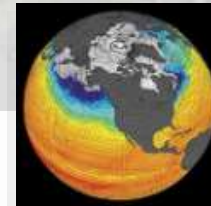
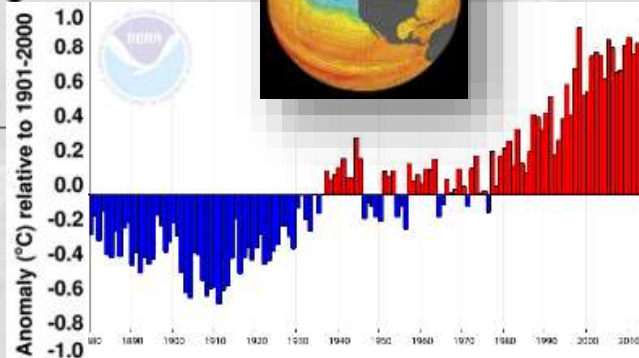
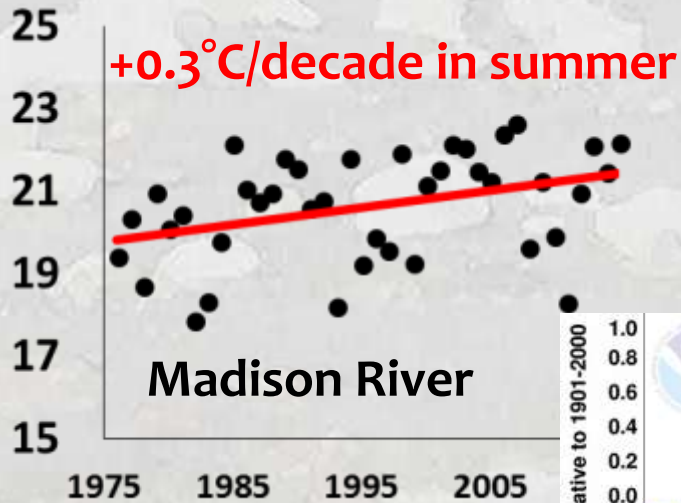
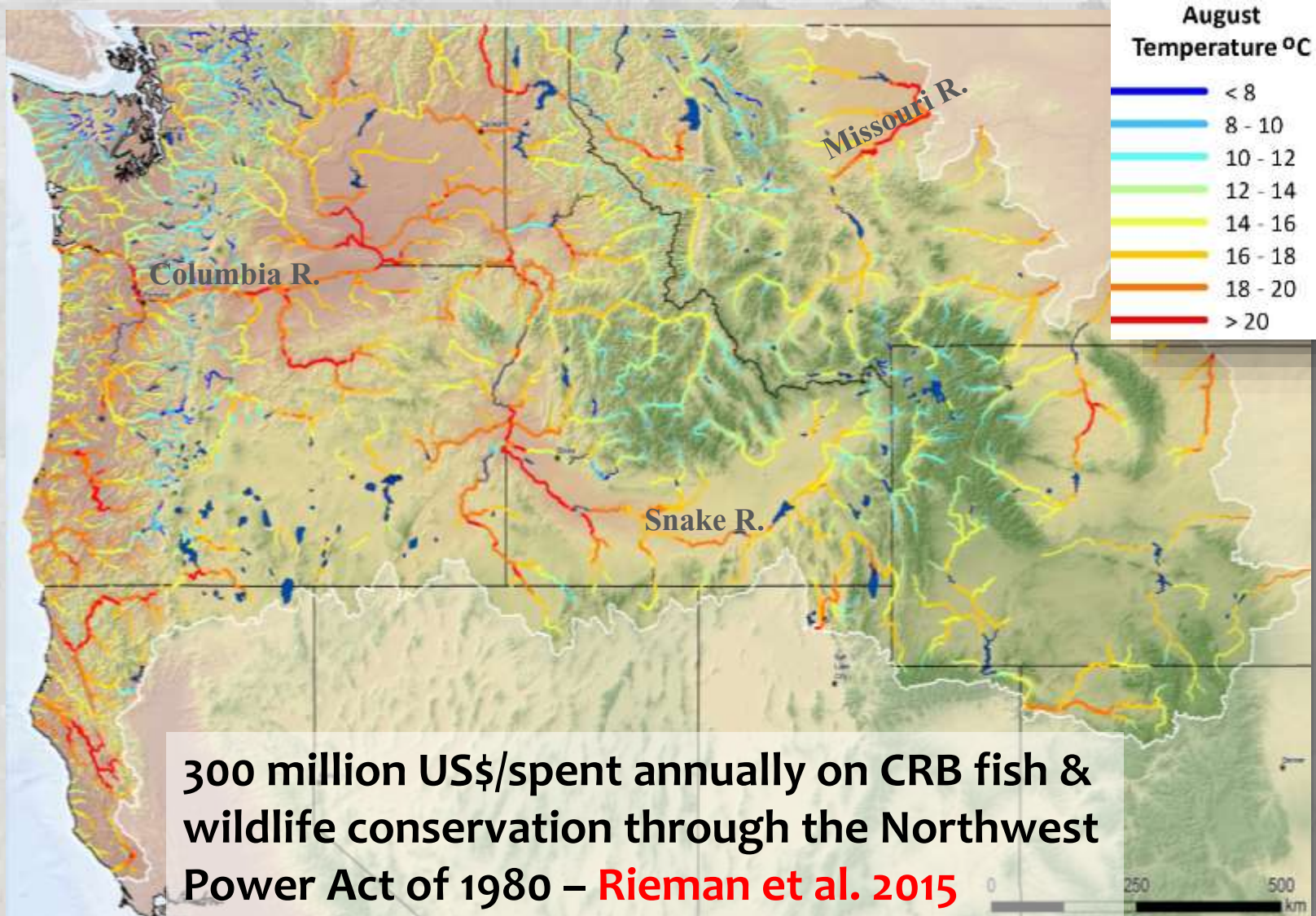


Climate Warming Rates of Salmon and Trout Rivers in the West



The Billion \$ Network of Concern

60,000 kilometers of rivers >100 cfs annual flow



High Value Resources & Key Habitats



Thermal Constraints on Cold-Water Fish Populations are Common...

Symptoms include...

- 1) Migration delays & clustering in coldwater refuges
- 2) Selective gradients based on run timing
- 3) Mass mortality events:
 - a) upriver stocks of Fraser river sockeye “disappear”
 - b) spawning ground fish kills

Keefer et al. 2010; Crozier 2011; Caudill et al. 2013

- 4) Fishing season closures
- 5) Fish disease outbreaks?
- 6) Shifting distributions

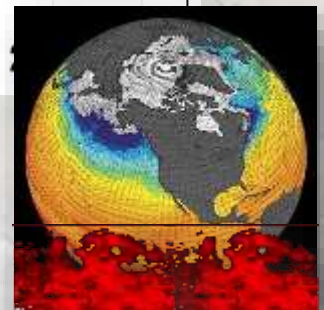
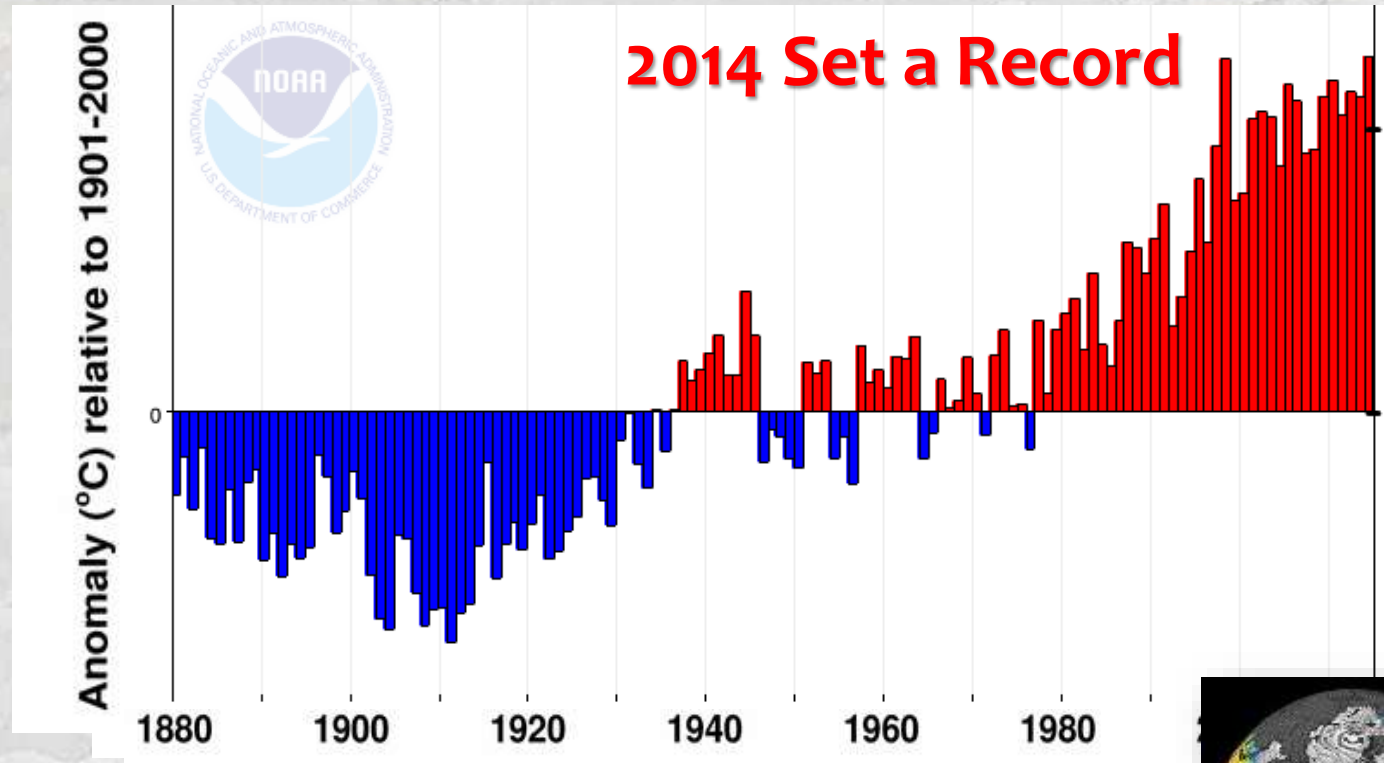
Eby et al. 2014; Al-Chokhachy et al. 2016

High Water Temperature In Grande Ronde Kills 239 Adult Spring Chinook
Columbia Basin Bulletin, August 14, 2009 (PST)

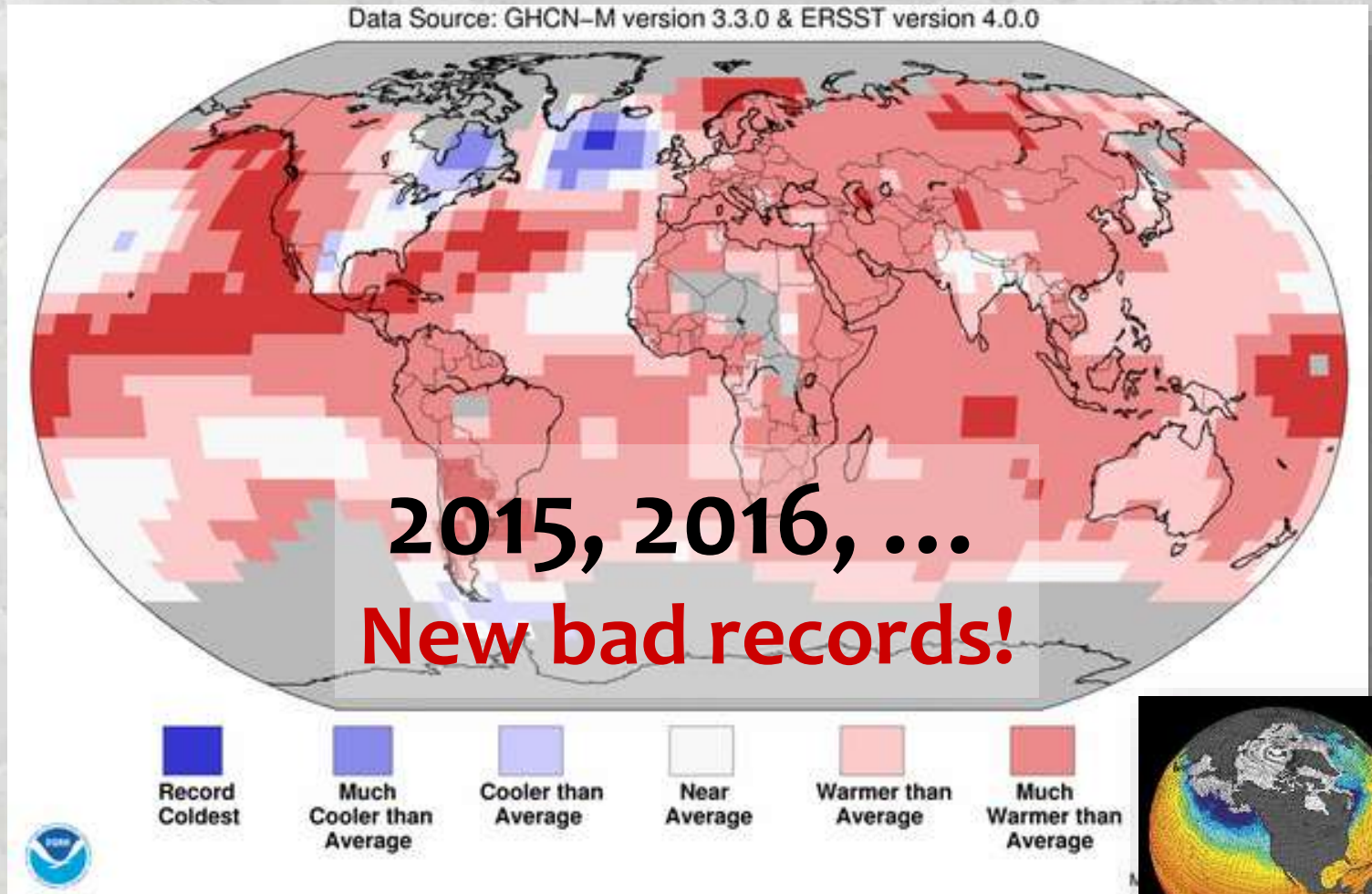


Thermal Constraints Will be More Common

1880-2014 Global Air Temperature Trend



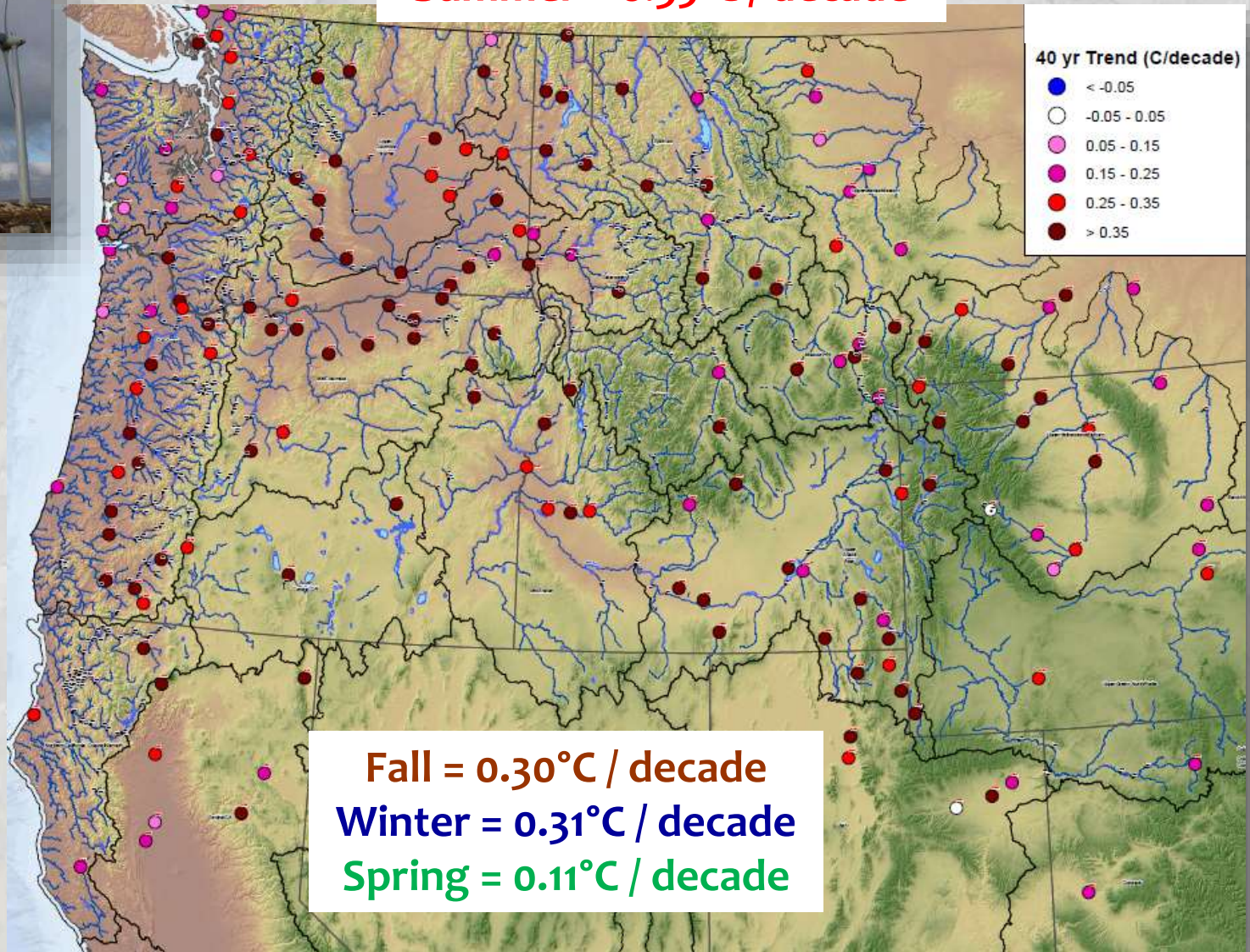
Thermal Constraints Will be More Common



Regional Air Temp Trends (1976–2015)

