

Projections of *near-term* **hydrological** changes over the U.S. using a **high-resolution** *hierarchical modeling framework*

Moetasim Ashfaq

Mar 29, 2019

Fifth Workshop on Water Resources in Developing Countries:
Hydroclimate Modeling and Analysis, ICTP, Italy



**Climate Change
Science Institute**

AT OAK RIDGE NATIONAL LABORATORY



OAK RIDGE NATIONAL LABORATORY

MANAGED BY UT-BATTELLE FOR THE U.S. DEPARTMENT OF ENERGY

Projecting changes in annual hydropower generation using regional runoff data: An assessment of the United States federal hydropower plants

Shih-Chieh Kao^{a, b, c, d, e}, Michael J. Sale^c, Moetasim Ashfaq^{b, d}, Rocío Uria Martínez^a, Dale P. Kaiser^{a, b}, Yaxing Wei^{a, b}, Noah S. Diffenbaugh^e

JOURNAL OF GEOPHYSICAL RESEARCH

Atmospheres

AN AGU JOURNAL

Climate and Dynamics | [Free Access](#)

Influence of climate model biases and daily-scale temperature and precipitation events on hydrological impacts assessment: A case study of the United States

Moetasim Ashfaq^{a, b}, Laura C. Bowling, Keith Cherkauer, Jeremy S. Pal, Noah S. Diffenbaugh

JGR Atmospheres

Regular Article | [Open Access](#)

Near-term acceleration of hydroclimatic change in the western U.S.

Moetasim Ashfaq^{a, b}, Subimal Ghosh, Shih-Chieh Kao, Laura C. Bowling, Philip Mote, Danielle Touma, Sara A. Rauscher, Noah S. Diffenbaugh

nature
geoscience

ARTICLES

PUBLISHED ONLINE: 12 OCTOBER 2014 | DOI: 10.1038/NNGEO2269

Snowfall less sensitive to warming in Karakoram than in Himalayas due to a unique seasonal cycle

Sarah B. Kapnick^{1,2*}, Thomas L. Delworth², Moetasim Ashfaq³, Sergey Malyshev⁴ and P. C. D. Milly^{2,5}

Journal of Geophysical Research: Atmospheres

RESEARCH ARTICLE

10.1002/2016JD025285

Key Points:

- Surface T in every region will reach a new climate norm well before mid



High-resolution ensemble projections of near-term regional climate over the continental United States

Moetasim Ashfaq^{1,2}, Deeksha Rastogi^{1,2}, Rui Mei^{1,2}, Shih-Chieh Kao^{2,3}, Sudershan Gangrade^{2,3}, Bibi S. Naz^{2,3}, and Danielle Touma⁴

Journal of Hydrology
Volume 540, September 2016, Pages 397–411



Conjunctive management of surface and groundwater resources under projected future climate change scenarios

Amir Mani^{a, b, c}, Frank T.-C. Tsai^{a, b, c, d, e}, Shih-Chieh Kao^{b, c, d, e}, Bibi S. Naz^{b, c, d, e}, Moetasim Ashfaq^{b, d, e}, Deeksha Rastogi^{b, d, e}

LETTER

Extreme hydrological changes in the southwestern US drive reductions in water supply to Southern California by mid century

Brianna R Pagán^{1,2}, Moetasim Ashfaq^{3,4}, Deeksha Rastogi^{3,4}, Bibi S Naz^{3,5}, Rui Mei^{3,4} and Jeremy S Pal¹

Hydrol. Earth Syst. Sci., 18, 67–84, 2014
www.hydrol-earth-syst-sci.net/18/67/2014/
doi:10.5194/hess-18-67-2014
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A large-scale, high-resolution hydrological model parameter data set for climate change impact assessment for the conterminous US

A. A. Oubeidillah¹, S.-C. Kao¹, M. Ashfaq¹, B. S. Naz¹, and G. Tootle²



Global and Planetary Change
Volume 143, August 2016, Pages 100–117

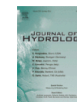


Regional hydrologic response to climate change in the conterminous United States using high-resolution hydroclimate simulations

Bibi S. Naz^{a, b}, Shih-Chieh Kao^{a, b, c, d, e}, Moetasim Ashfaq^{a, c}, Deeksha Rastogi^{a, c}, Rui Mei^{a, c}, Laura C. Bowling^d



Journal of Hydrology
Volume 556, January 2018, Pages 359–370

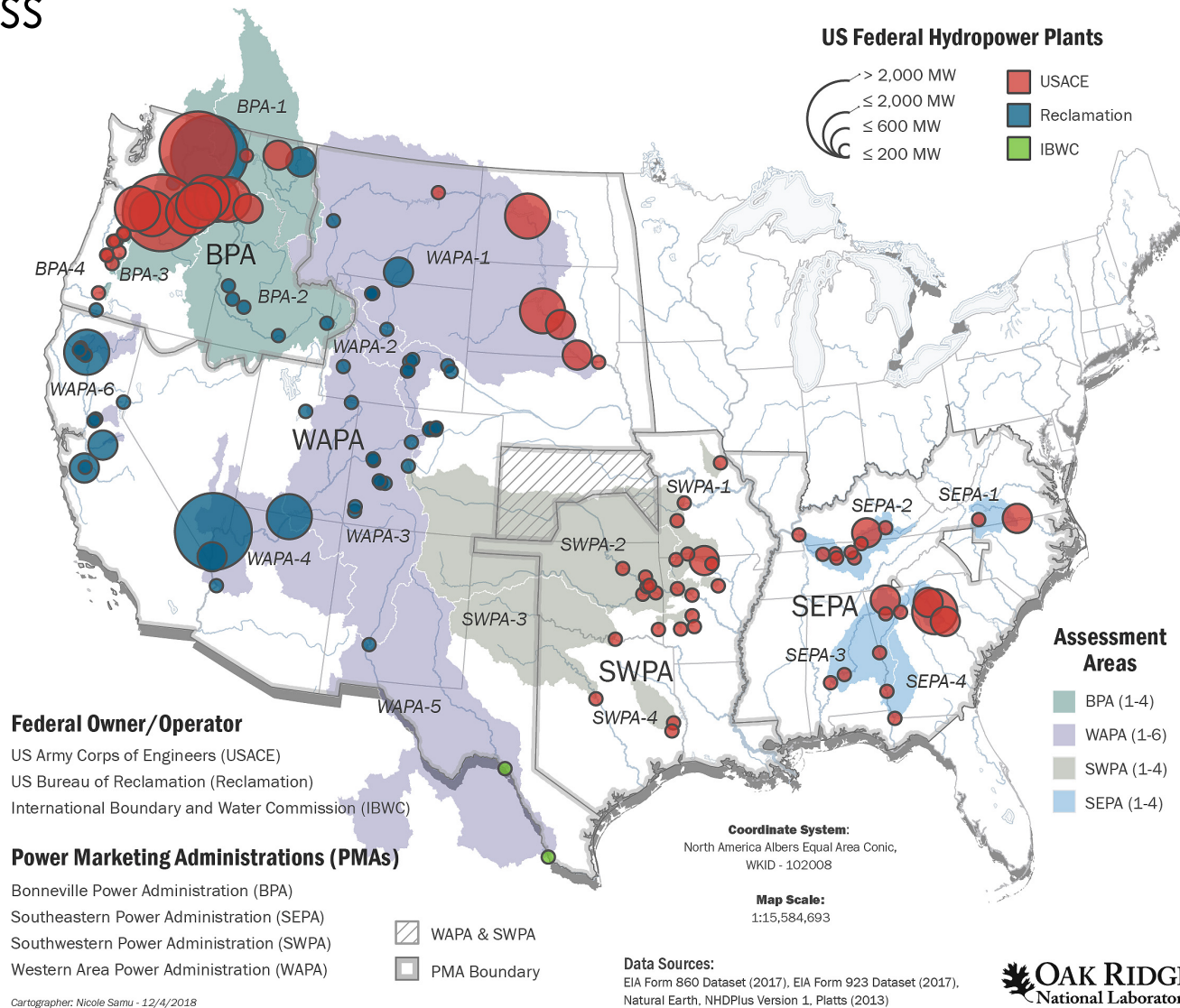


Research papers

Effects of climate change on streamflow extremes and implications for reservoir inflow in the United States

Bibi S. Naz^{a, b, c, d, e}, Shih-Chieh Kao^{a, b}, Moetasim Ashfaq^{a, c}, Huilin Gao^d, Deeksha Rastogi^{a, c, e}, Sudershan Gangrade^{a, b, e}

Future Assessment of Federal Hydropower for the U.S. Congress



Future Assessment of Federal Hydropower for the U.S. Congress



ORNL/TM-2011/251

Assessment of the Effects of Climate Change on Federal Hydropower

An Assessment Prepared in Response to Section 9505(c) of the SECURE Water Act of 2009

