Yellowstone River Basin Climate: Past, Present, and Future

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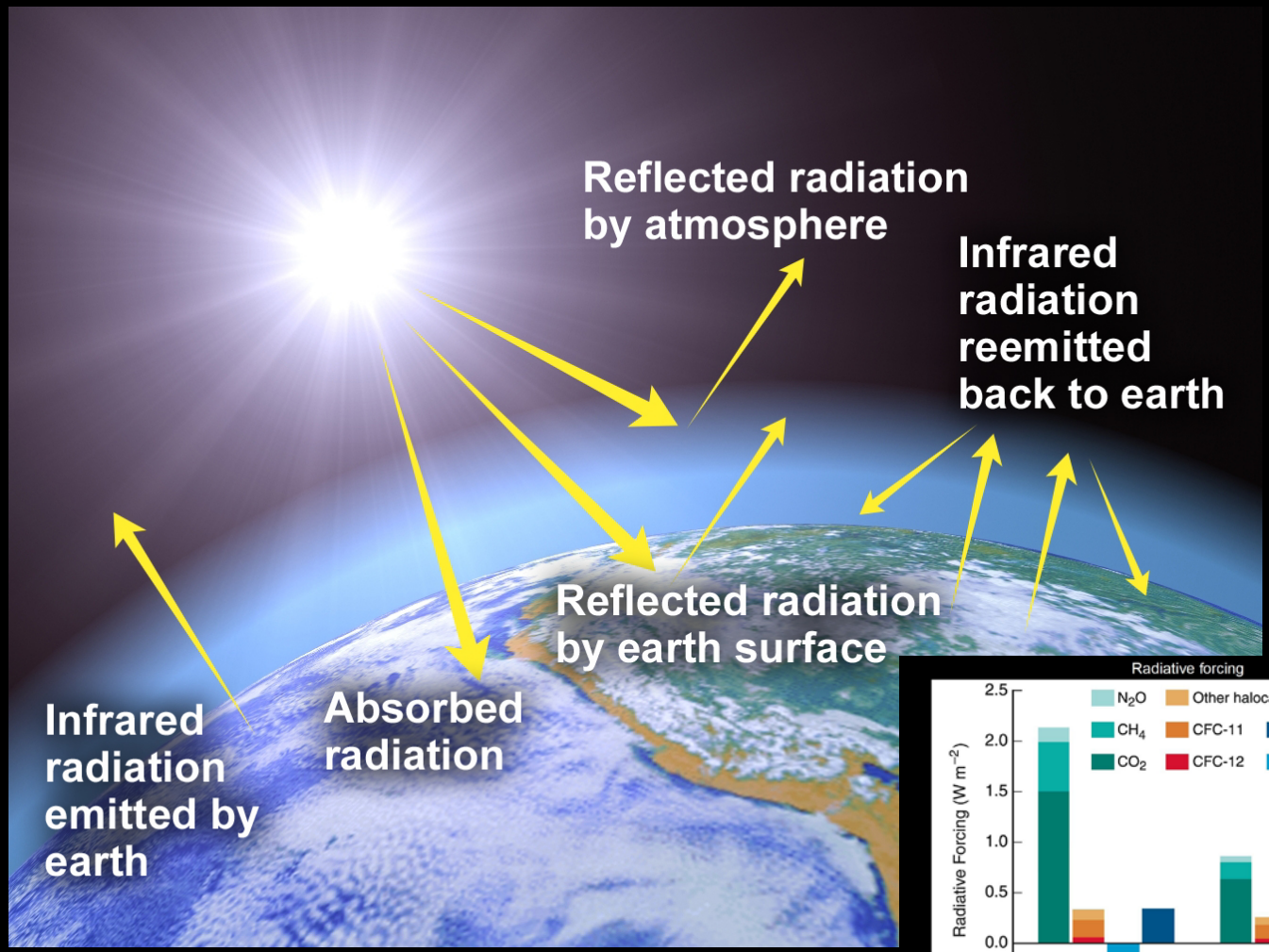
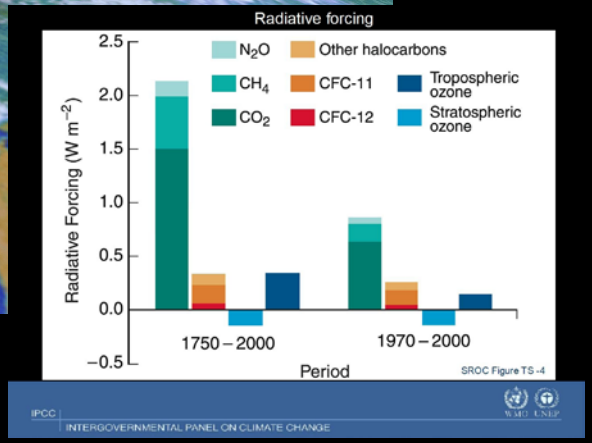
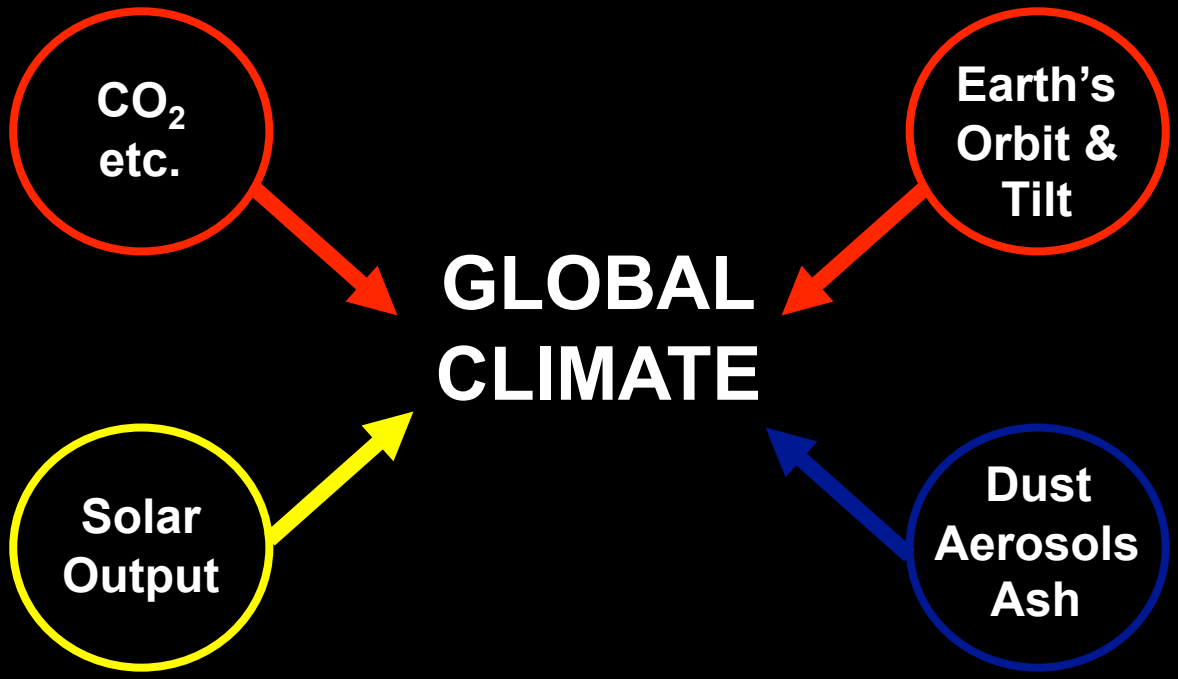
Roadmap

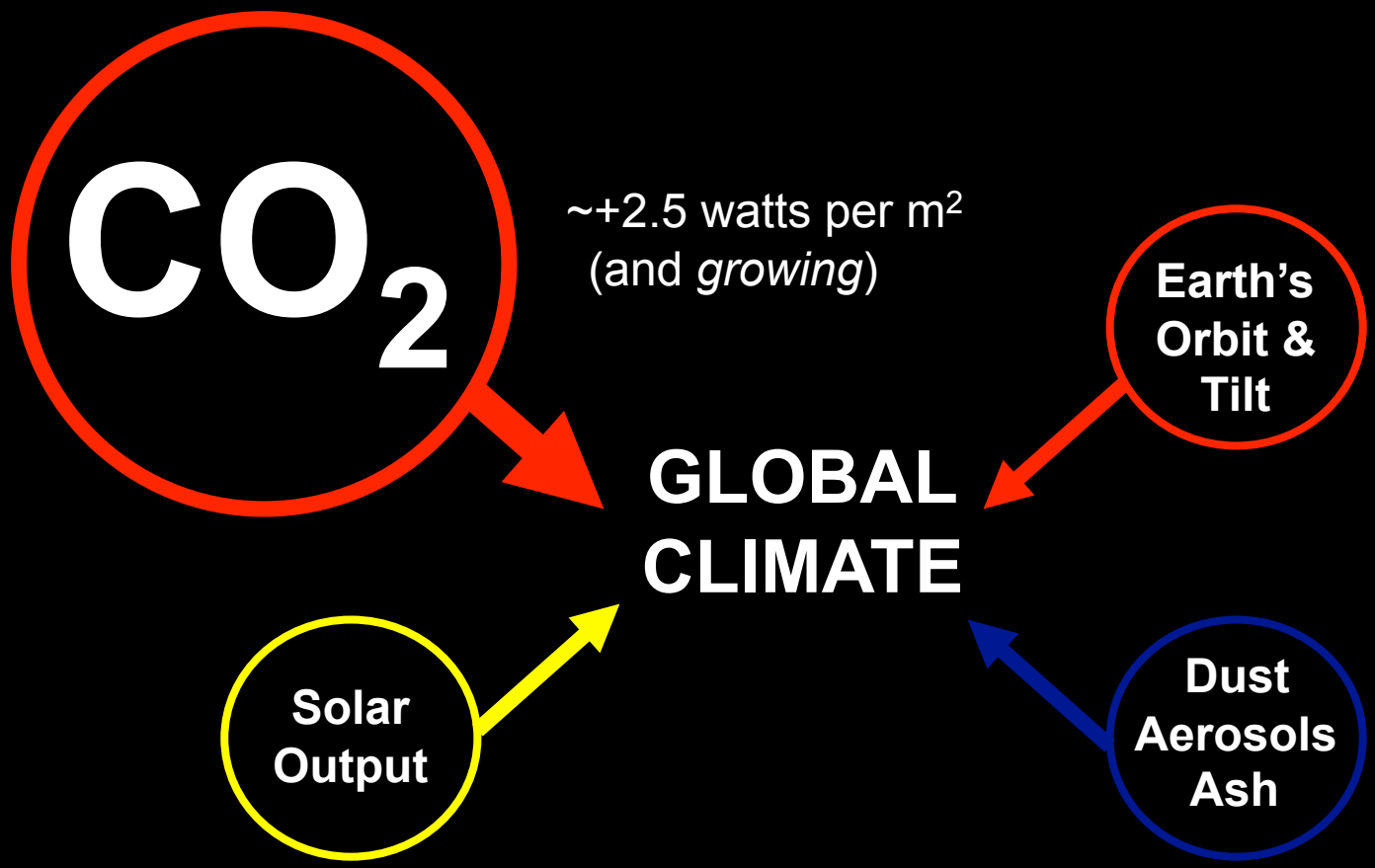
- **2013 Global and Regional Temperatures**
  - Brief retreading of GHG role in recent warming
- **Documented 20th Century Snowpack Decline**
  - Recent documented warming across the west
  - Linkages with phenology, glaciers, and water resources
- **1,000 year Snowpack and Streamflow Records for the Yellowstone Region**
  - Places the short modern record in a long-term context
  - Implications for water
- **Projections for snow and water resources in the Yellowstone Region**

The “Greenhouse Effect”

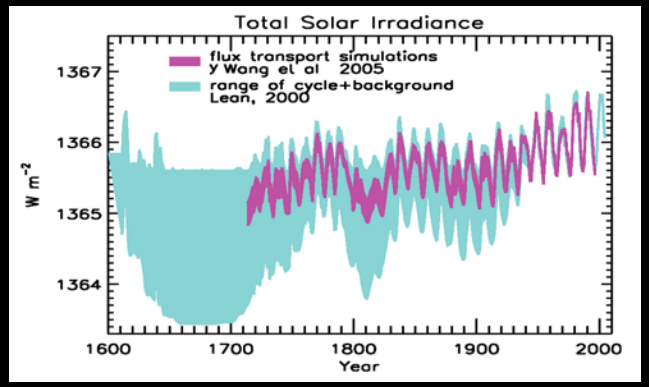





CO_2 etc.
Earth's Orbit & Tilt
GLOBAL CLIMATE
Solar Output
Dust Aerosols Ash

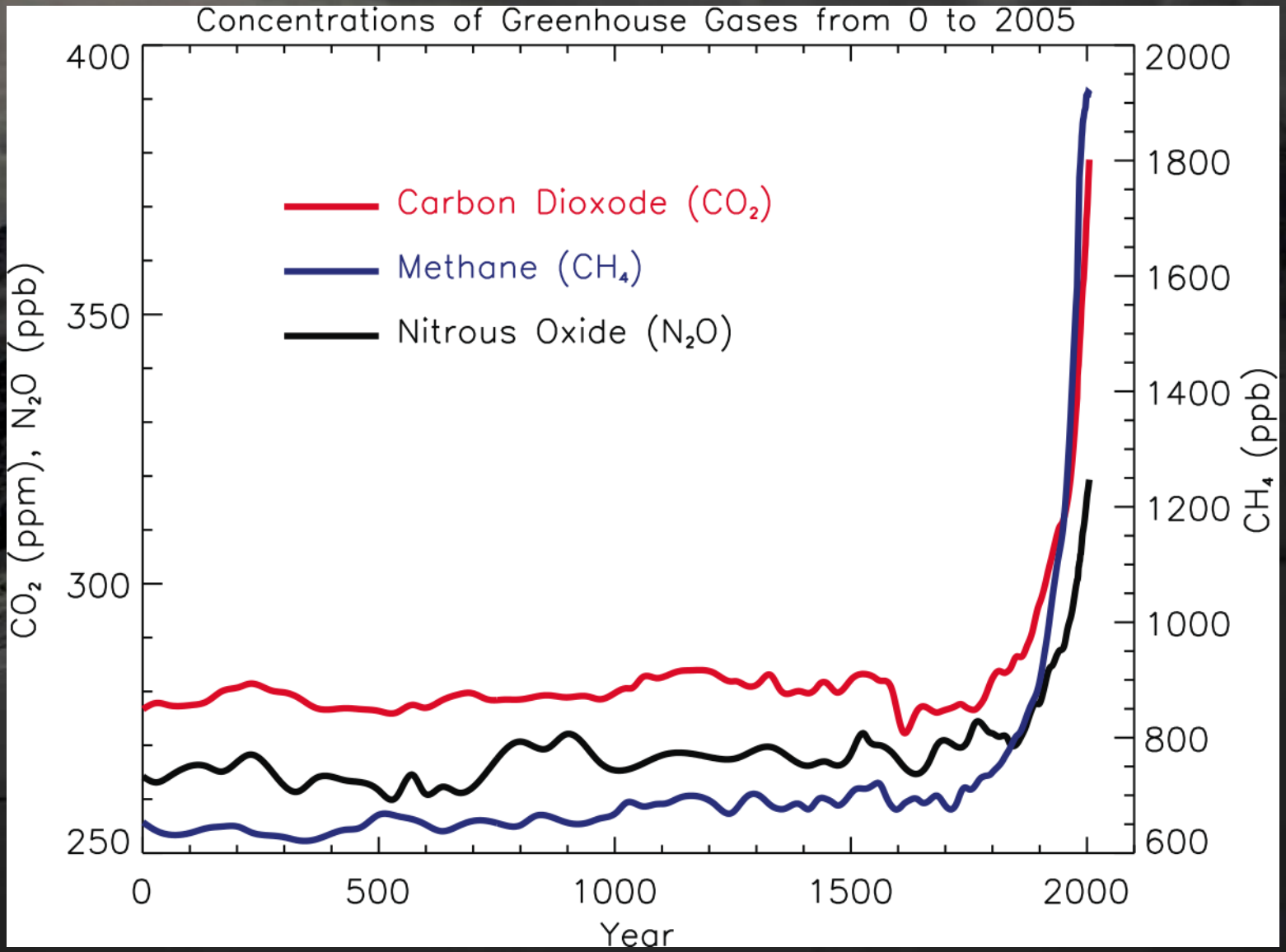


~+0.06 to +0.1 watts per m^2 since 1750
due only to amplification of 11 year cycle



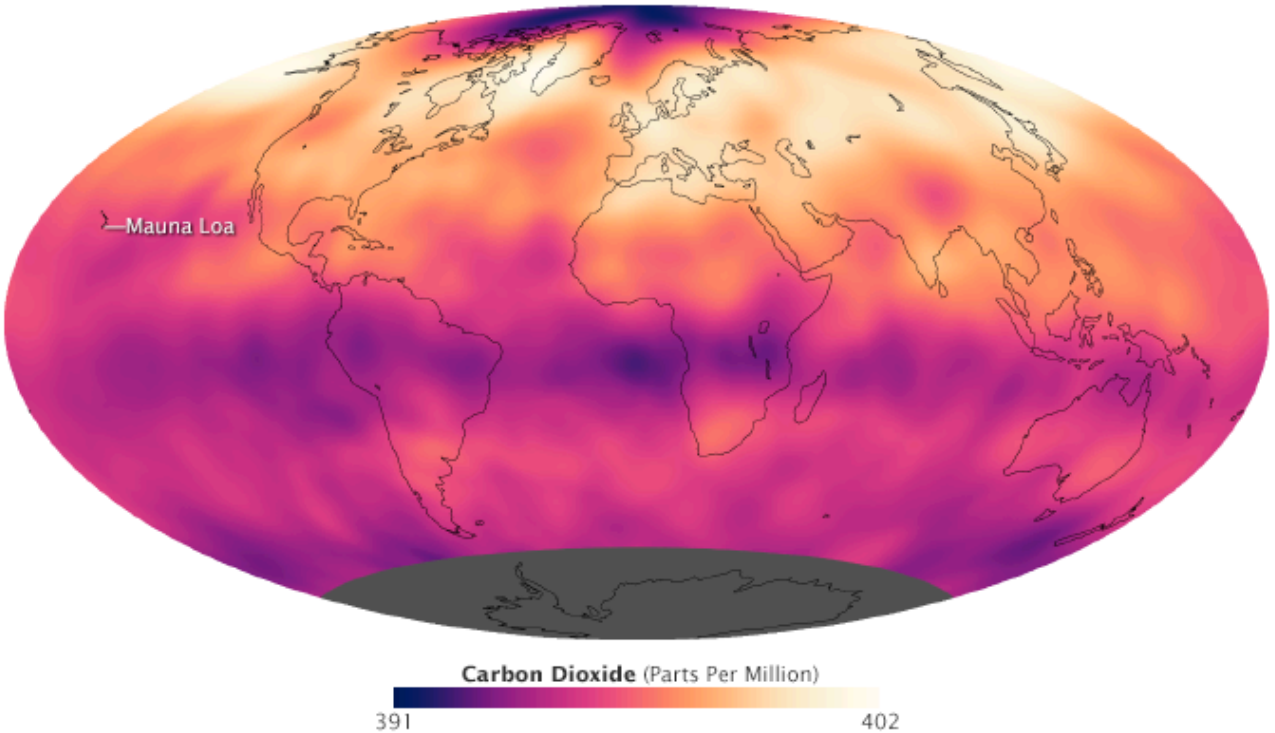
Ice cores and other archives give us information on past climate and CO_2

2000 Years of GHG Change



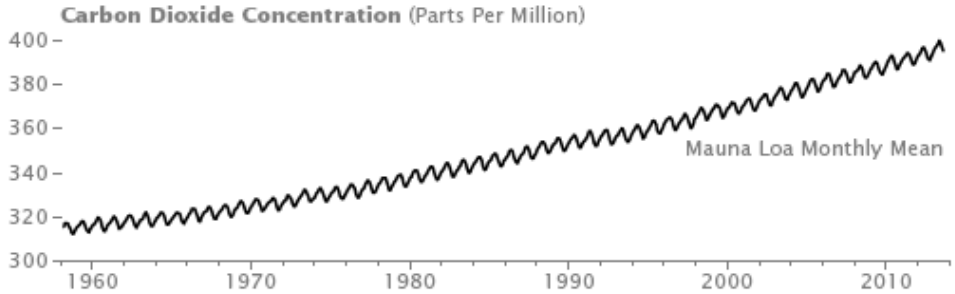
Source: IPCC 2007

Recent GHG Change



download large image (498 KB, JPEG, 2610x1306)

acquired May 1 – 31, 2013



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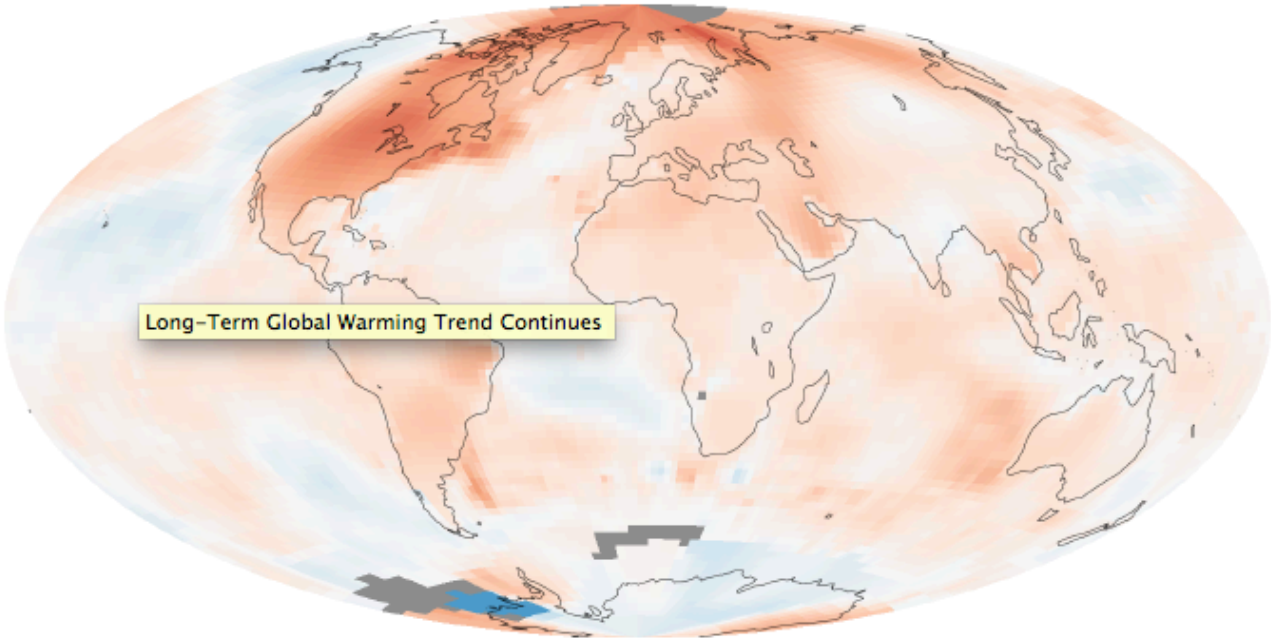
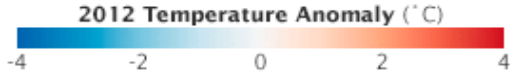
acquired March 1, 1958 – August 31, 2013

