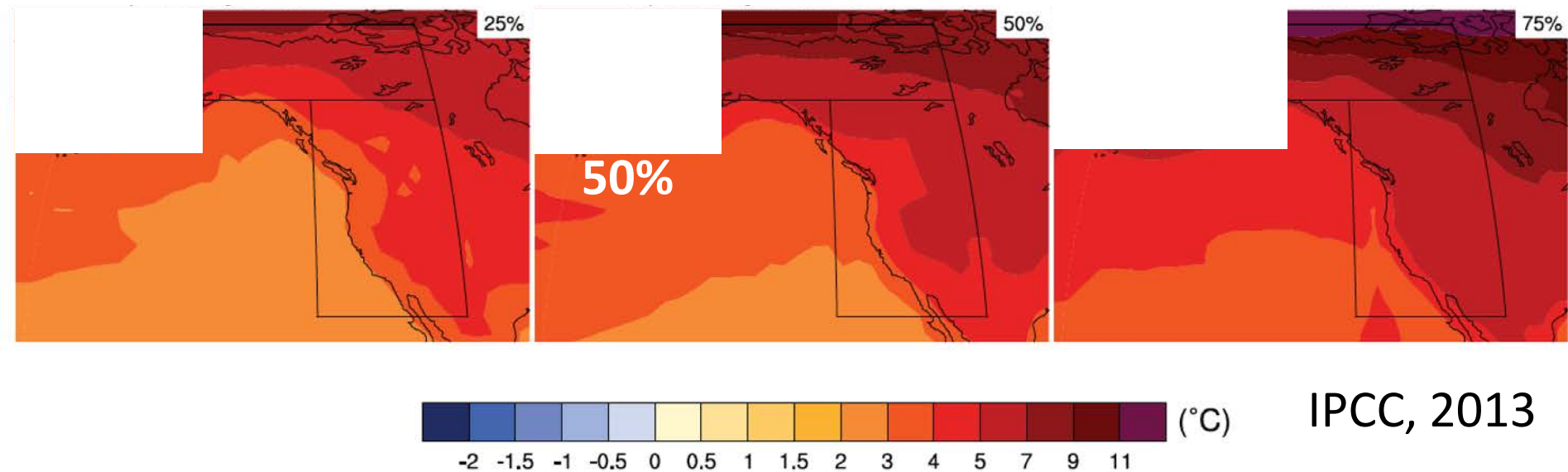
## Projected Annual Precipitation Change by the End of Century Given Continued High Emissions



Bottom-line: North gets wetter, South drier. But note that precip is not runoff.

# Latest Climate Model Projections (Ensemble average of 39 global models)

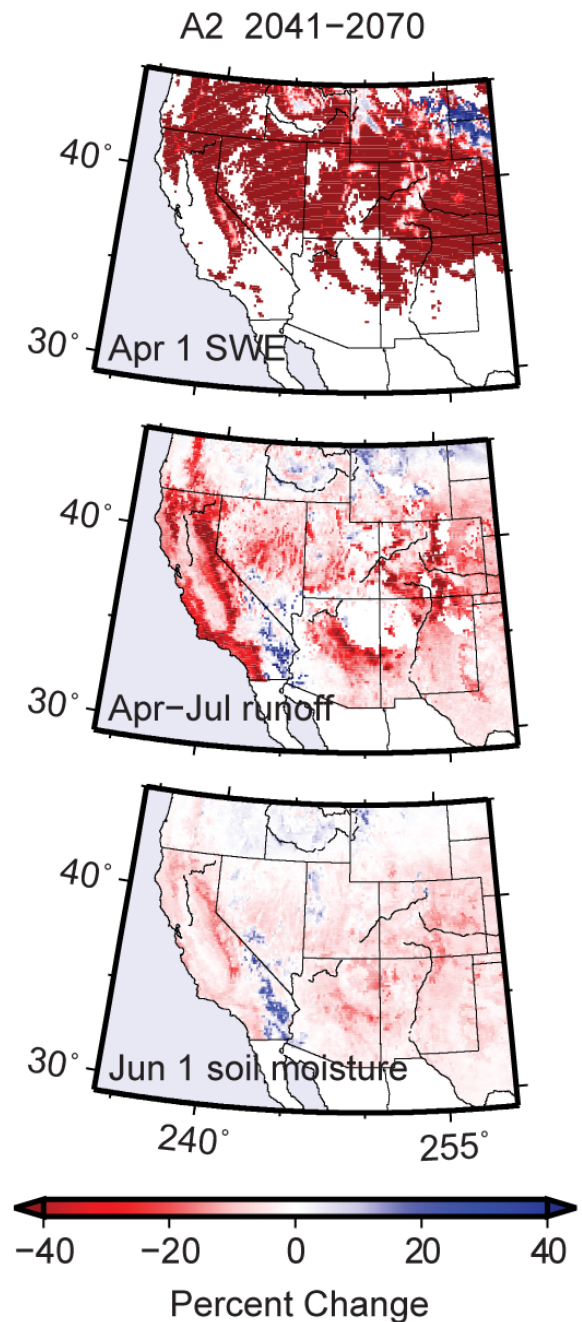
Projected Annual Temperature Change by the End of Century  
Given Continued High Emissions