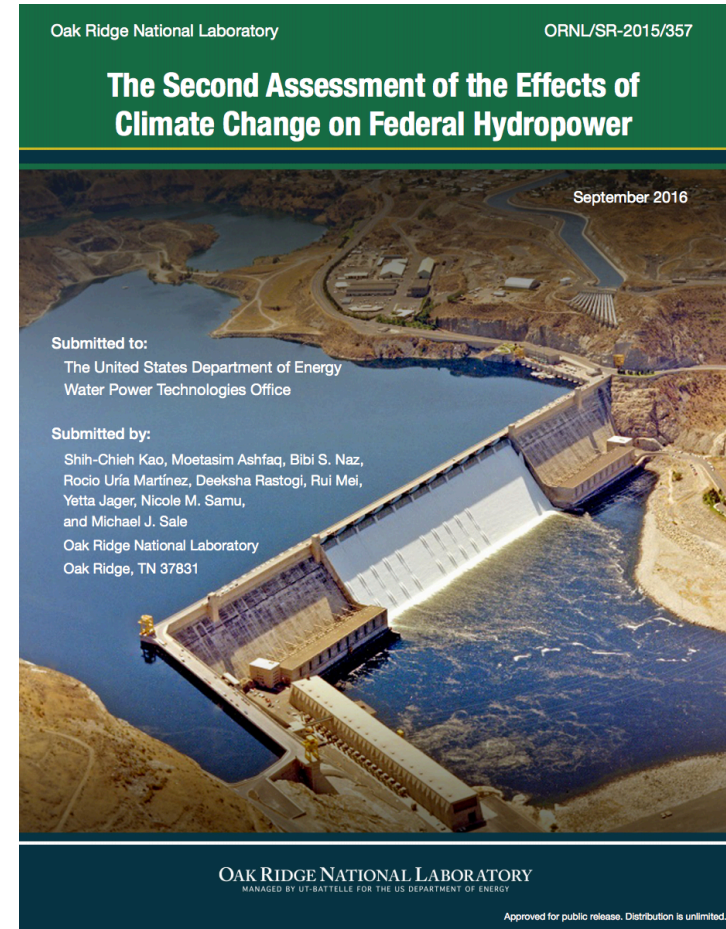


Prepared by

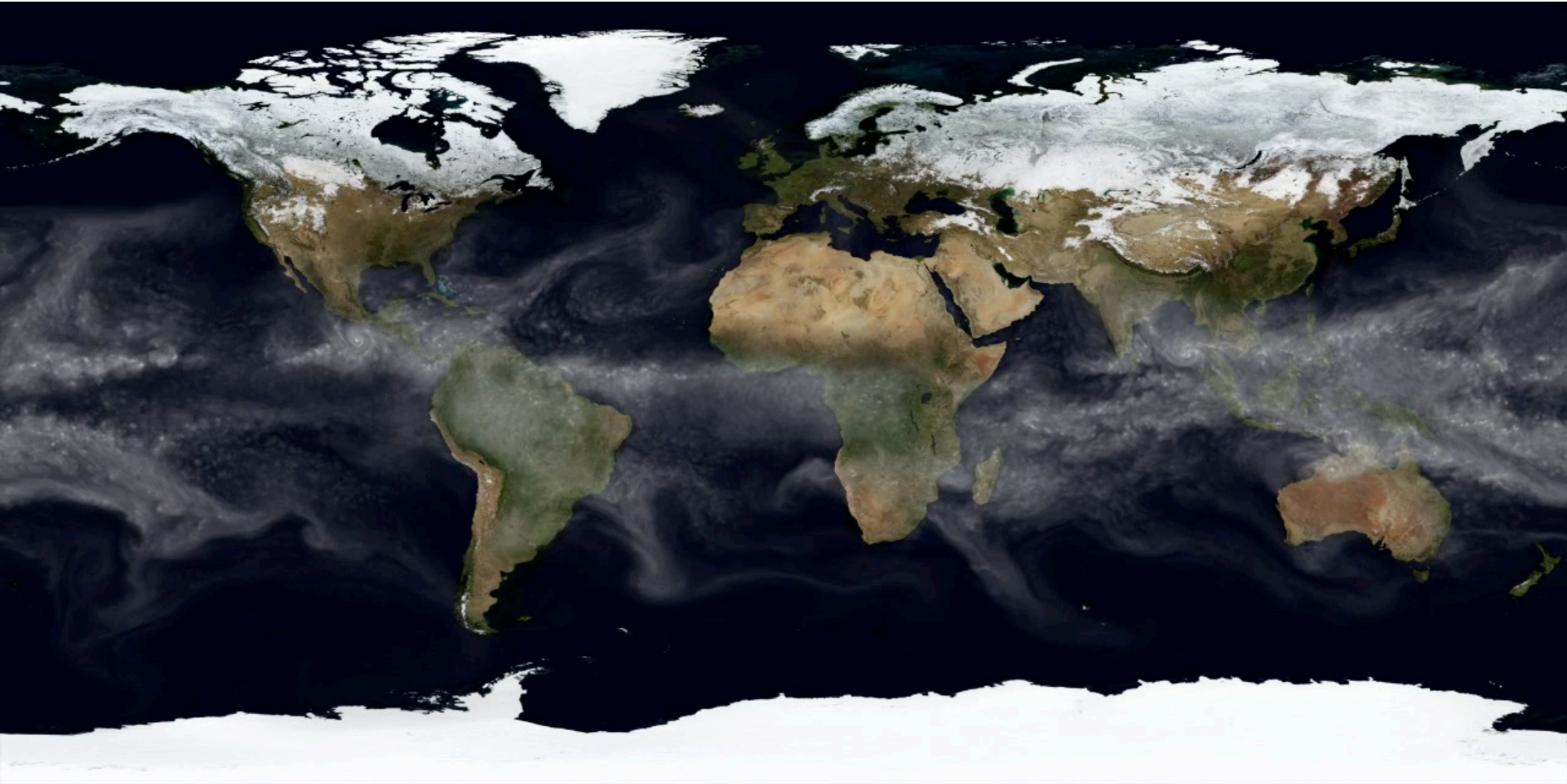
Lead Authors: Michael J. Sale and Shih-Chieh Kao

Contributing Authors: Moetasim Ashfaq, Dale P. Kaiser, Rocio Martinez, Cindy Webb, and Yaxing Wei

Final Report: October 2012

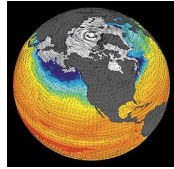


Ideal World: An ensemble of “perfect” global-scale **all-inclusive cloud resolving earth system models** for climate change impact assessments

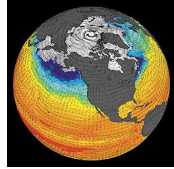


This animation will not run in the pdf version of presentation

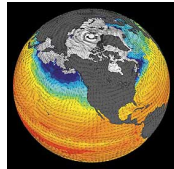
Global Climate Model (GCM)



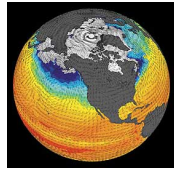
GCM



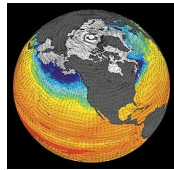
GCM



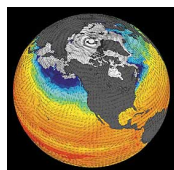
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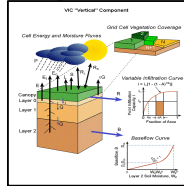
GCM



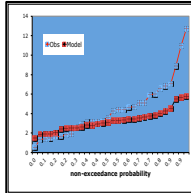
GCM



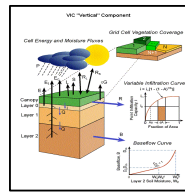
Hydrological Model (HM)



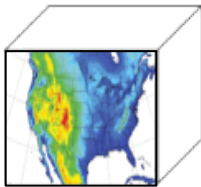
Bias Correction (BC)



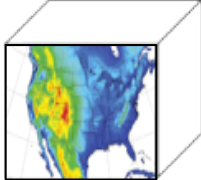
HM



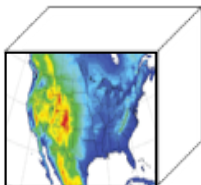
Regional Climate Model (RCM)



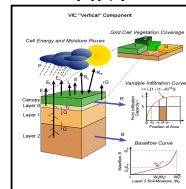
RCM



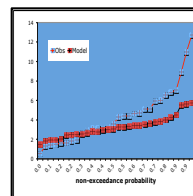
RCM



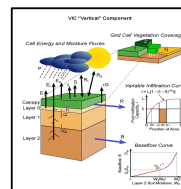
HM



BC



HM



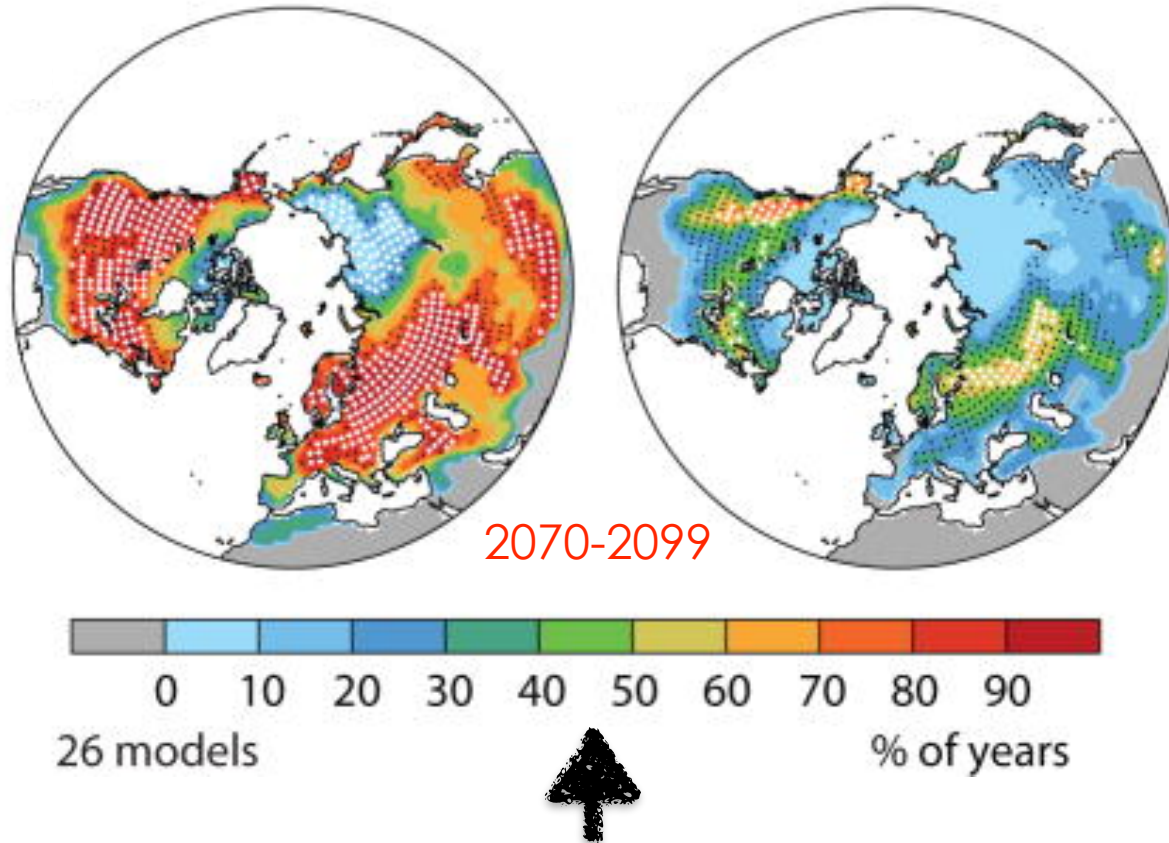
Real World

Hydrological
Impact
Assessment

Direct use of GCMs output is **useful** for understanding **global-scale responses**

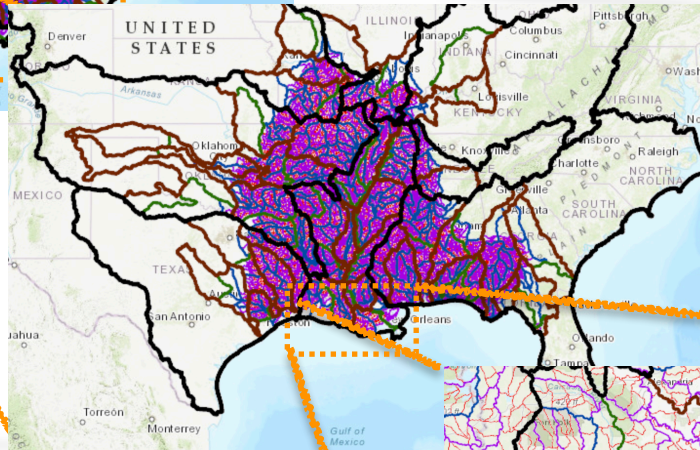
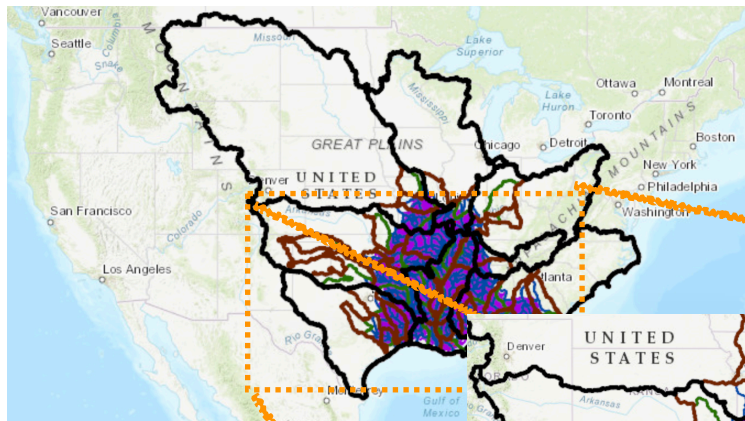
Below 1976-2005 Median

Below 1976-2005 Minimum



Emergence of Low and Extreme Low Snow years

However, for **impact assessments**, scales of interest are mostly **regional / sub-regional**



▼ HUC 2 (intersecting GCPO)

■ HUC 2

▼ HUC 4 (intersecting GCPO)

■ HUC 4

▼ HUC 6 (intersecting GCPO)

■ HUC 6

▼ HUC 8 (intersecting GCPO)

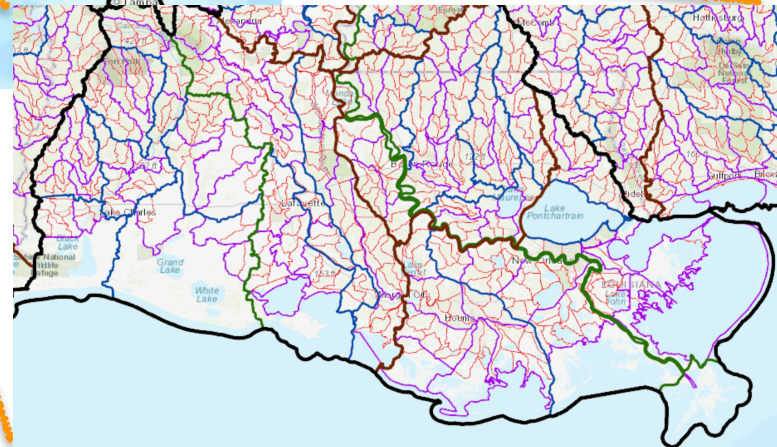
■ HUC 8

▼ HUC 10 (intersecting GCPO)