Source: NASA

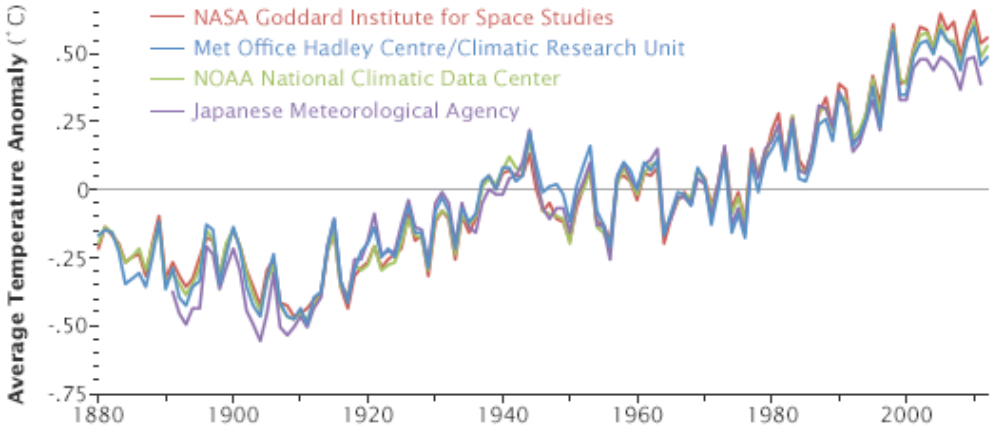
Historic Observed Changes: A Global Context



- 2012 Hottest Year in US history

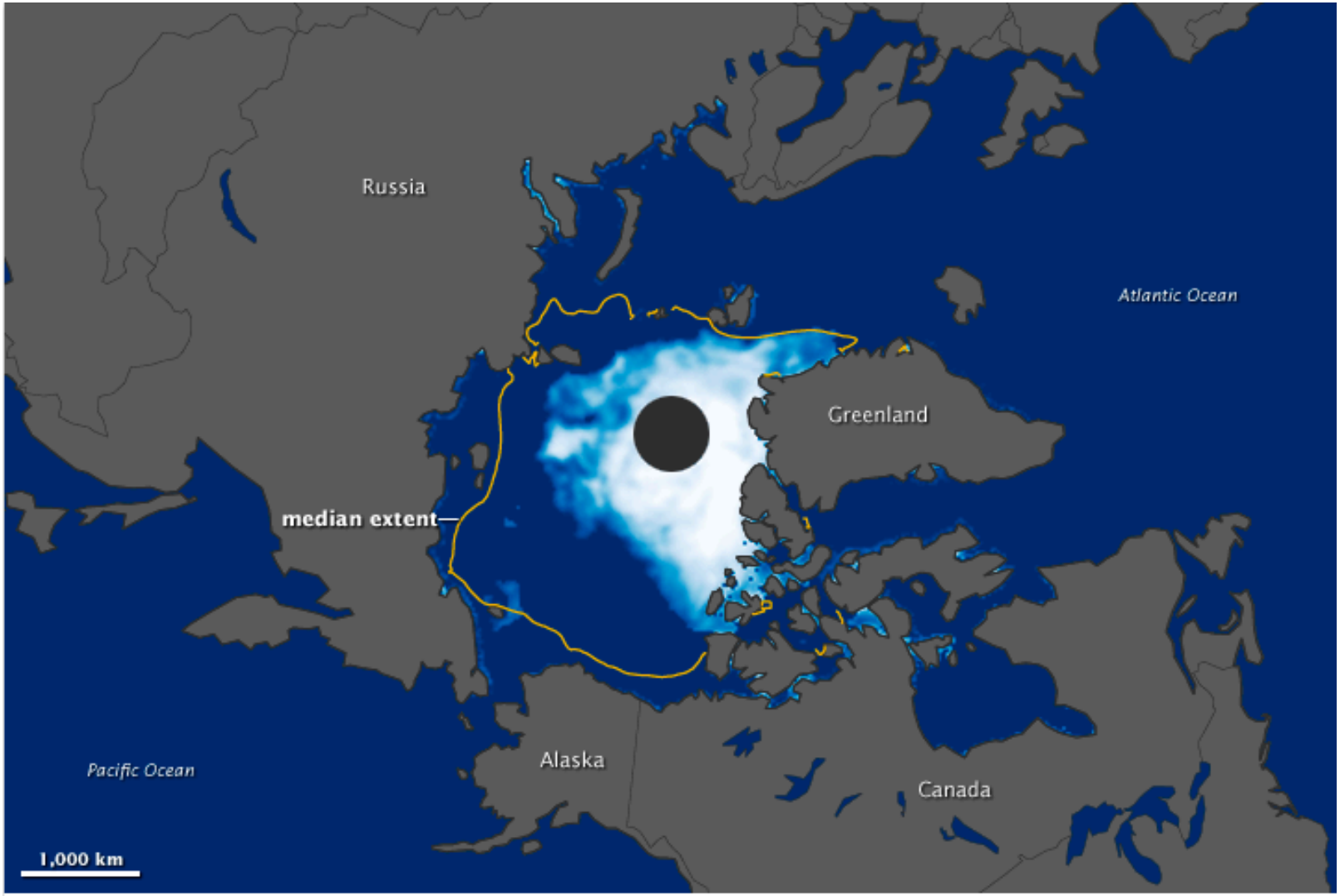


- 2012 9th Warmest Year
- 2010 Warmest Year on Record



-NASA GIS, 2012 Data

Record Breaking Summer Ice Retreat

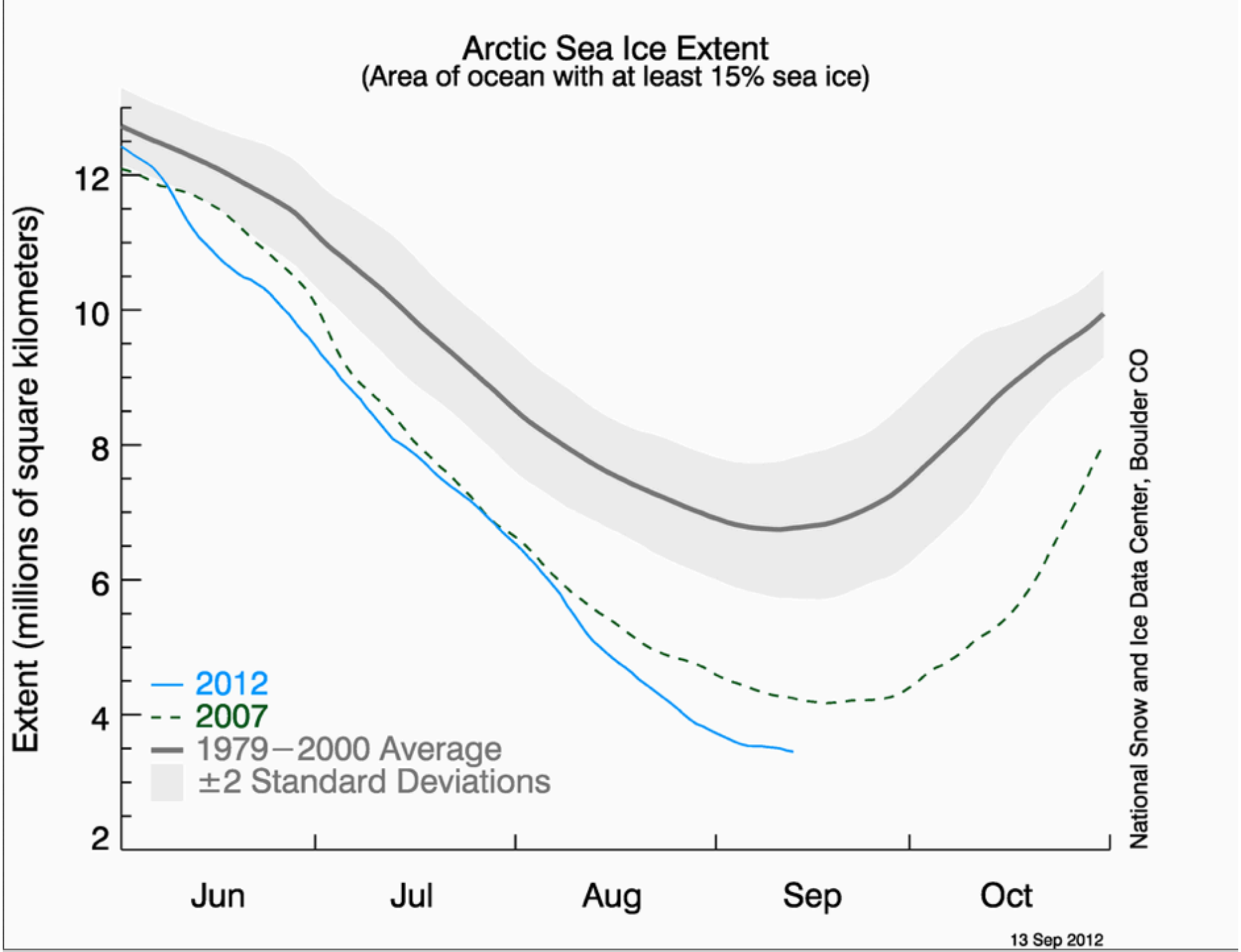


acquired August 26, 2012

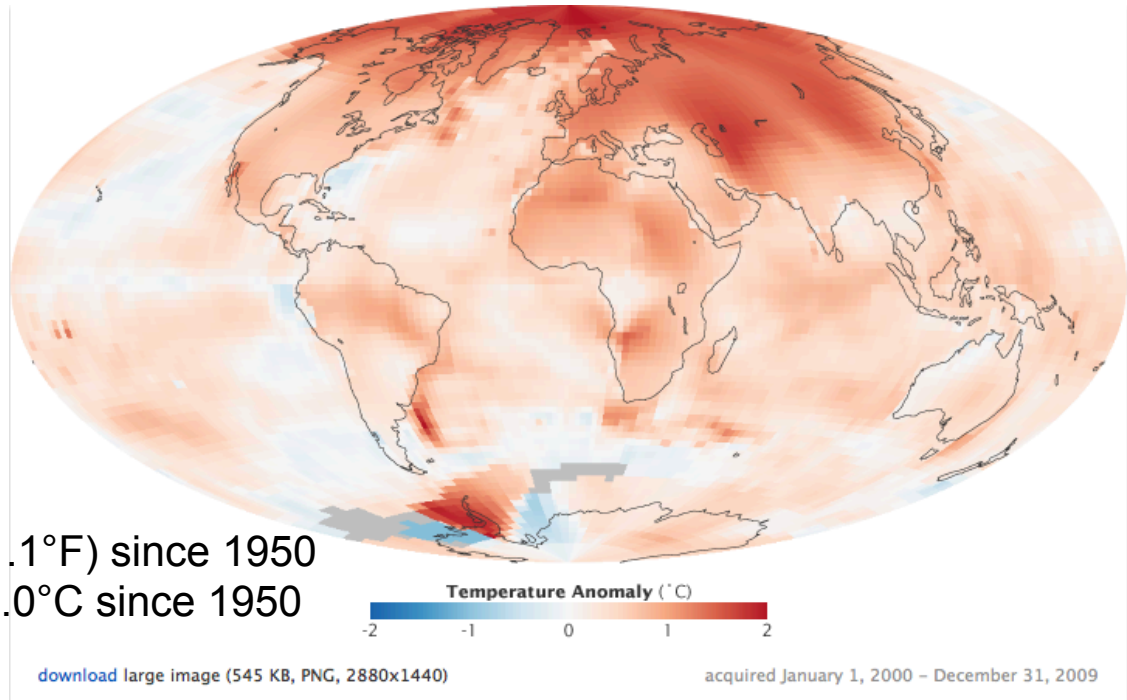
Sea Ice Concentration (percent)

0 50 100

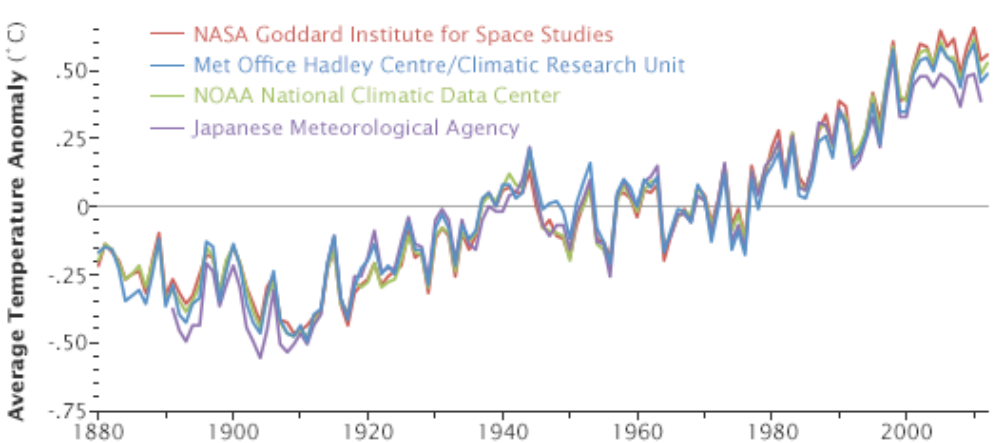
http://earthobservatory.nasa.gov/IOTD/view.php?id=77671


Arctic Sea Ice Extent
(Area of ocean with at least 15% sea ice)
Extent (millions of square kilometers)
12
10
8
6
4
2
2012
2007
1979–2000 Average
±2 Standard Deviations
Jun
Jul
Aug
Sep
Oct
National Snow and Ice Data Center, Boulder CO
13 Sep 2012

Arctic Amplification: Implications for mid-latitudes as well

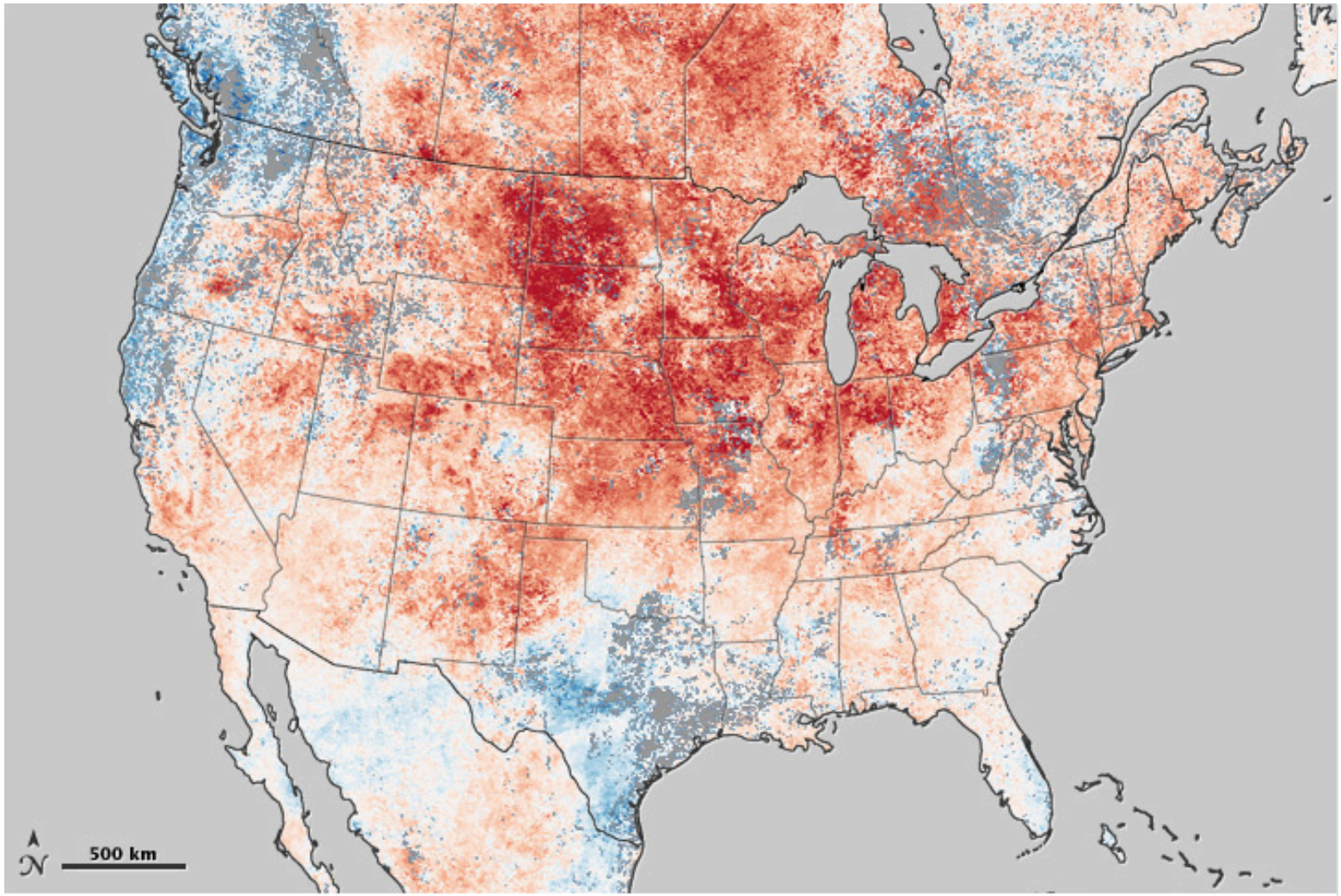


- Global: 0.6°C (1.1°F) since 1950
- Arctic Region: 2.0°C since 1950



-NASA GIS, 2013 Data

Historic High Temperatures



Land Surface Temperature Anomaly (˚C)