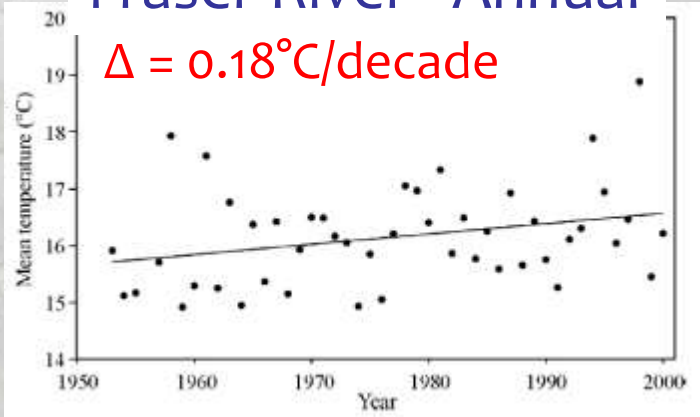
Global Historical Climatologic Network V3 Dataset

Summer = $0.35^{\circ}\text{C} / \text{decade}$



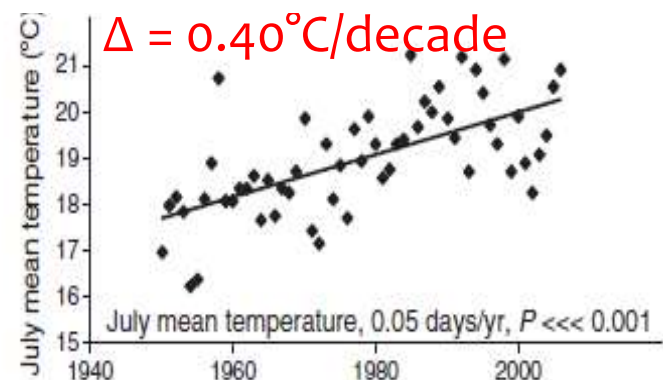
What are the trends in Salmon and Trout Rivers?

Fraser River - Annual



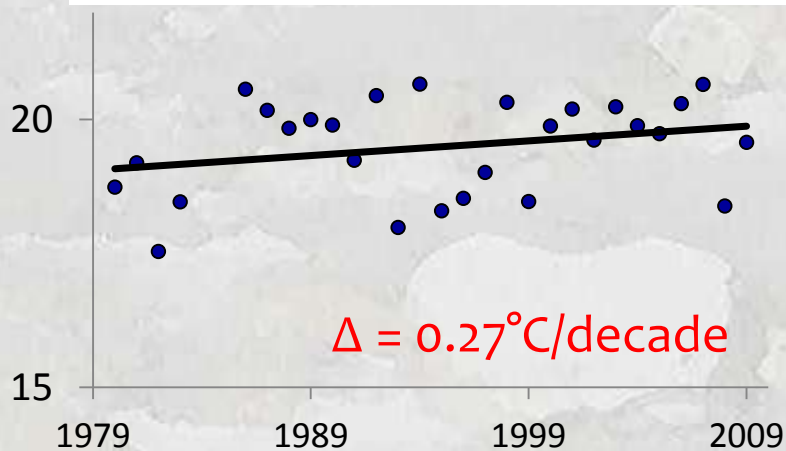
Morrison et al. 2001

Columbia River - Summer



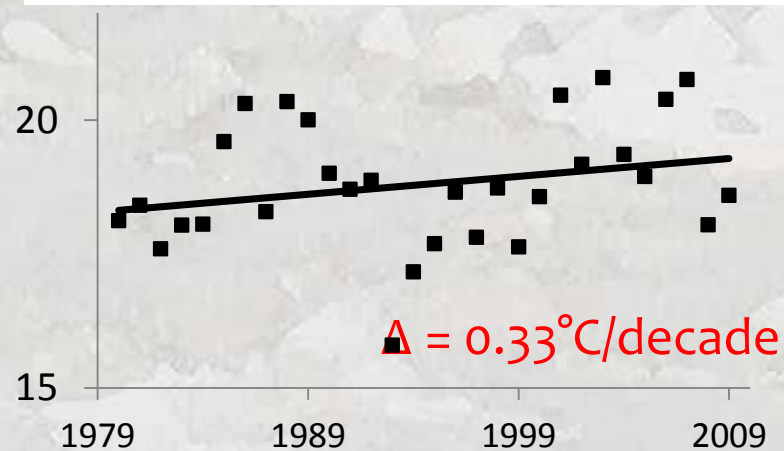
Crozier et al. 2008

Snake River, ID - Summer



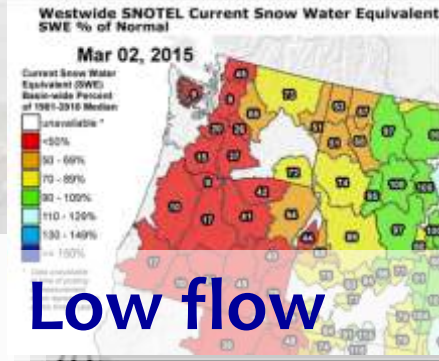
Isaak et al. 2012. *Climatic Change* 113:499-524.

Missouri River, MT - Summer



Stream Temperature Records in 2015

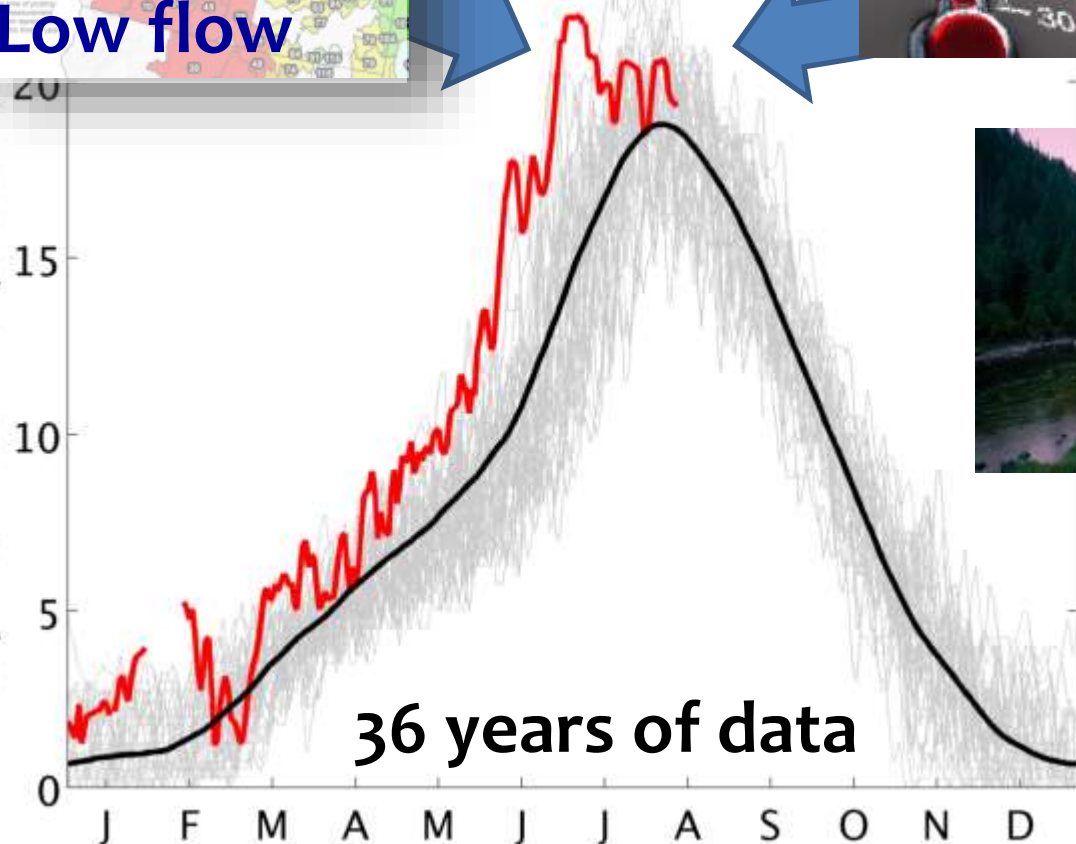
NFK Clearwater River in North Idaho



+

Low flow

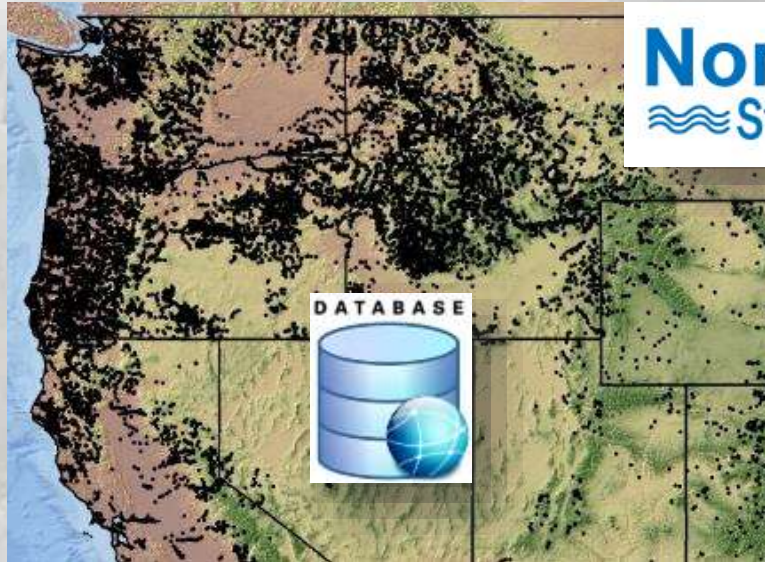
Daily Water Temp ($^{\circ}\text{C}$)



Where are Best Long-term River Records?

>220,000,000 hourly recordings

>22,700 stream sites



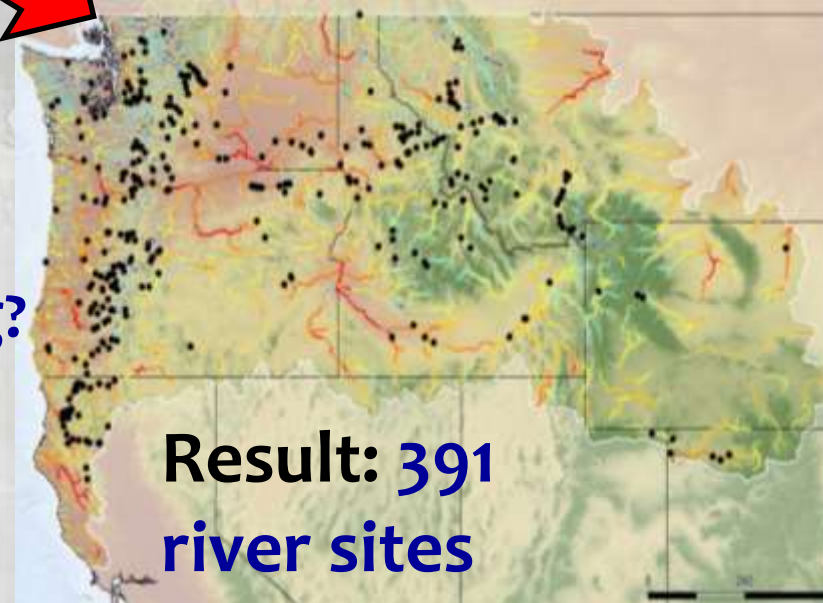
NorWeST
Stream Temp



>100 agencies

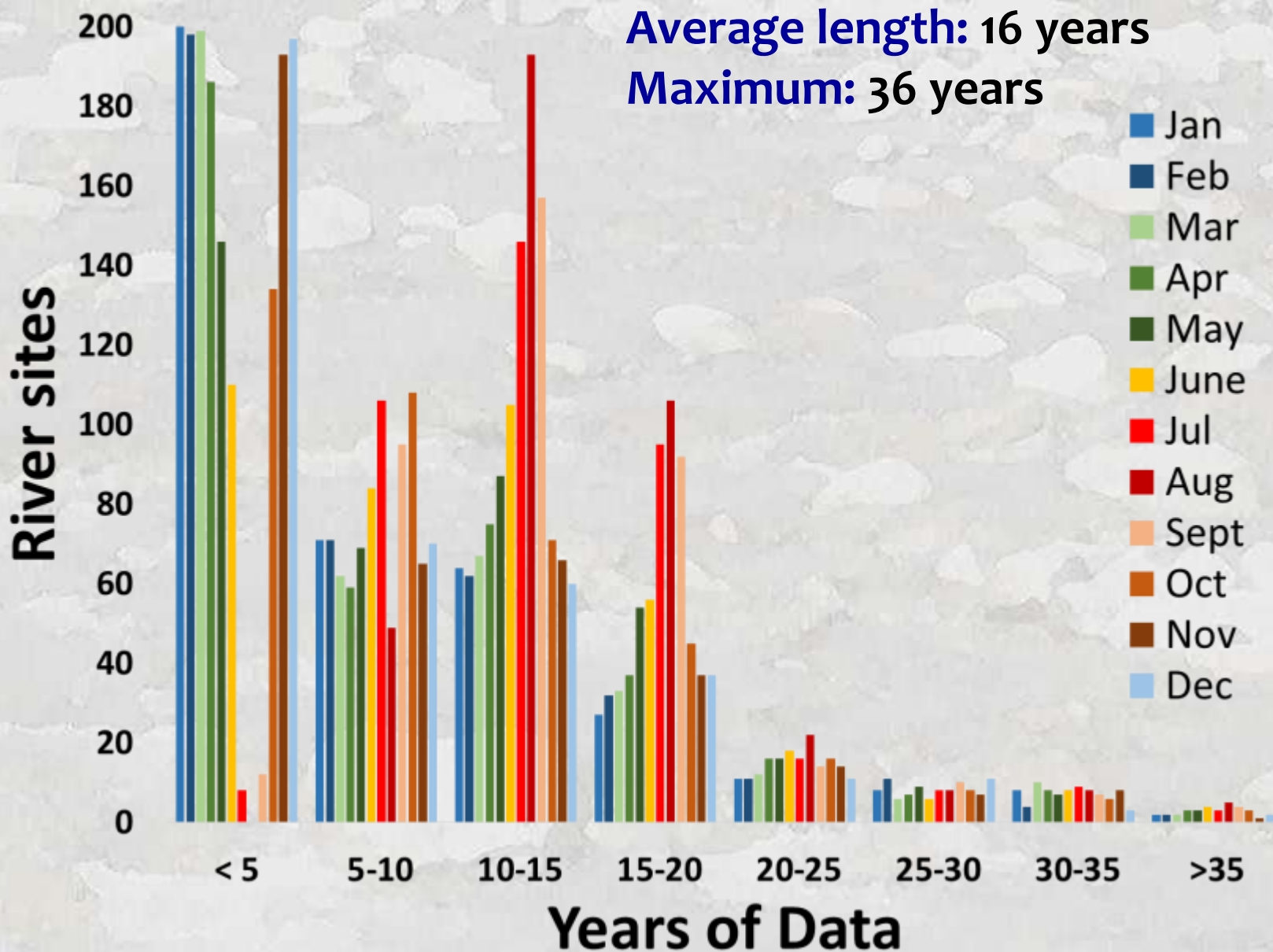
Database query:

- 1) How many sites have >10 years of August monitoring?
- 2) How many sites occur on rivers with >100 cfs flow?