■ HUC 10

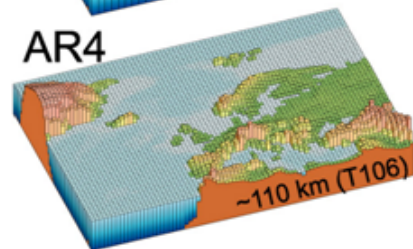
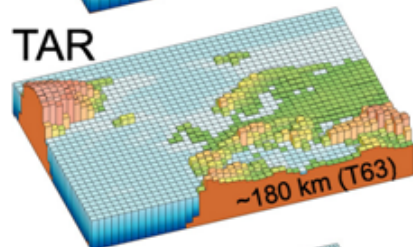
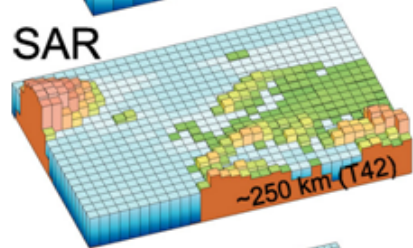
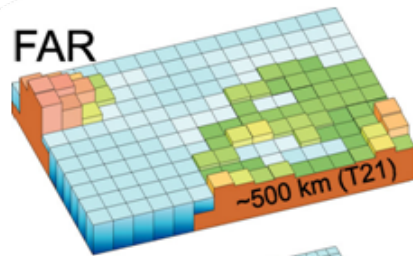
▼ HUC 12 (intersecting GCPO)

■ HUC 12

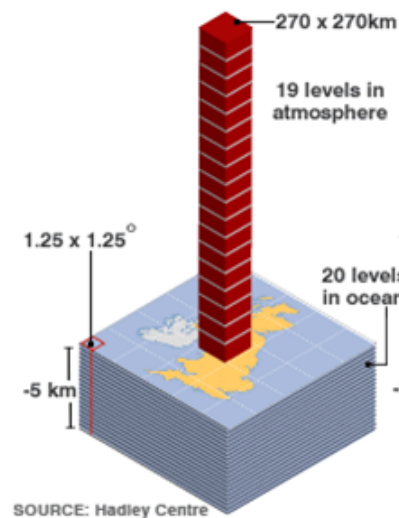


Conterminous U.S.: HUC 2 = 18, HUC 8 ~2200, HUC 12 ~90,000

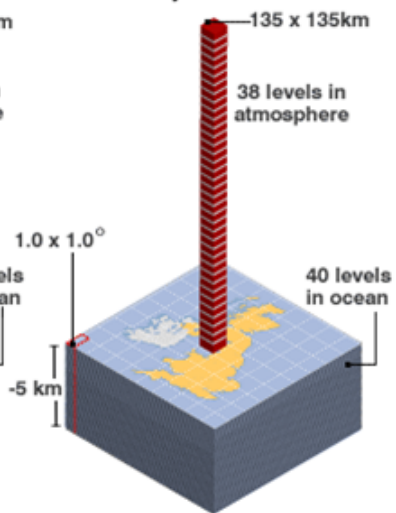
..and **GCMs** are still **too coarse** for such scales



PROGRESSION OF CLIMATE MODELS
1990s



Present day



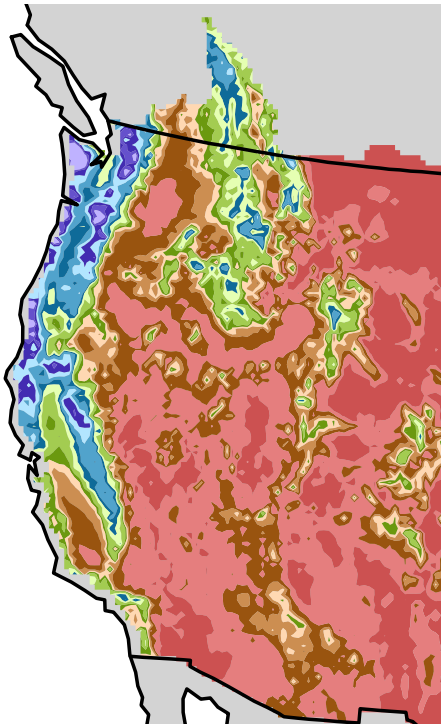
SOURCE: Hadley Centre

AR5: ~70km maximum horizontal resolution; up to 90 layers in the atmosphere and over 60 in the ocean.

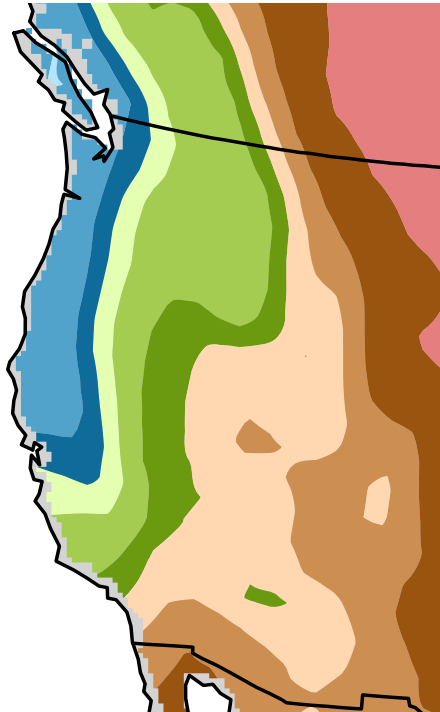
Source: IPCC

For instance, GCMs struggle with accurate **precipitation distribution** over **complex topography**

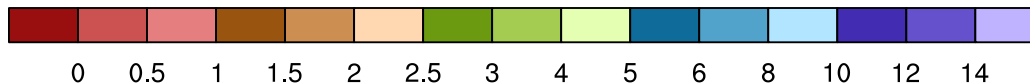
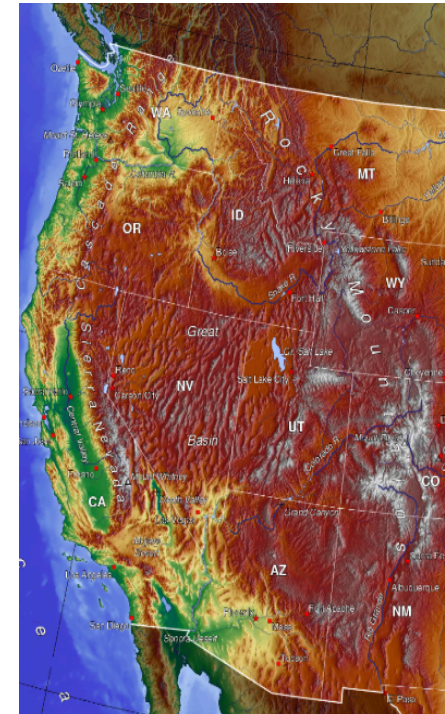
Observations



Global Climate Model



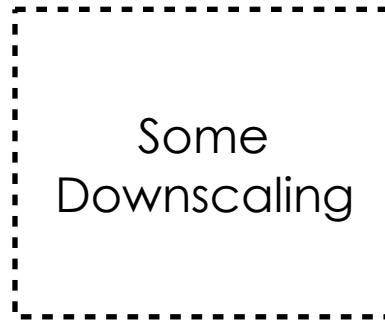
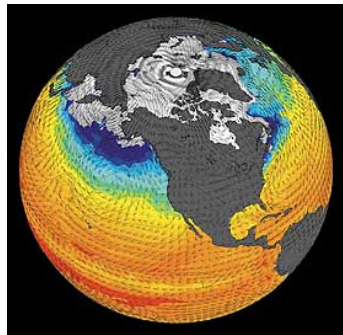
Topography



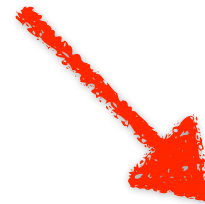
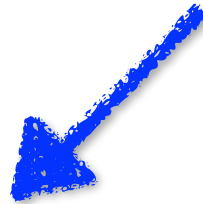
mm/day

Therefore, **GCMs** are “**downscaled**” over the regions of interest

Global Climate Model



Statistical
Downscaling



Dynamical
Downscaling

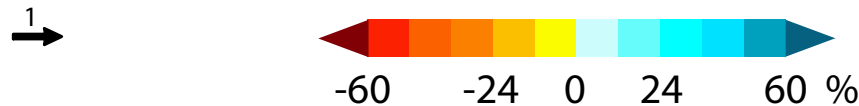
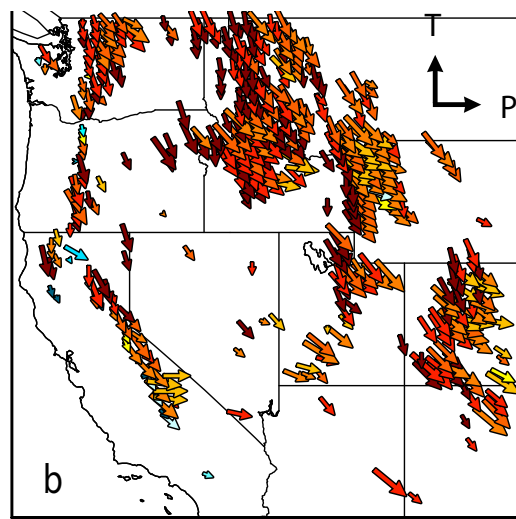
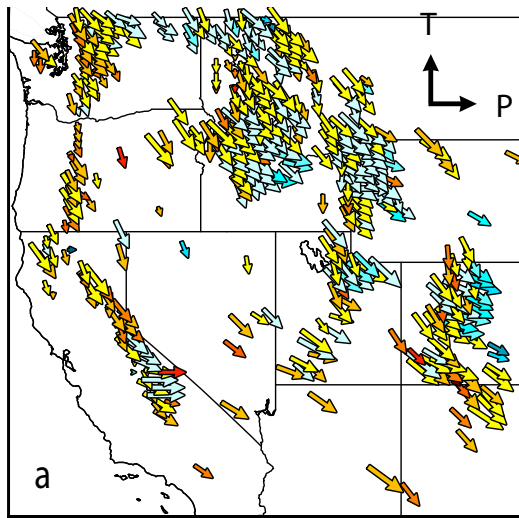
Intermediate Complexity Dynamical
Downscaling

Statistical Downscaling **cannot** account for **non-stationarity**

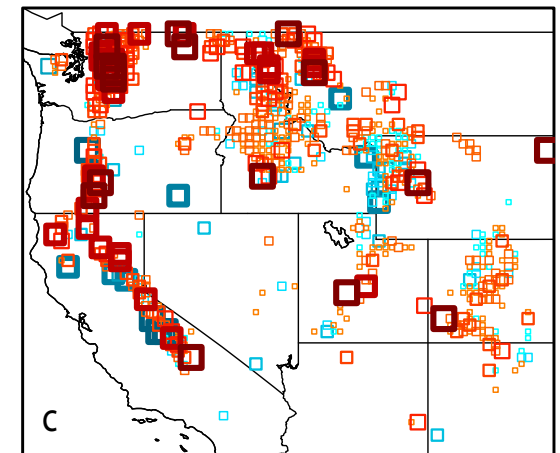
Trends in April 1st SWE (Color)
Partial Correlation of **P** and **T** with **April 1st SWE**

Historical

Future



Future Changes in
relationship between
April 1st SWE and **P, T**



30< 18< 6< 0< 12< 24<
24< 12< 0< 6< 18< 30<
degrees

Partial correlation of **SWE** with **T** and **P** changes over time...a predictor - predictant based downscaling would fail to account for such a change