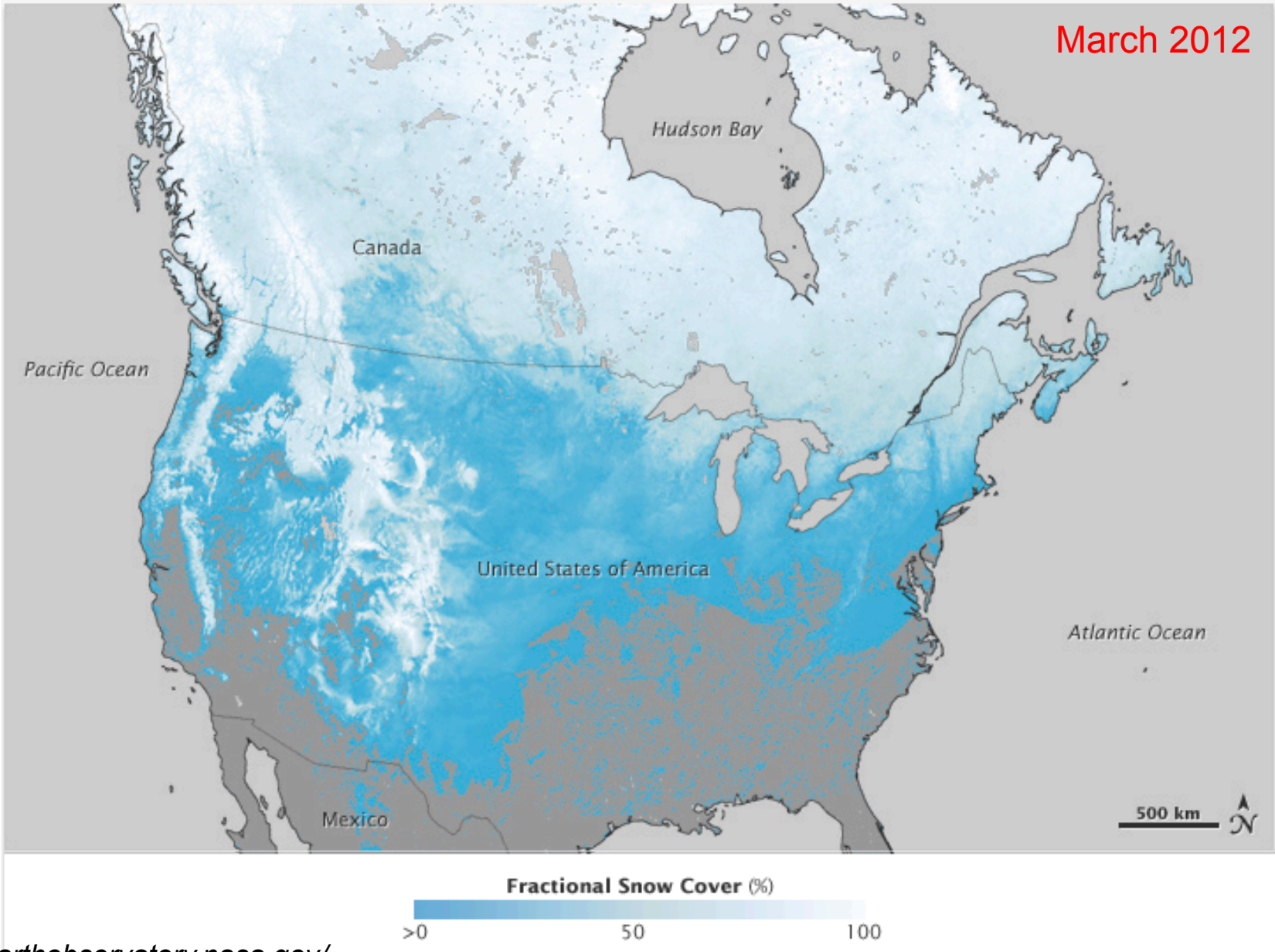
-15 0 15

download large image (3 MB, PNG, 1800x1800)

acquired March 8 – 15, 2012

http://earthobservatory.nasa.gov/

Drive Low Spring Snowpack



http://earthobservatory.nasa.gov/

Recent Changes Across the Western U.S. & Region

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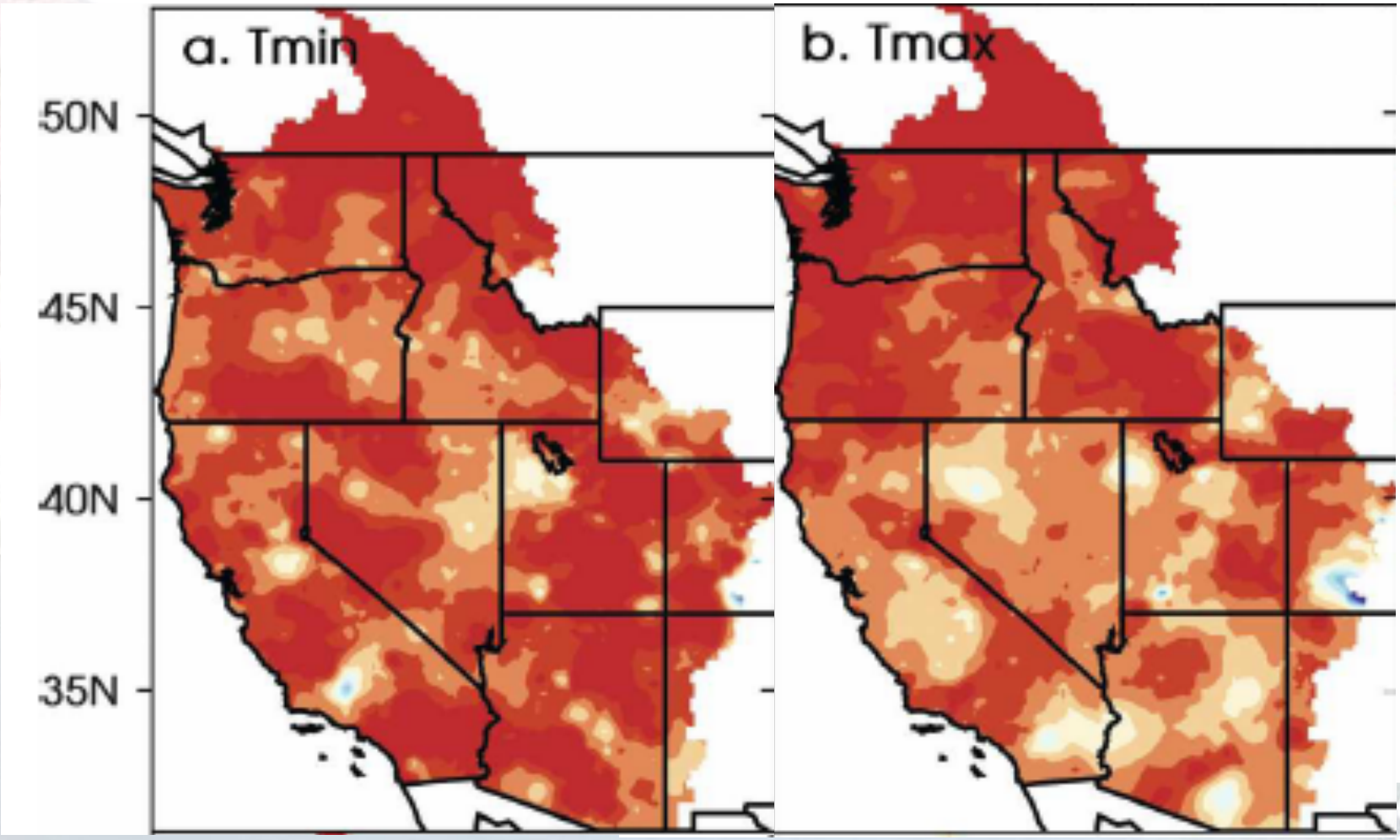
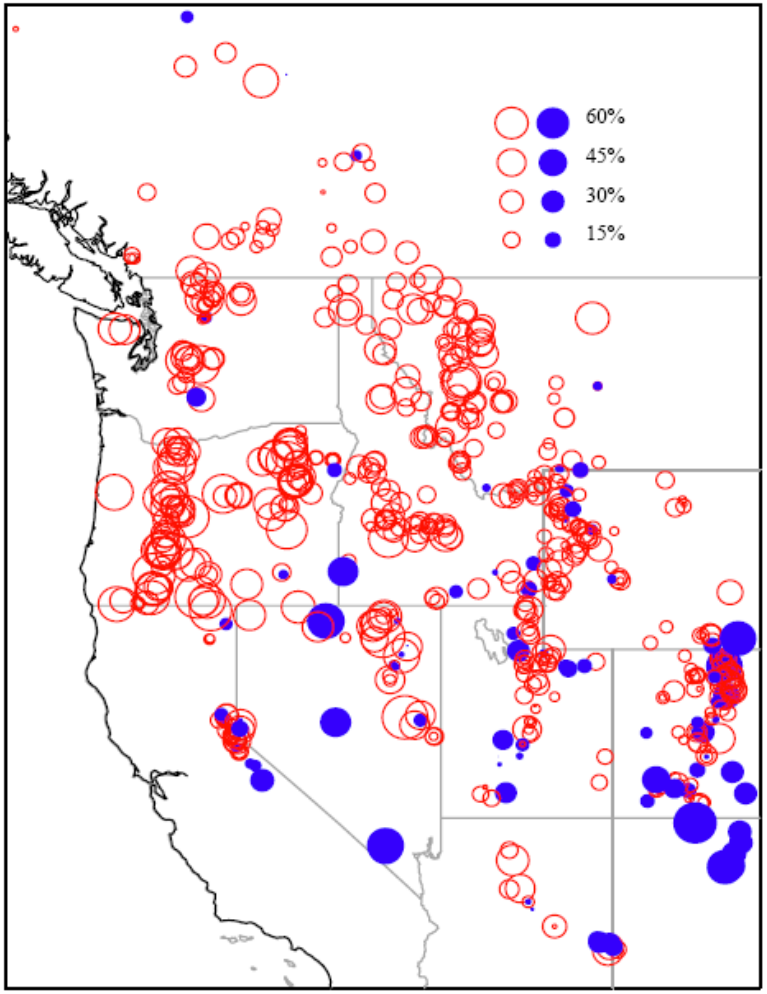
Recent Warming: 1950-2000



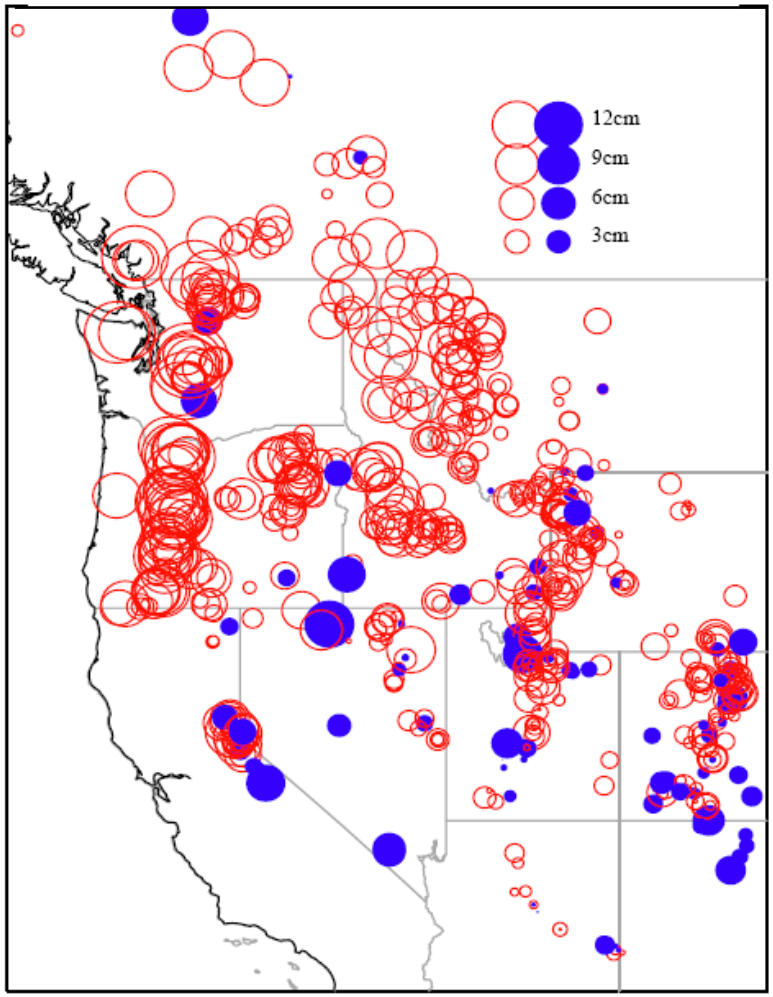
- Minimum Temperatures have warmed faster than maximums
- Greatest warming in the Northern Rockies.
- Strong GHG signal

-Bonfils et al. 2009 J Clim

Trends in *APRIL 1* snow pack: 1950-2000



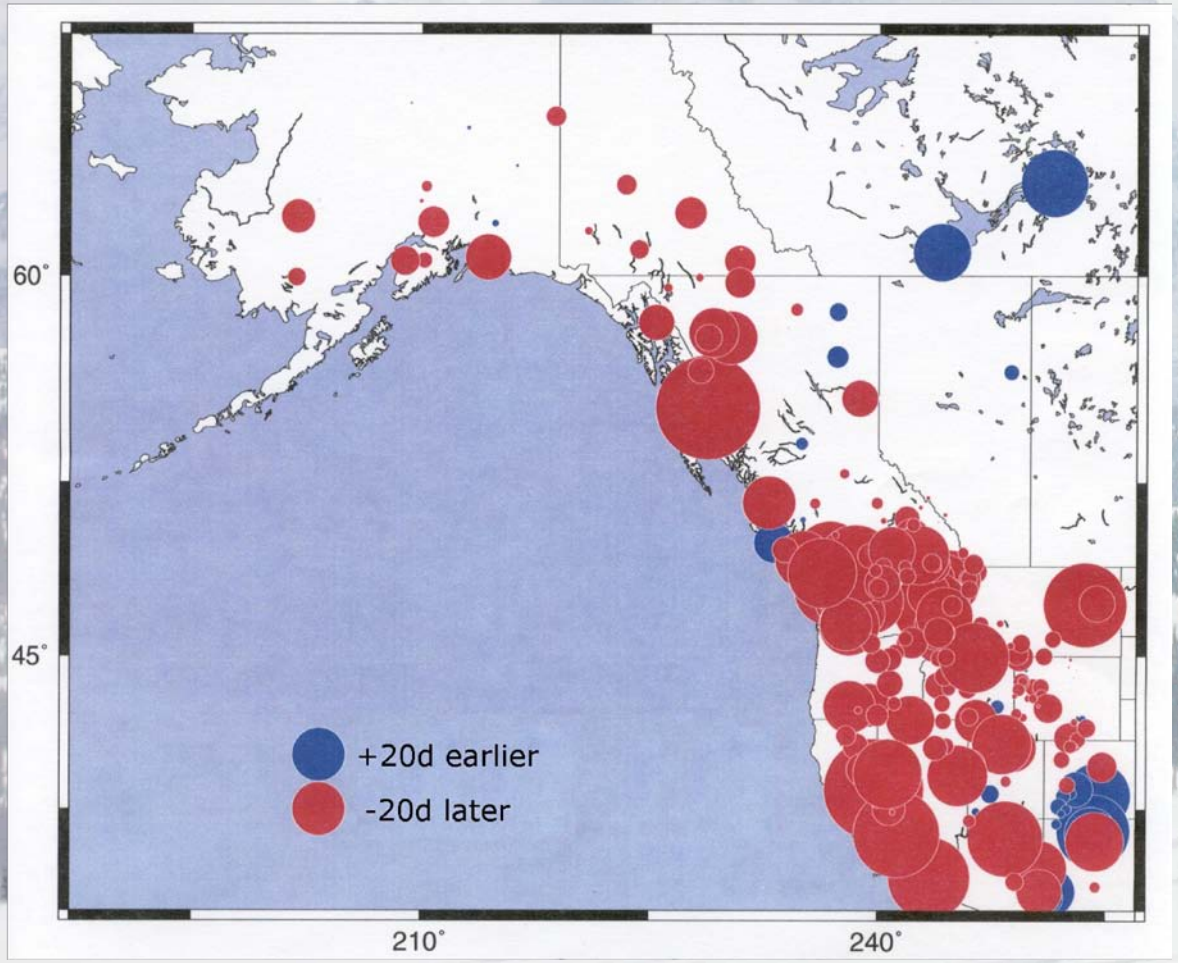
Percent change since 1950



Absolute change since 1950

From Mote et al. 2006

Trends in Snowmelt Timing

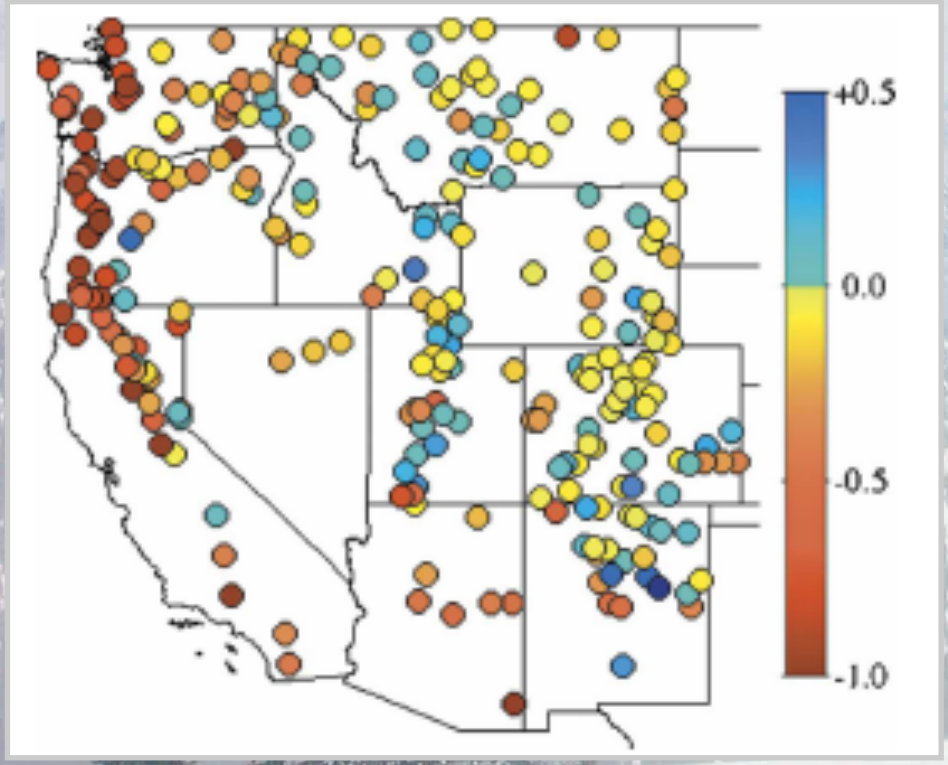


Stewart et al. 2005 J Climate

- 302 gauges
- trend:1948-2002
- center of mass of spring pulse

- 1-4 week advance in pulse

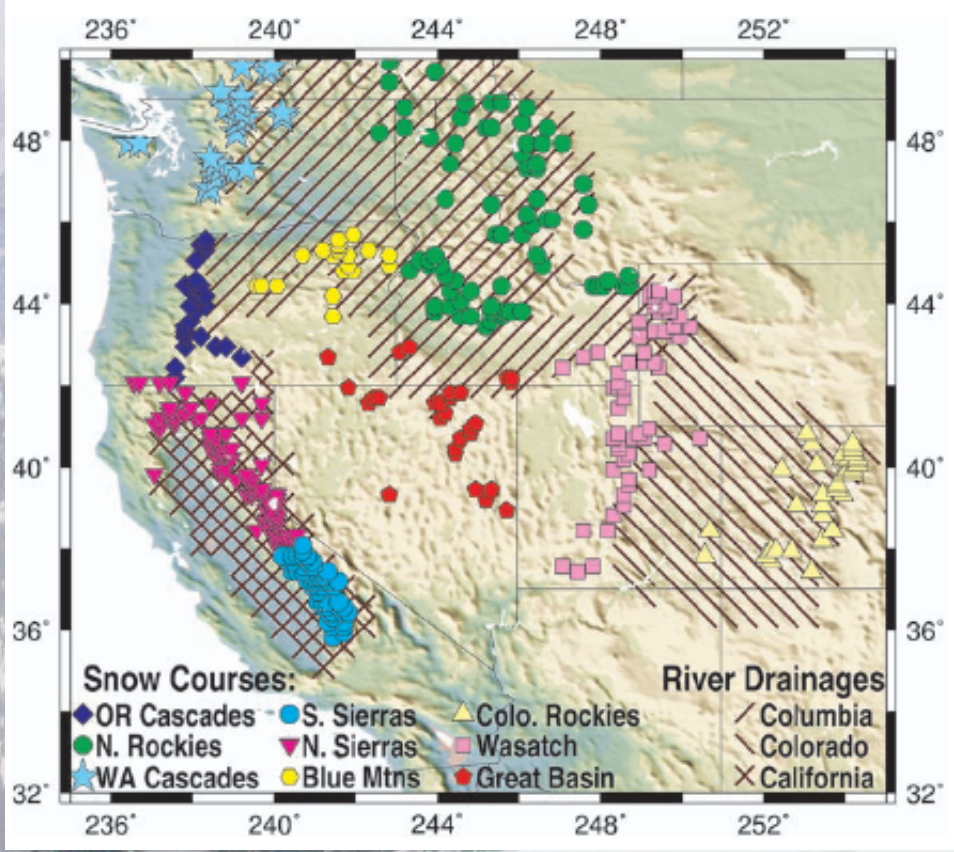
More Rain and Less Snow

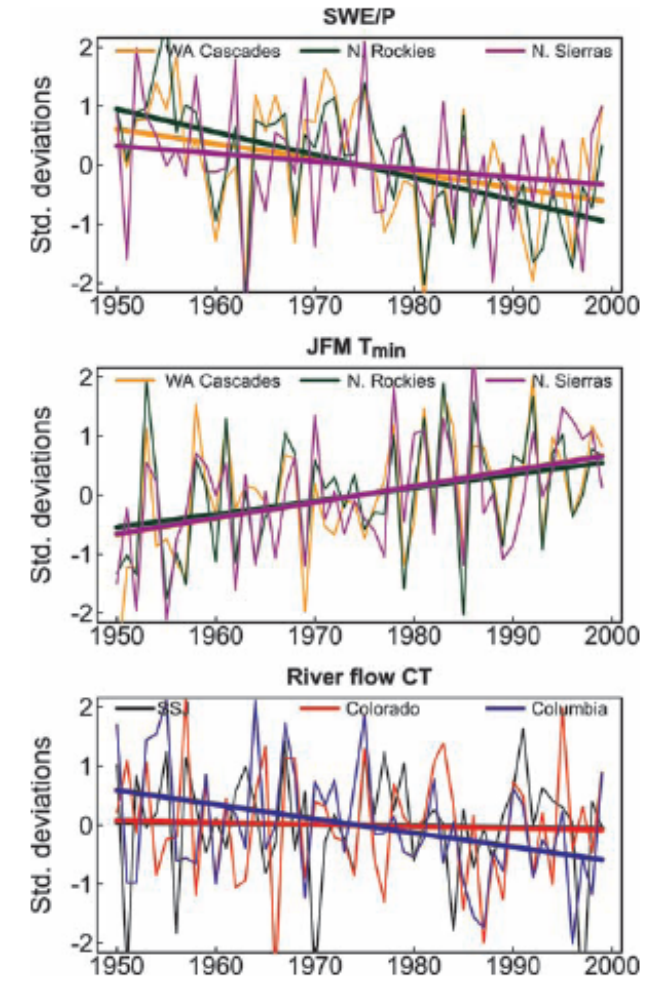


Knowles et al. 2006 J Climate

- Trend:1949-2002
- Fractional change in winter SFWE after removing effects of trends in precipitation
- ***75%*** *of stations experienced snowfall reductions as a result of warming*