**Result: 391
river sites**

Monitoring Record Length by Month at 391 sites



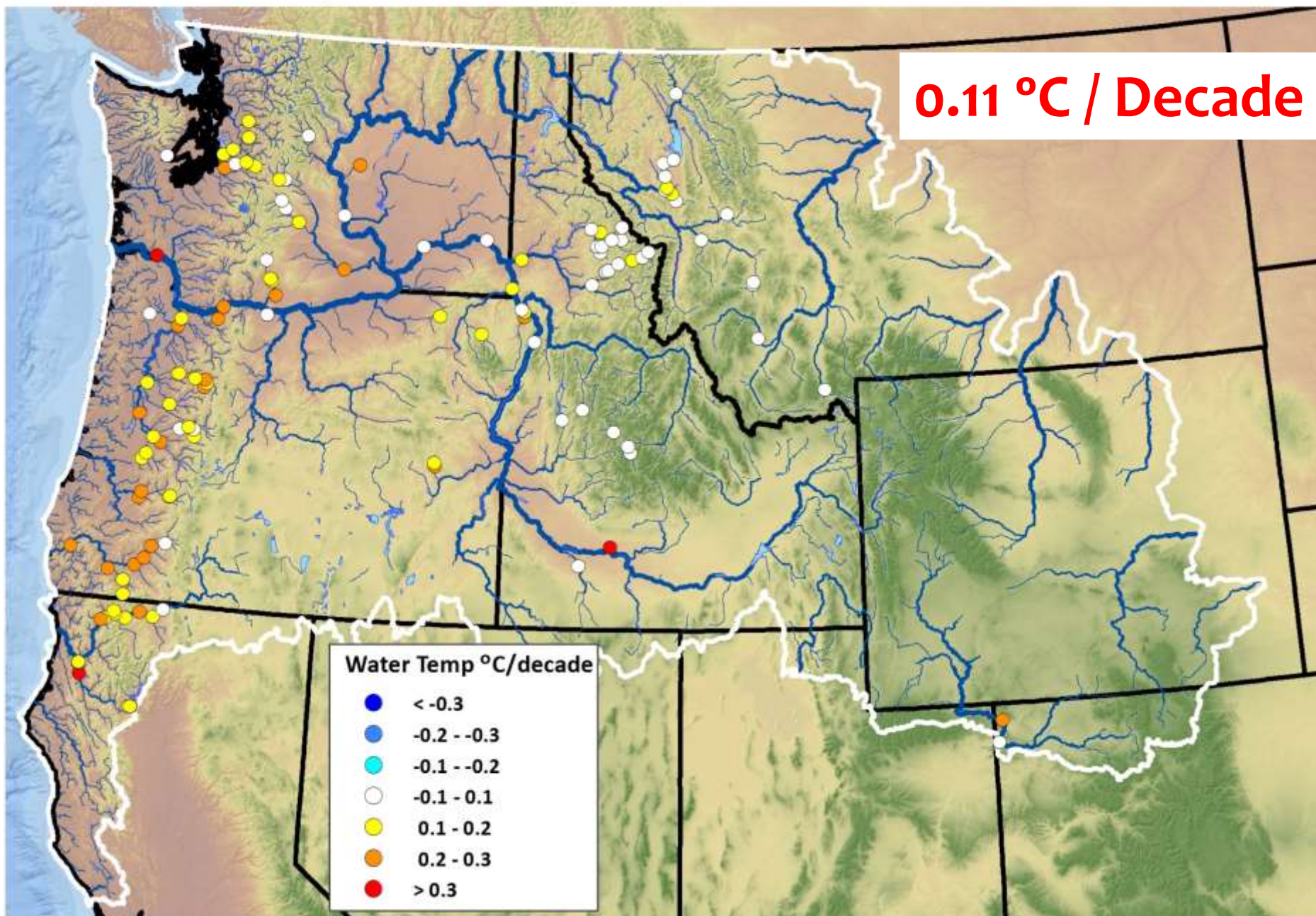
Methods for Completing Time-Series:

- Summarized monthly air temperatures for forty year period of 1976-2015 from Global Historical Climate Network V3 dataset for 168 sites
- Summarized monthly river discharge from USGS NWIS, BOR HydroMet, & DART for 320 gage and dam sites
- Aligned data series for RivTemp, air temperature, and discharge into twelve monthly matrices (40 years x 879 sites)
- Imputed missing monthly RivTemp values using PCAs calculated with the MissMDA package in R (Missing Values with Multivariate Data Analysis)
- Retained completed RivTemp time series if $r > 0.8$ between observed and fitted values (average $r = 0.9$)
- Regressed RivTemp on year & calculated decadal trends for 20 & 40 year periods that end in 2015



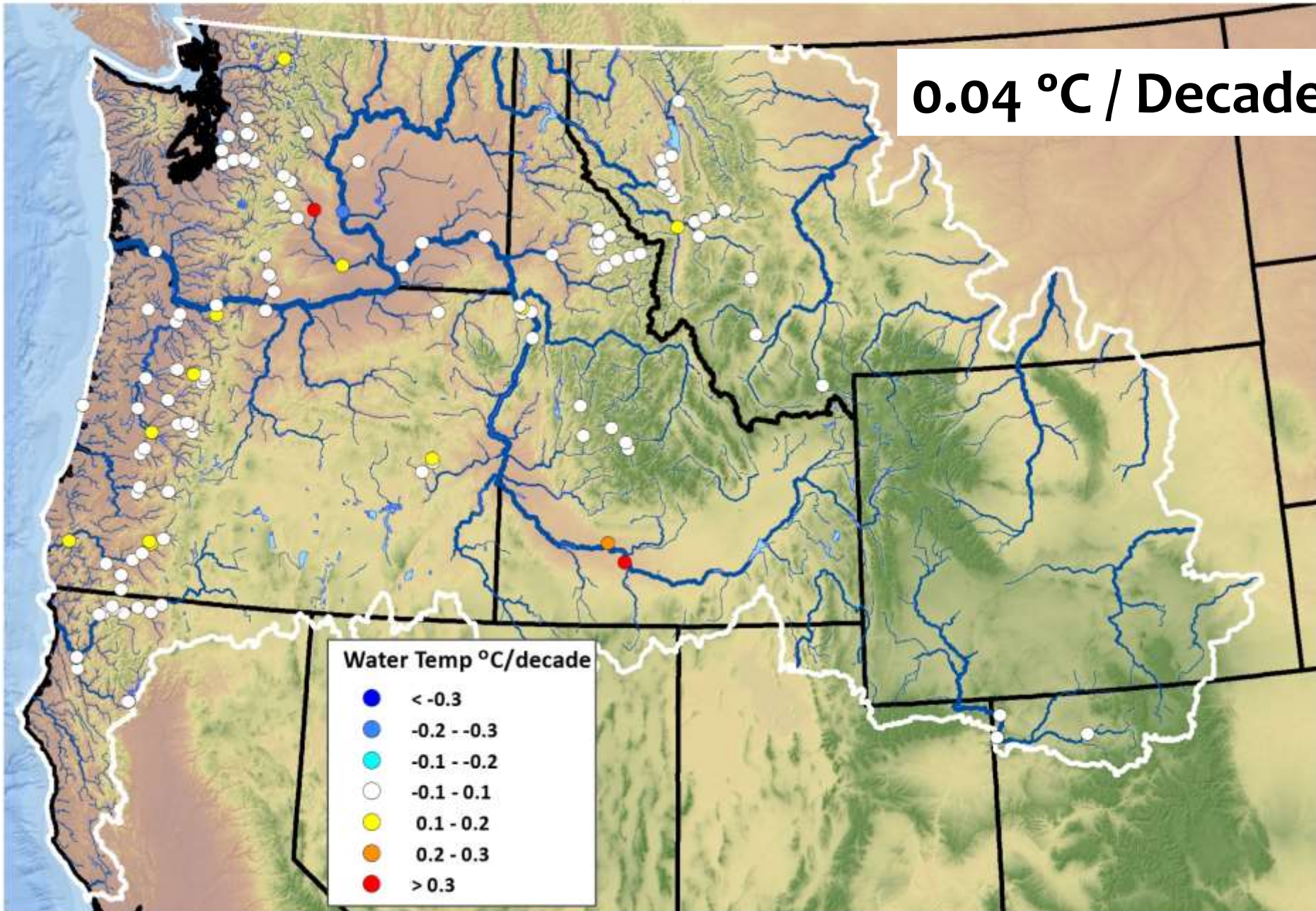
40 Year (1976–2015) Monthly River Temperature Trend - January