Bottom-line: Western US will get hotter for sure,  
perhaps much hotter

# Projected Changes in Snowpack, Runoff, and Soil Moisture

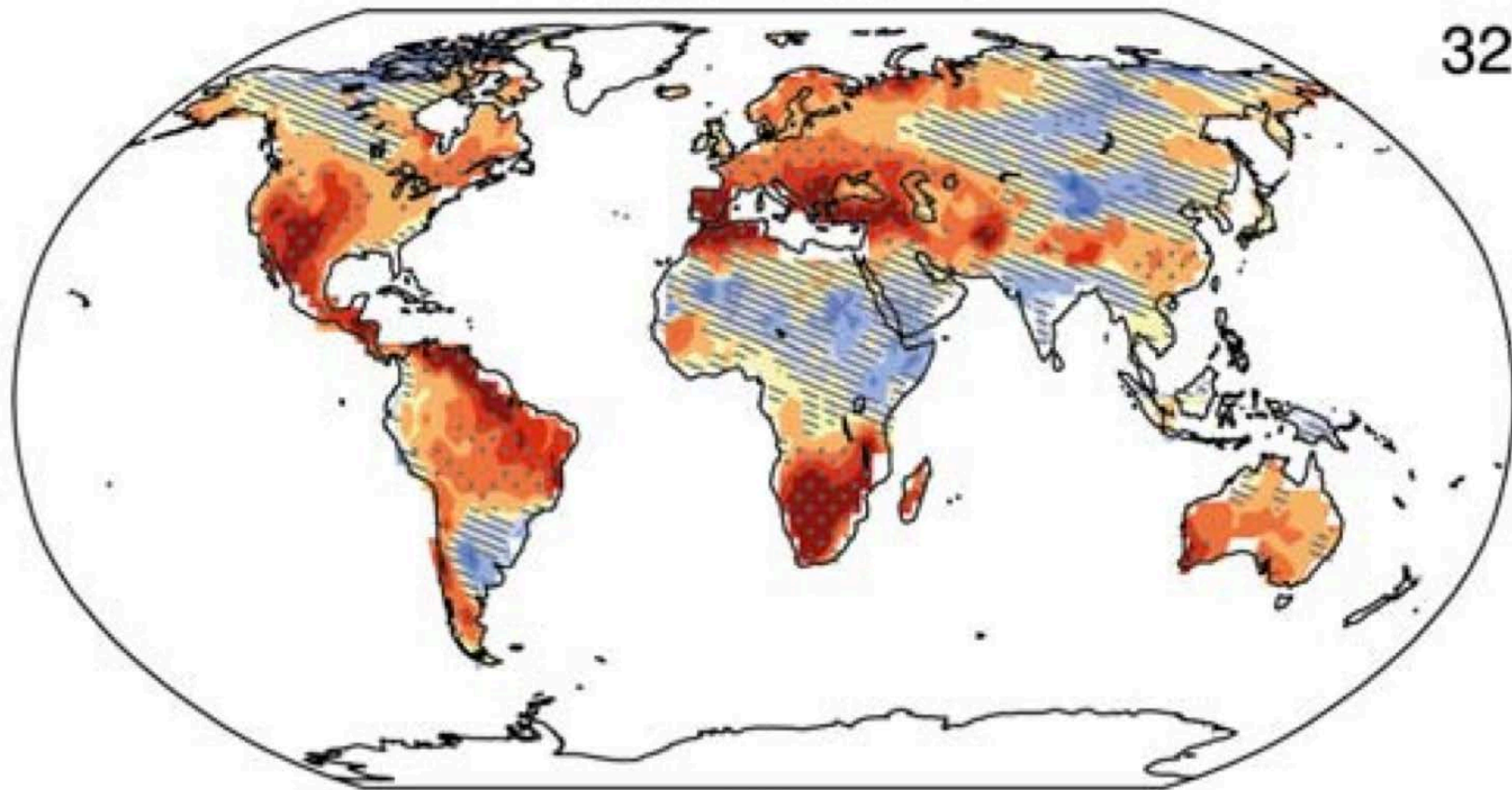
- Declines in April 1 Snow (SWE) indicate the start of runoff will advance into March
- Total Snow may or may not change depending on precipitation changes
- Not shown: increases in runoff during the Winter



# IPCC FAR Results RCP 8.5 at 2081 to 2100

## Soil moisture

32



(%)



-10 -7.5 -5 -2.5 0 2.5 5 7.5 10

# Dry Times Ahead

Jonathan Overpeck<sup>1</sup> and Bradley Udall<sup>2</sup>

The climate of the western United States could become much drier over the course of this century.