Temperature ↑ = Snow↓ & Streamflow ↓

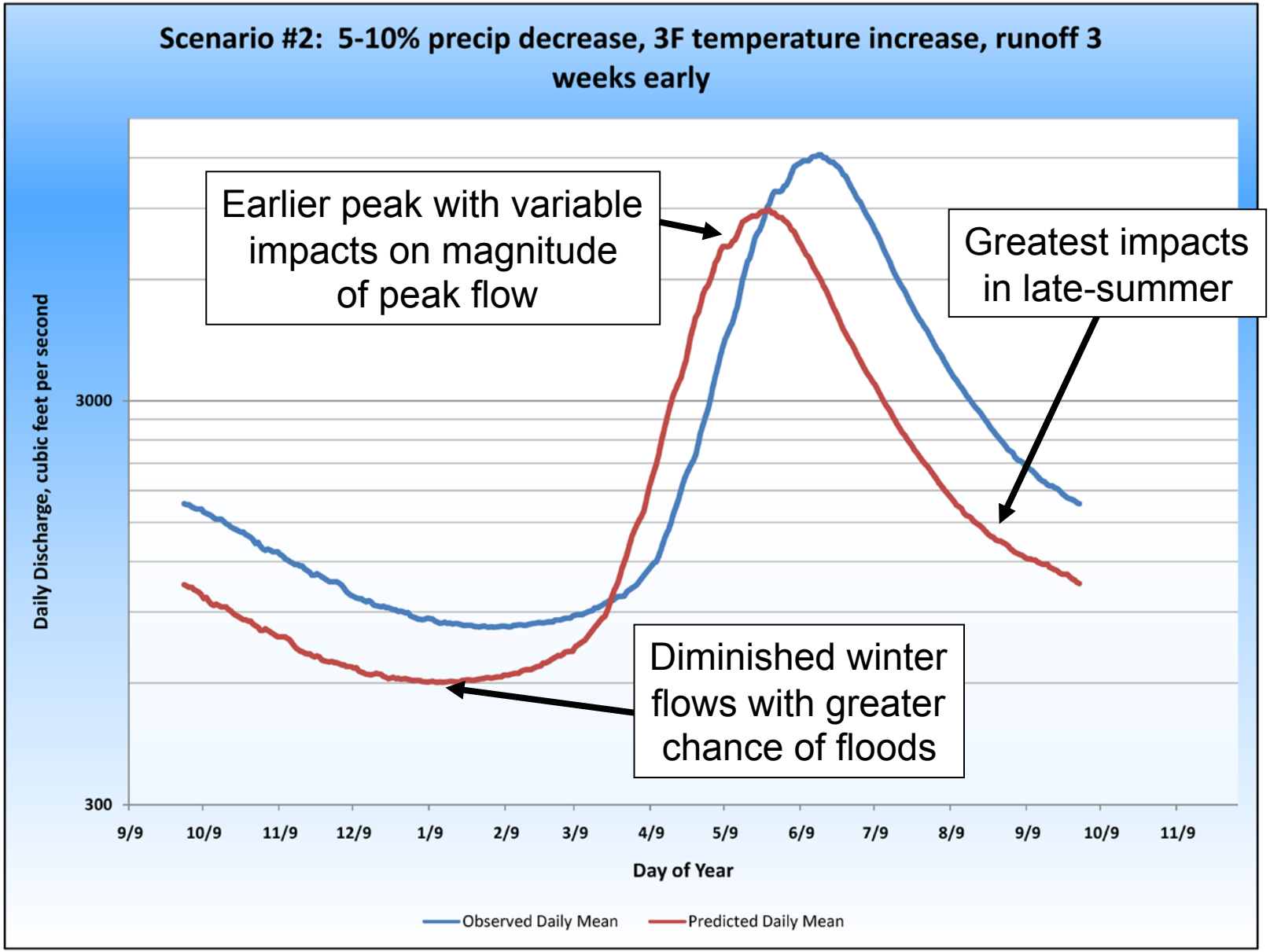




30 to 60% of declines caused by GHG enhanced warming

--Barnett et al. 2008, Science

Projected Impacts of Increasing Evaporation & Earlier Snowmelt



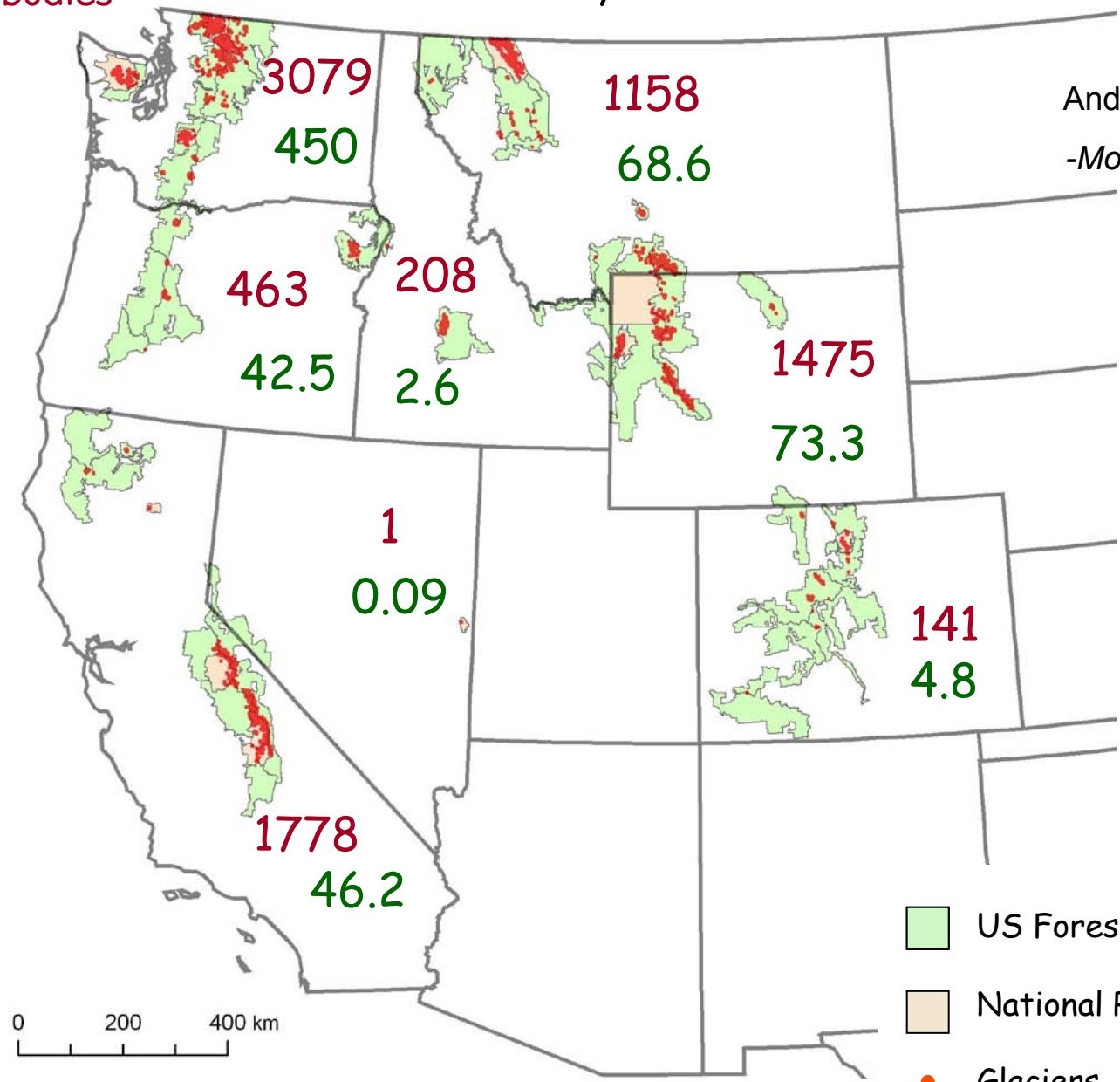
"Glaciers" in the American West
1 : 24,000

8303 permanent snow and ice bodies

688 km²

Andrew G. Fountain

-Moore et al. 2008

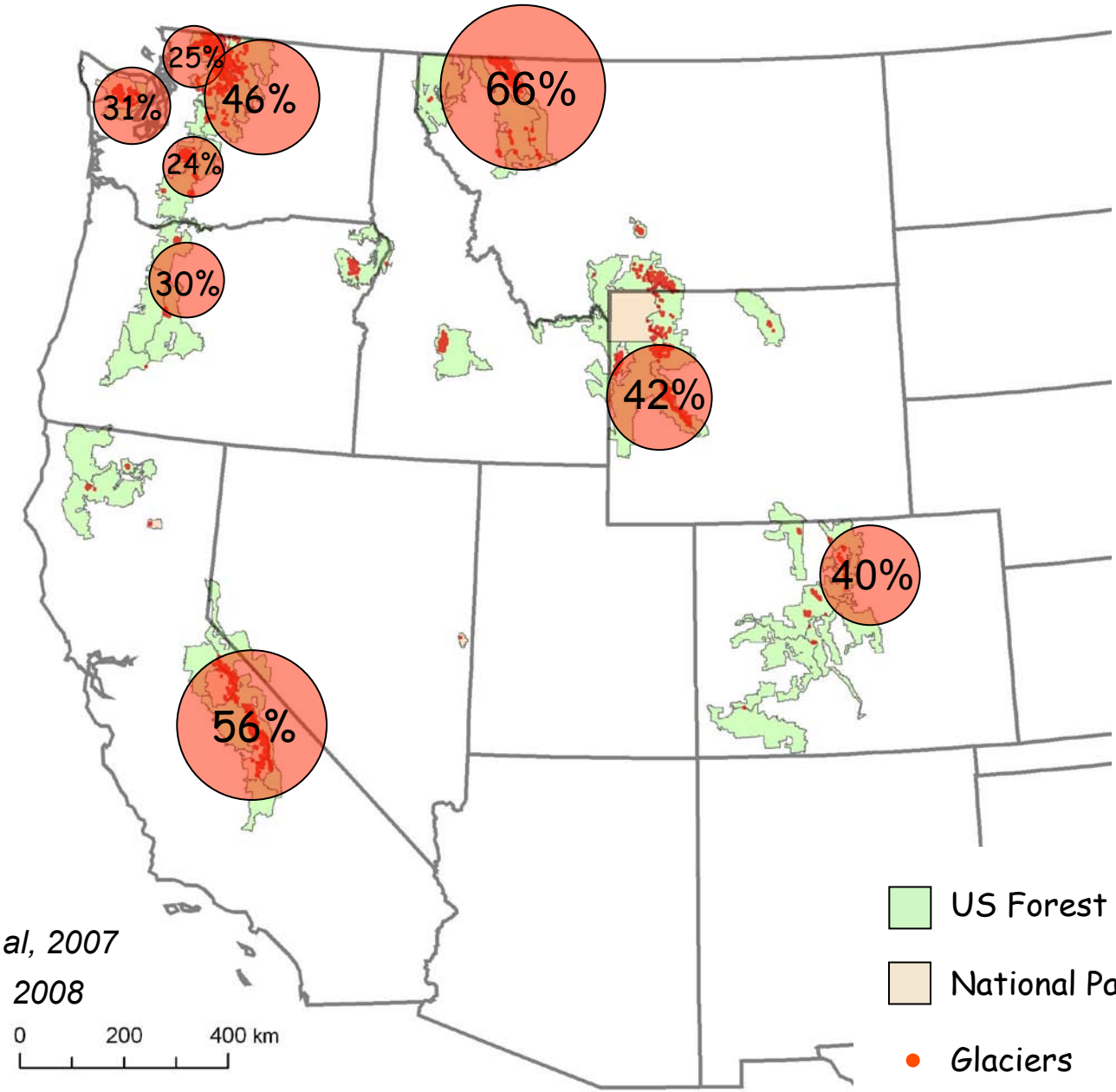


US Forest Service lands

National Park Service lands

Glaciers

Fraction of Glacier Area Lost since 1900



US Forest Service lands

National Park Service lands

Glaciers

-Fountain et al, 2007

-Moore et al. 2008

20th Century Retreat

Boulder Glacier

Glacier National Park, MT

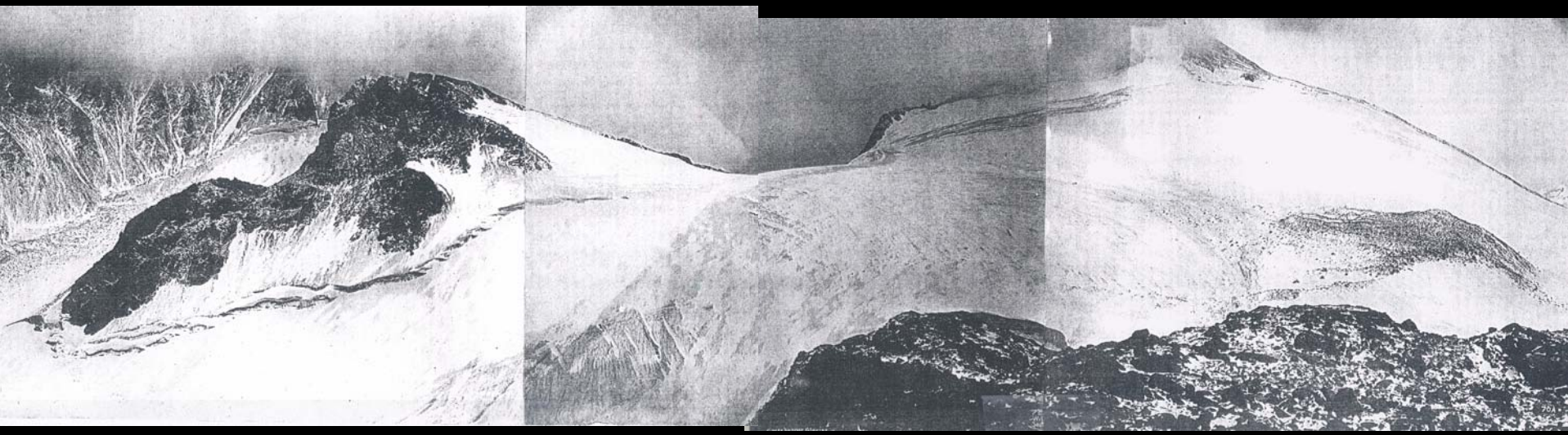
Morton Elrod photo
Courtesy of GNP Archives

Pederson & Fagre photo
USGS

Sperry Glacier

Alden, USGS

K. Holzer, USGS



Grasshopper Glacier and middle branch of Glacier in 1898 photographed by Anders Wilse

Wilse Glacier (far left), Middle Wilse Glacier, and Grasshopper Glacier in 2001

Yellowstone Region Snow and Streamflow Histories

USGS
science for a changing world

The unusual nature of recent snowpack declines in the North American Cordillera

Gregory T. Pederson[1,2], Stephen T Gray[3], Connie A Woodhouse[2], Julio L. Betancourt, Daniel B. Fagre[1], Jeremy Littell[4], Brian Luckman[5], Emma Watson, and Lisa J. Graumlich[2]

1. U.S. Geological Survey
2. University of Arizona
3. University of Wyoming
4. University of Washington
5. University of Western Ontario

Science, 9 June 2011: [DOI:10.1126/science.1201570]

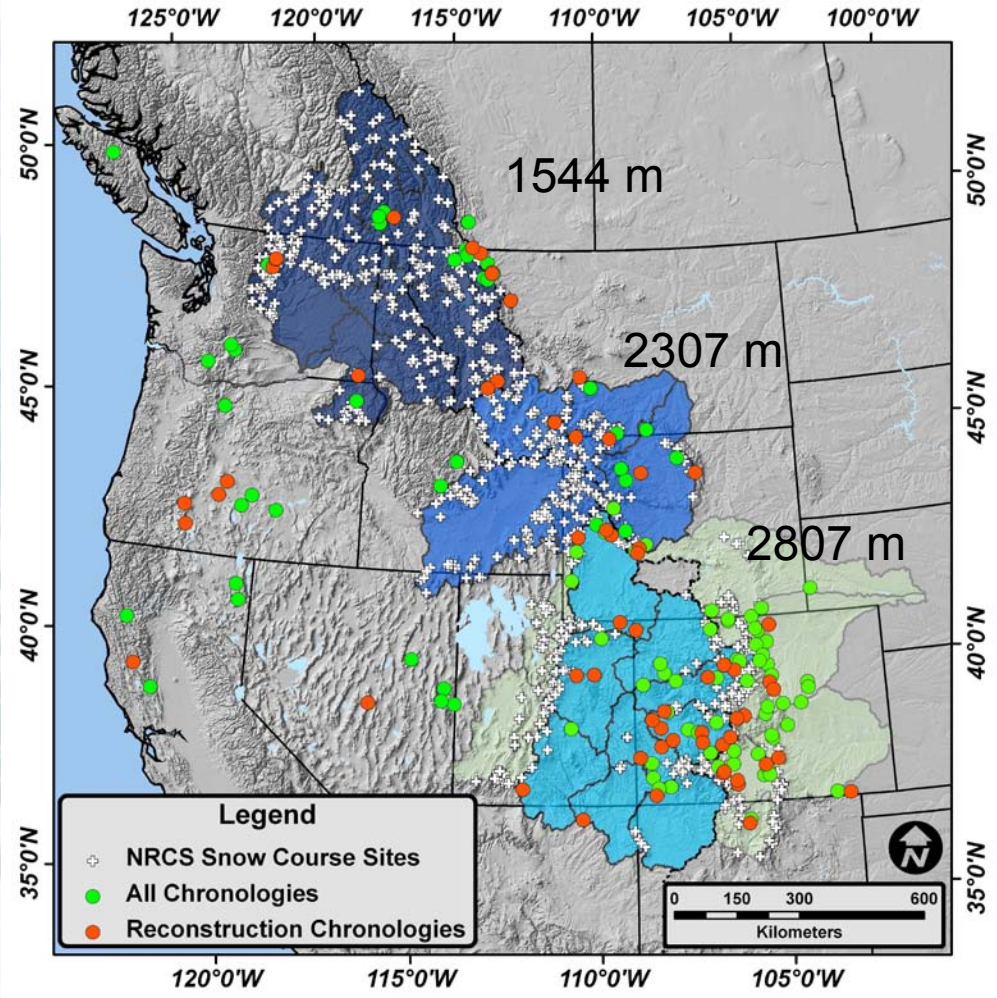
Primary Data

Major River Headwaters

- Colorado River Headwaters
- Yellowstone / Missouri River Headwaters
- Columbia River Headwaters

Data:

- USGS Hydrologic Units
- NRCS Snow Course Records
- ITRDB, personal, and collaborators moisture sensitive tree-ring chronologies