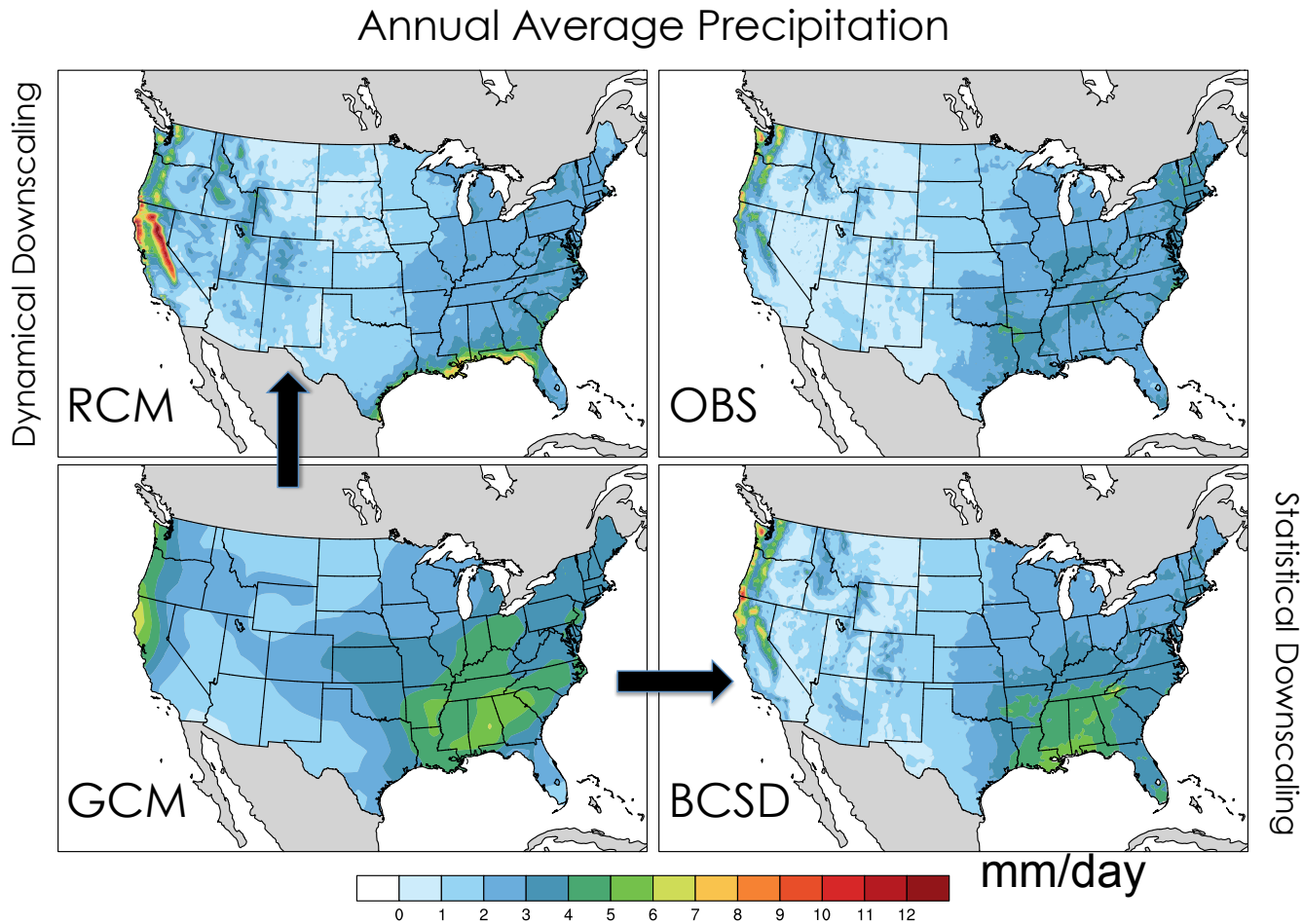
Today, use of **predictor - predictant based*** **statistical downscaling** is quite **uncommon** in future hydrological change applications

Statistical bias correction and spatial disaggregation techniques are **commonly termed*** as statistical downscaling these days

*21st century **machine learning** is based on similar concepts

*which is perhaps incorrect terminology, in my opinion

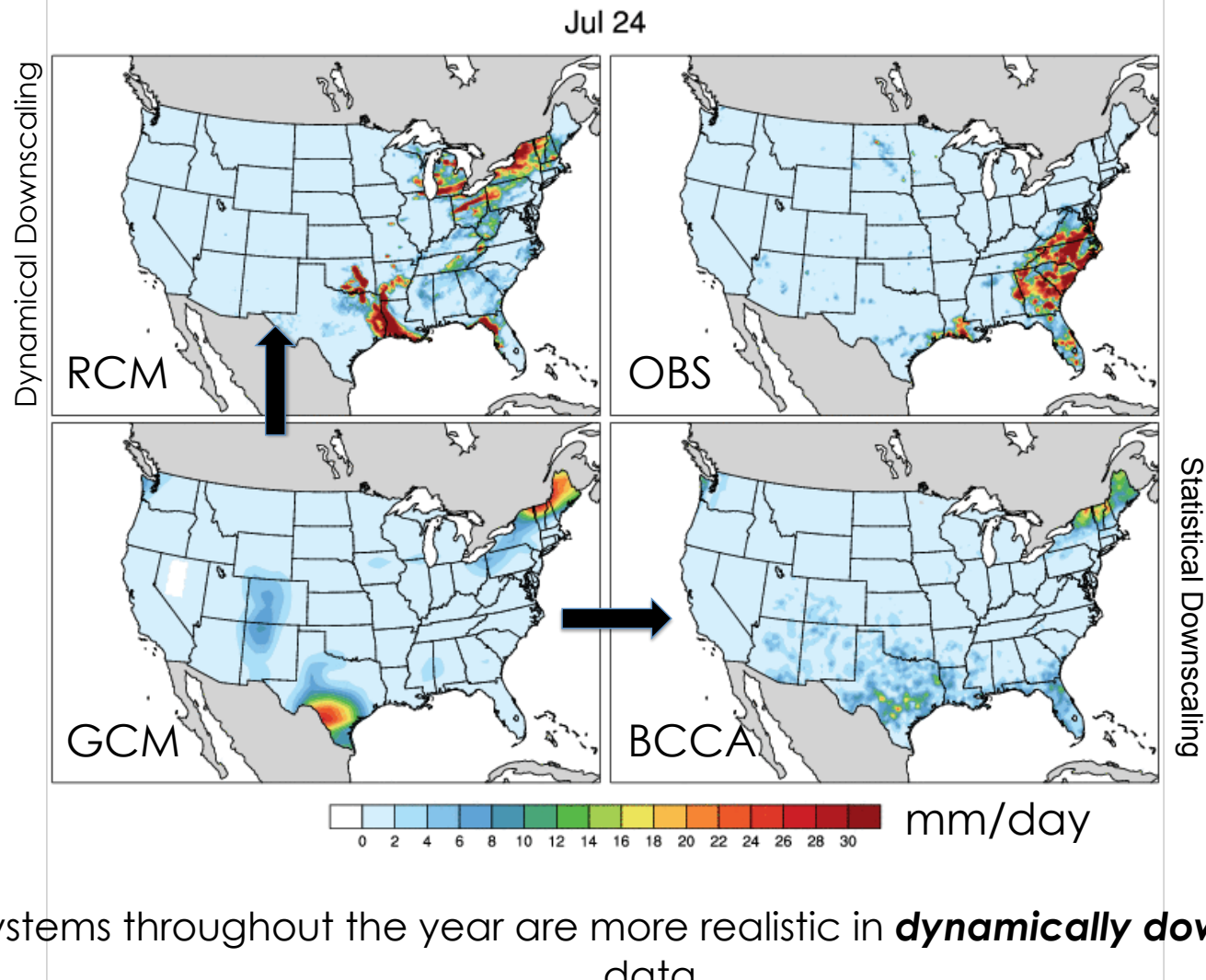
Downscaling **adds spatial details**, regardless of methodology



Comparison of precipitation from **ACCESS1-0 (CMIP5 GCM)** for a random year (**2000***) with same year from *dynamically downscaled RCM* and *statistically downscaled BCSD* data and observations (**OBS**)

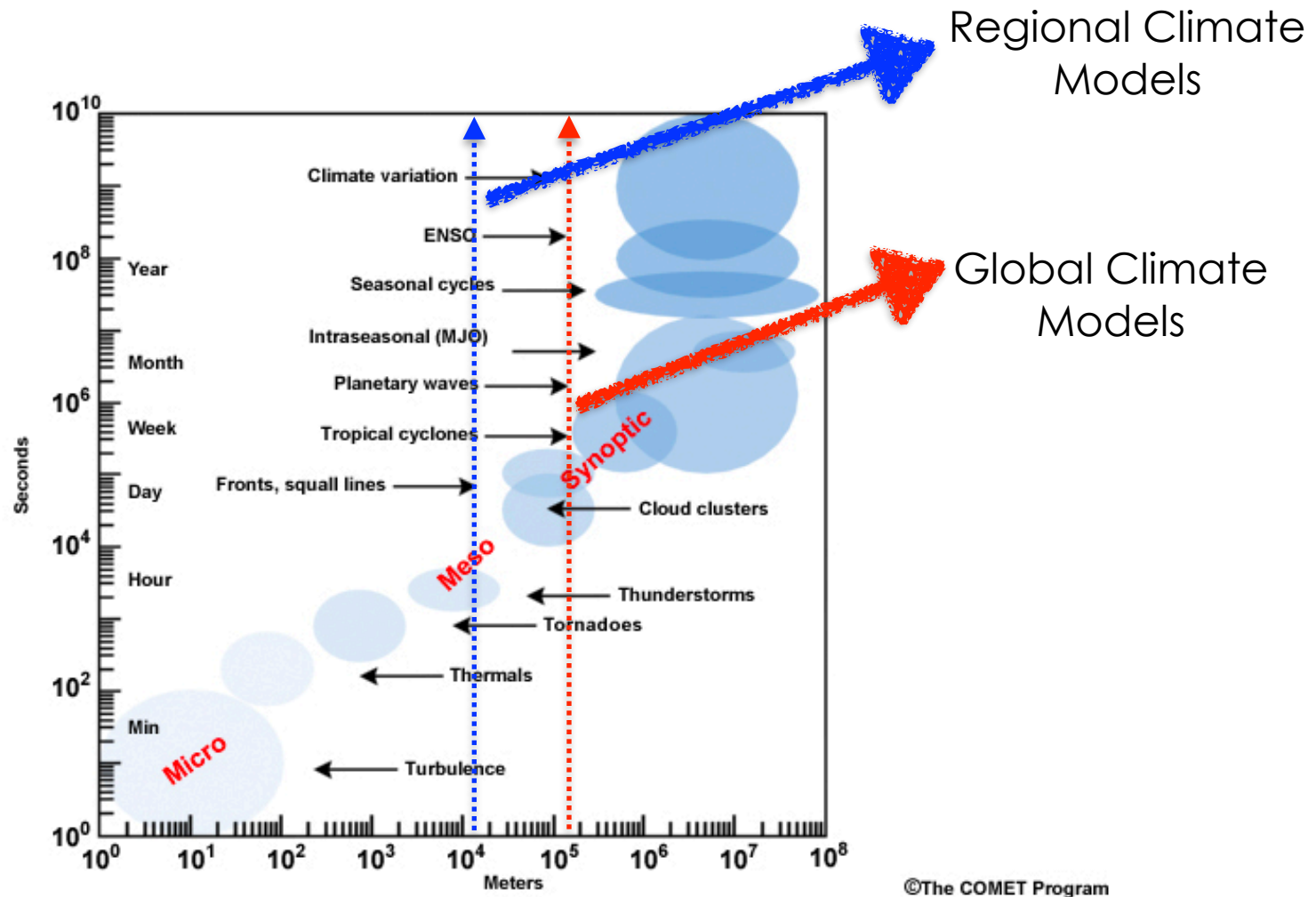
* model years do not represent actual years, comparison is just meant for understanding a typical annual precipitation distribution

But **only dynamical downscaling** is capable of **adding/correcting** the representation of **unresolved fine-scale processes**



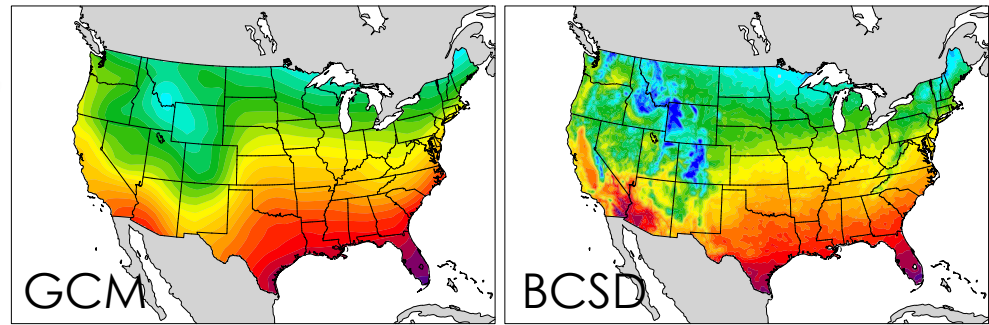
Weather systems throughout the year are more realistic in **dynamically downscaled (RCM)** data