0.11 °C / Decade

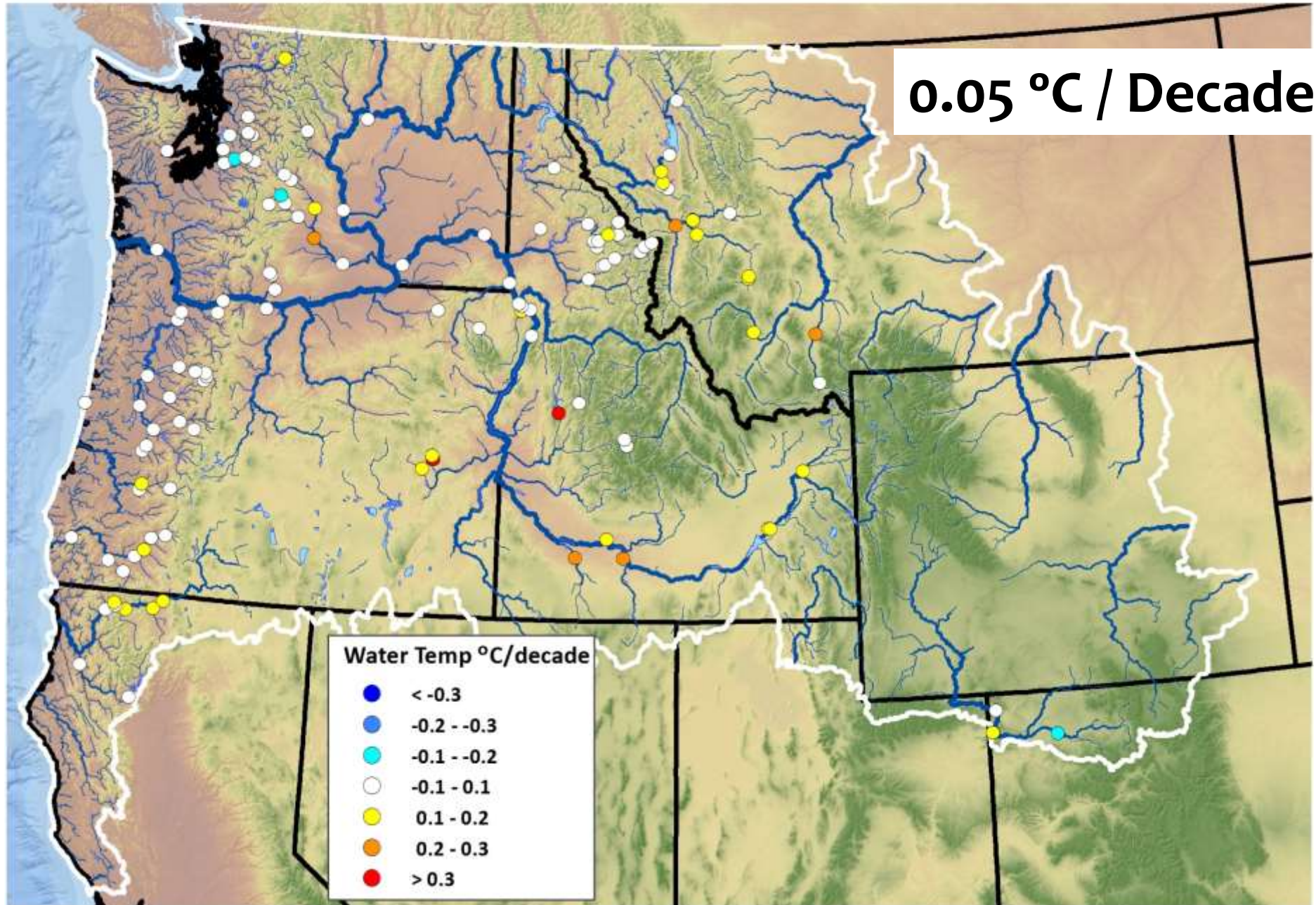


40 Year (1976–2015) Monthly River Temperature Trend - February

0.04 °C / Decade

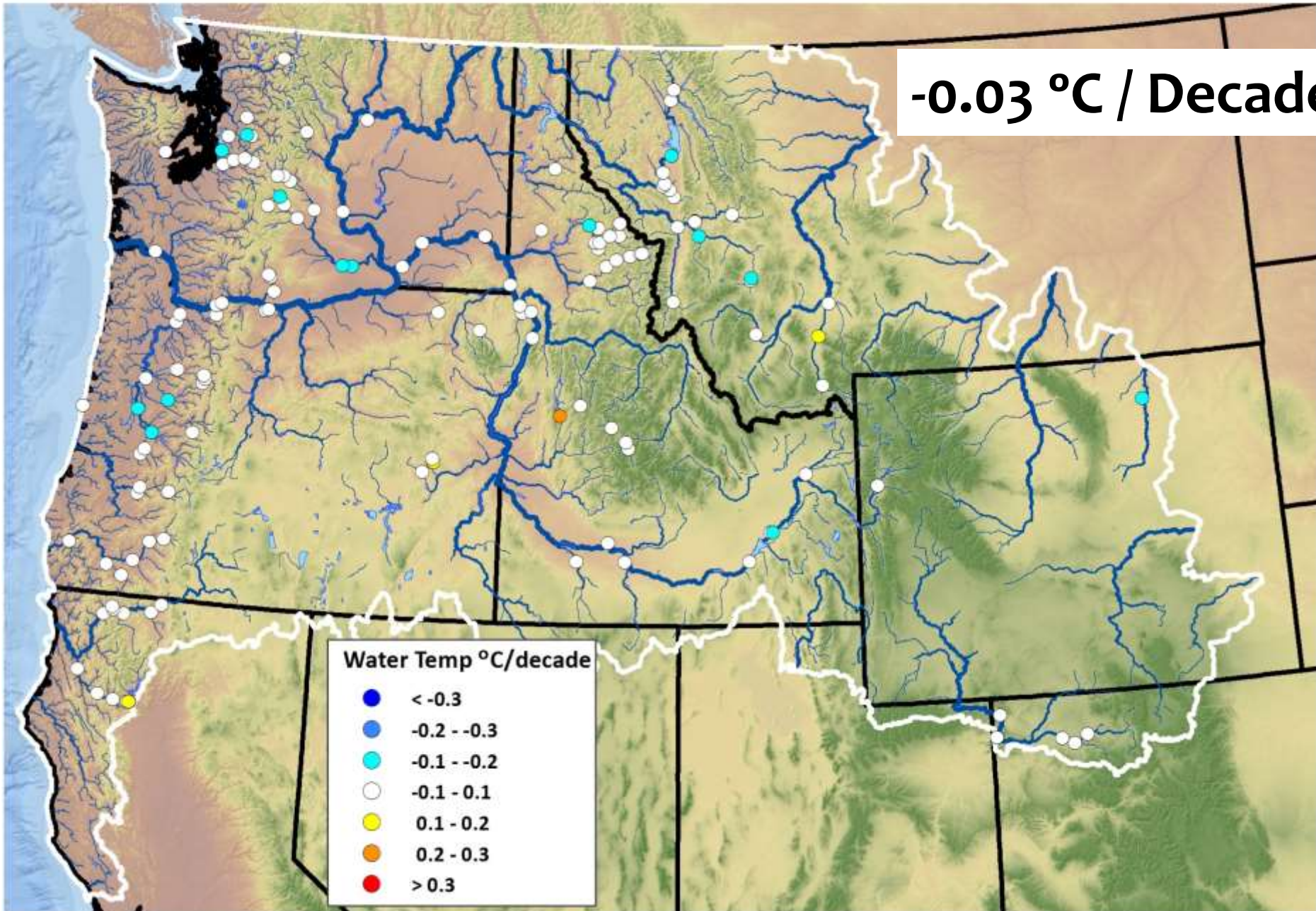


40 Year (1976–2015) Monthly River Temperature Trend - **March**

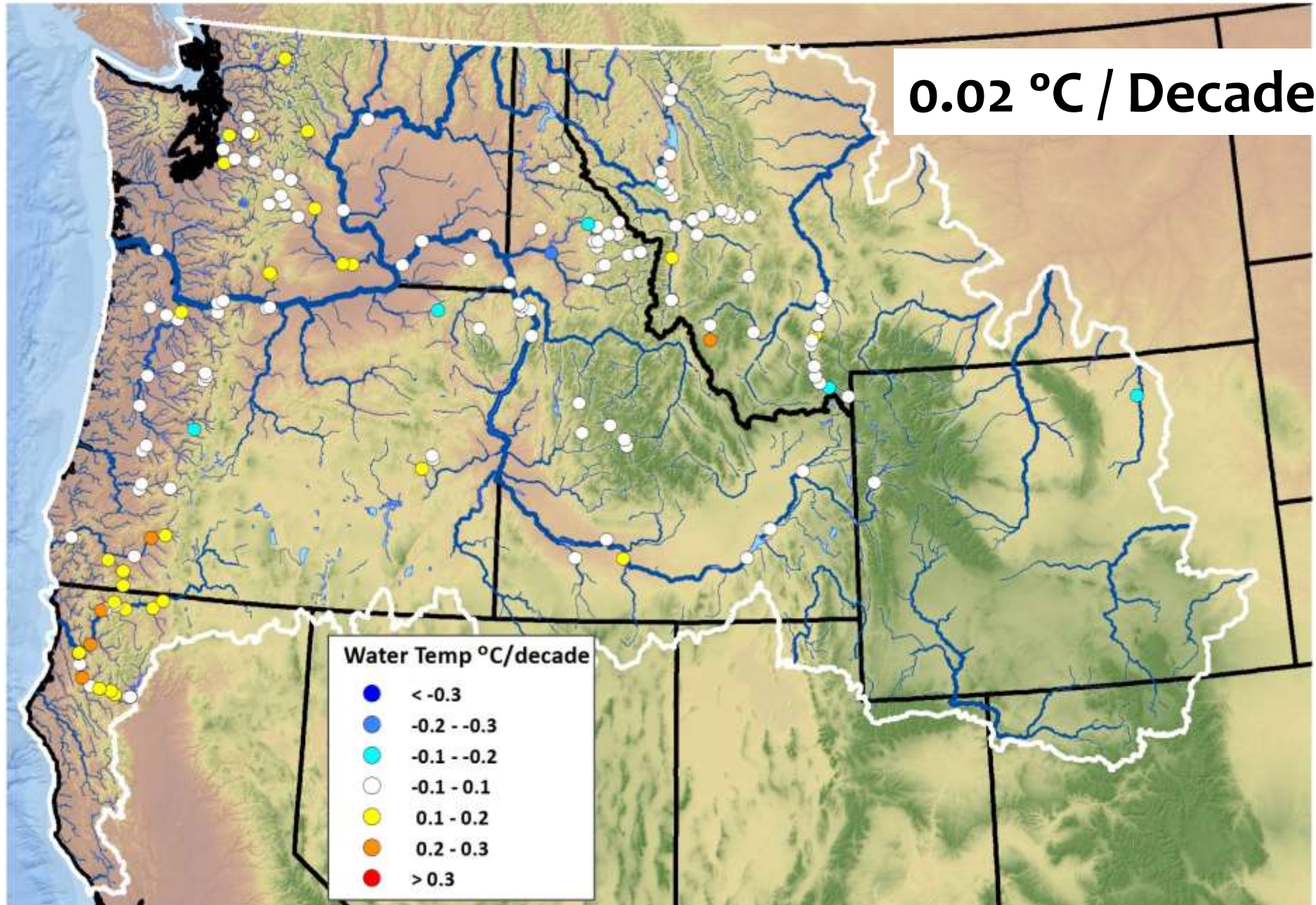


40 Year (1976–2015) Monthly River Temperature Trend - April

-0.03 °C / Decade

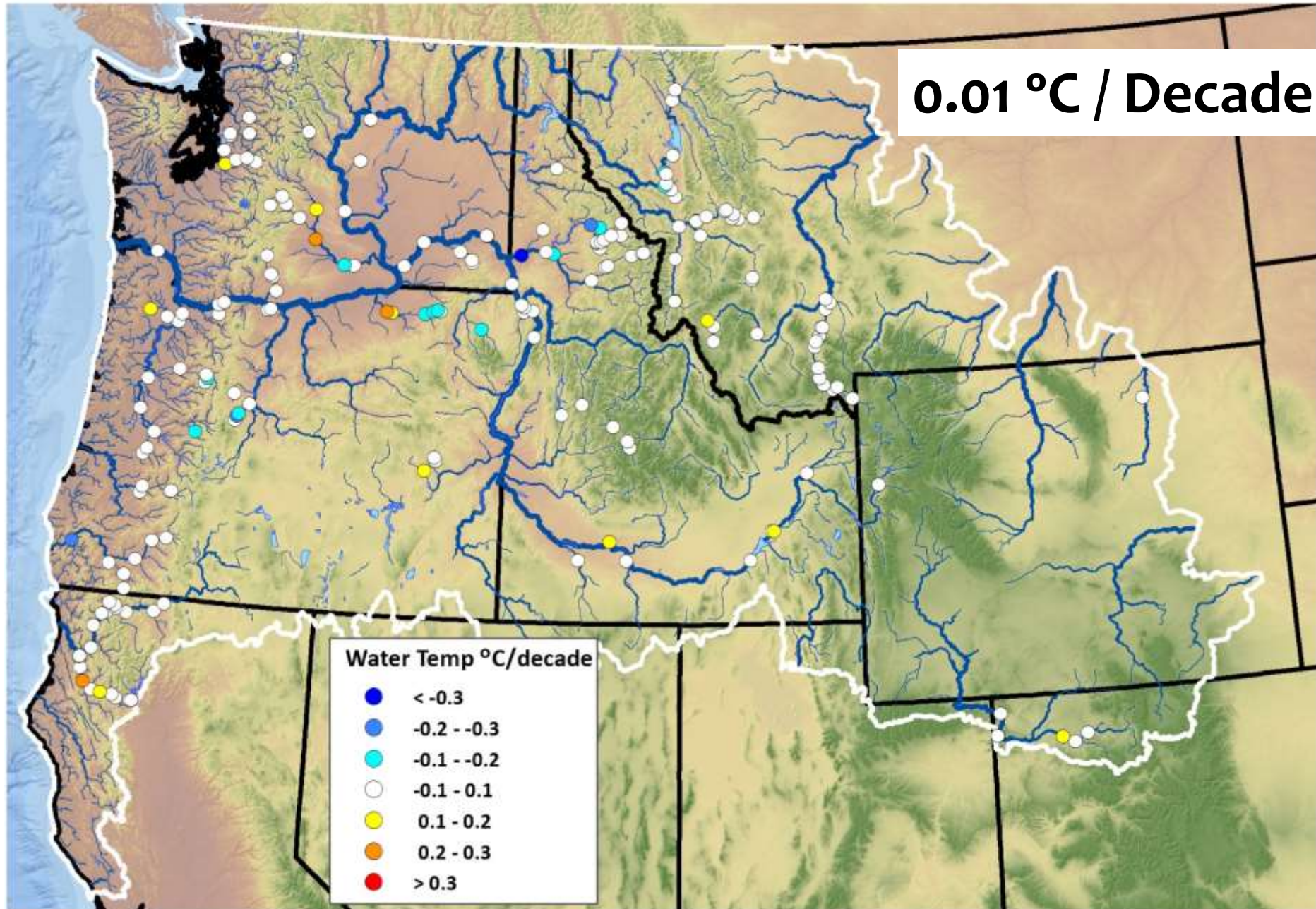


40 Year (1976–2015) Monthly River Temperature Trend - **May**



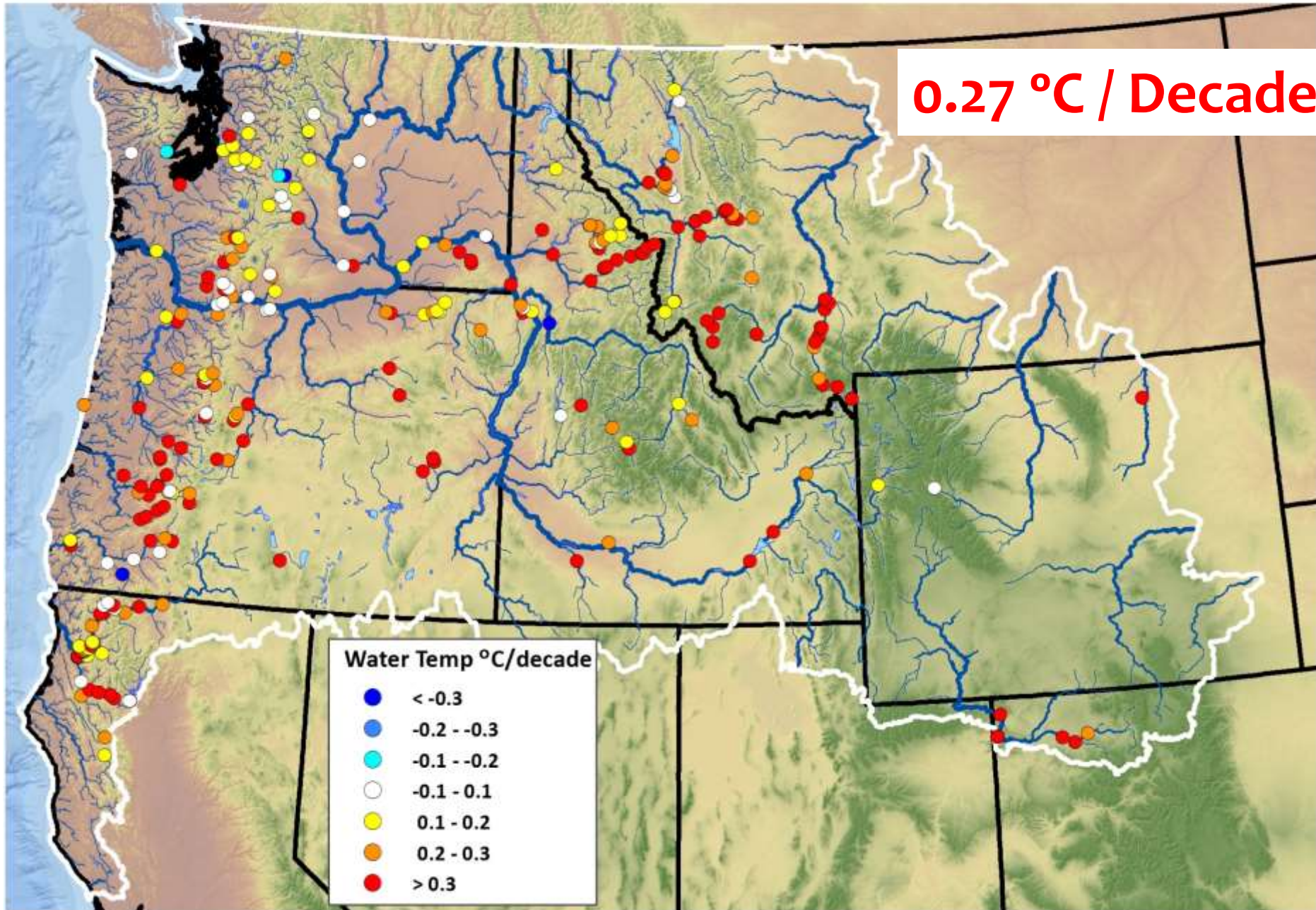
40 Year (1976–2015) Monthly River Temperature Trend - June

0.01 °C / Decade



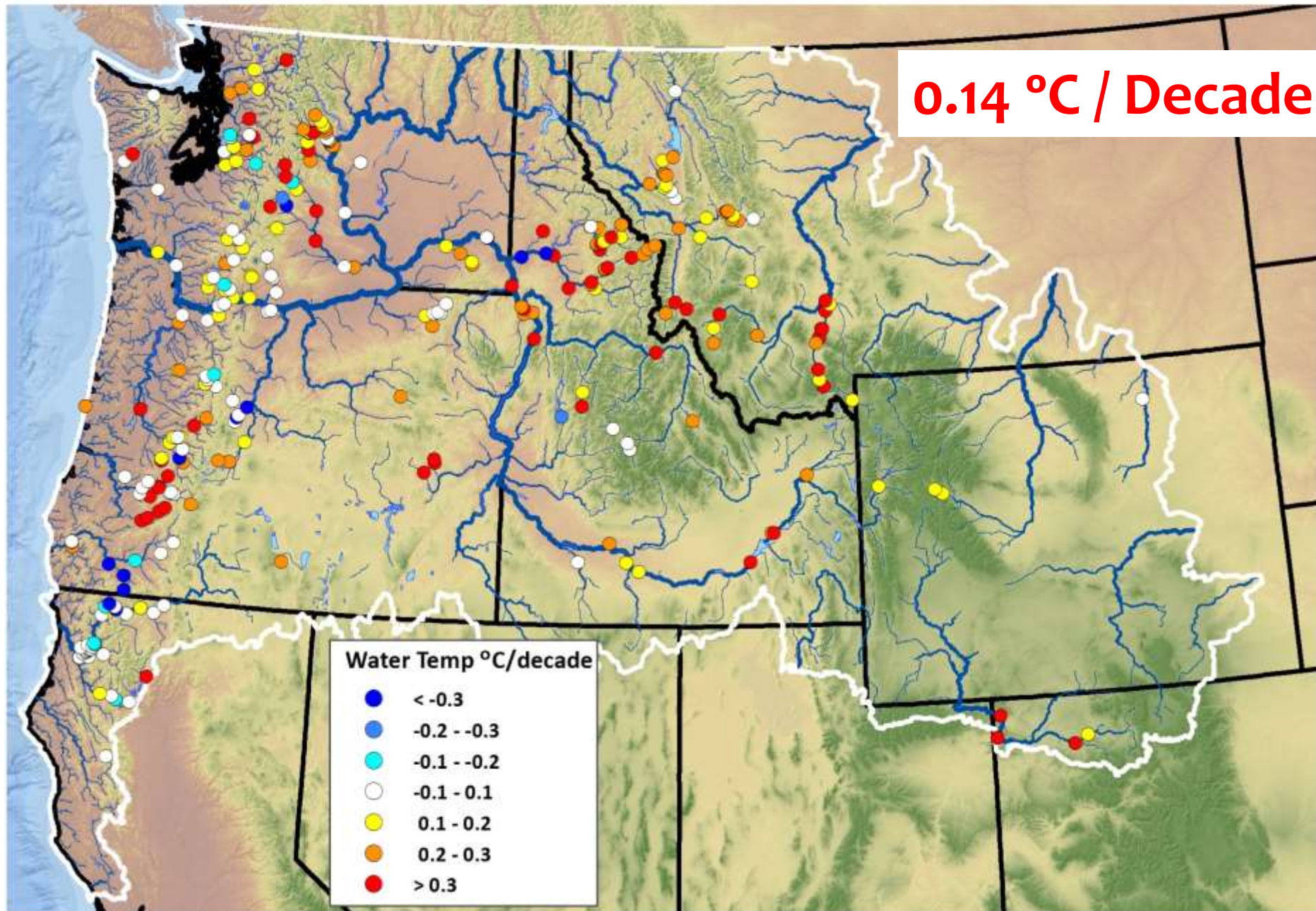
40 Year (1976–2015) Monthly River Temperature Trend - July

0.27 °C / Decade



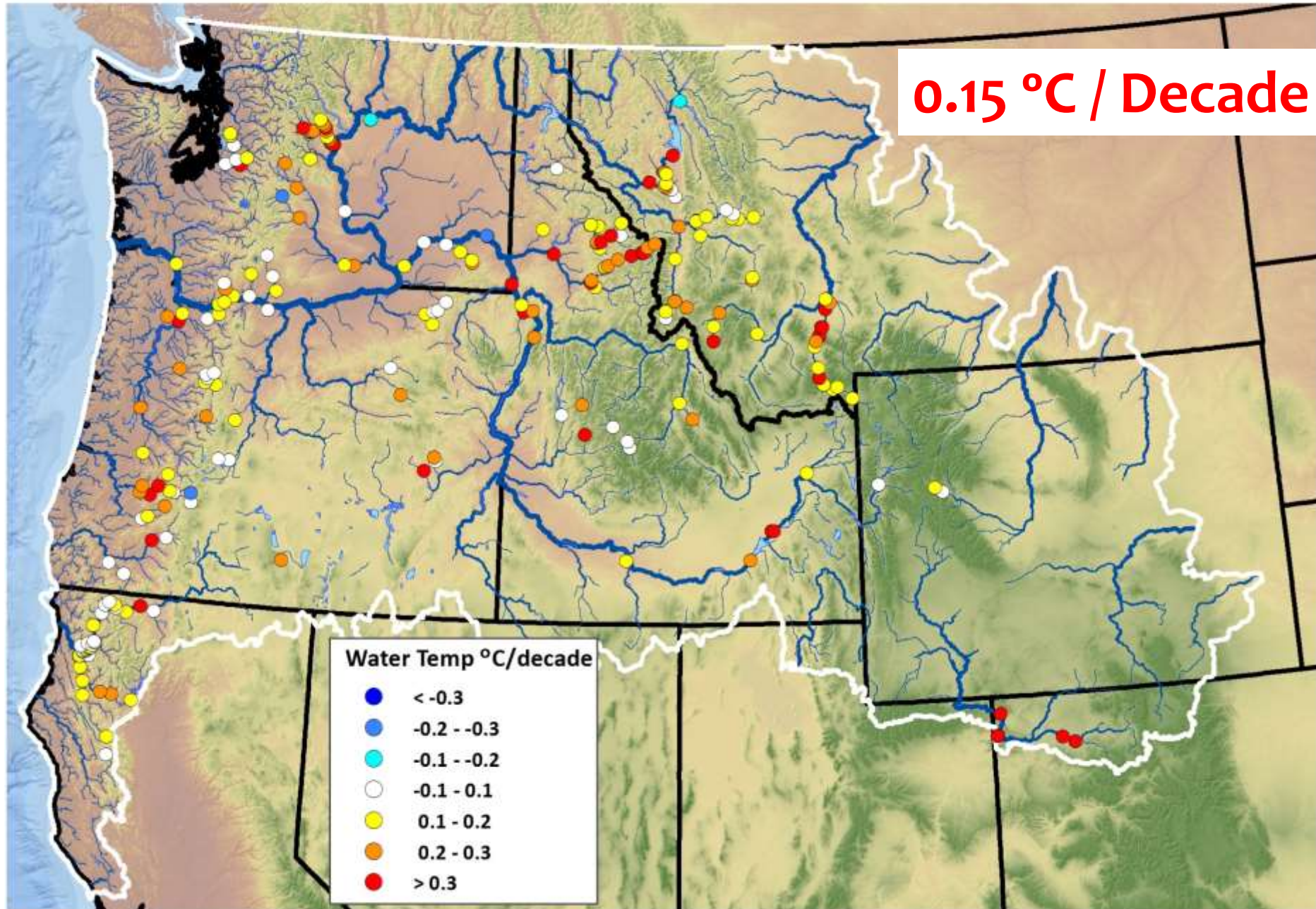
40 Year (1976–2015) Monthly River Temperature Trend - August