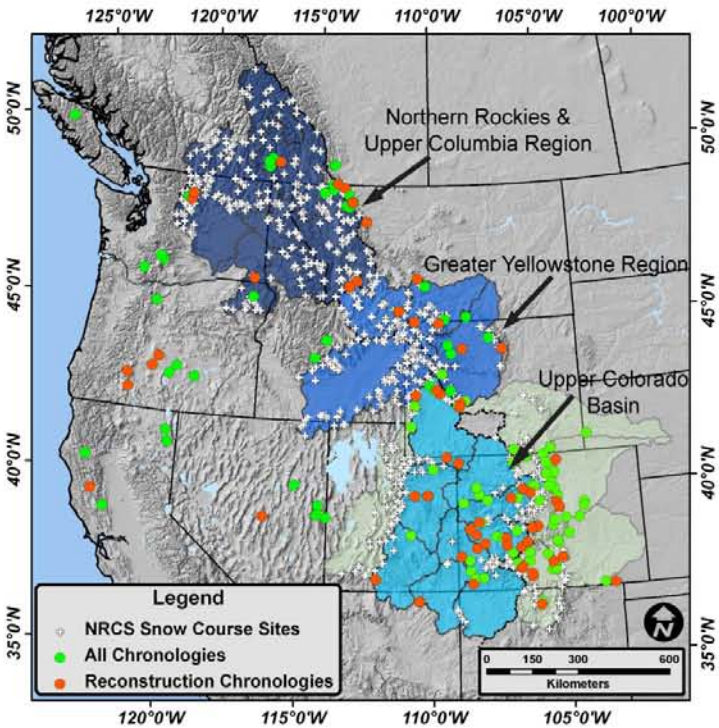


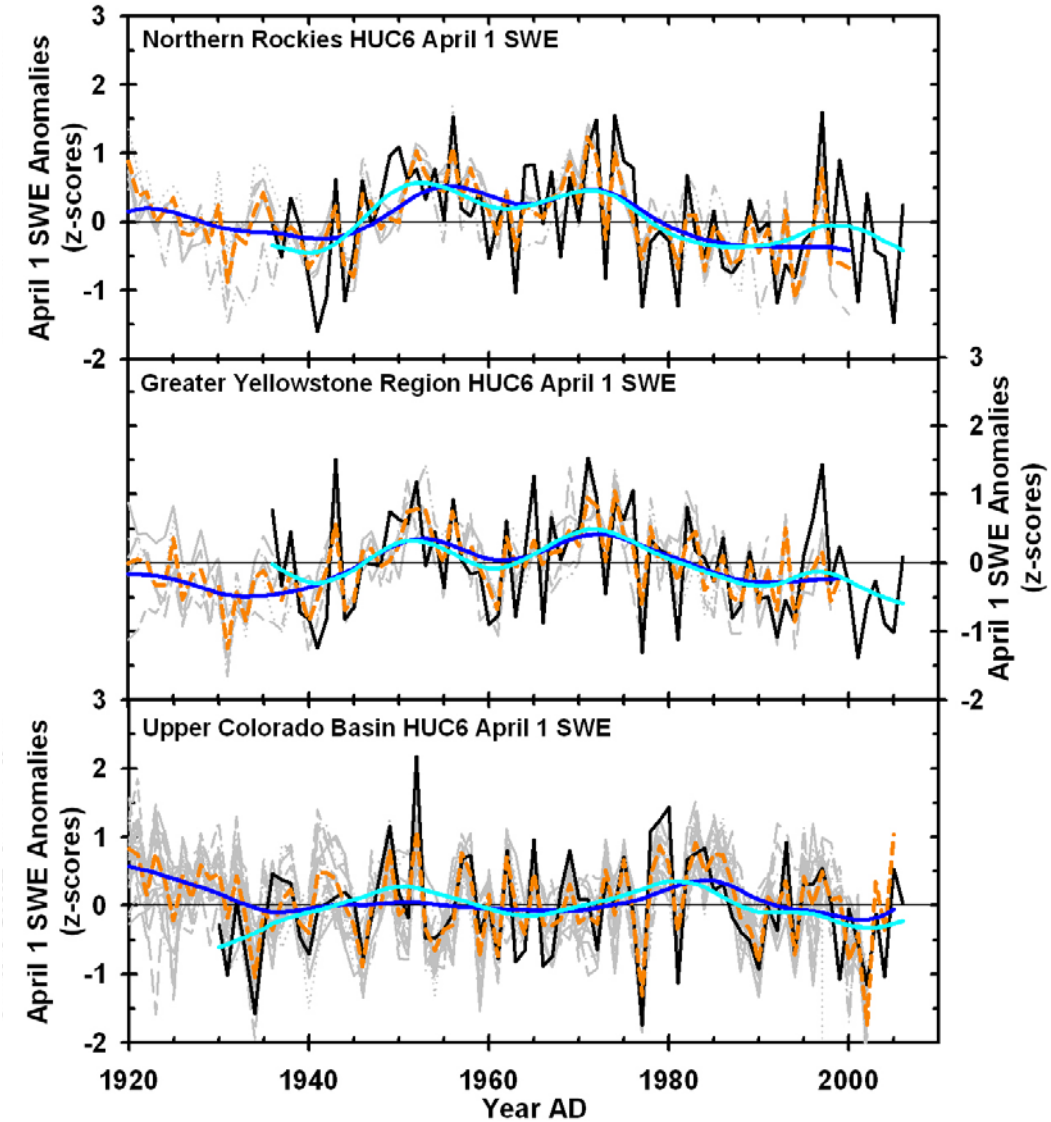
- Pederson Photo
Subalpine Larch

- Littell Photo

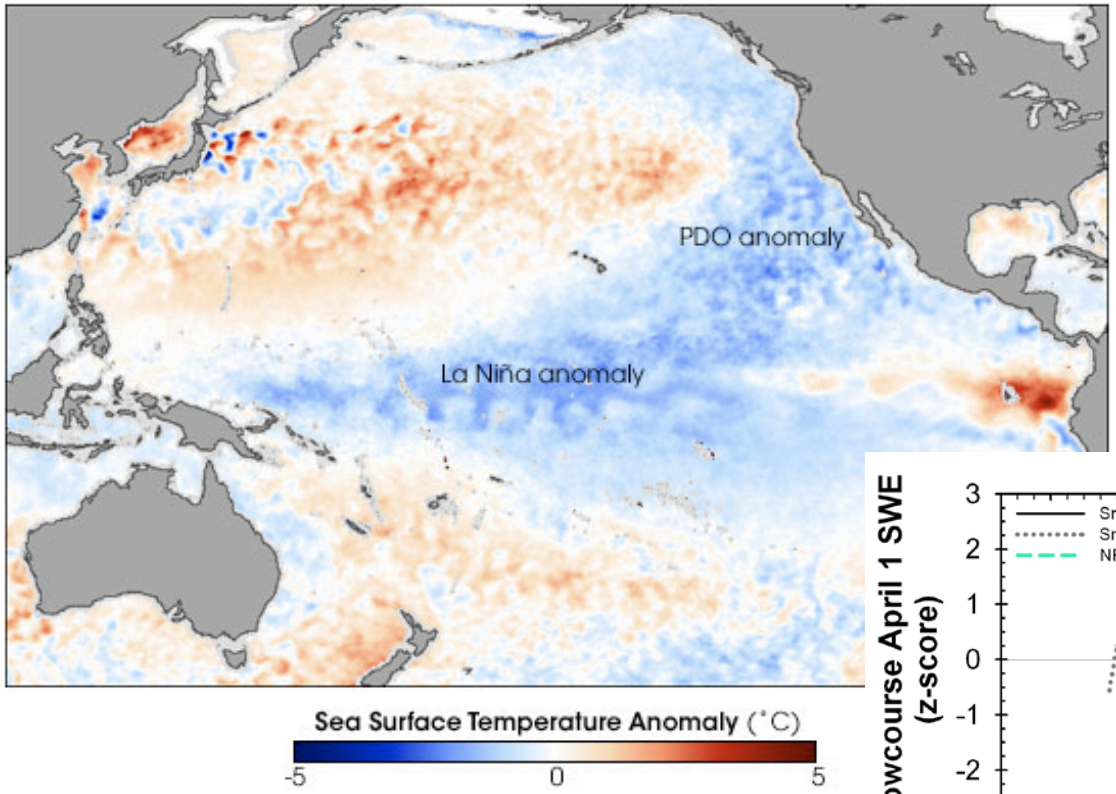
Mountain
Hemlock
- Littell Photo

Results: Calibration

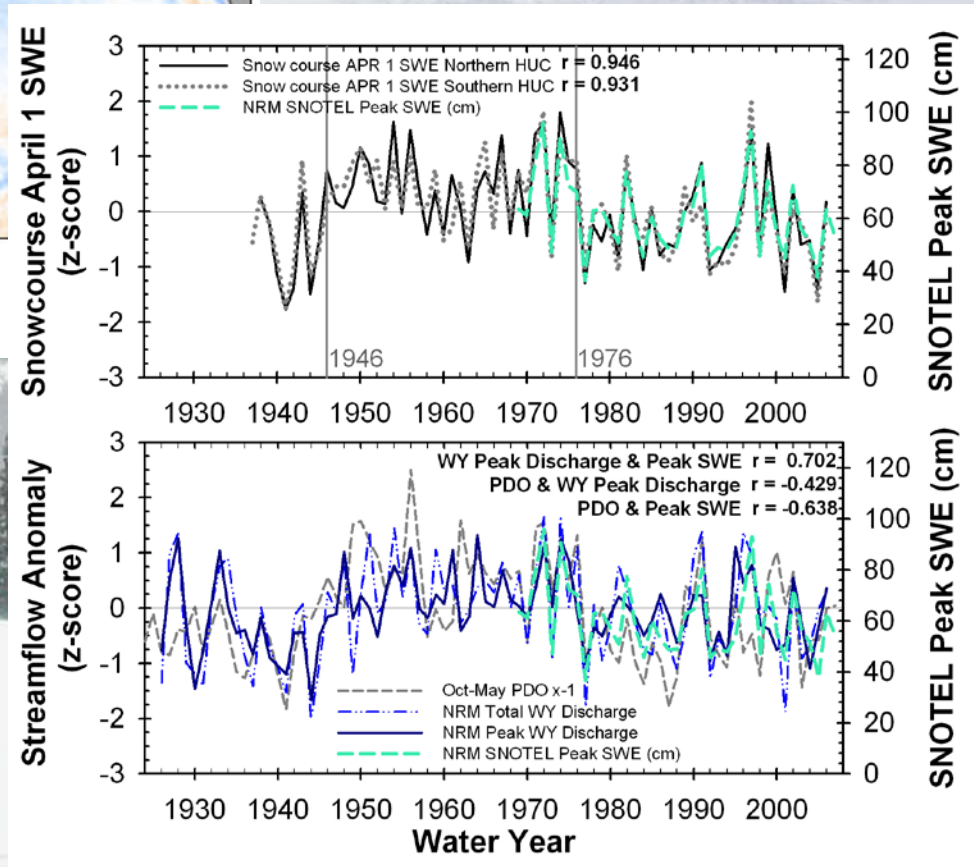




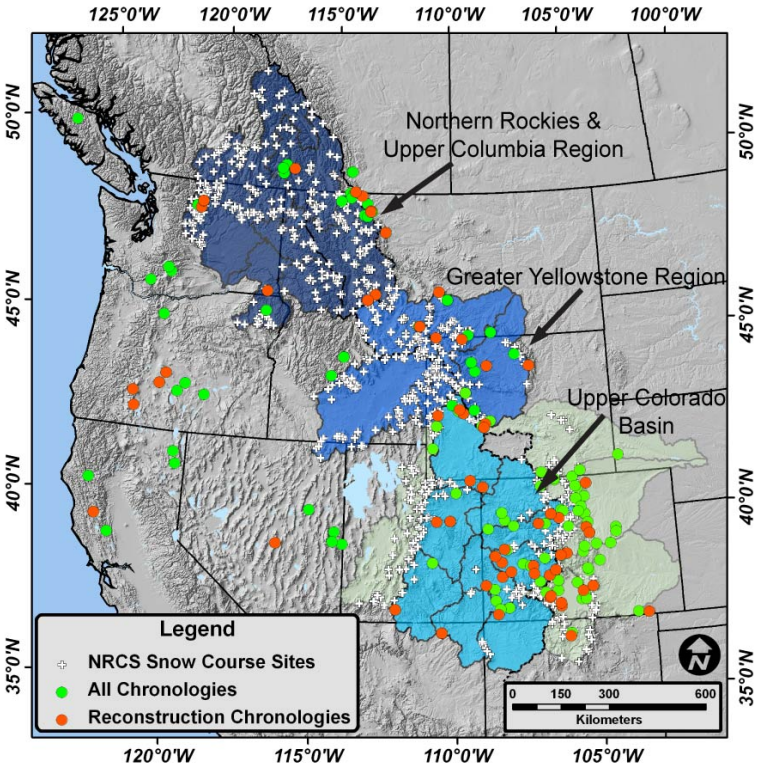
- Pederson et al, Science, 2011

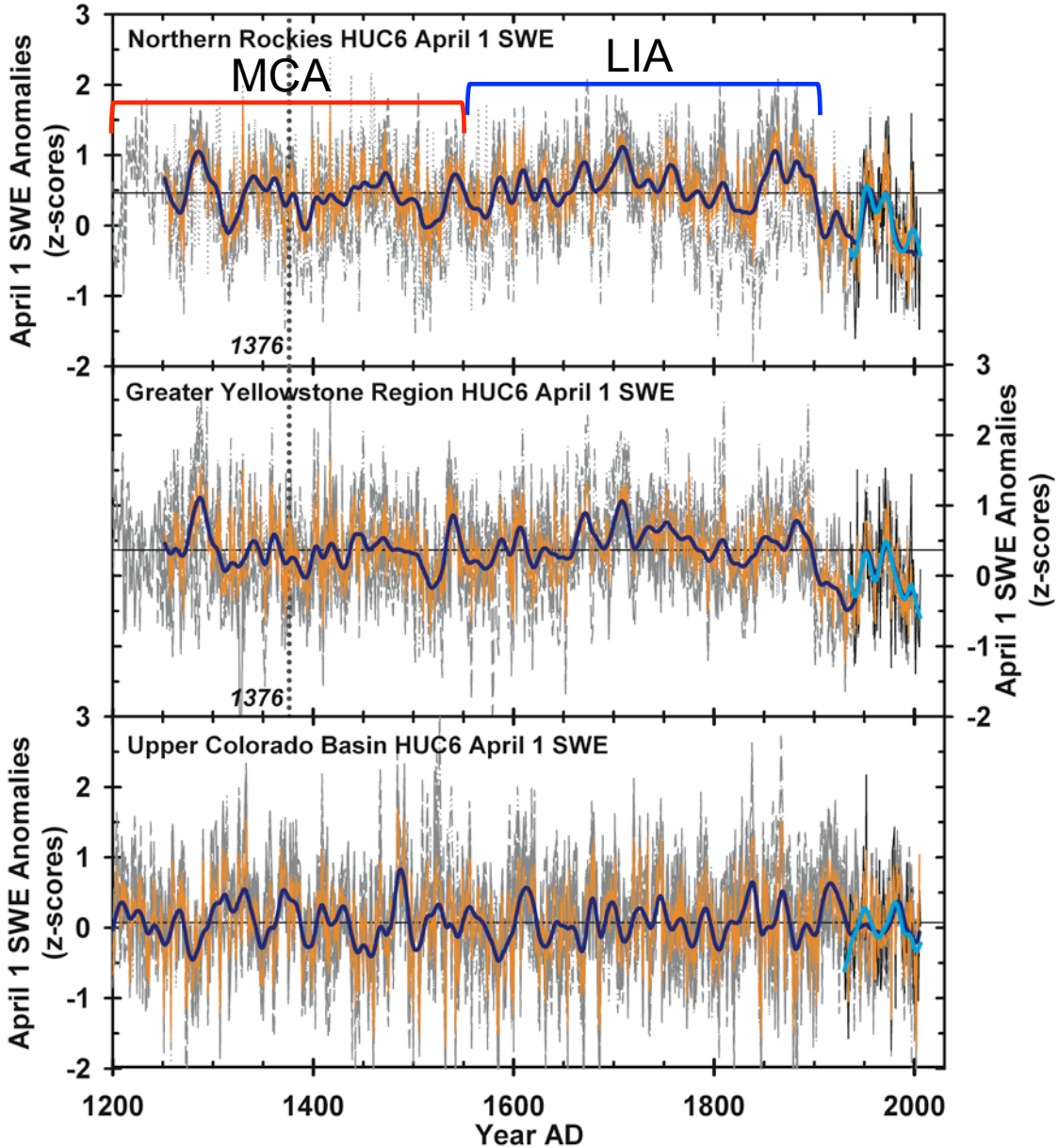


1. Ocean-Atmosphere teleconnections drive Peak SWE & Streamflow



2. Spring Warming & Precipitation account for remaining variation in Peak SWE & Streamflow

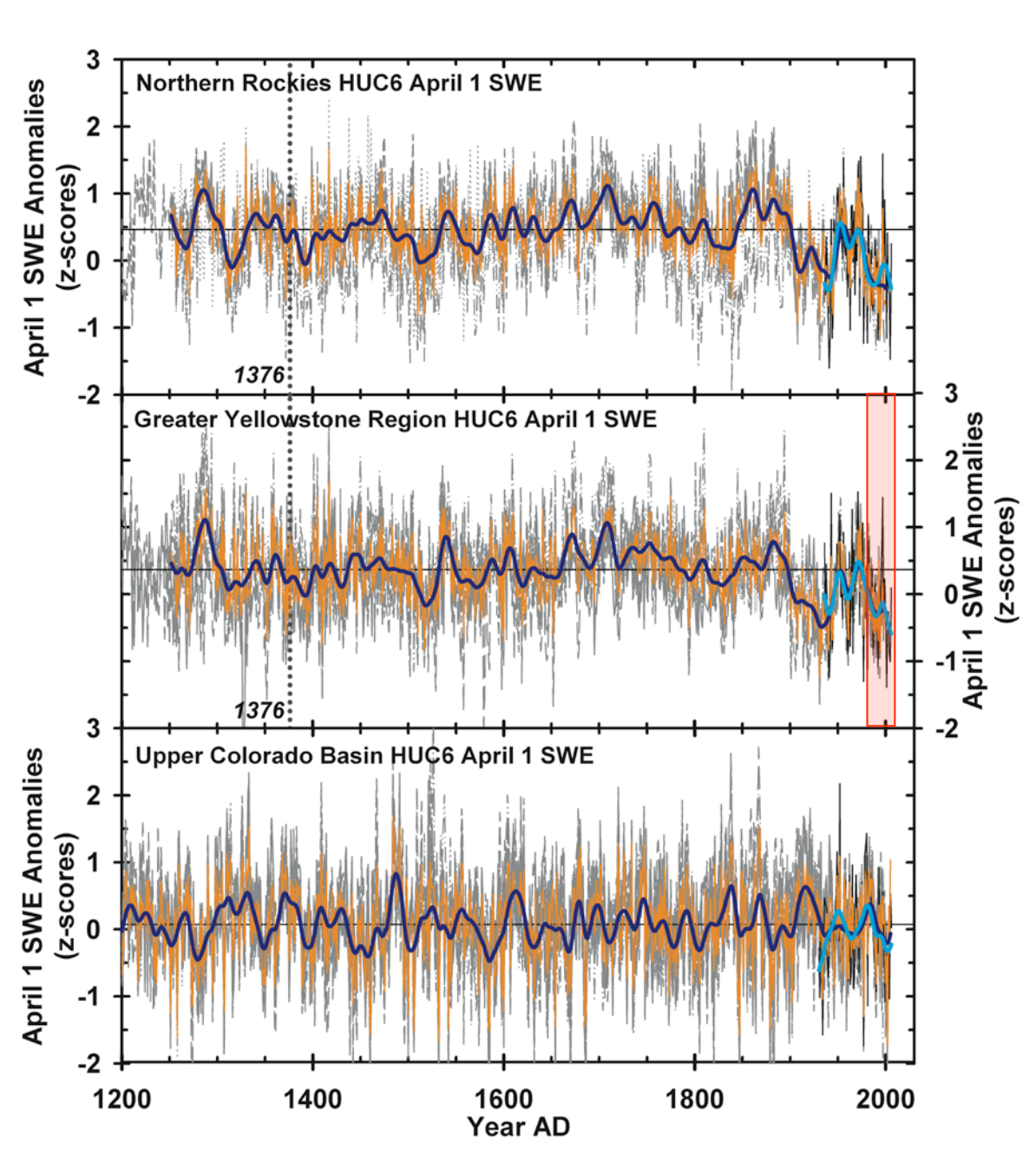




- Pederson et al, Science, 2011

To contextualize 100% of 1981-2010 mean SWE conditions…

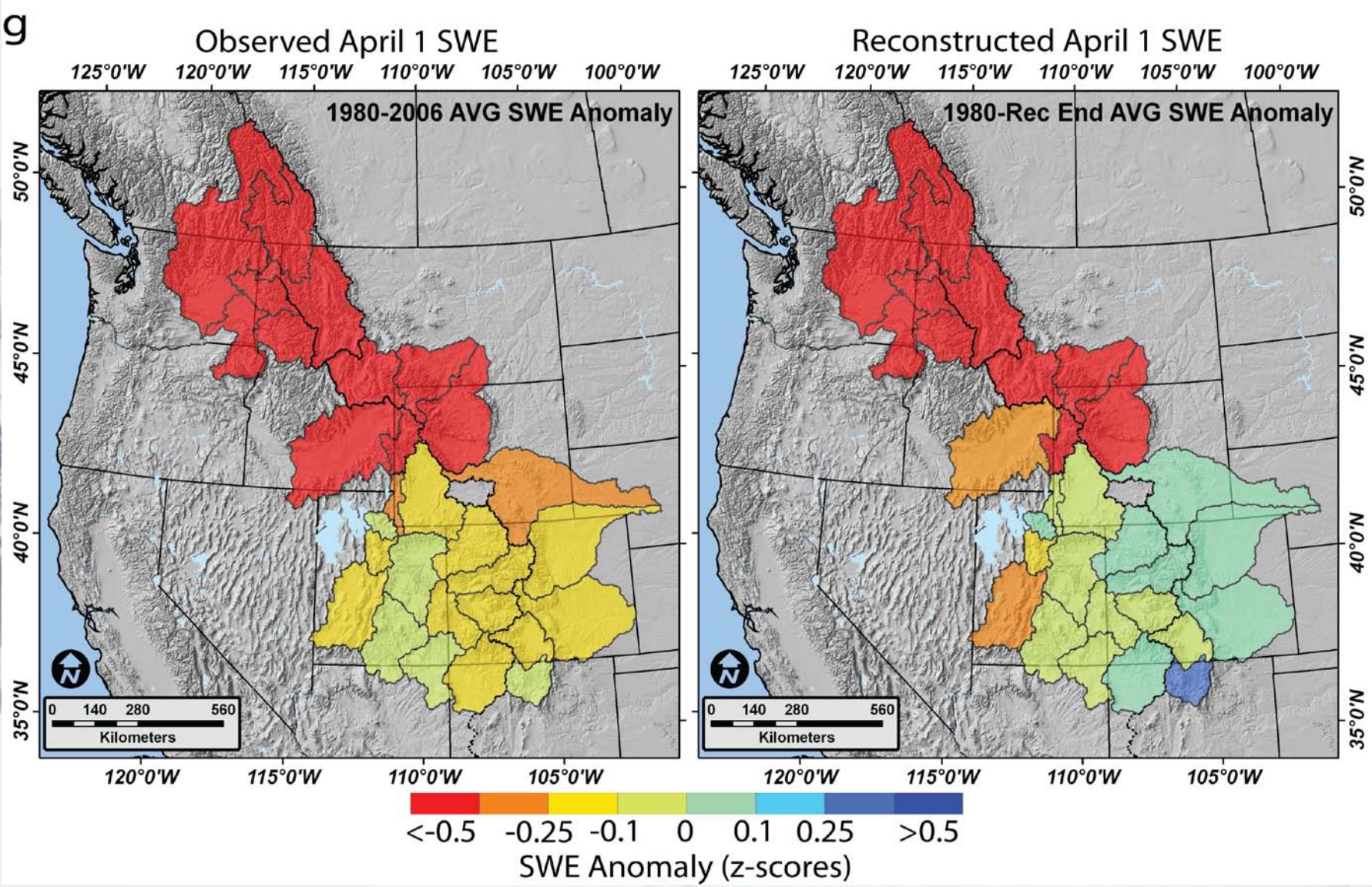
…we have reached average snow conditions for a period of record *LOW* snowpack compared to conditions of the past 800 years…



- Pederson et al, Science, 2011

Meaning…

The current conditions maps should look more like this…



Synchronized Western Snowpack Declines

So how can we be sure warming temperatures play a major role in west-wide snow declines? Test the idea with a Snow Model

Regional patterns and proximal causes of the recent snowpack decline in the Rocky Mountains, U.S.