Higher grid spacing means **capability** to represent **fine-scale processes**



Temperature

1950-2005

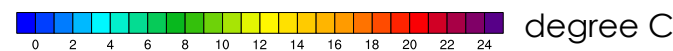
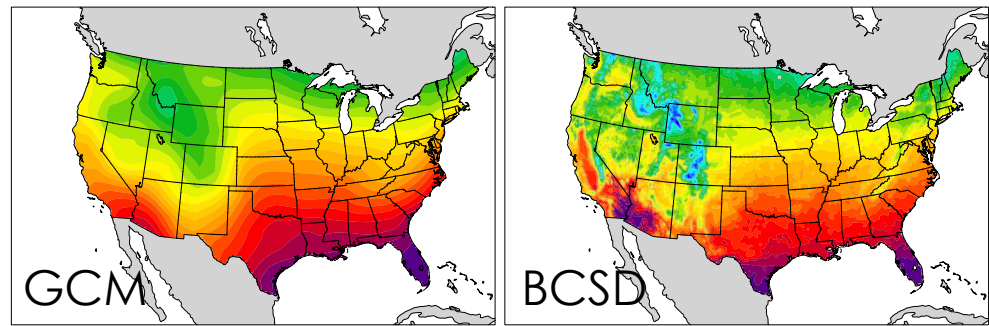


1.5 degree
grid spacing



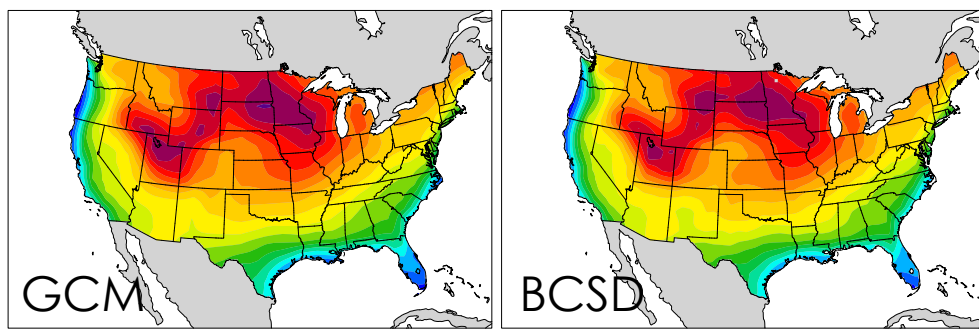
0.125 degree
grid spacing

2006-2056



2006-2056 minus 1950-2005

1.5 degree

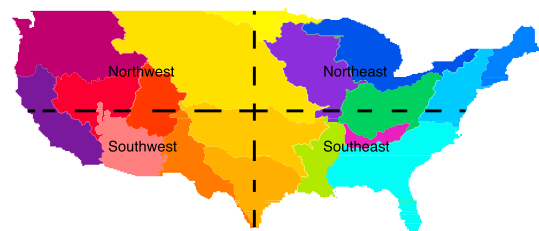


0.125 degree

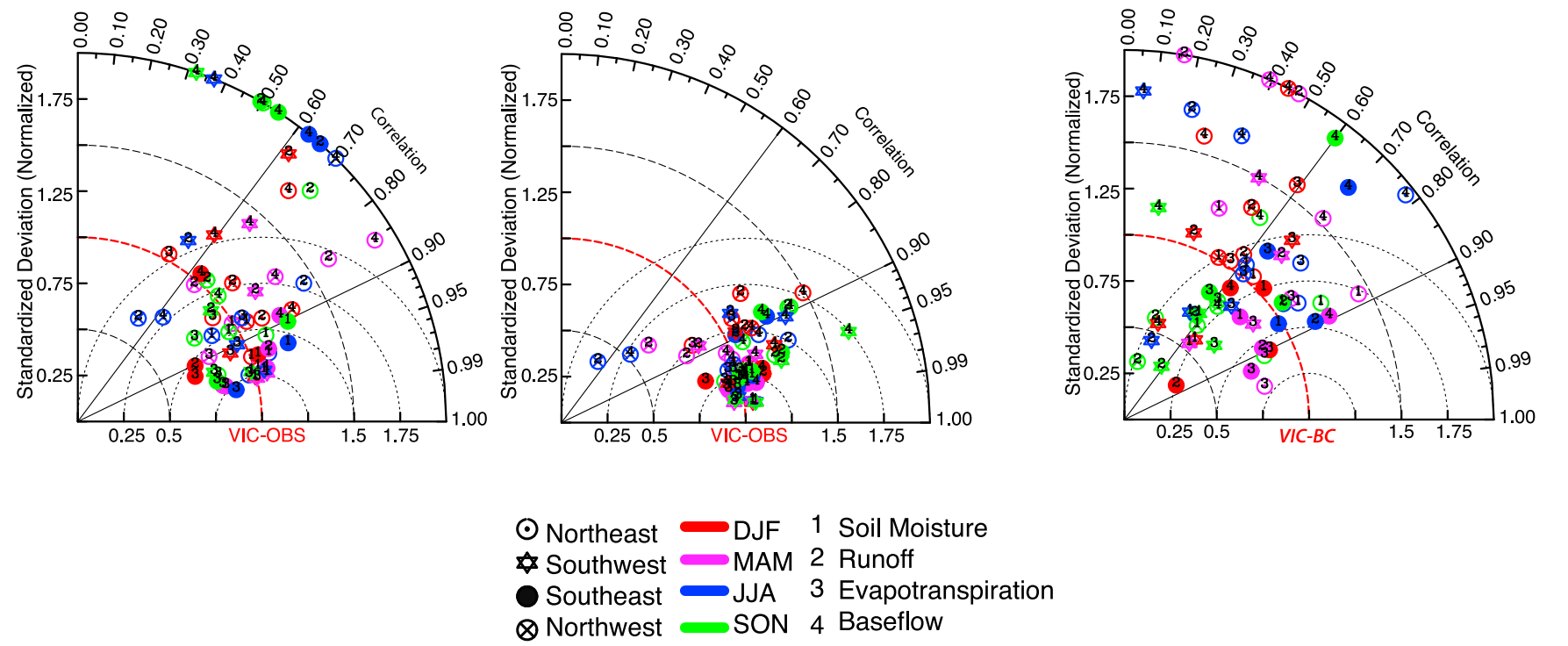


Statistical downscaling doesn't refine climate change signal and physical justifications are hard **if it does**

While we **do need bias correction!!!** (a.k.a Statistical downscaling)...



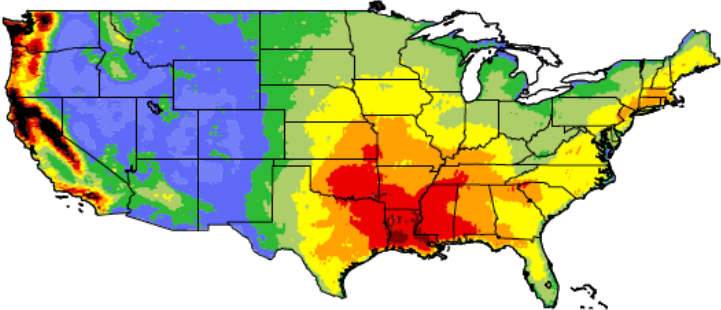
Modeling errors **without** bias correction Modeling errors **with** bias correction Simulated Future Changes **with** and **without** Bias Correction



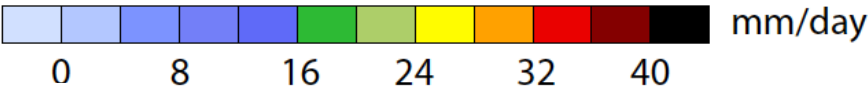
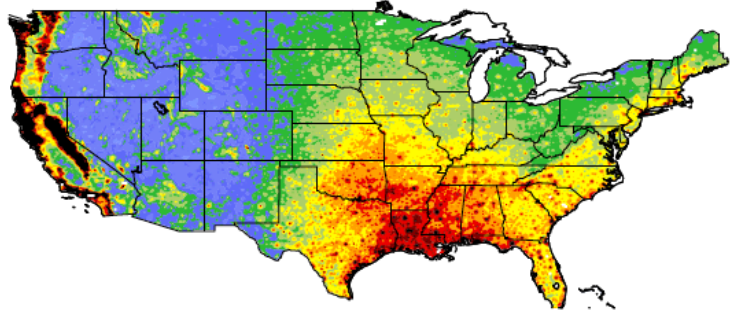
Both historical hydrological simulations and future hydrological response are **statistically different with** and **without** bias correction

...statistical bias correction is **not enough**...

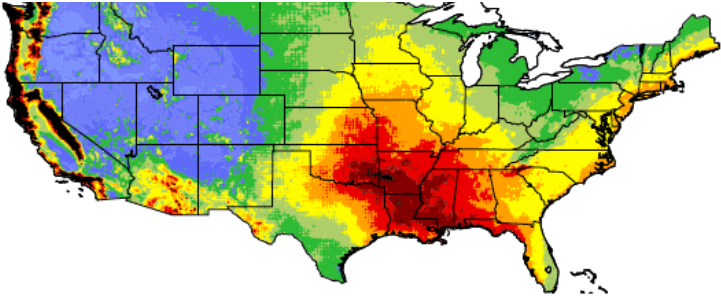
NARR Reanalysis



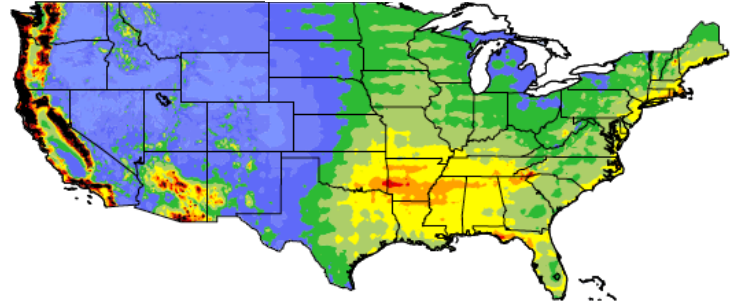
Observations



Regional Climate Model



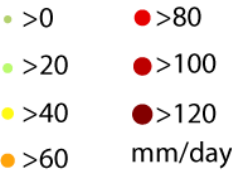
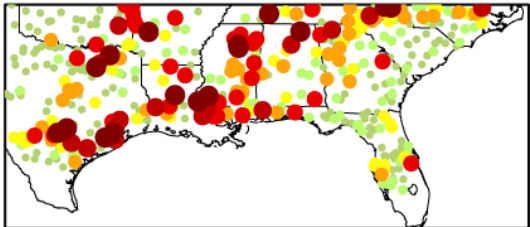
Global Climate Model



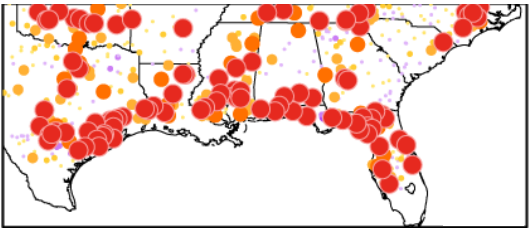
95th percentile of P

...statistical bias correction is **not enough**...