0.14 °C / Decade

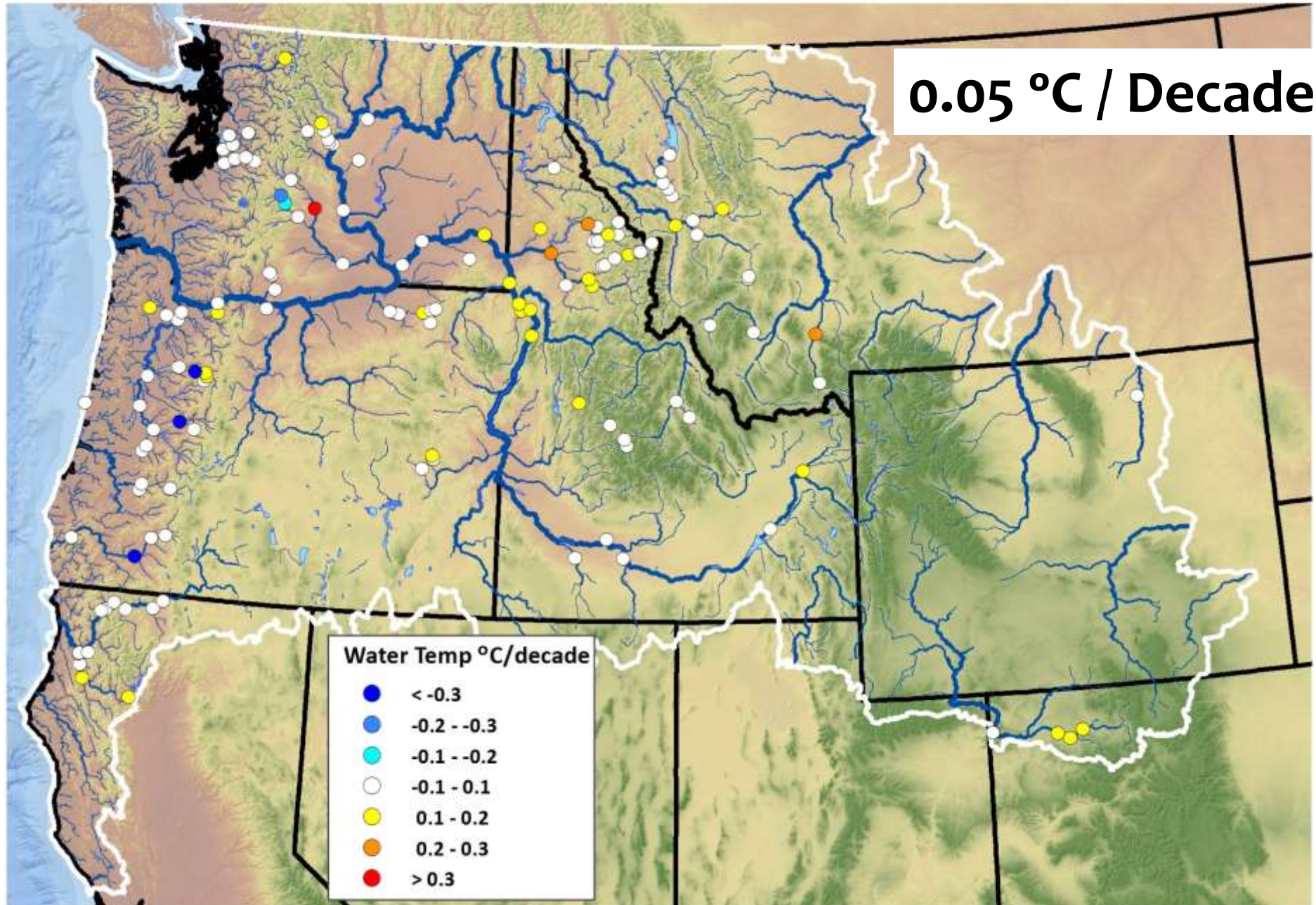


40 Year (1976–2015) Monthly River Temperature Trend - September

0.15 °C / Decade

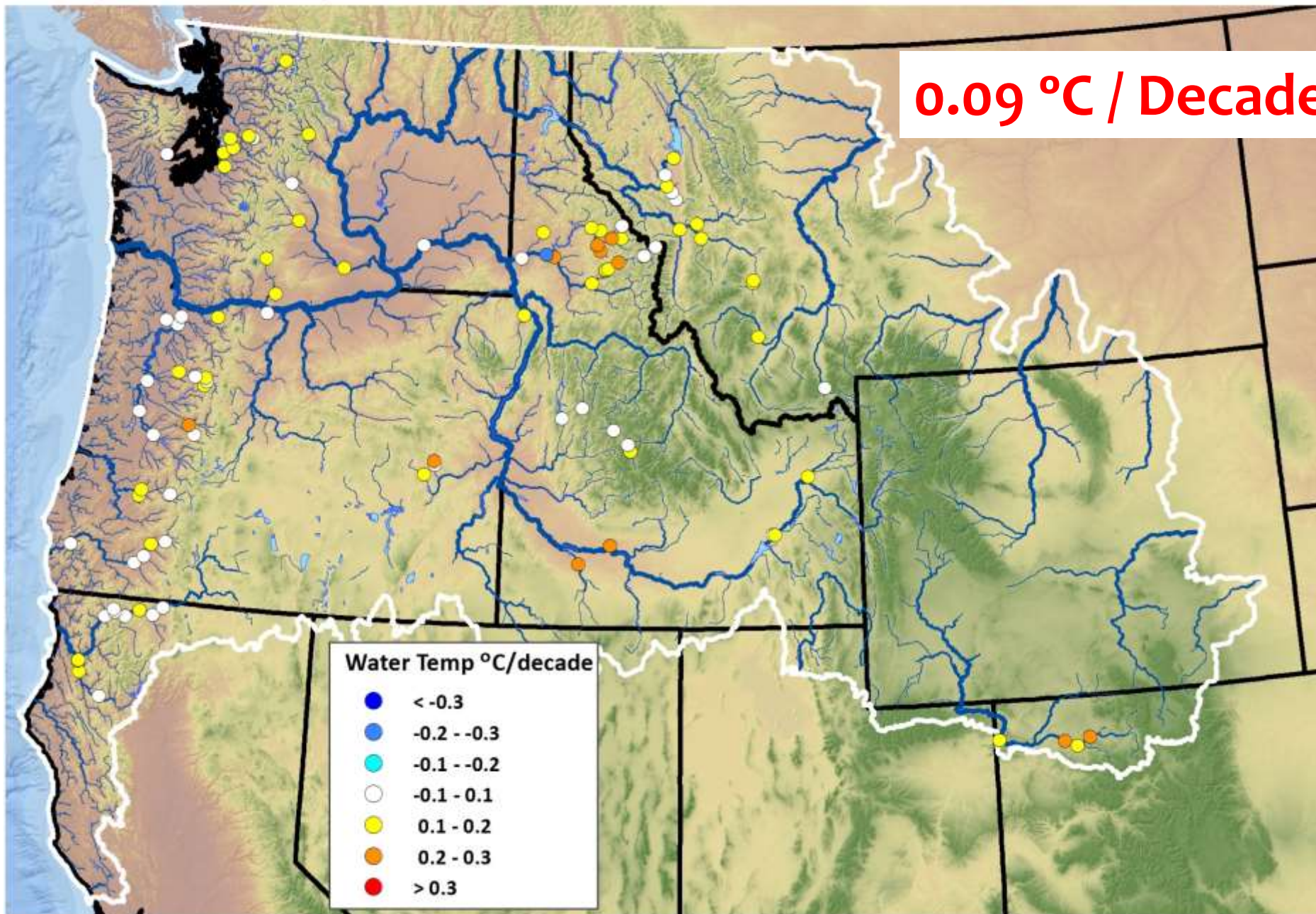


40 Year (1976–2015) Monthly River Temperature Trend - **October**



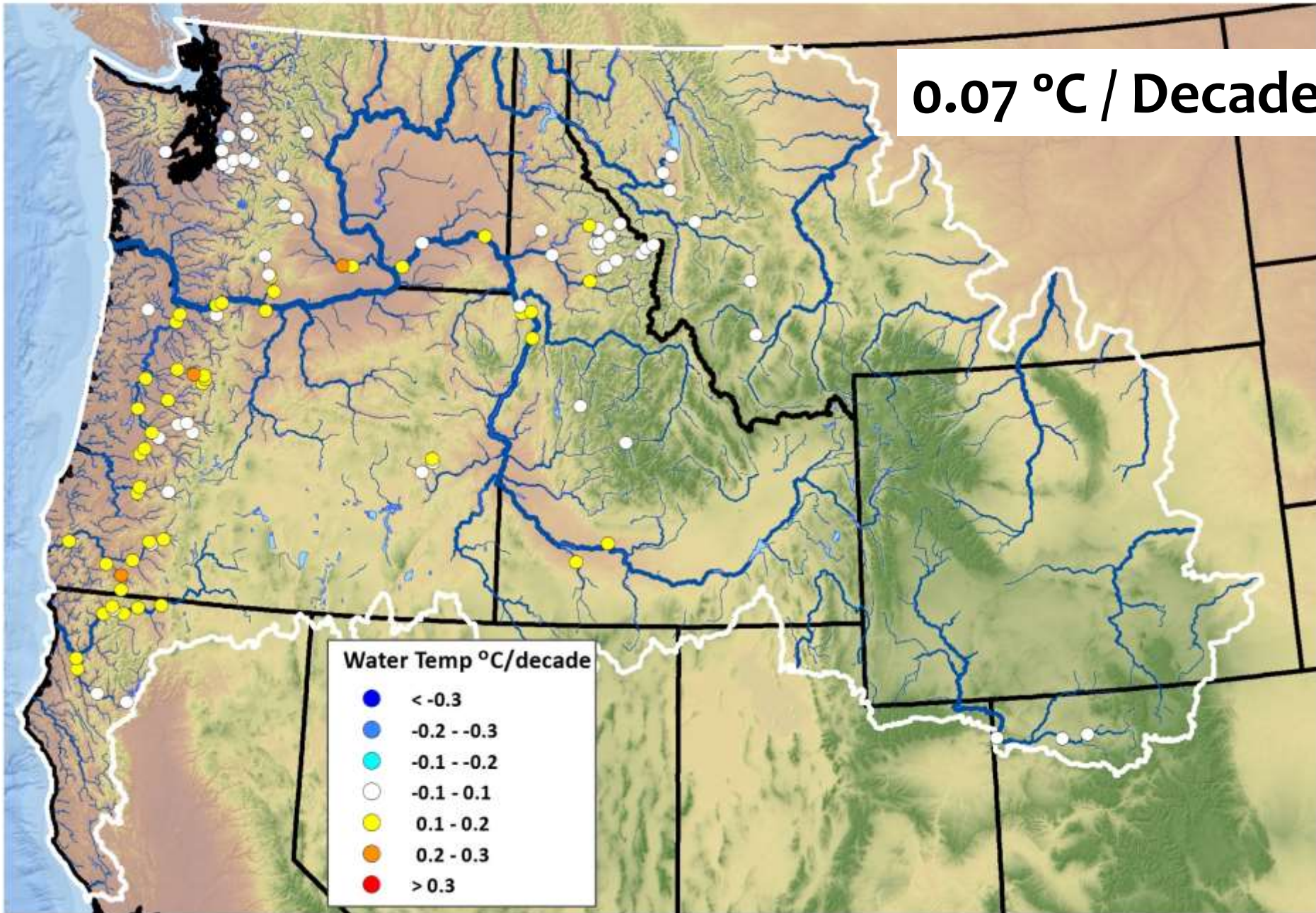
40 Year (1976–2015) Monthly River Temperature Trend - November

0.09 °C / Decade



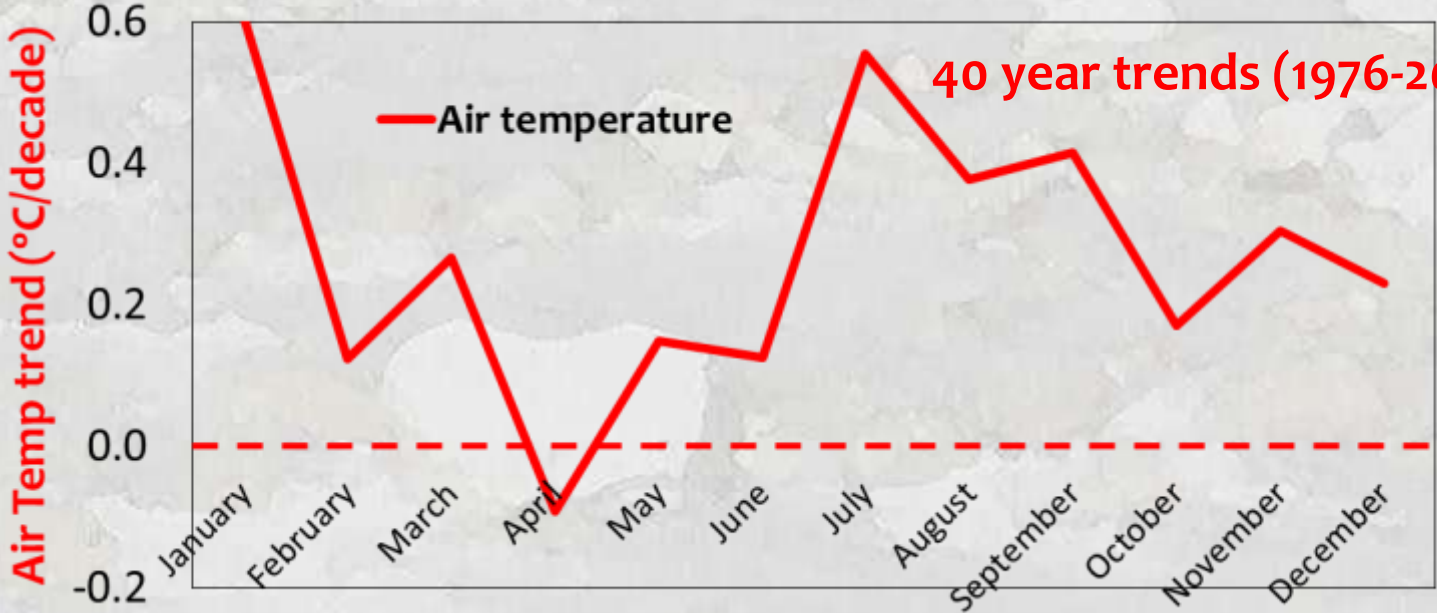
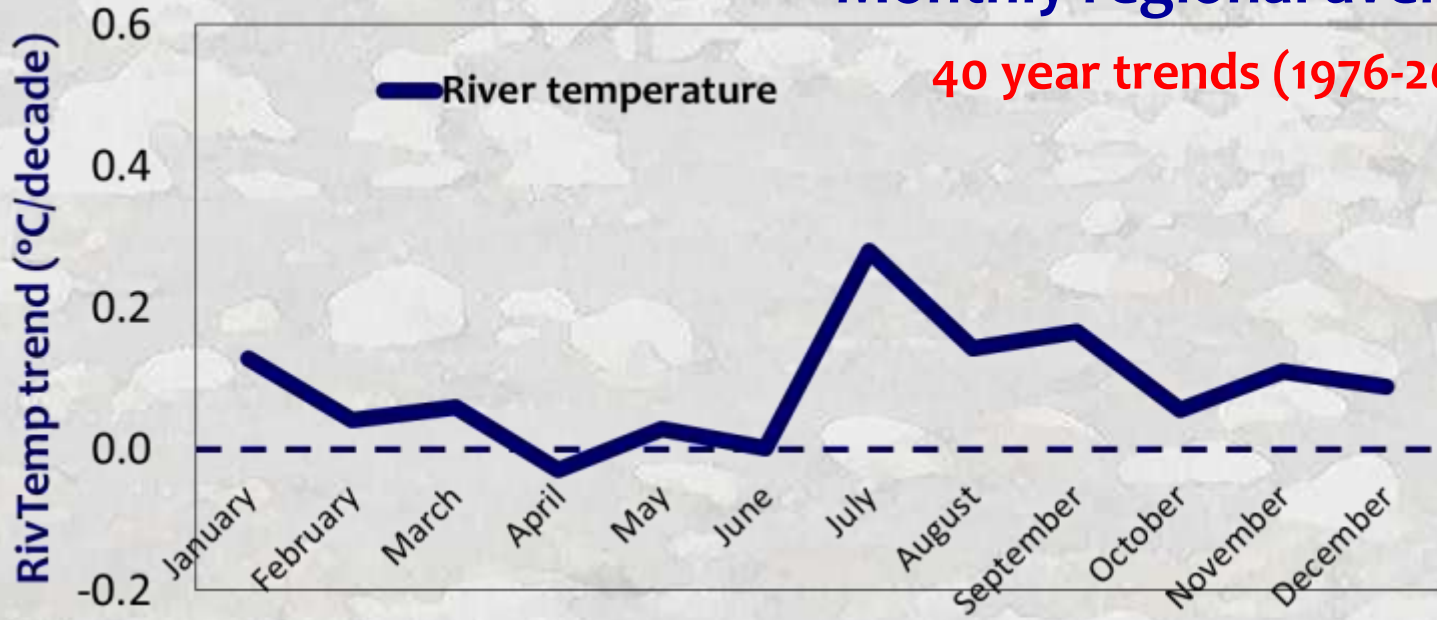
40 Year (1976–2015) Monthly River Temperature Trend - December