Gregory T. Pederson[1,2,*], Julio L. Betancourt[3], Gregory J. McCabe[4]

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Issue

Geophysical Research Letters

Volume 40, Issue 9, pages 1811–1816, 16 May 2013

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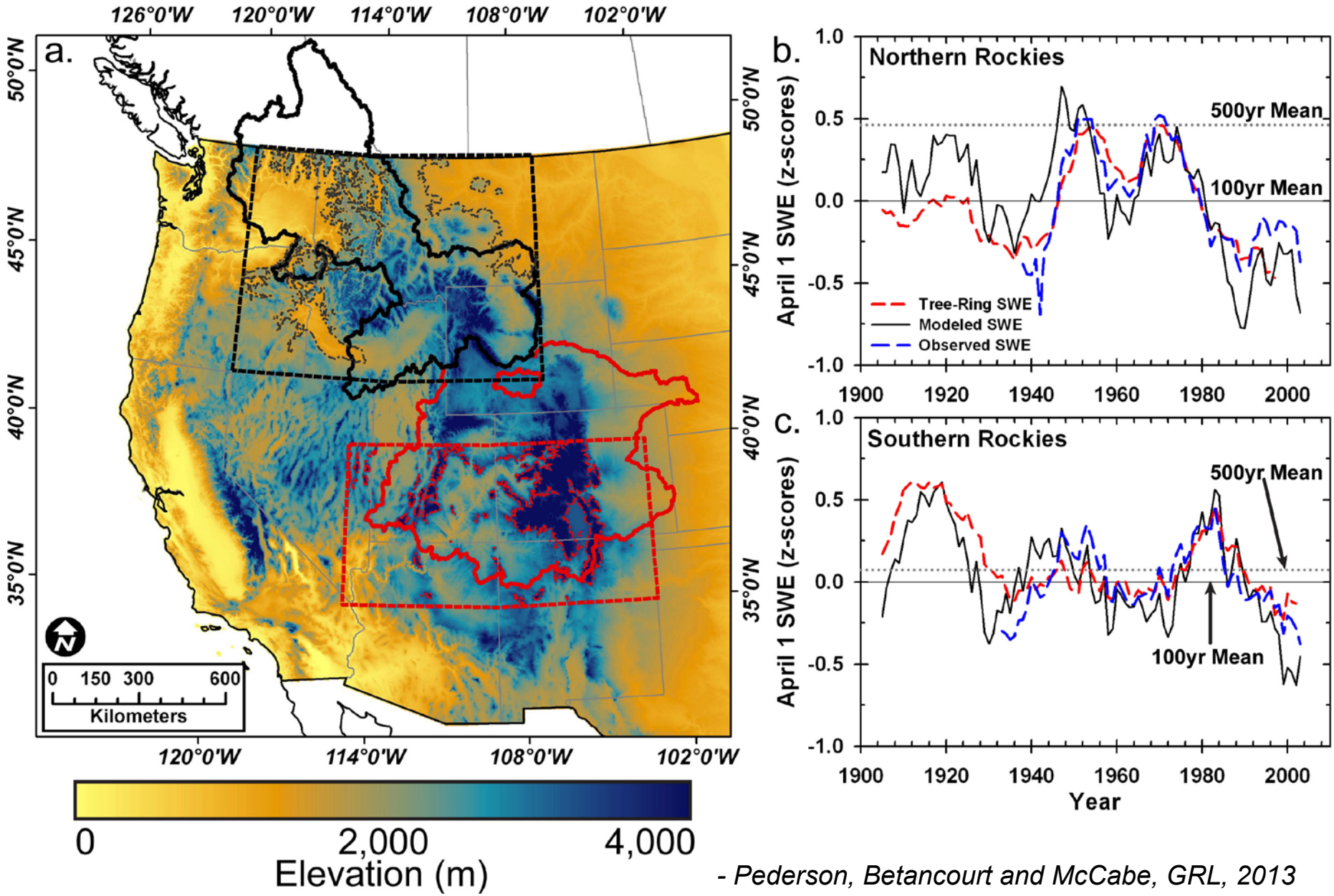
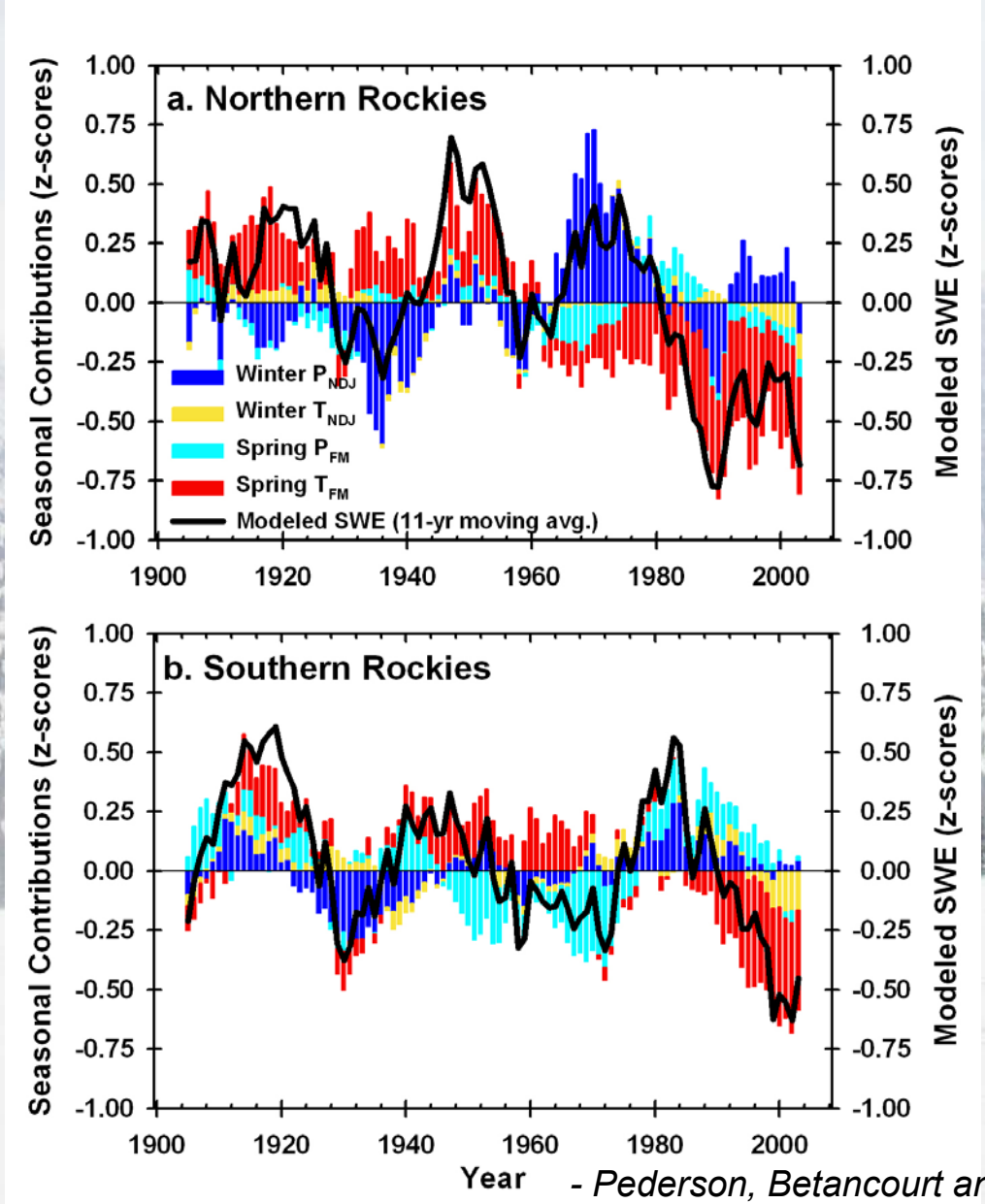
Snow Model: Temperature Relationship



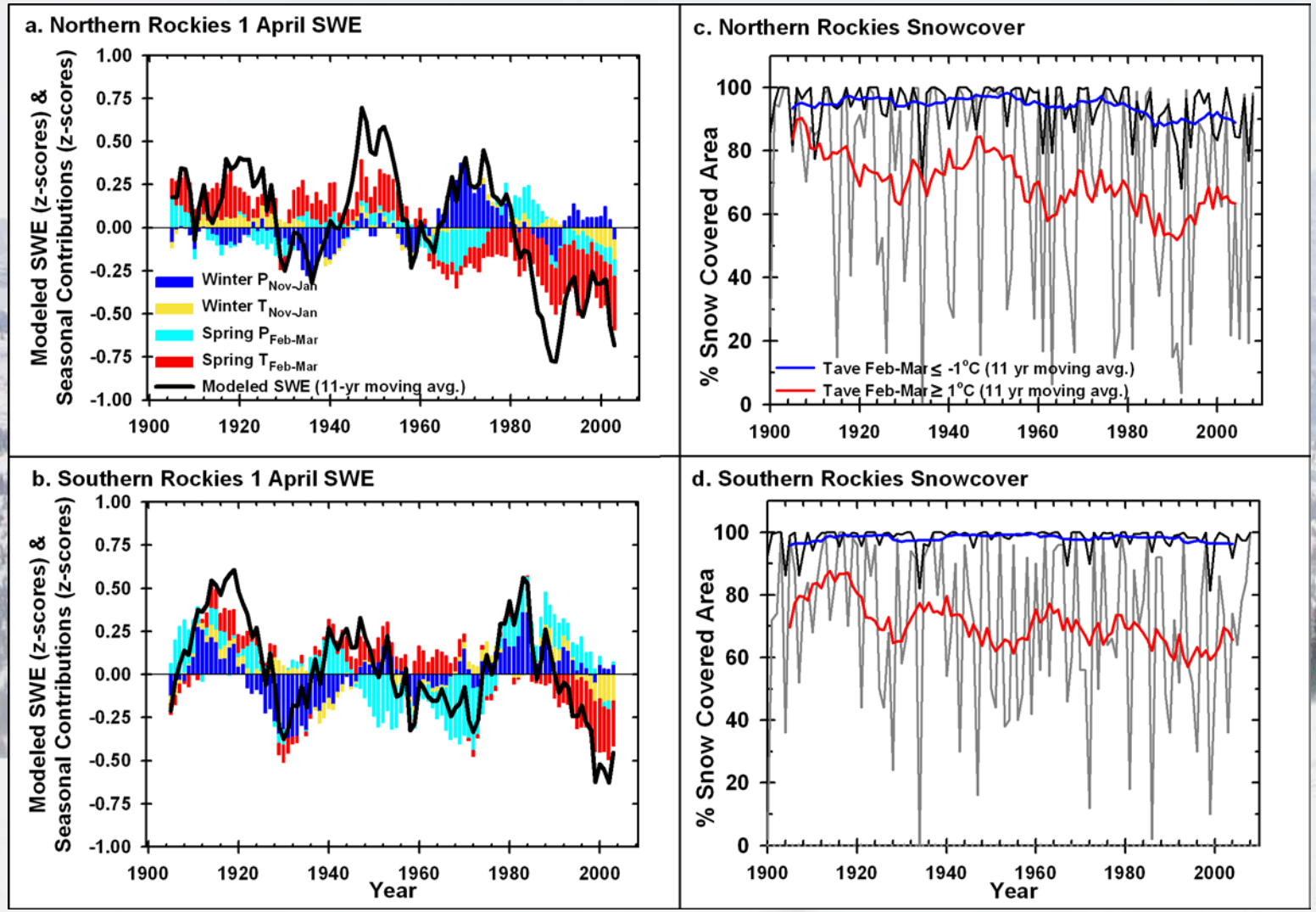
- Pederson, Betancourt and McCabe, GRL, 2013

Post-1980s Synchronous Snowpack Declines



- Pederson, Betancourt and McCabe, GRL, 2013

20% Decline in Snowcover



- Pederson, Betancourt and McCabe, GRL, 2013

Implications

- *The post-1980s synchronous snowpack declines may be the inflection point for a new era of non-stationarity in Western water resources*
- *The last few decades may in fact signal a fundamental shift from precipitation (i.e. stormtrack) to temperature as the dominant influence on snowpack in the North American Cordillera*
- *Increased warming will likely continue to modify the annual hydrograph and stream temperatures altering aquatic habitats and challenging water resource managers*

Western US River Sensitivity Study

Case study showing how seemingly small changes in temp. could have a major impact on aquatic ecosystems

Gray and McCabe, WRR 2010

Yellowstone River Sensitivity Study

Tree-ring precipitation
(range of natural variability)

↓ ↓

Temperature Scenarios
(Past, Present and Future)

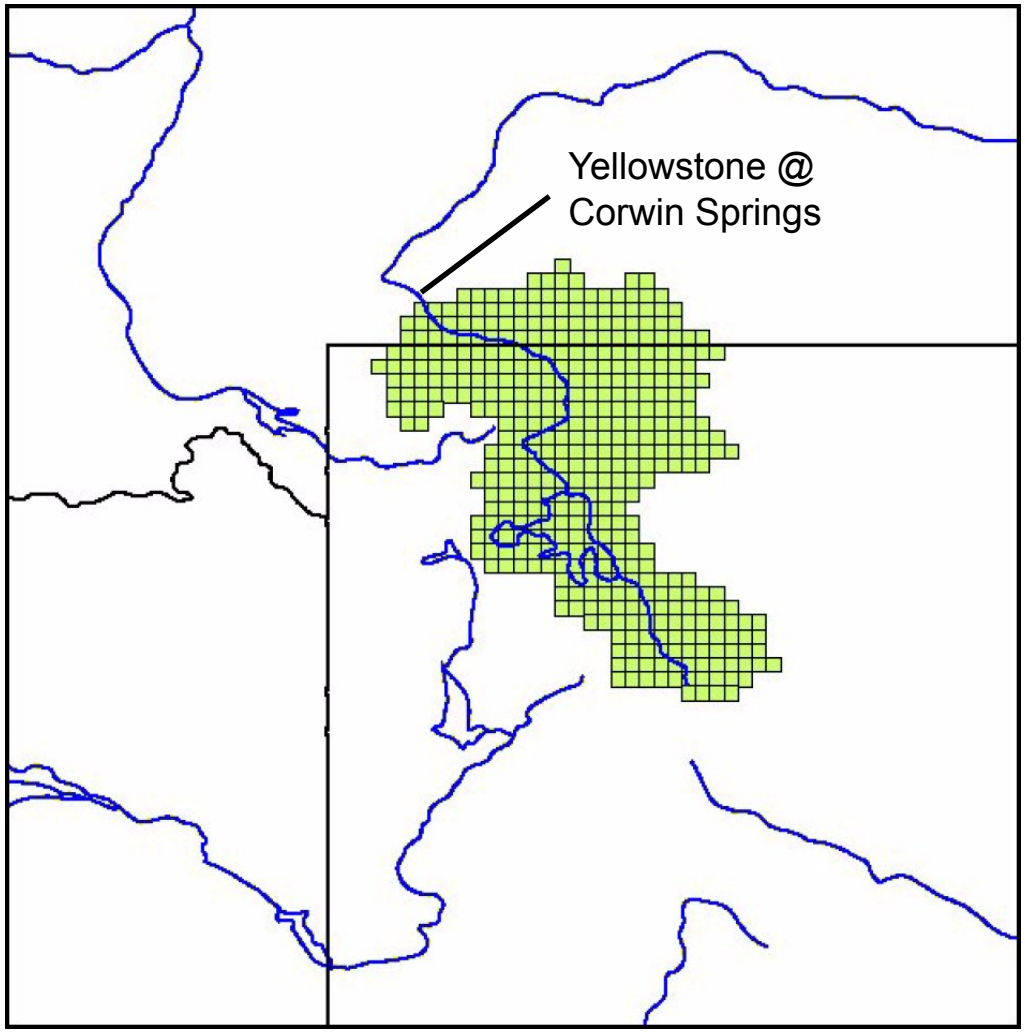
↓ ↓

RIVER FLOW MODEL

↓ ↓

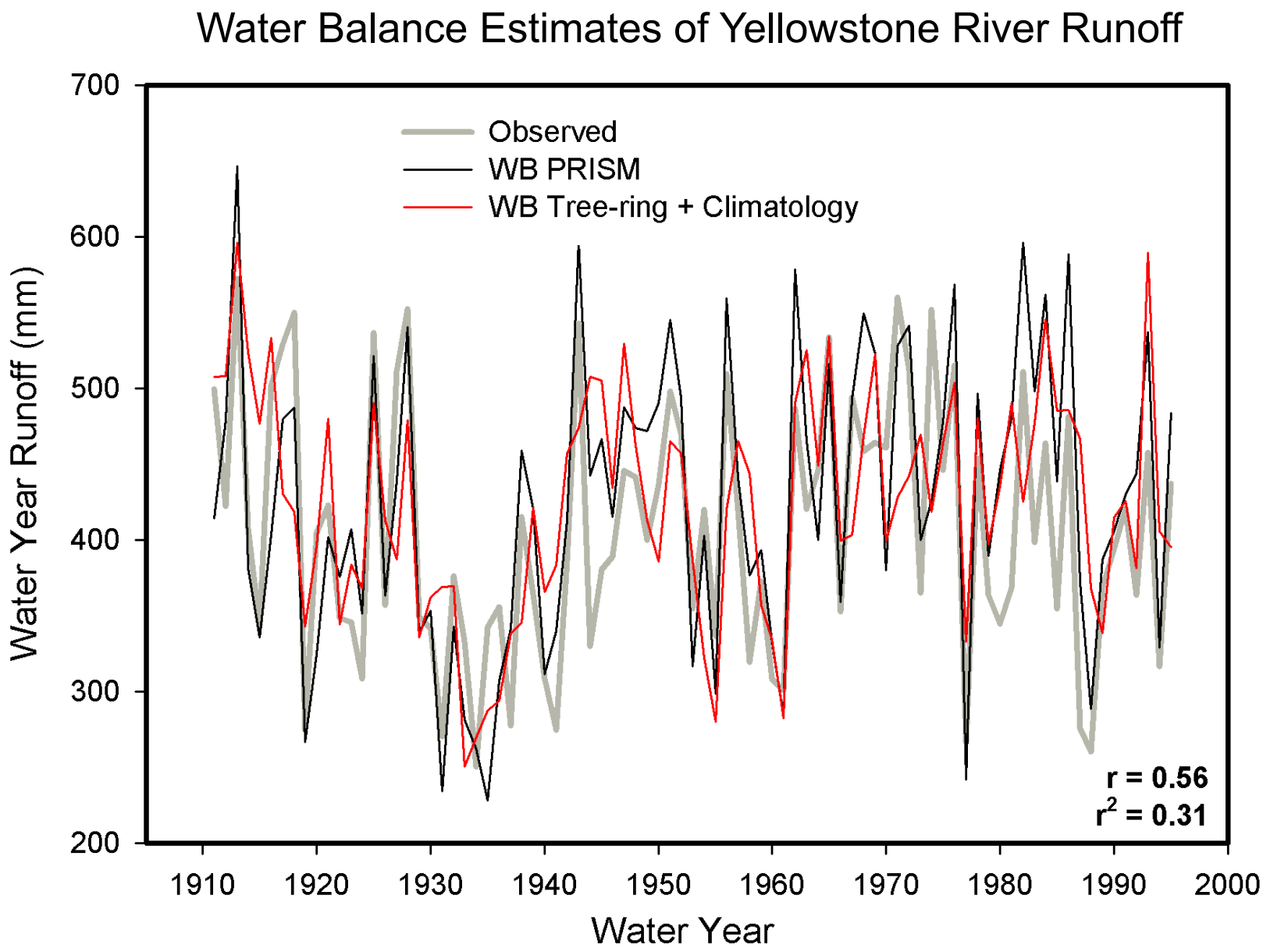
Estimates of Discharge
(Flow at Corwin Springs)