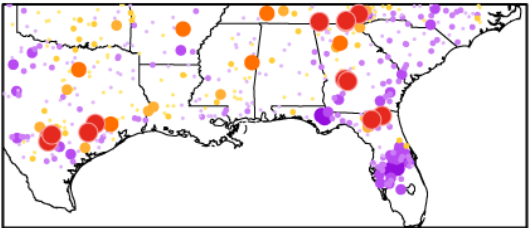
Observed 40 years max Q (USGS)



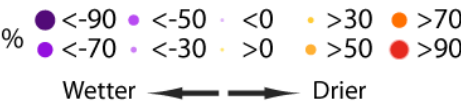
Errors in Hydrological Simulation



When bias corrected
GCM drives hydrology model

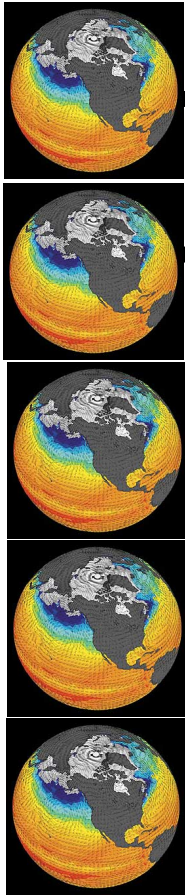


When bias corrected
GCM-RCM drives hydrology model

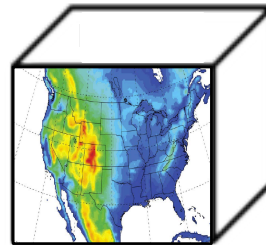


A **hierarchical modeling** framework is needed

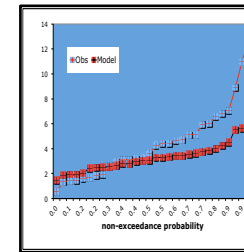
Global Climate
Models



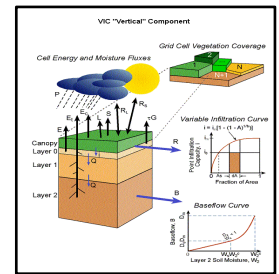
Regional Climate
Models



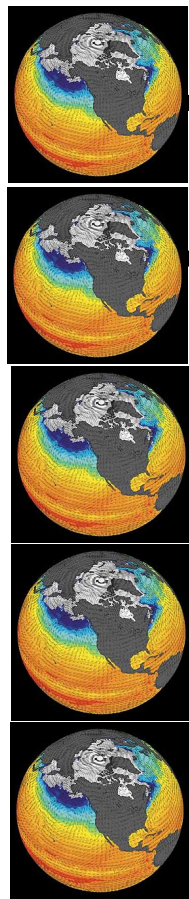
Statistical
Correction



Hydrological
Models

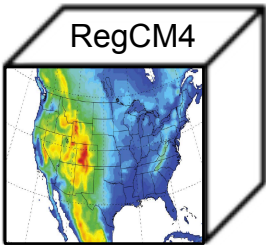


Global Climate Models (11)



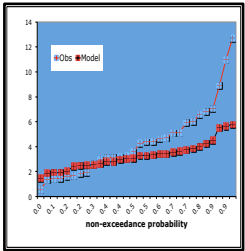
Regional Climate Model (18km)

Ashfaq et al, 2016



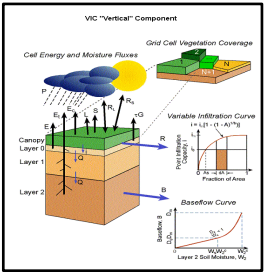
Statistical Correction

Ashfaq et al, 2010, 2013



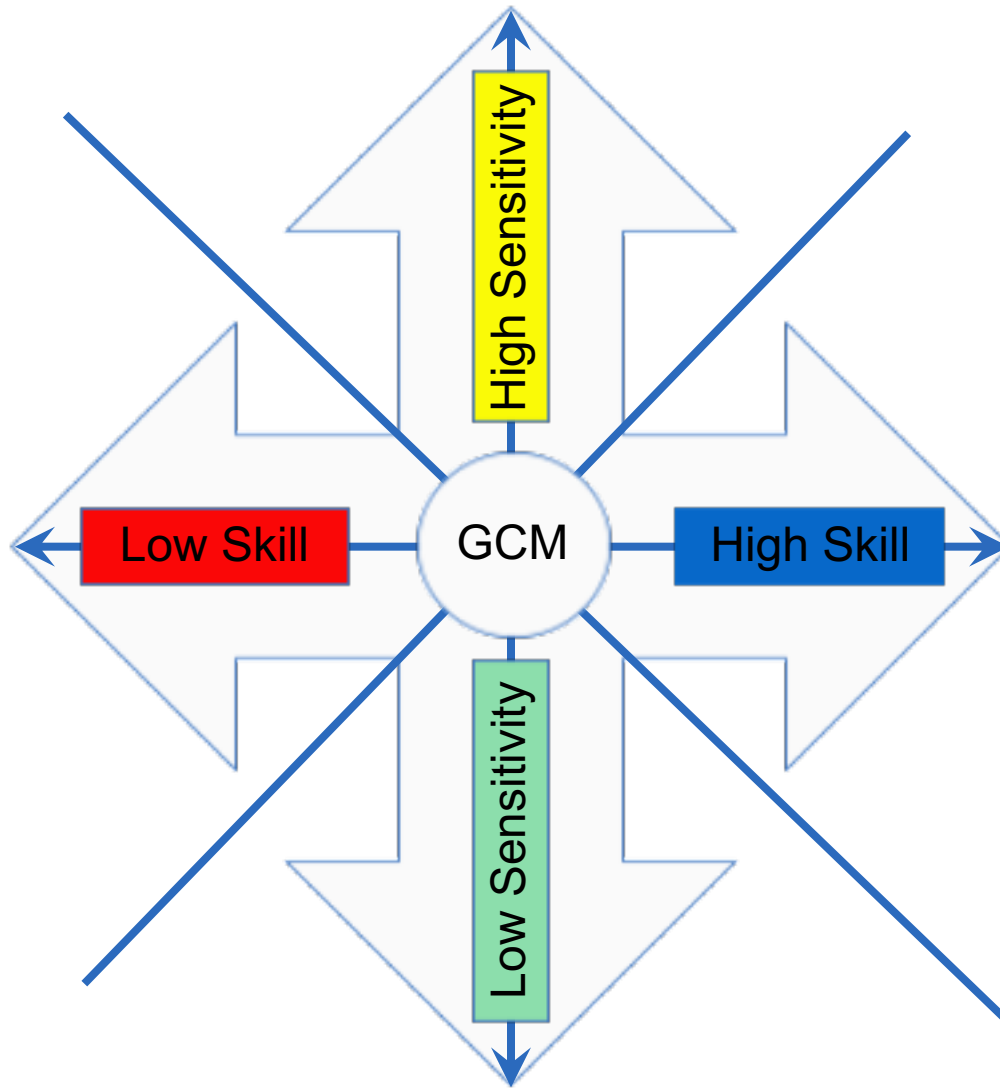
Hydrological Model (4km)

Naz et al, 2016, Pagan 2016



Baseline Period 1966-2005
Future Period (RCP8.5) 2011-2050
Total GCMs downscaled **11**

GCMs selection **criteria**



Evaluate Models in the Historical Period and categorize them as ***Implausible***, ***Significant Biased*** and ***Biased***

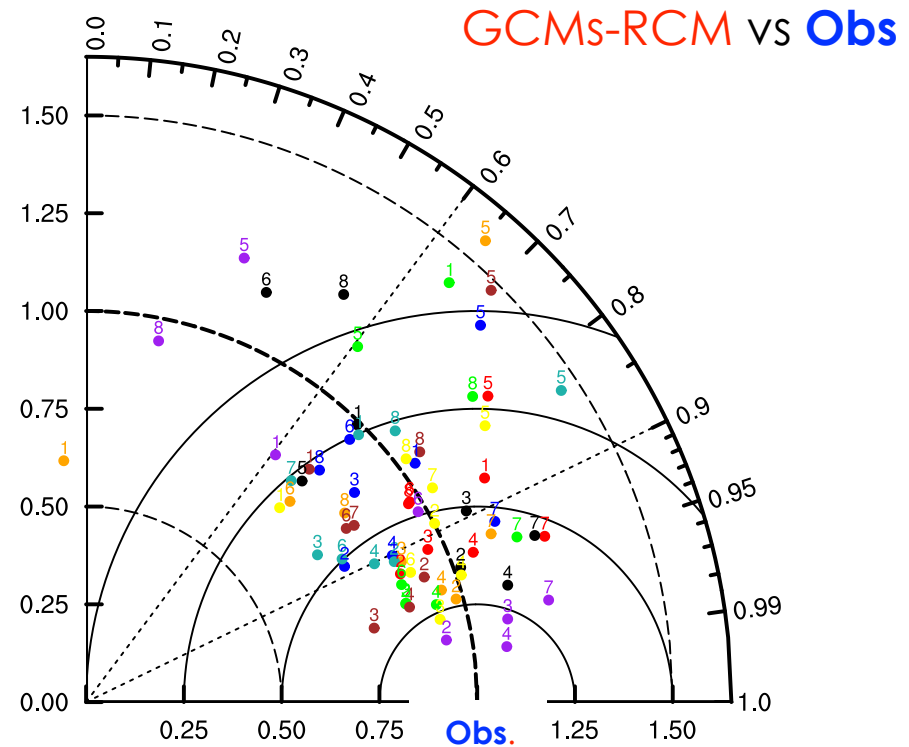
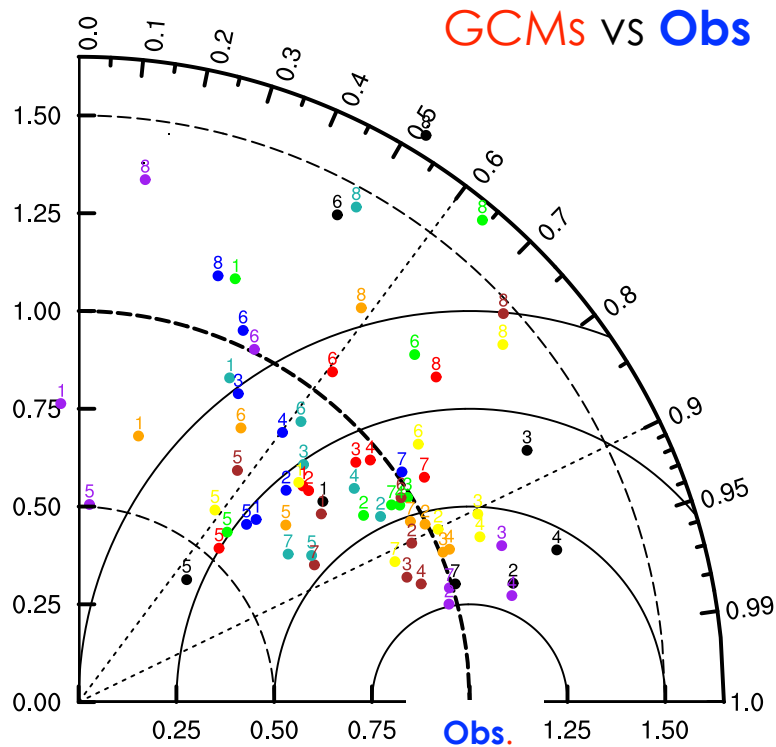


Refer to each Model Future Projection for complete decision making ***Metrix*** based on ***performance*** and ***sensitivity***



Sub-select final set of models from the remaining based on their ***diversity***, ***resolution*** etc.