0.07 °C / Decade



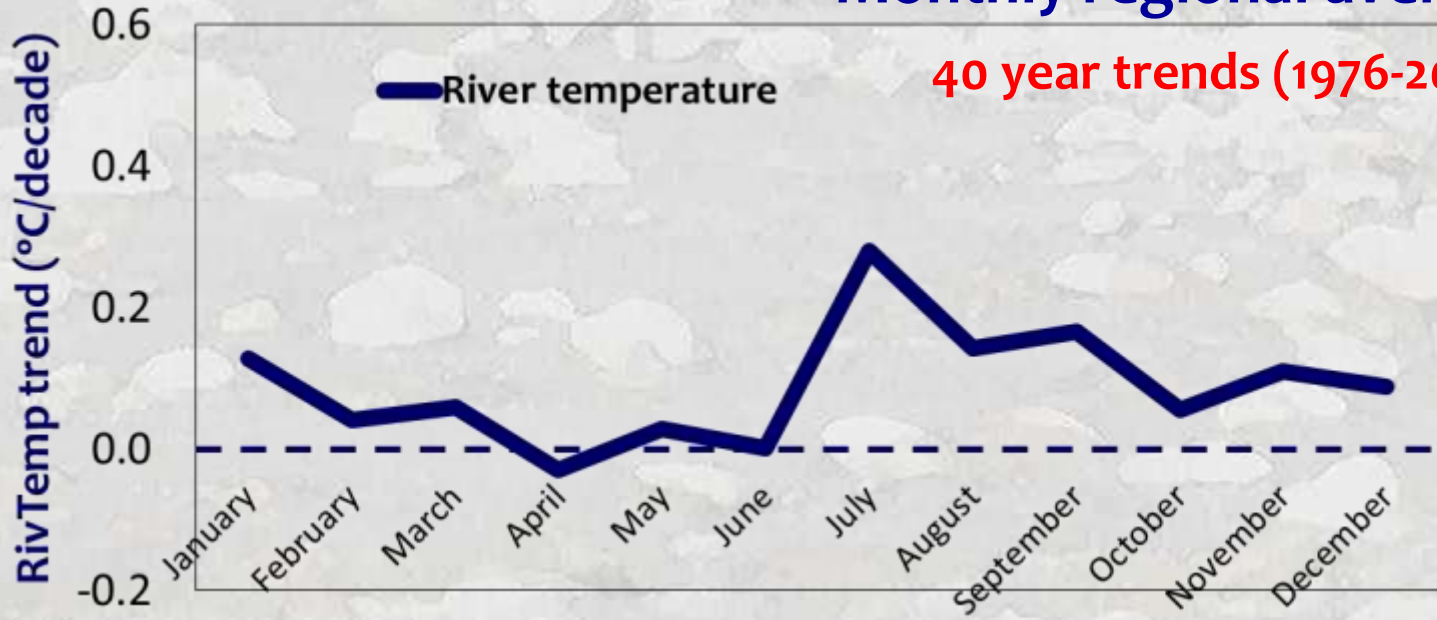
What's Driving River Temperature Trends?

Monthly regional averages

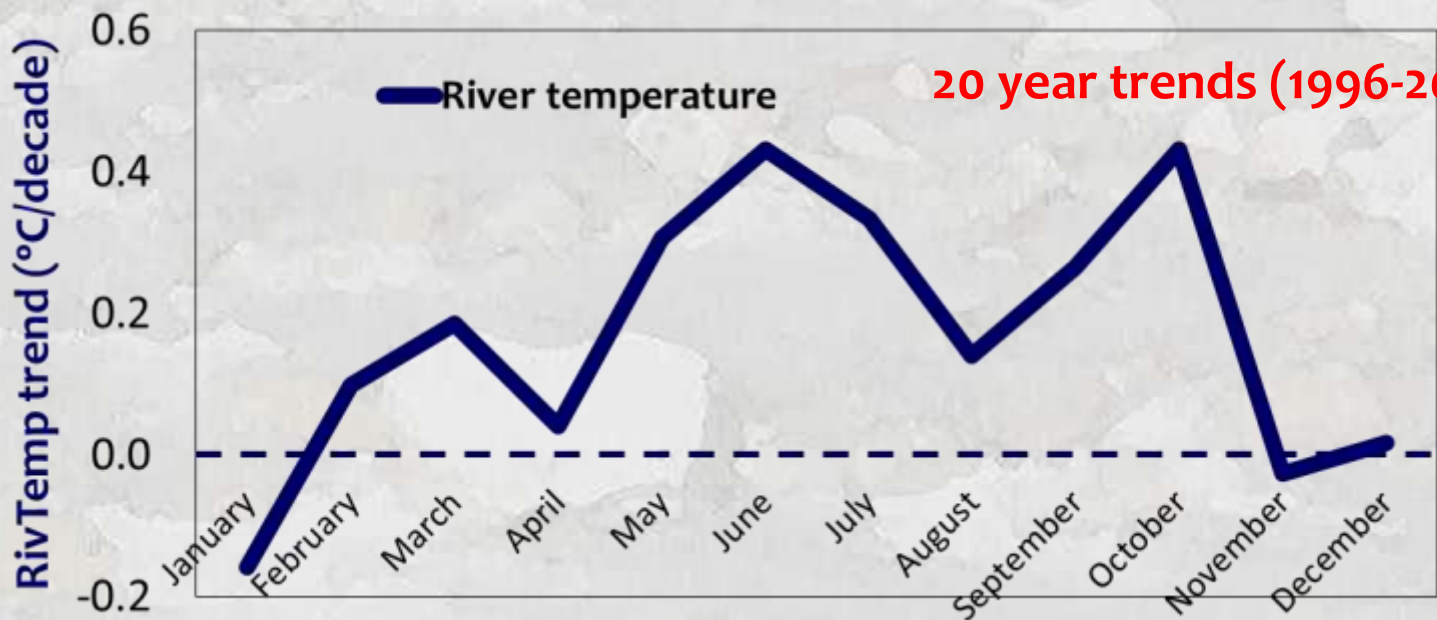


What's Driving River Temperature Trends?

Monthly regional averages



40 year trends (1976-2015)



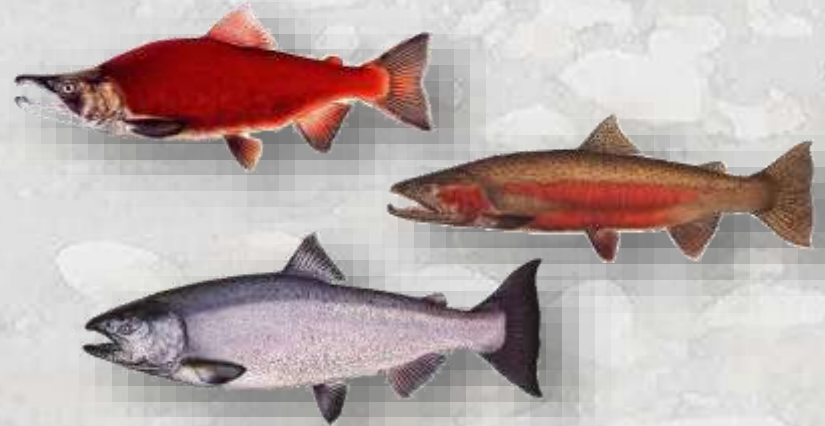
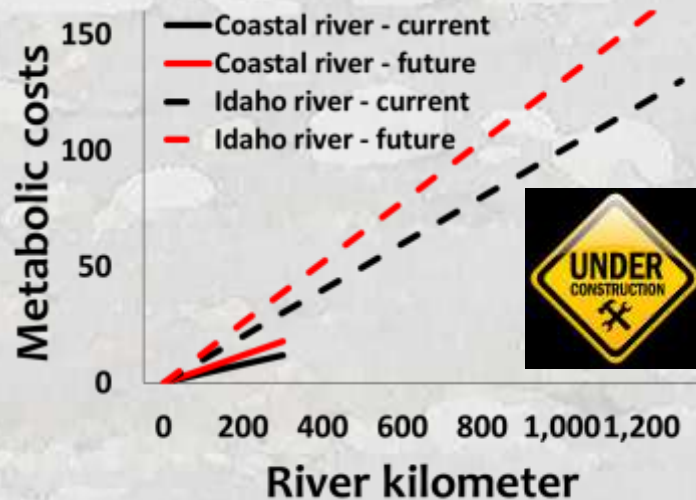
20 year trends (1996-2015)



Biological Consequences for Trout & Salmon?

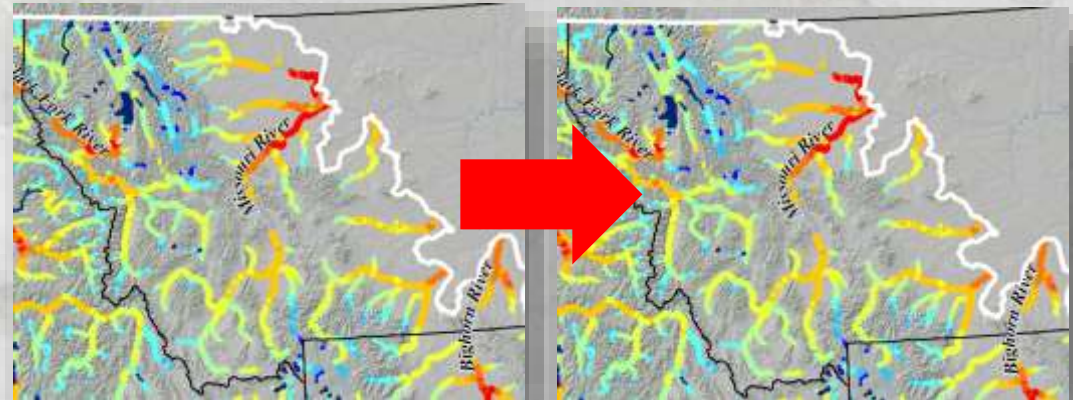
A. Thermal exposure during adult salmon migration

Exp = Distance \times temperature \times time \times species-specific physiological parameter (sockeye, summer Chinook, summer steelhead)



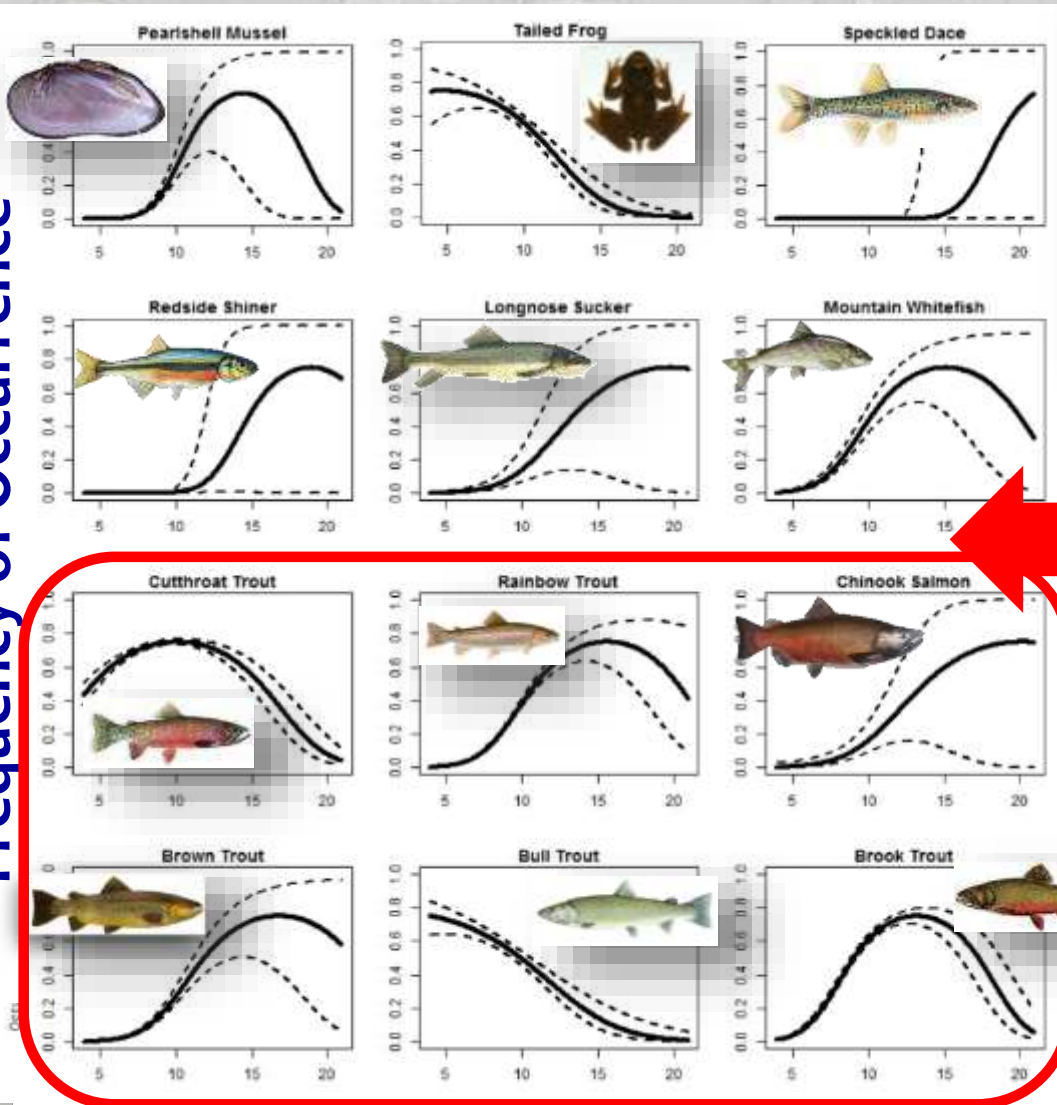
B. Thermal habitat distribution shifts for resident species