Gray and McCabe, WRR 2010

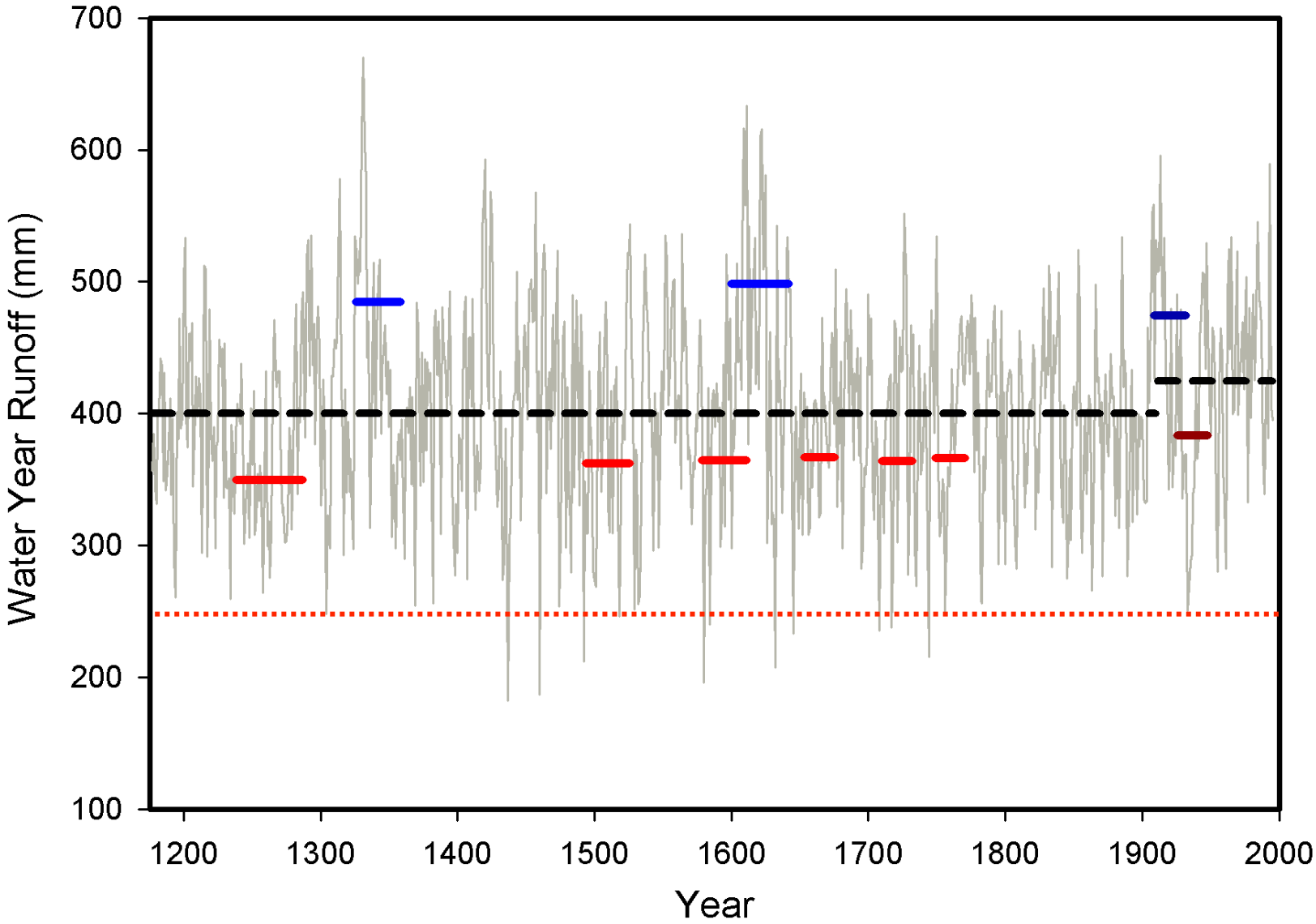


Upper Yellowstone River

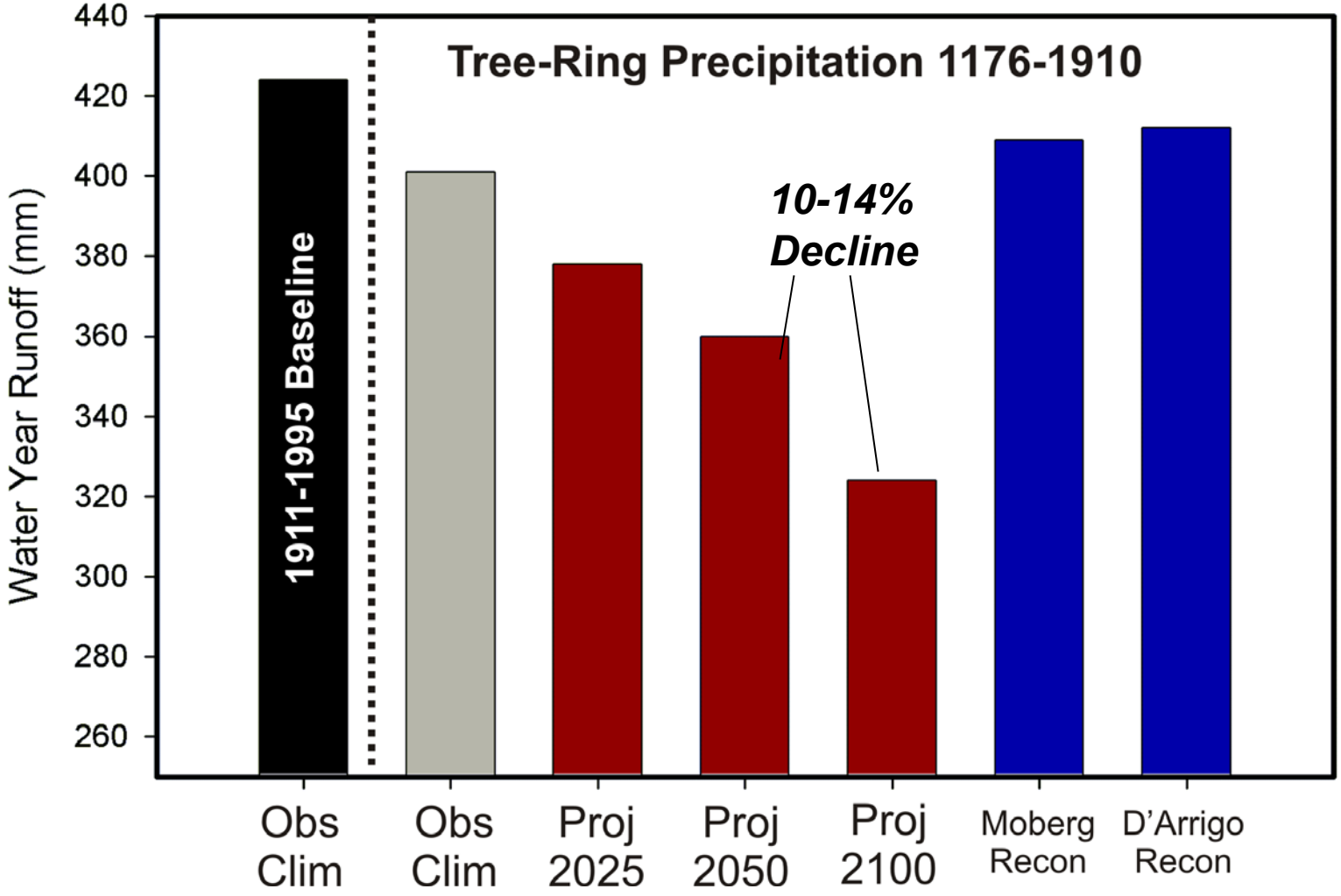
- Headwaters above Corwin Springs, Montana
- Drains approx. 6794 km^2
- Majority in Yellowstone National Park
- Unregulated flows
- Gage in continuous operation since 1911


Water Balance Estimates of Yellowstone River Runoff
Observed
WB PRISM
WB Tree-ring + Climatology
r = 0.56
r2 = 0.31
Water Year Runoff (mm)
Water Year
700
600
500
400
300
200
1910
1920
1930
1940
1950
1960
1970
1980
1990
2000

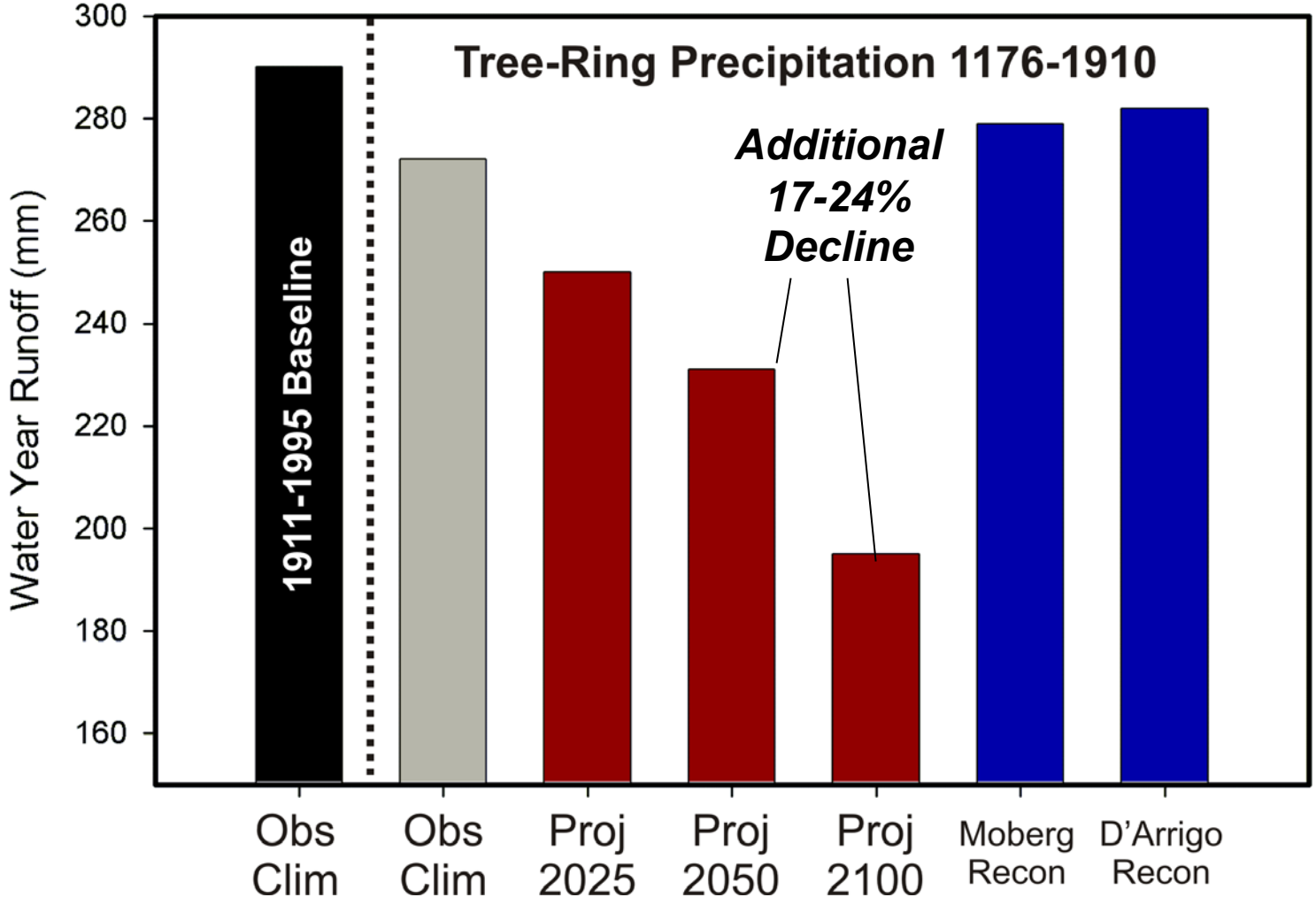
Baseline Scenario: Tree-ring Precip & Temperatures from Climatology

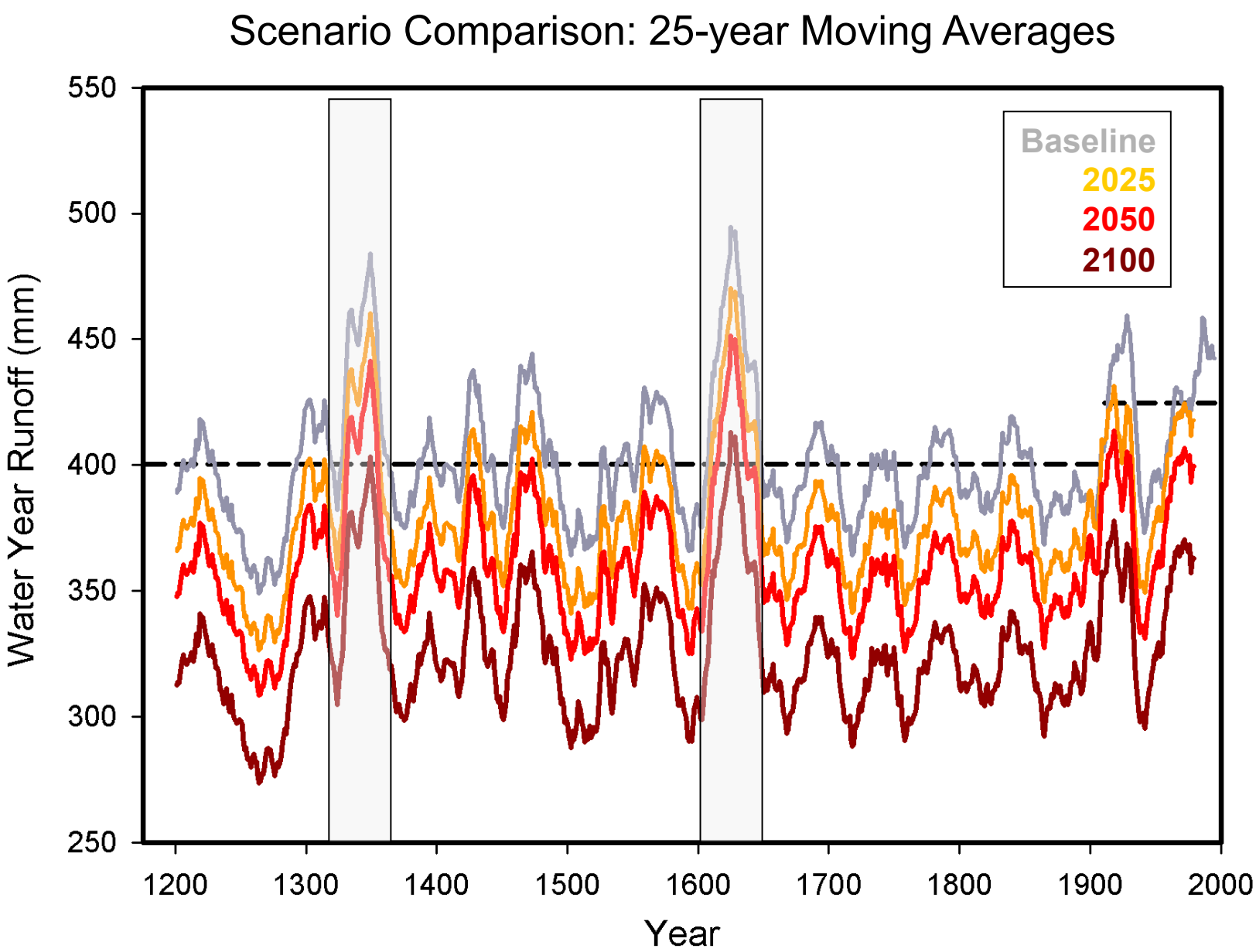


Average Long-term Runoff: All Scenarios



Average Runoff: Driest 10th percentile




Scenario Comparison: 25-year Moving Averages
Baseline
2025
2050
2100
Water Year Runoff (mm)
550
500
450
400
350
300
250
1200
1300
1400
1500
1600
1700
1800
1900
2000
Year

Yellowstone Region Climate Projections:

And what we don't know…

aka. Uncertainties…

a bad word I've been told…

USGS
science for a changing world

Projected 21st century changes in Northern Rockies Temperature

Table 1. Expected Northern Rockies regional climate changes

	Temperature change (°F)		Precipitation change (%)	
	B1 (low)	xA1B (med.)	B1 (low)	A1B(med)
2020s	+2.1 (+1.2 to +3.9)	+2.3 (+1.3 to +3.3)	+3 (-27 to +29)	+3 (-14 to +25)
2040s	+3.0 (+1.5 to +5.5)	+3.9 (+2.5 to +5.9)	+1 (-18 to +20)	+7 (-2 to +34)
2080s	+4.8 (+3.2 to +7.9)	+6.7 (+3.8 to + 10.4)	+8 (-8 to +27)	+10 (-12 to +36)

Changes in temperature and precipitation are relative to 1970 -1999, averaged over 117W-105W and 42N-49N. 2020s = 2010- 2039; 2040s = 2030 – 2059; 2080s = 2070 – 2099. B1 is a low greenhouse gas emissions scenario; A1B is higher until about the 2040s, then is moderate (see right). Data: CMIP3 (IPCC AR4 GCMs)[3]

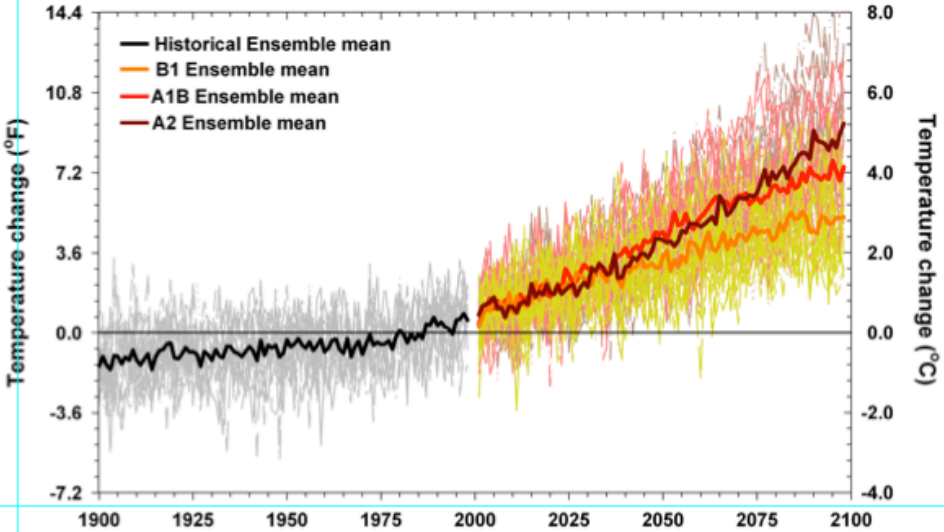


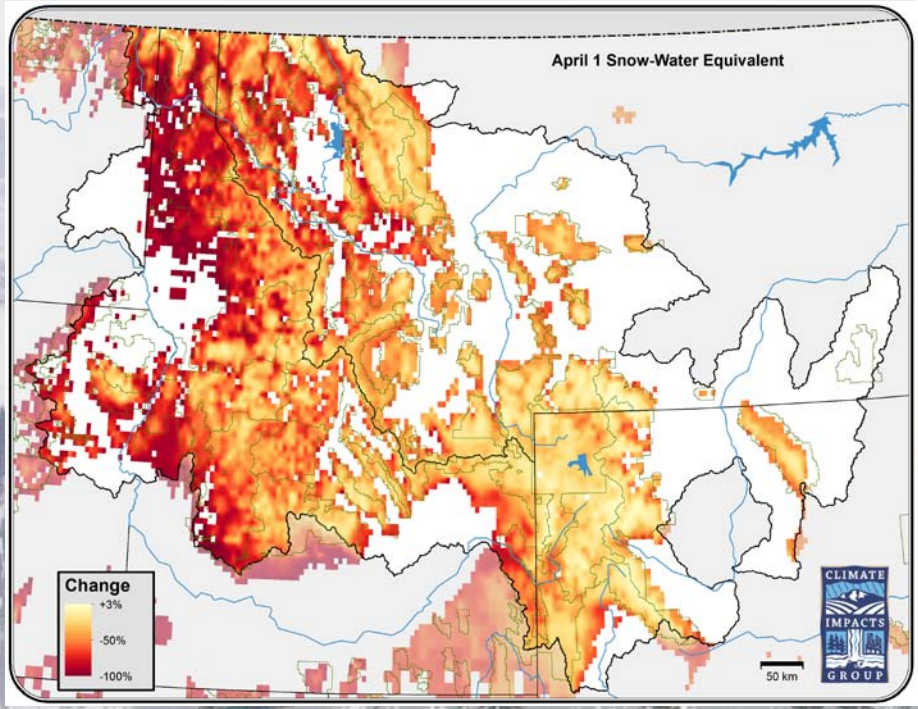
Figure 1. Northern Rockies and 2001-2099 (color). Heavy lines are ensemble (multiple climate model) averages for B1, A1B, and A2 emissions scenarios.

Prepared by the UW Climate Impacts Group – http://cses.washington.edu/cig/

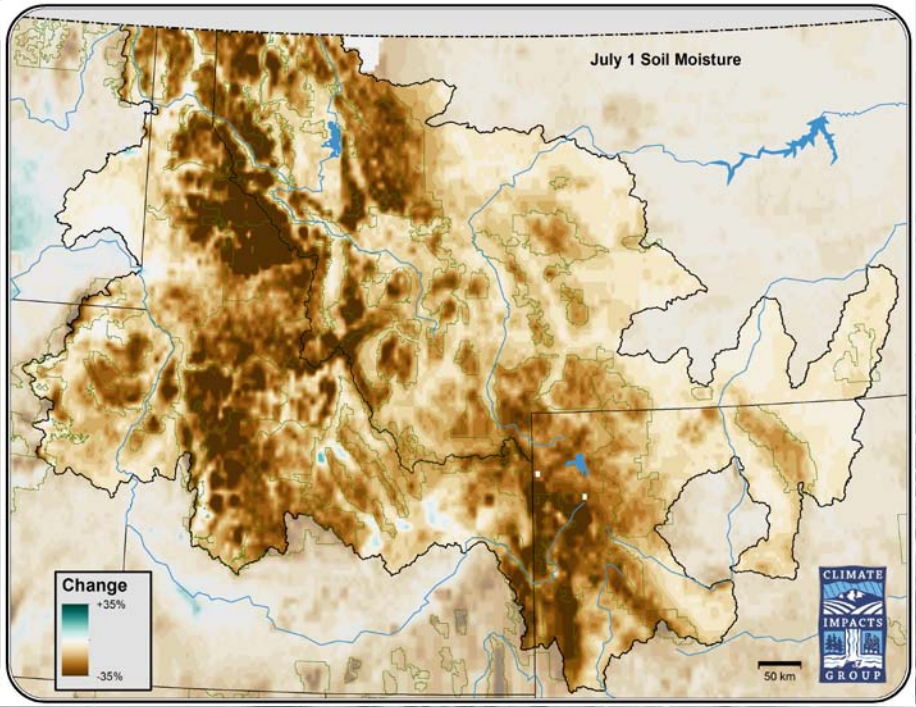
Projected 21st century changes in Northern Rockies hydrology