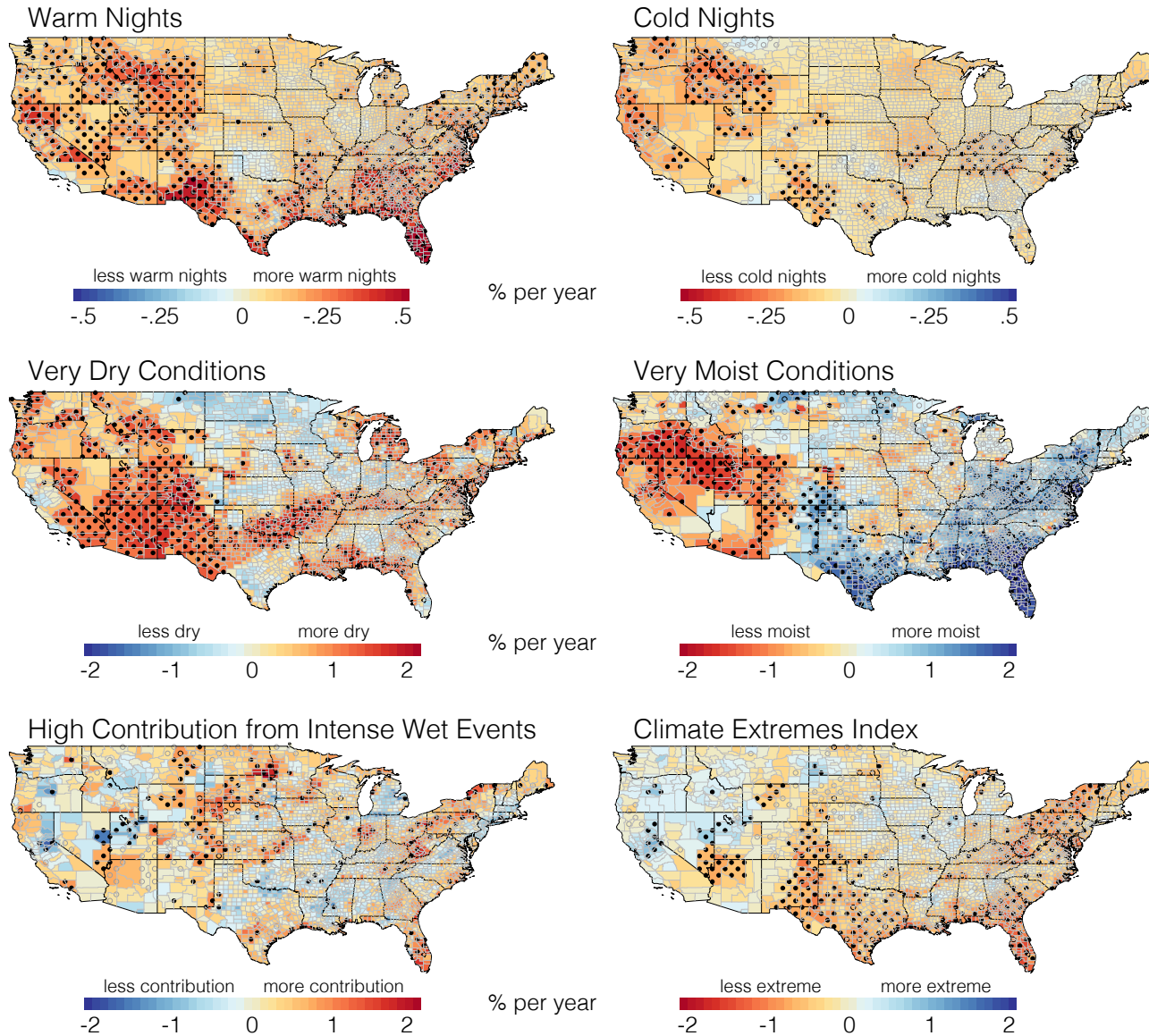
RCM's Added Value



Northern Rockies Upper Midwest Ohio Valley South West Southeast
 Northeast Southwest Northwest

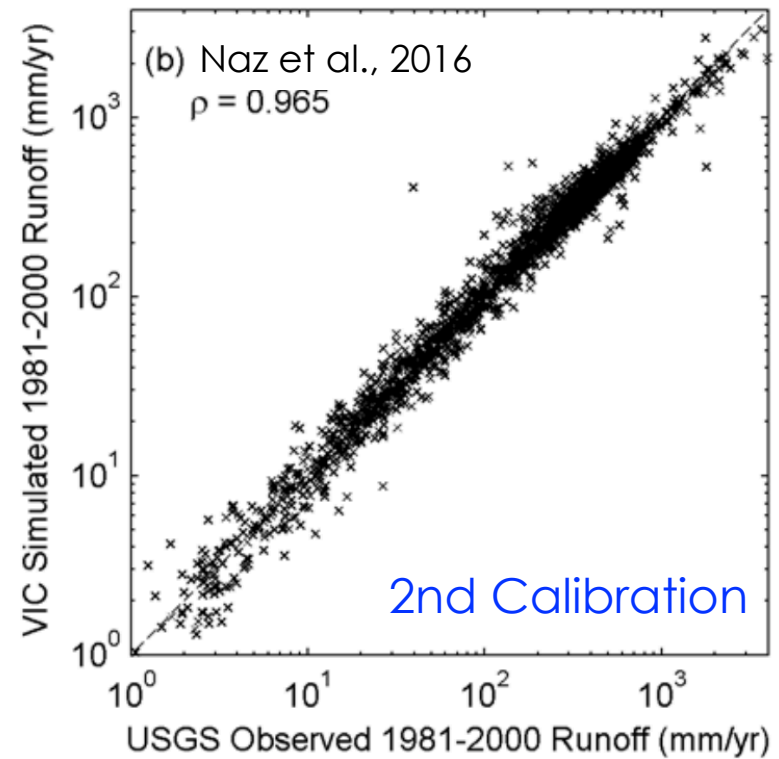
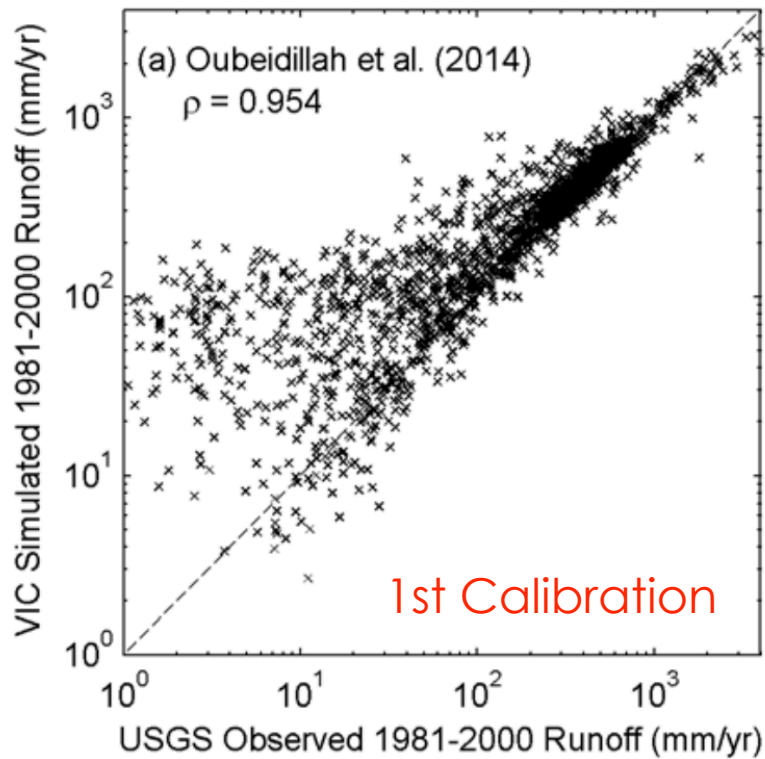
1) Precipitation 2) Minimum Daily Temperature 3) Maximum Daily Temperature 4) Average Daily Temperature
 5) 95th Percentile of Precipitation 6) 95th Percentile of Maximum Daily Temperature 7) 5th Percentile of Minimum Temperature 8) Number of Precipitation Days

Observed versus RCM simulated Trends

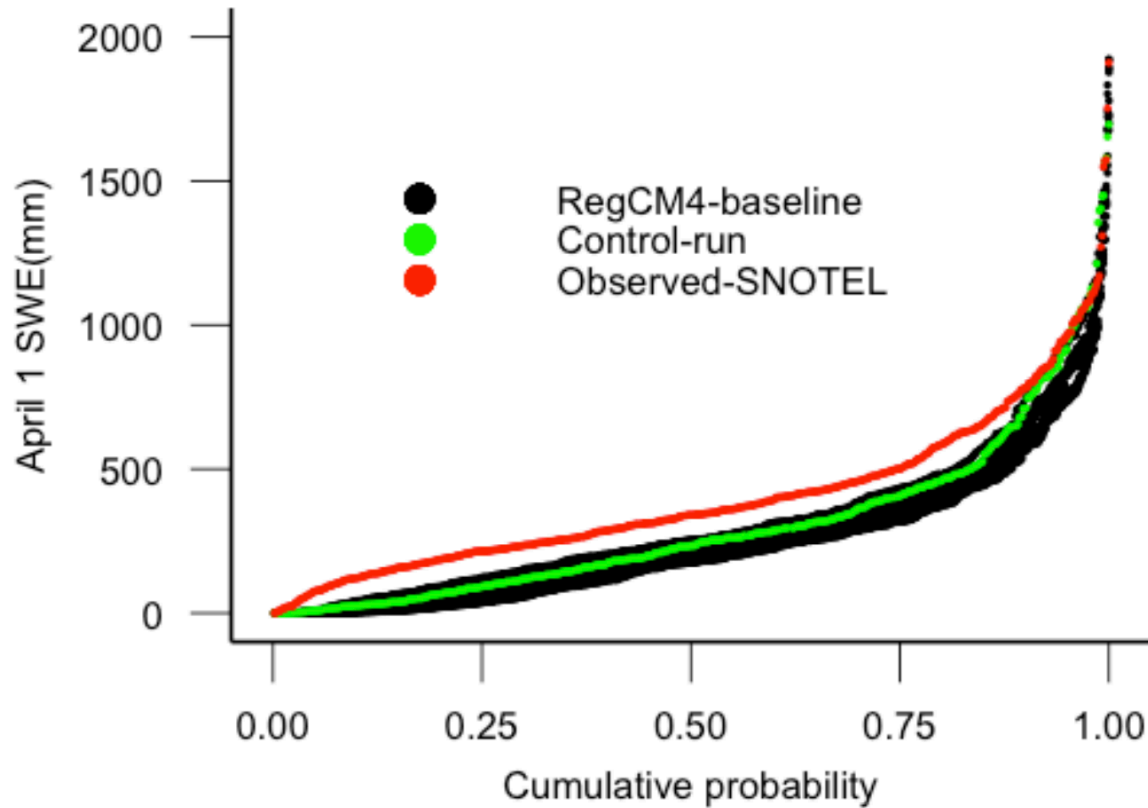


Stippling means observed trends are **significant**. **Stippling with filled circles** means **majority** of RCM ensemble members **capture the trend**

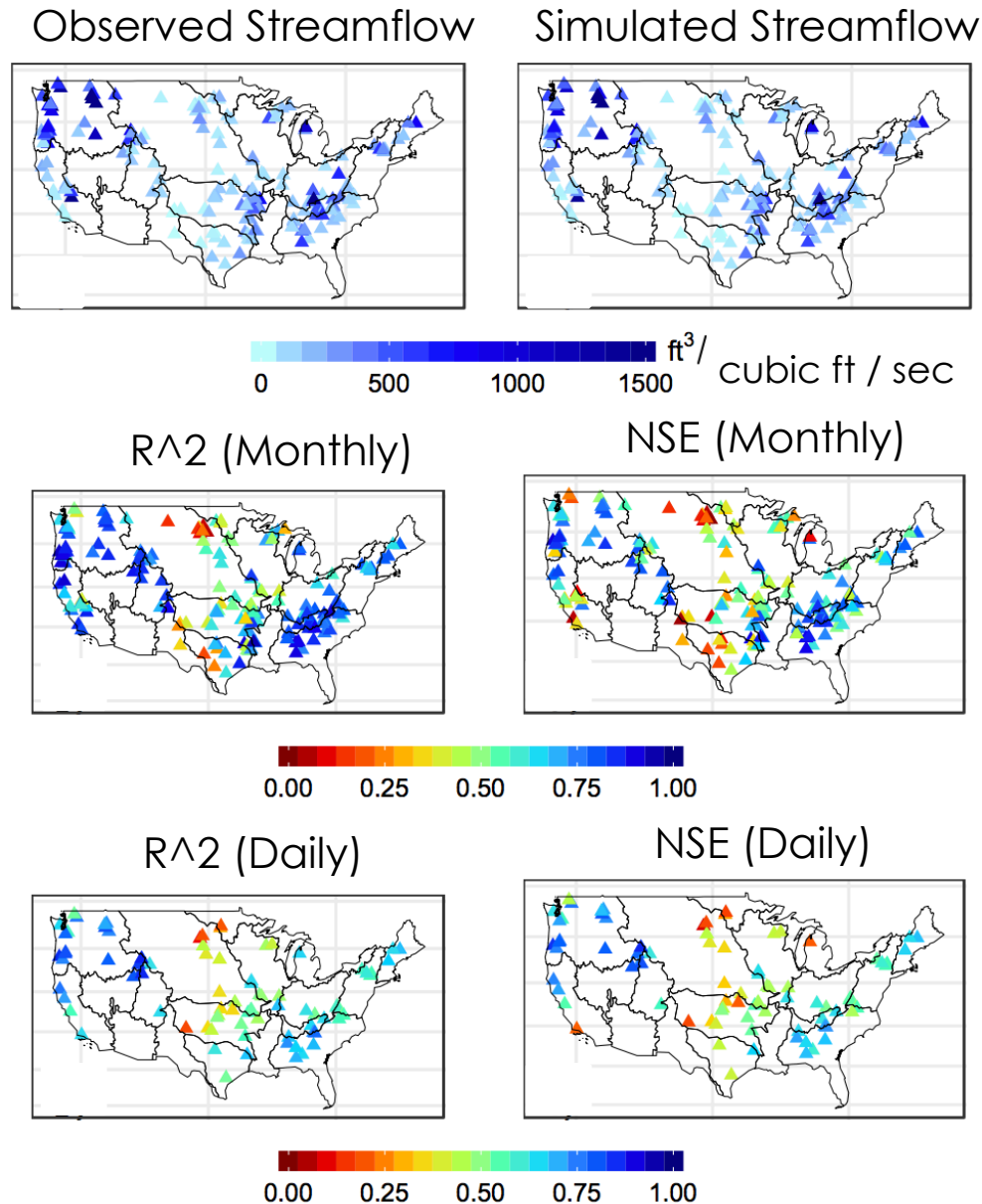
Hydrological Model **Calibration**



Observed vs Simulated seasonal **snow** accumulation over the Western U.S.