- 2F Warming since 1900
- Snowpack Reductions and Changes in Runoff Timing Already Present
- Most Severe Drought since records kept
- Powell and Mead at 50% of capacity now, full 2000
- Tree Mortality Rates High
- Increase in Wildfire Frequency
- Drought may be natural, but exacerbated by higher temperatures
- Snowpack Reductions and Runoff Timing attributed to climate change
- Continued drying likely as temperatures increase and storm tracks shift
- Megadroughts independent of climate change a possibility with severe consequences if combined with warming

# Reasons for Climate Optimism

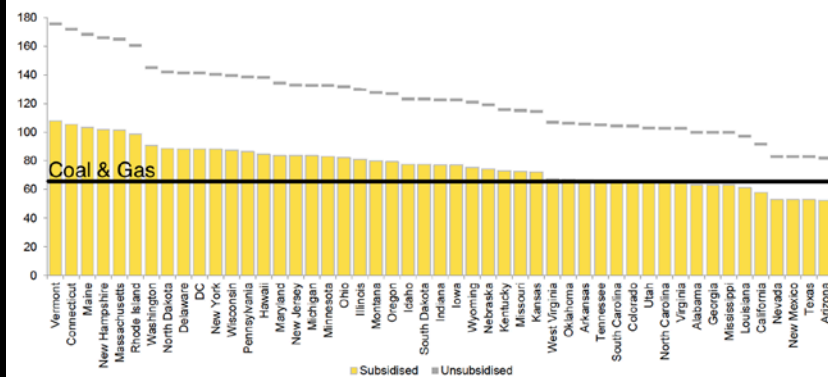
- Technology
  - PV - \$10 to \$0.50 over 2 decades
  - Wind less than Gas Now
  - 200 Fewer Coal Plants (325 now)
  - LED Lights
  - Nissan Leaf Battery \$15k to \$5k
  - Storage a top priority but not needed for a while
- International Commitments at Paris
  - First Ever Agreement with 195 Countries
- US Efforts
  - Clean Power Plan – no more coal built
  - 32% by 2032 relative to 2005
  - US GHG Emissions have likely peaked
- World Efforts
  - Emissions declined globally last year
- Science Implications
  - Will be able to rule out higher emissions soon
- Future still a challenge
  - Will blow by 2C warming most likely
  - We just spent 20 years wasting time on getting an interanational agreement

BloombergBusiness

Bloomberg Business

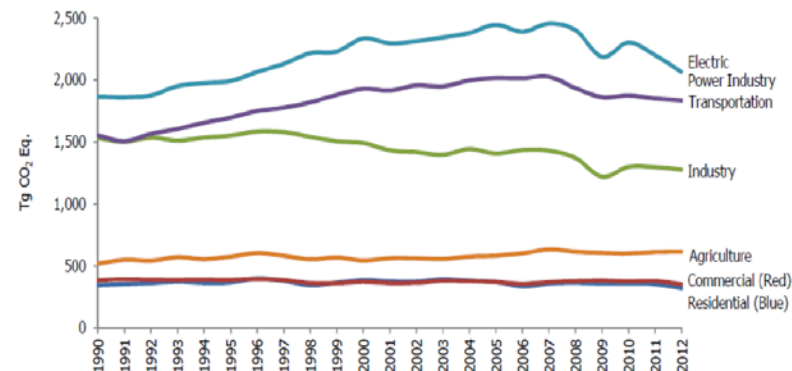
## Solar and Wind Just Passed Another Big Turning Point

Latest Solar Costs by State



Source: BNEF, Annotated by Bloomberg

Figure ES-13: Emissions Allocated to Economic Sectors



# Future cost-competitive electricity systems and their impact on US CO<sub>2</sub> emissions

Alexander E. MacDonald<sup>1</sup>★†, Christopher T. M. Clack<sup>1,2</sup>★†, Anneliese Alexander<sup>1,2</sup>, Adam Dunbar<sup>1</sup>, James Wilczak<sup>1</sup> and Yuanfu Xie<sup>1</sup>