Time 1 vs. **Time 2**

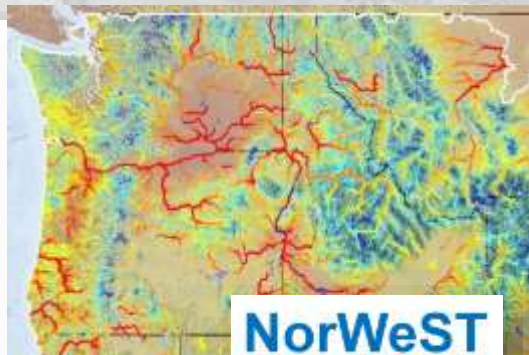


Realized Thermal Niche Descriptions

Frequency of Occurrence



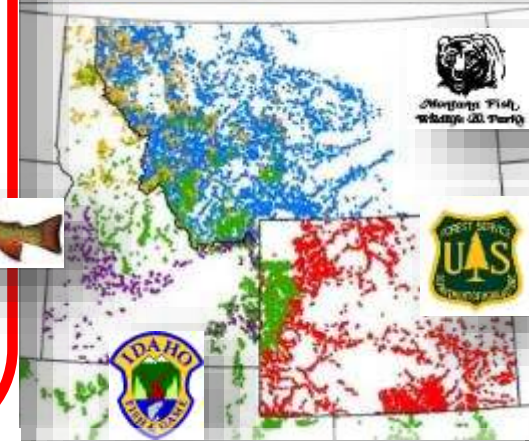
NorWeST Stream Temperature



NorWeST
Stream Temp



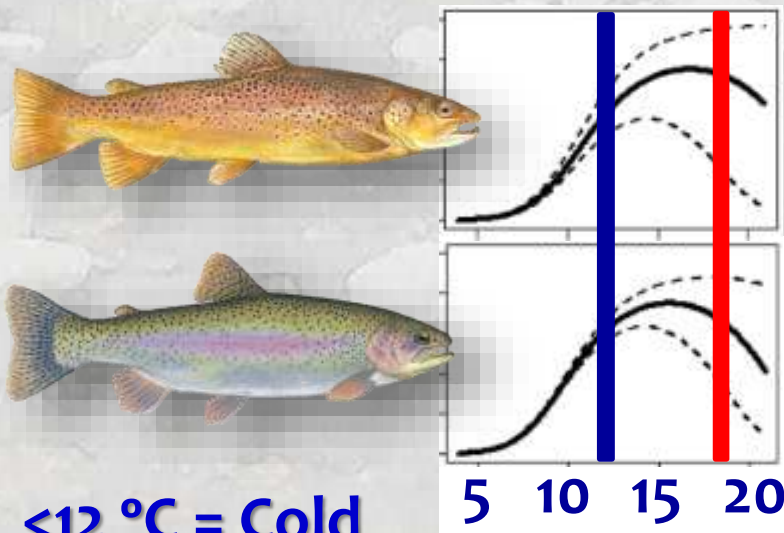
BIG FISH Data



>13,000 surveys

Mapping Thermal Habitat Distributions

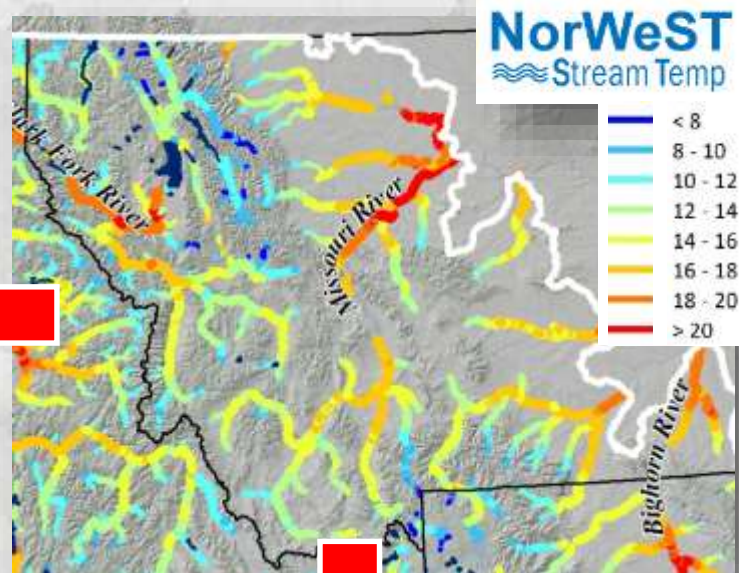
August mean RivTemps



<12 °C = Cold

12-18 °C = Optimal

>18 °C = Warm (~22 °C MWMT)



Thermal Habitat Maps:

Baseline: 1993-2011 (Scenario 1)

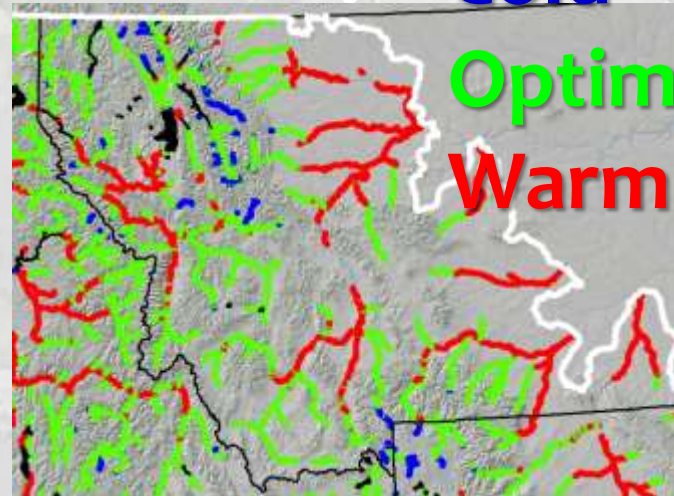
Mid century: +1 °C (Scenario 23)

Late century: +2 °C (Scenario 25)

Cold

Optimal

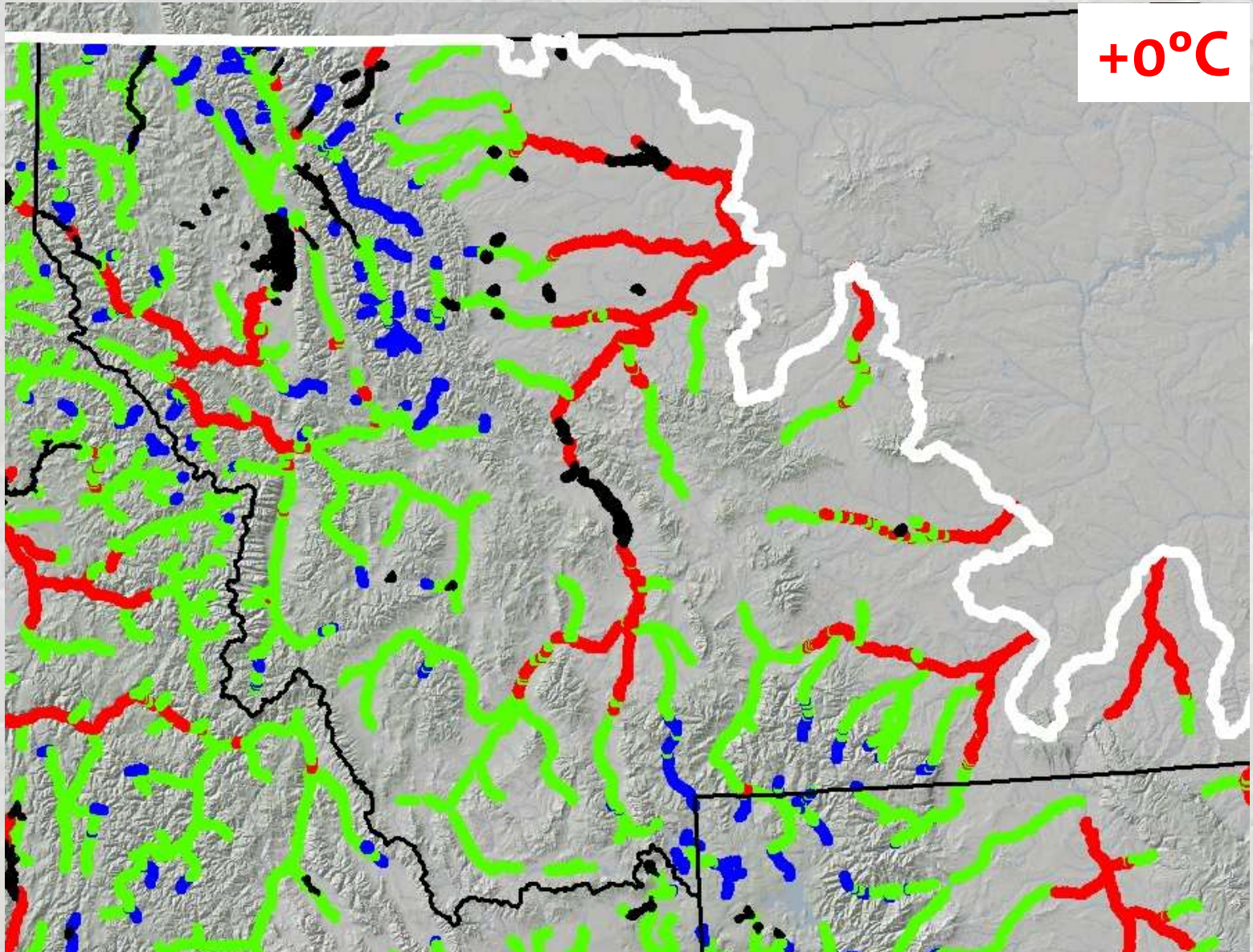
Warm



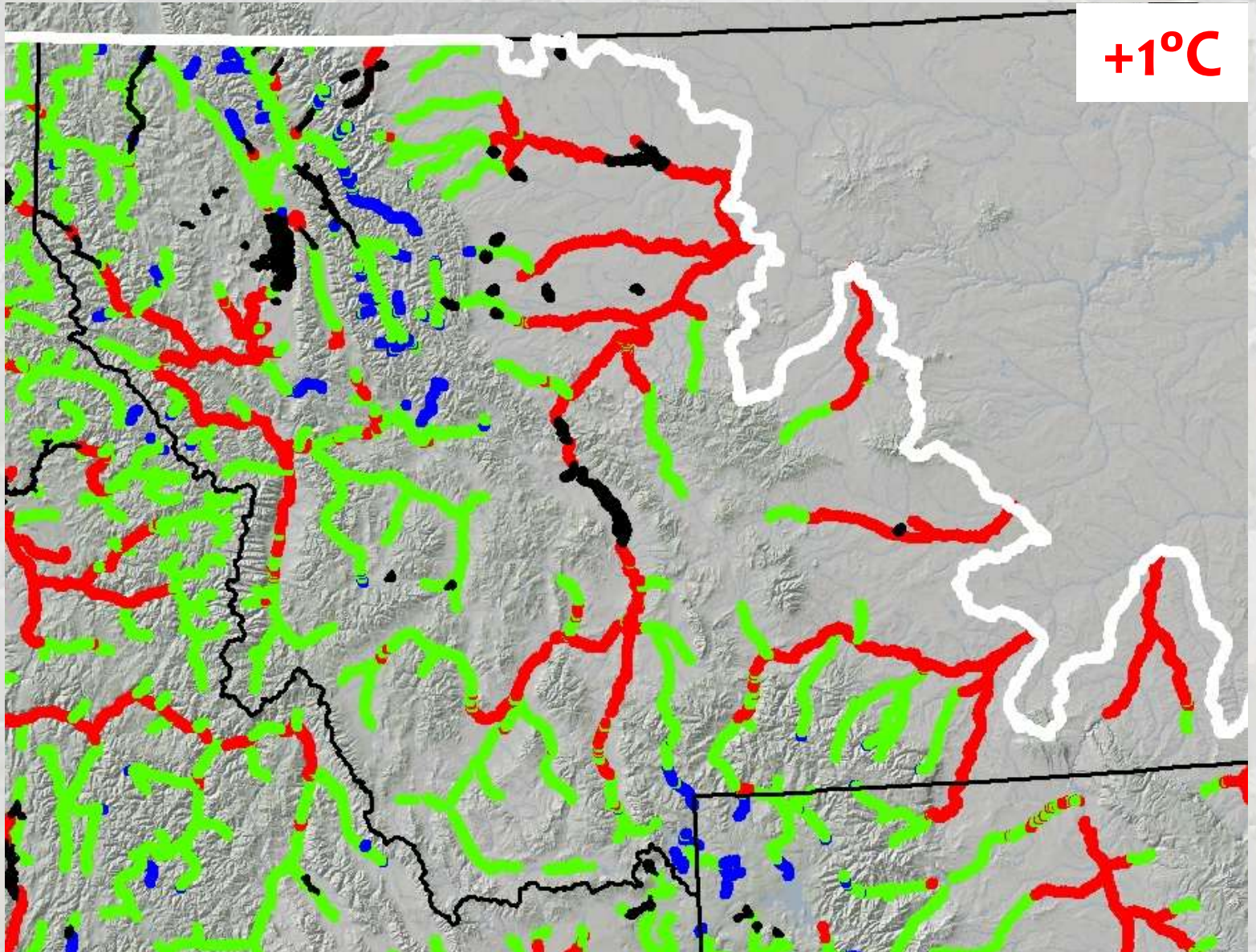
Thermal Habitat Distributions for Brown & Rainbow Trout in Montana Rivers

Baseline

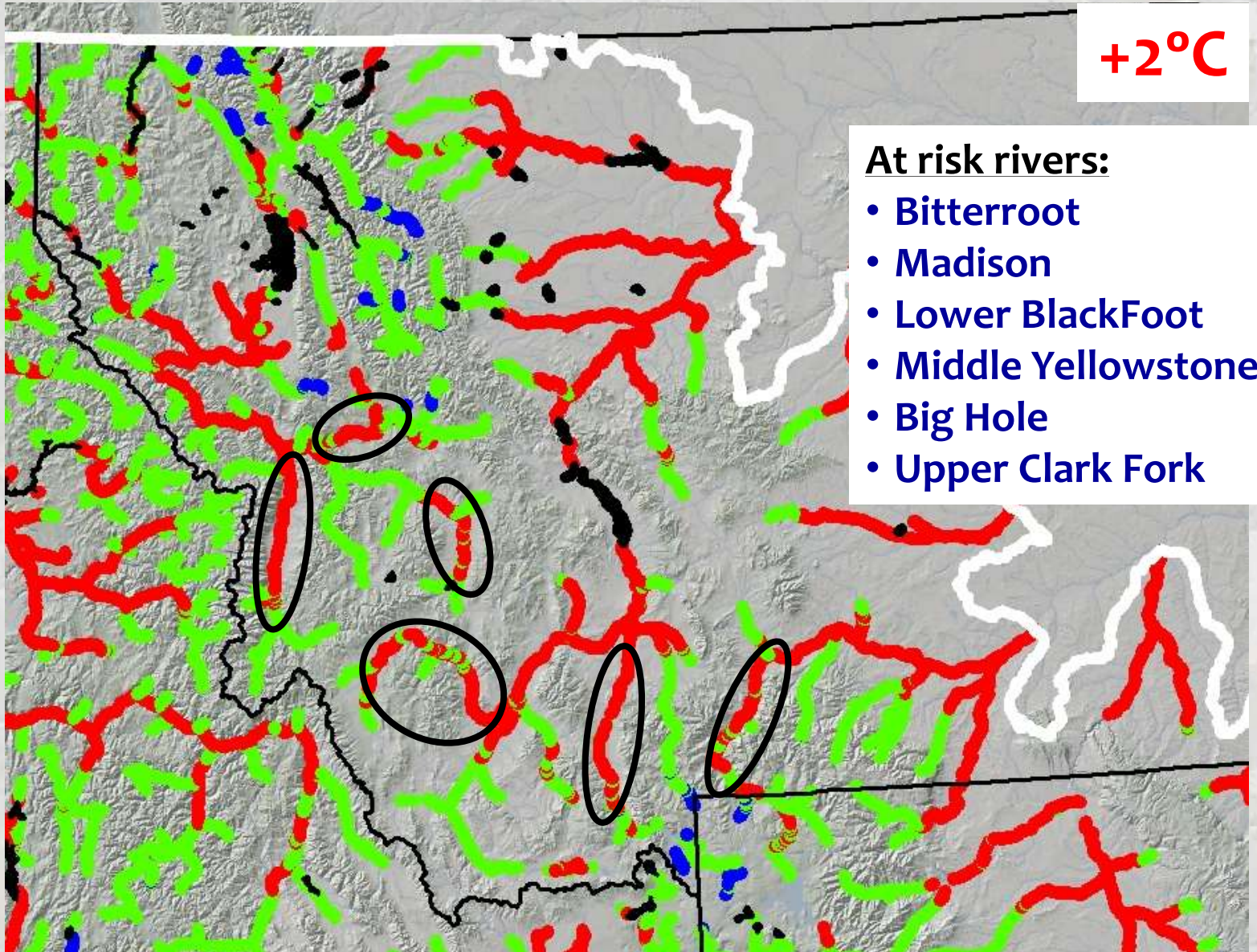
+0°C



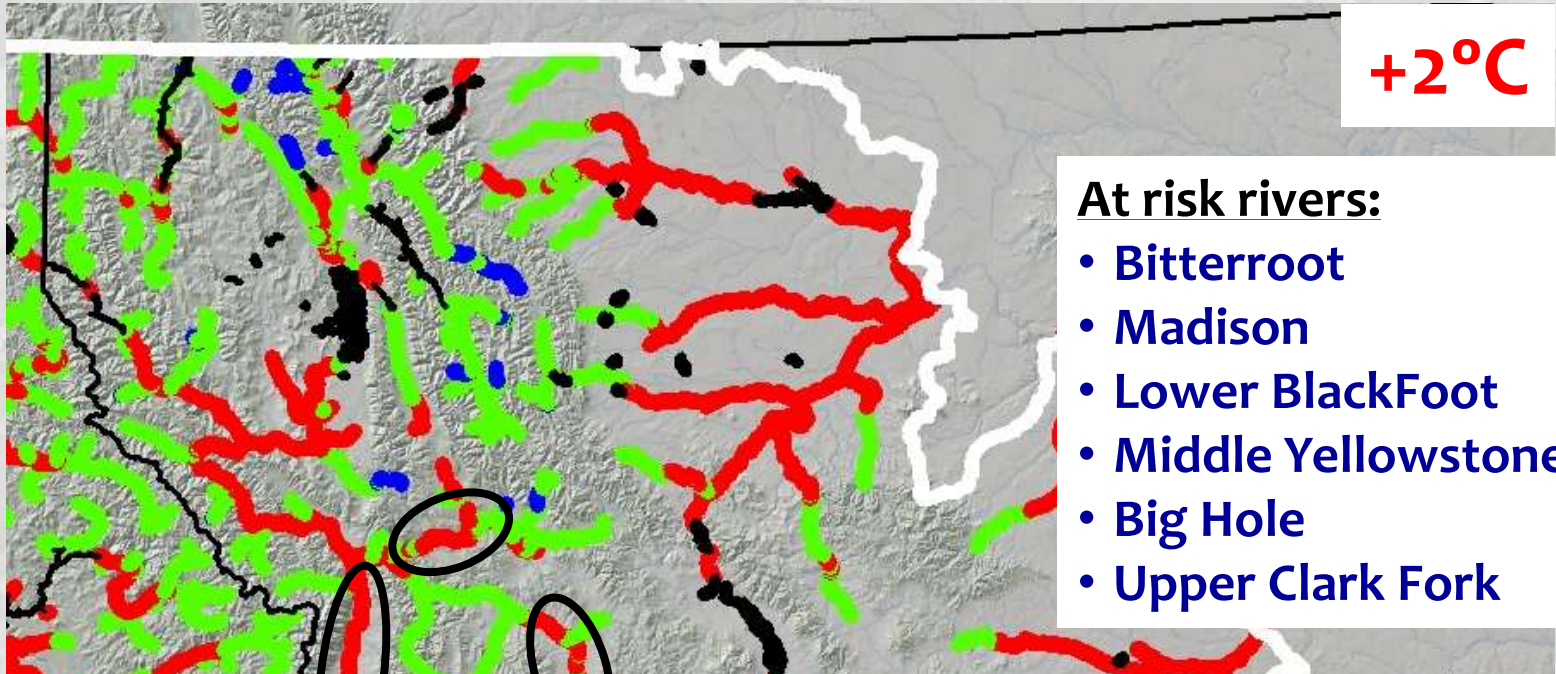
Thermal Habitat Distributions for Brown & Rainbow Trout in Montana Rivers