Projections for 2040s

Snowpack



Soil Moisture



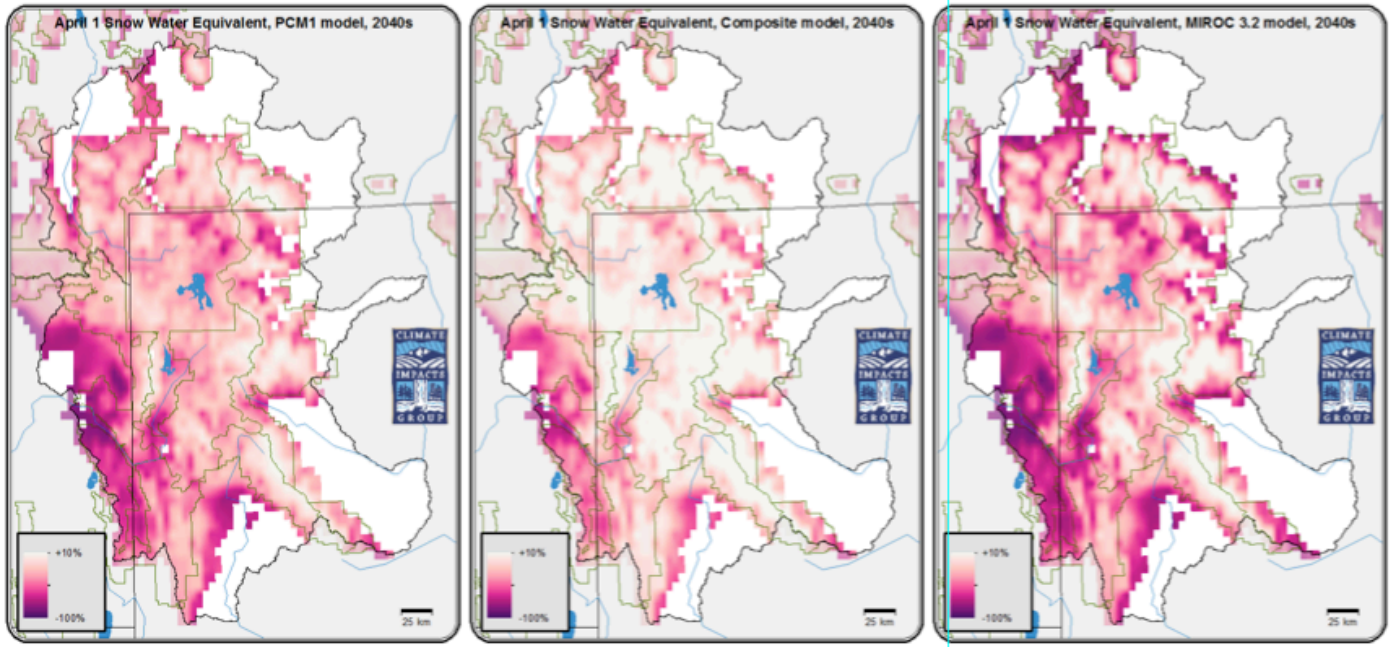
- Decreased snowpack and more precipitation falling as rain
- Earlier streamflow runoff, reduced peak flow, increasingly low summer flows
- Likely Increases in winter, spring and fall precipitation, but not summer

Prepared by the UW Climate Impacts Group – http://cses.washington.edu/cig/

Projected 21st century changes in GYA Snowpack

Projections for 2040s:

Average 34% decline



Projected changes in April 1st snowpack for the 2040s in the GYA (left). Scenarios are shown for a climate model that projects warmer, wetter winters (left), the average of 10 climate models (center), and a model that projects very warm, wet winters (right). The average across 10 models is a decline in April 1 SWE of -34% averaged over the GYA.

warm, wet winters

10 model average

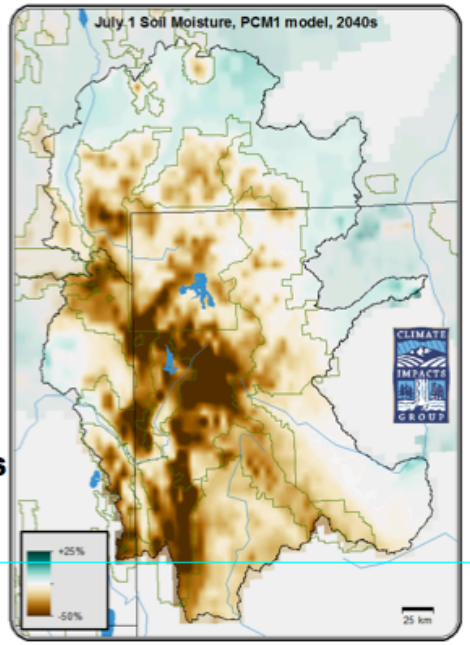
Very warm & wet winters

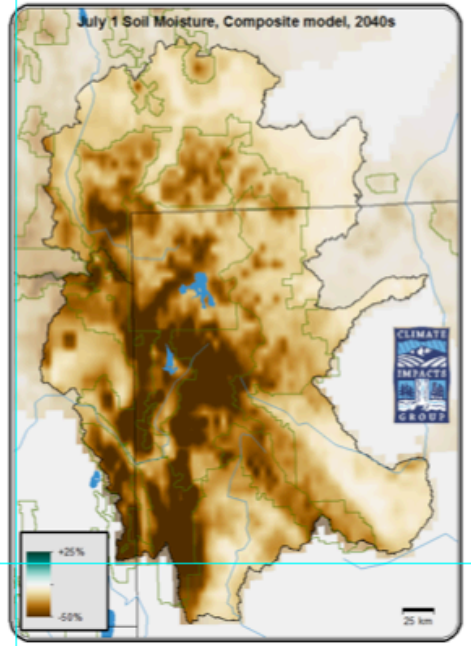
Prepared by the UW Climate Impacts Group – http://cses.washington.edu/cig/

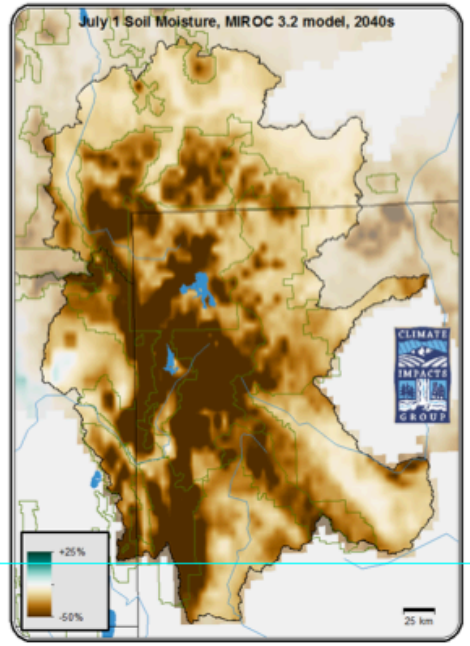
Projected 21st century changes in GYA Soil Moisture

Projections for 2040s

Projected changes in 2040s A1B July 1 soil moisture in the GYA (right). Scenarios are shown for a climate model that projects warmer, wetter summers (left), the average of 10 climate models (center) and warmer drier summers (right). Averaged over the GYA, projected ensemble mean July 1 soil moisture declines -7% (17mm).







warm, wet summers

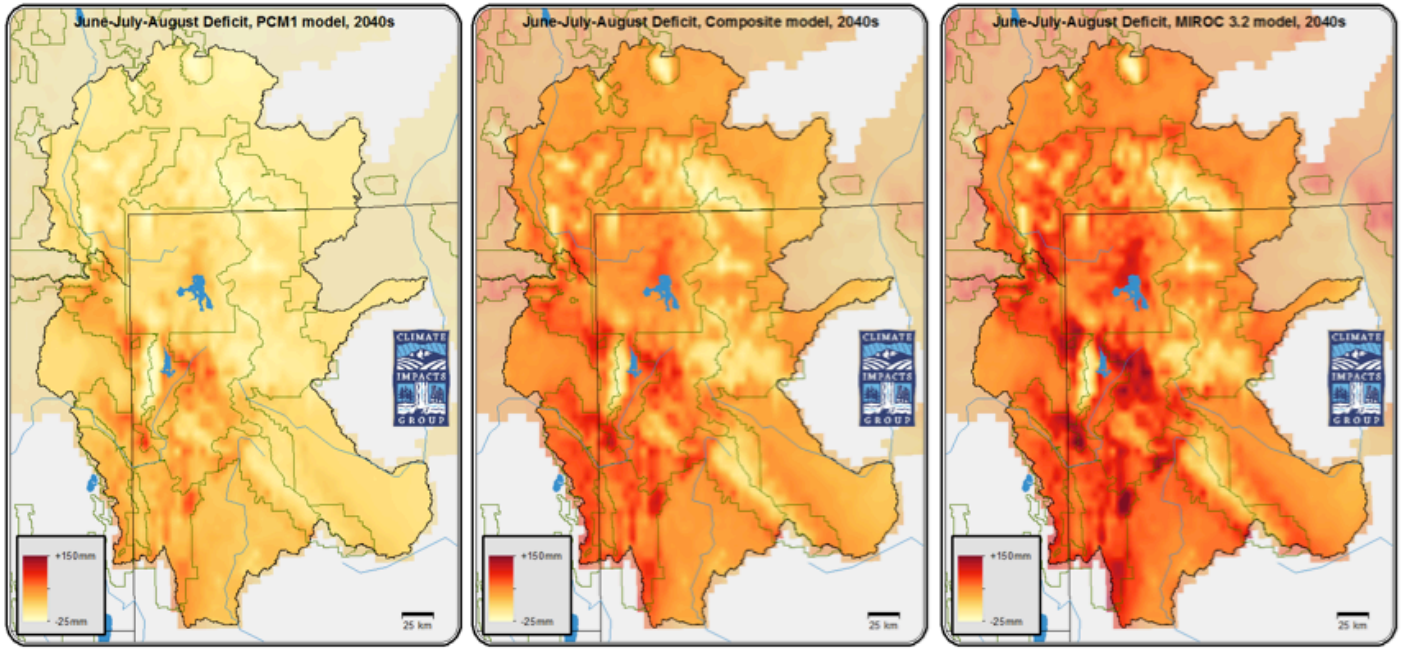
10 model average

Very warm & dry summers

Prepared by the UW Climate Impacts Group – http://cses.washington.edu/cig/

Projected 21st century changes in GYA Summer Drought

Projections for 2040s



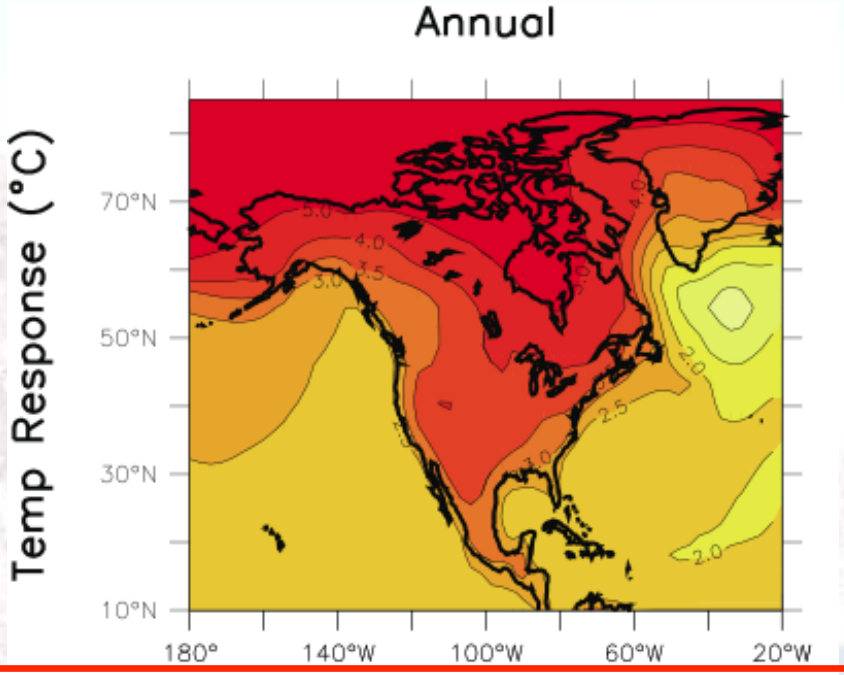
Projected changes in 2040s A1B summer (JJA) water balance deficit in the GYA (left). Warmer temperatures and decreasing precipitation increase deficit, and most of the increased deficit in the GYE is because potential evapotranspiration is projected to increase. For the 2040s, deficit increases by +31% (+30mm) averaged across he GYA.

warm, wet summers

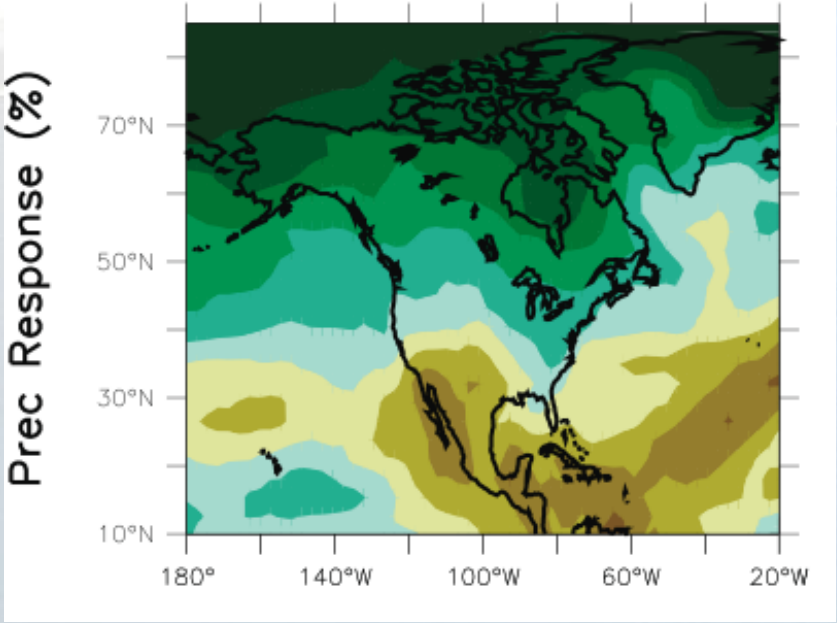
10 model average

Very warm & dry summers

Prepared by the UW Climate Impacts Group – http://cses.washington.edu/cig/



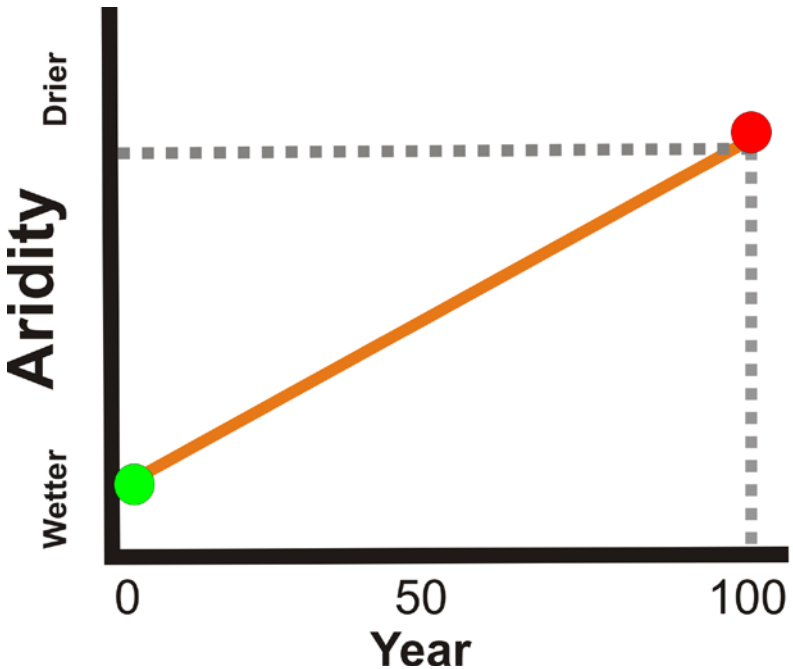
So yes the West will dry because of this…



But, we have real trouble saying where and how fast the West will dry because of errors associated with this…

What do we know?

Future Climate = Natural Variability + Warming



We tend to think of future climate change as a simple linear trend…

Gray et al. (2006), *Ecology* 87:1124-1130

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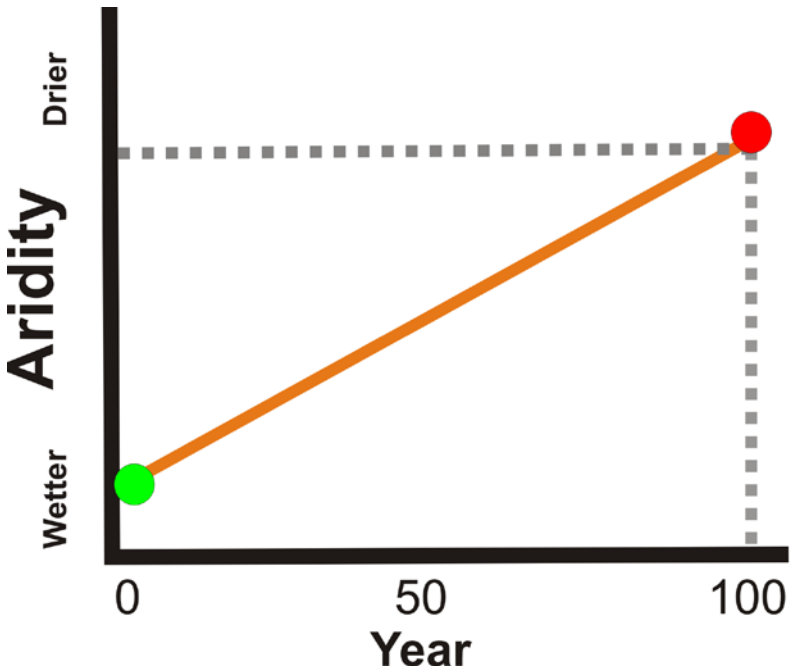

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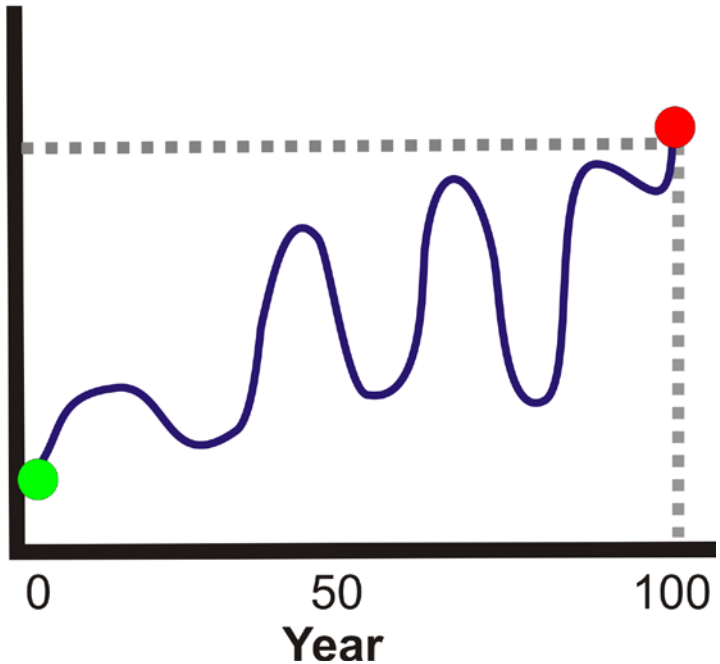

Future climate will be a combination of human-induced trends and natural variability

Gray et al. (2006), *Ecology* 87:1124-1130

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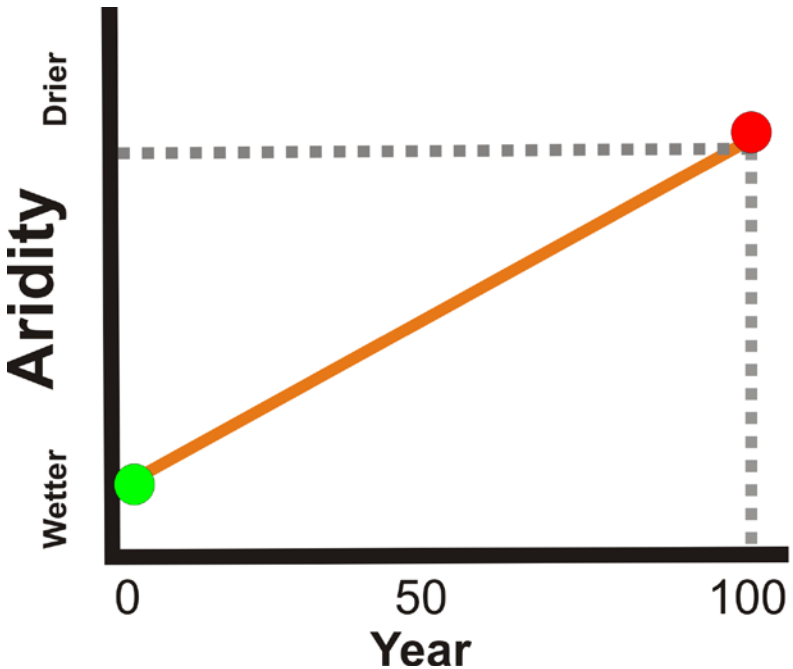

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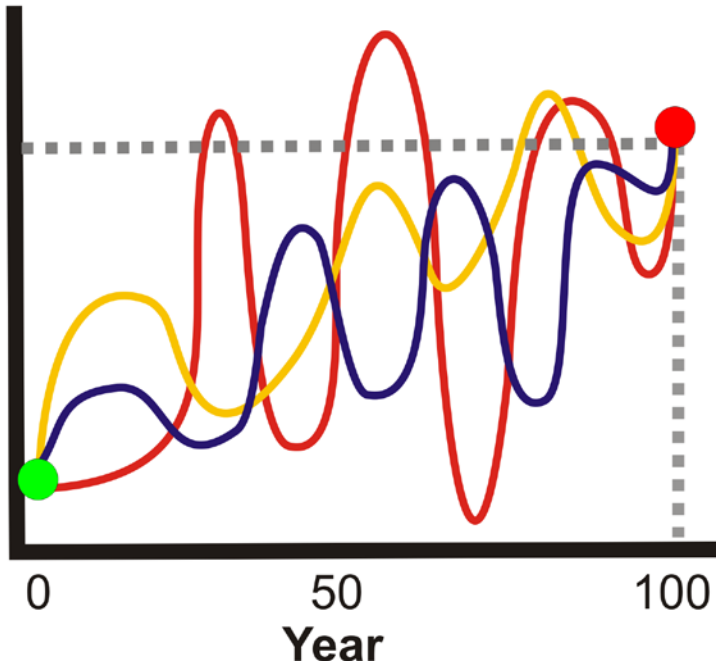

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Questions?

Greg Pederson:
Email: gpederson@usgs.gov

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