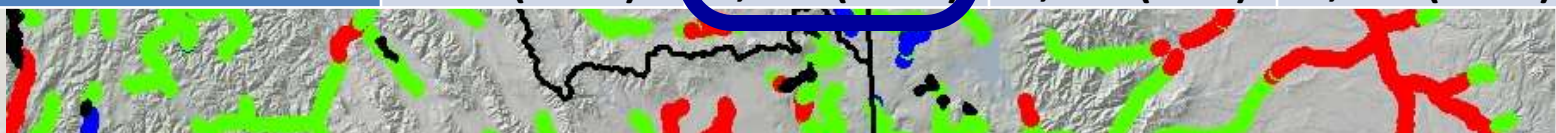
Thermal Habitat Distributions for Brown & Rainbow Trout in Montana Rivers



Thermal Habitat Distributions for Brown & Rainbow Trout in Montana Rivers



<u>River kilometers that are:</u>	< 12°C	12-18°C	18-21°C	TOTAL
Historical scenario	863	5,289	1,723	7,875
Mid century +1°C scenario	472 (-45%)	4,729 (-11%)	2,369 (37%)	7,570 (-4%)
Late century +2°C scenario	194 (-78%)	3,871 (-27%)	2,857 (66%)	6,922 (-12%)

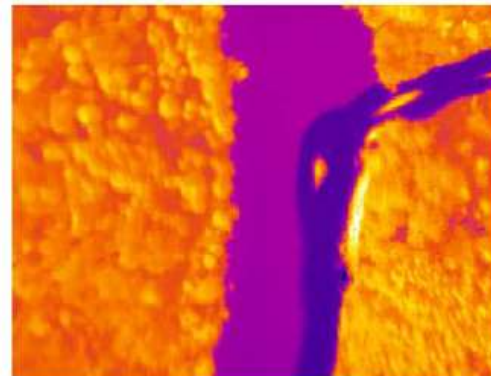


Options for Cooling Smaller Rivers

- 1) Maximize riparian shade
- 2) Maximize summer flows
- 3) Restore channel complexity to force hyporheic exchange



- 4) Identify, protect, & enhance cold microrefugia



Drone mounted cameras

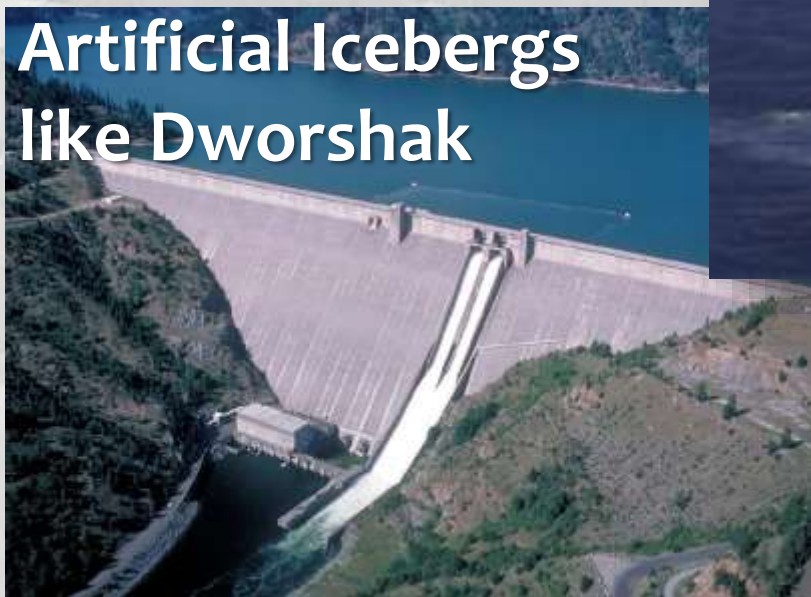
Options for Cooling Largest Rivers are Limited...



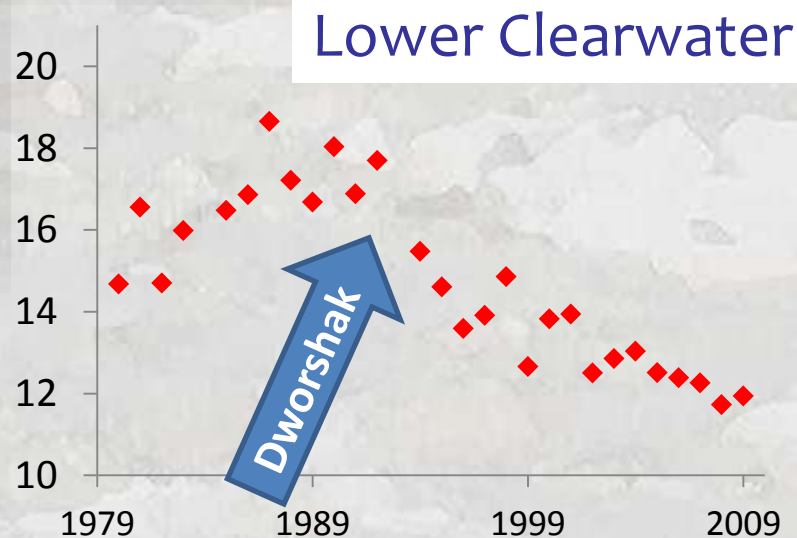
Options for Cooling Largest Rivers are Limited...

Icebergs

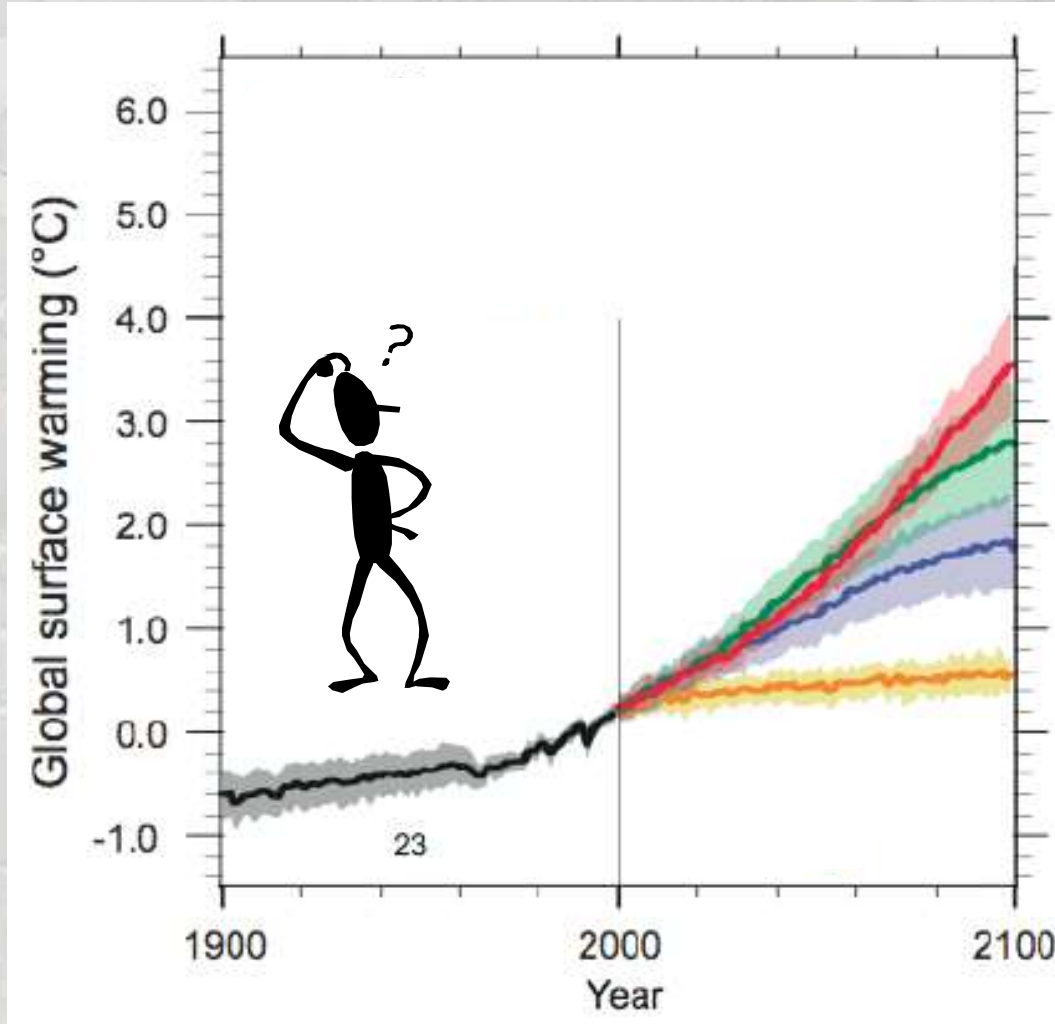
Artificial Icebergs like Dworshak



★ Deep reservoir needed for cold water creation



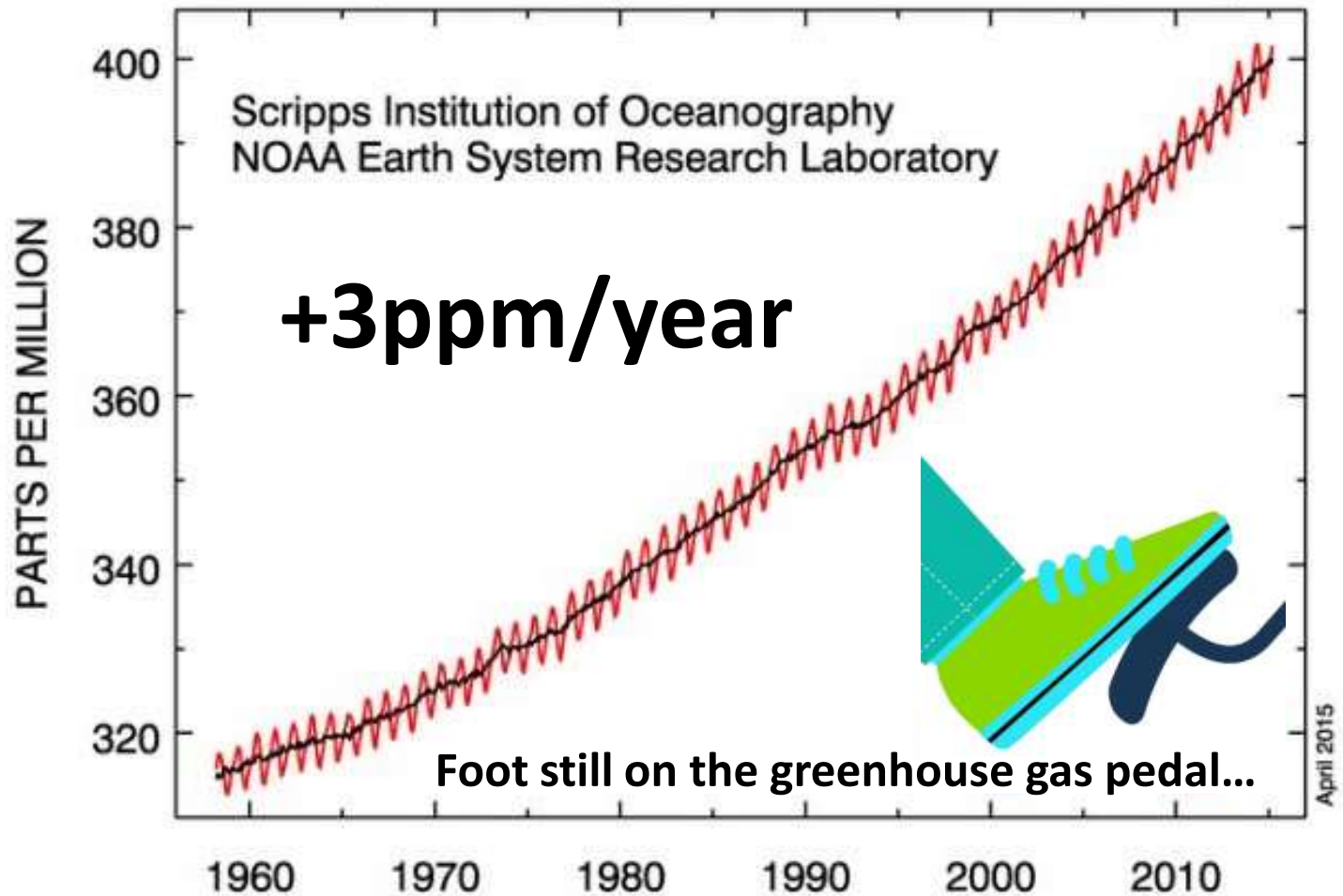
How Much Warmer Will it Get?



The Specifics are an “Unknowable Unknown”

How Much Warmer Will it Get?

Atmospheric CO₂ Concentration



Plan on continued warming for decades...

Human Adaptation in Future Decades

1) Accept that fish communities *in some rivers* will change & communicate that information to public

At risk Montana rivers: Bitterroot, Madison, Lower BlackFoot, Middle Yellowstone, Big Hole, Upper Clark Fork

2) Continue enjoying cold-water fisheries in many rivers this century

Refuge rivers: Rock Creek, Gallatin, NFK/SFK/MFK Flathead, Kootenai...

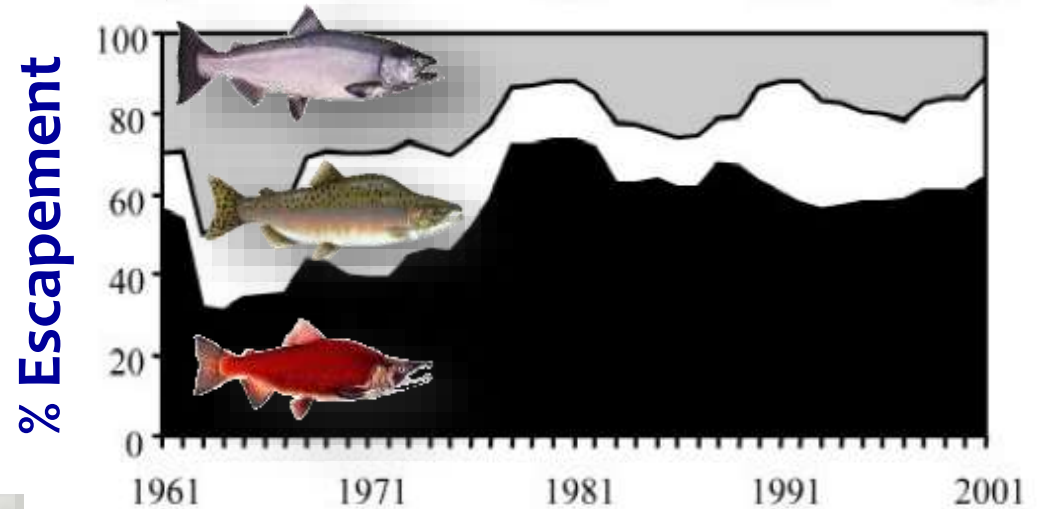
3) Diversify tackle box to include plugs for bass, snakeheads, & TBD critters



It's Bubba-time!

Biocomplexity Will Provide a Buffer

Extinction is unlikely...



... But some species (or runs) may experience long-term declines



Summer runs



Fall/winter runs