Observed vs Simulated streamflows at selected* gauges

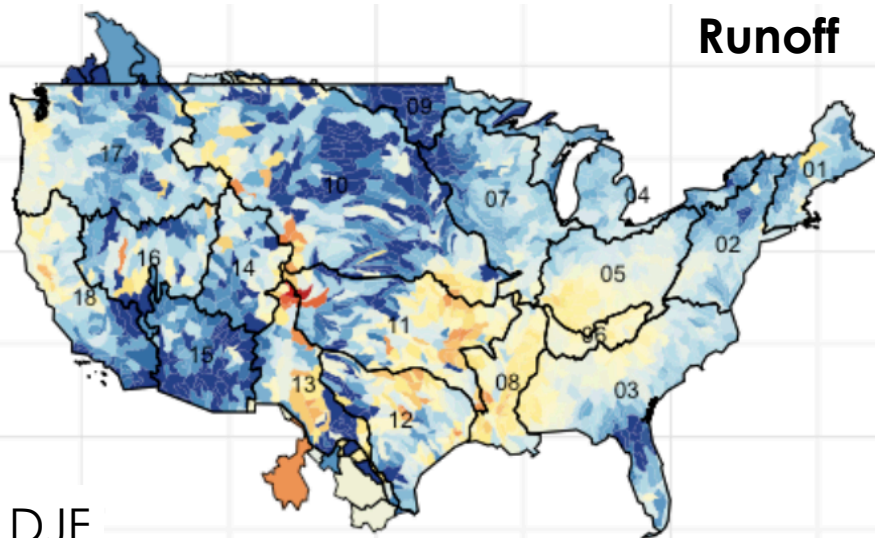


1980-2012

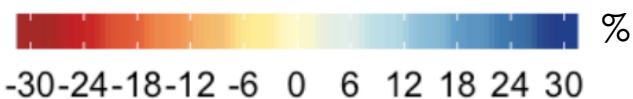
*unregulated, drainage area >100 sq km, >10 years of observations

Projected Runoff **Changes** at HUC8 level

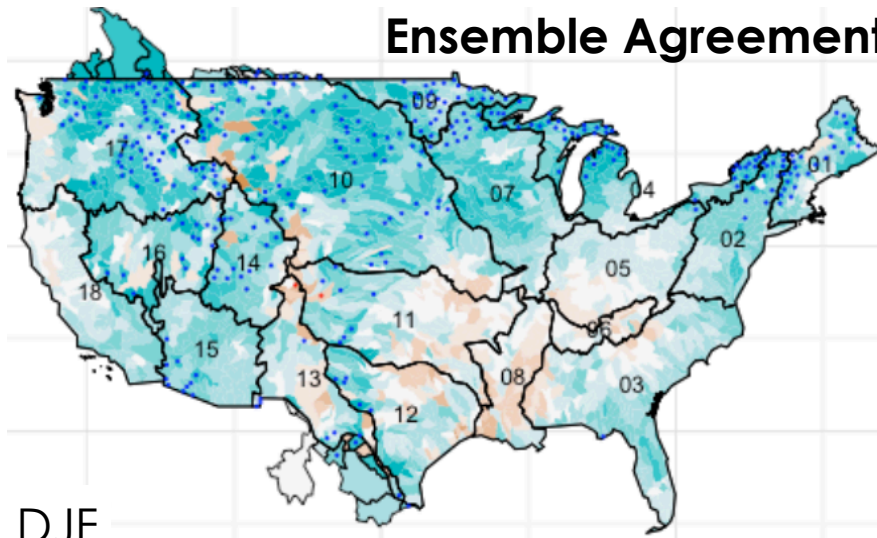
Runoff



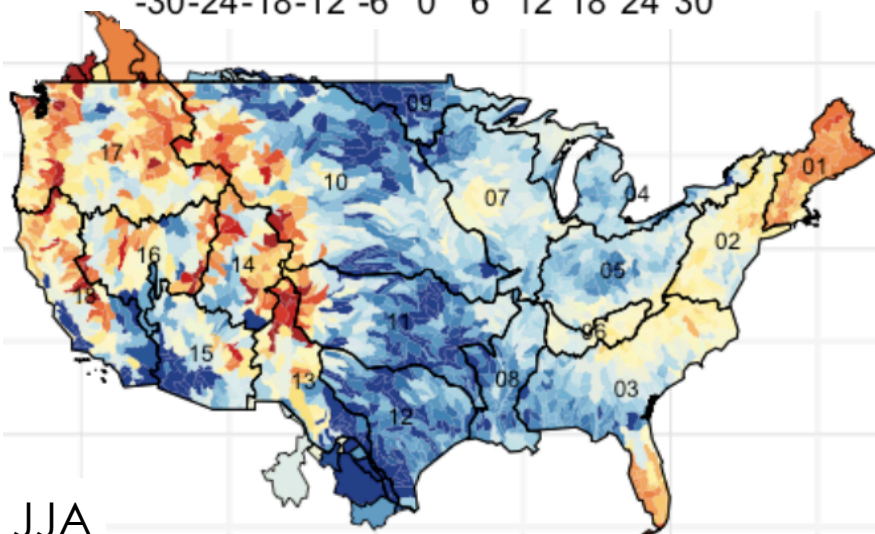
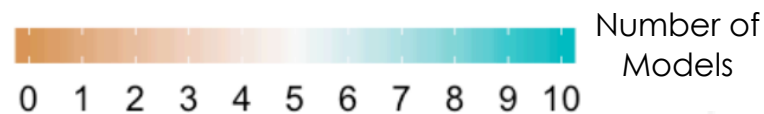
DJF



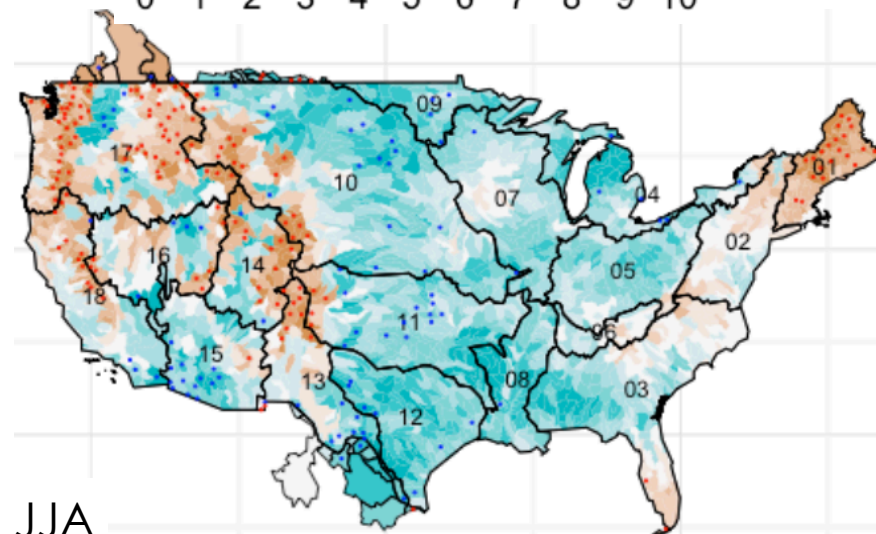
Ensemble Agreement



DJF



JJA



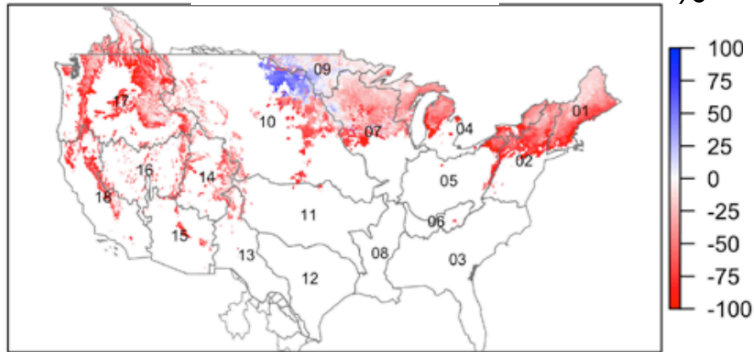
JJA

Stippling represents significant change

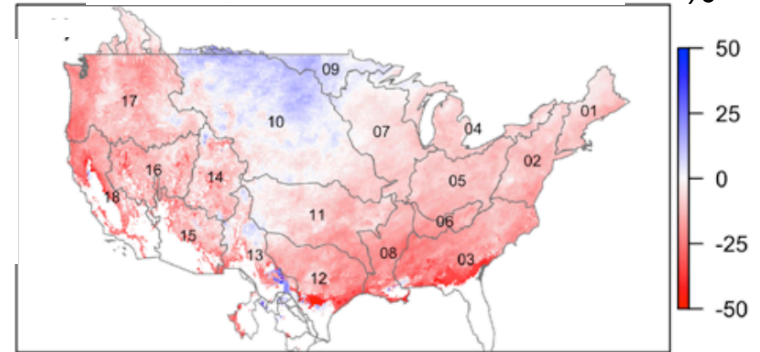
2011-2050 w.r.t 1966-2005

Projected **Changes** in Snow Hydrology

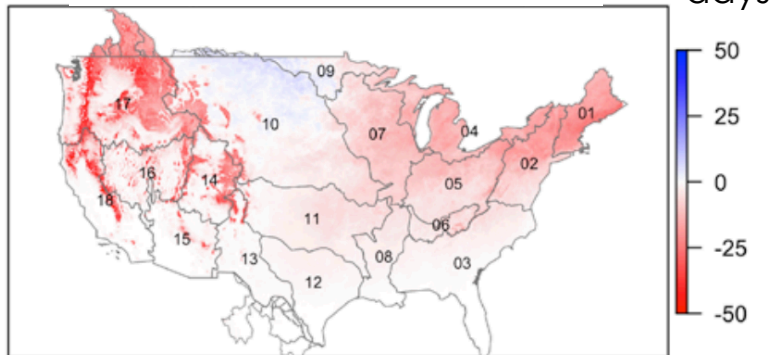
April 1st SWE



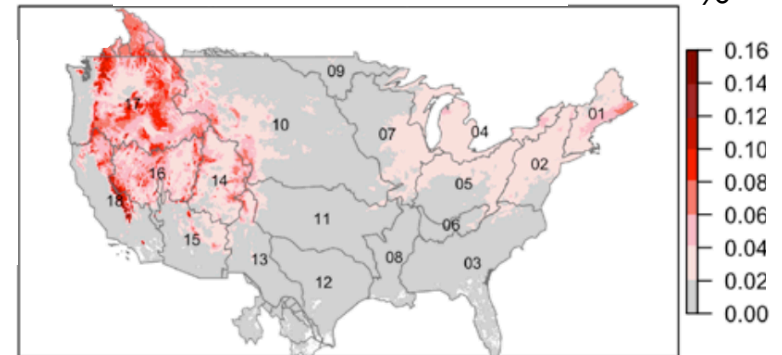
Maximum Annual SWE



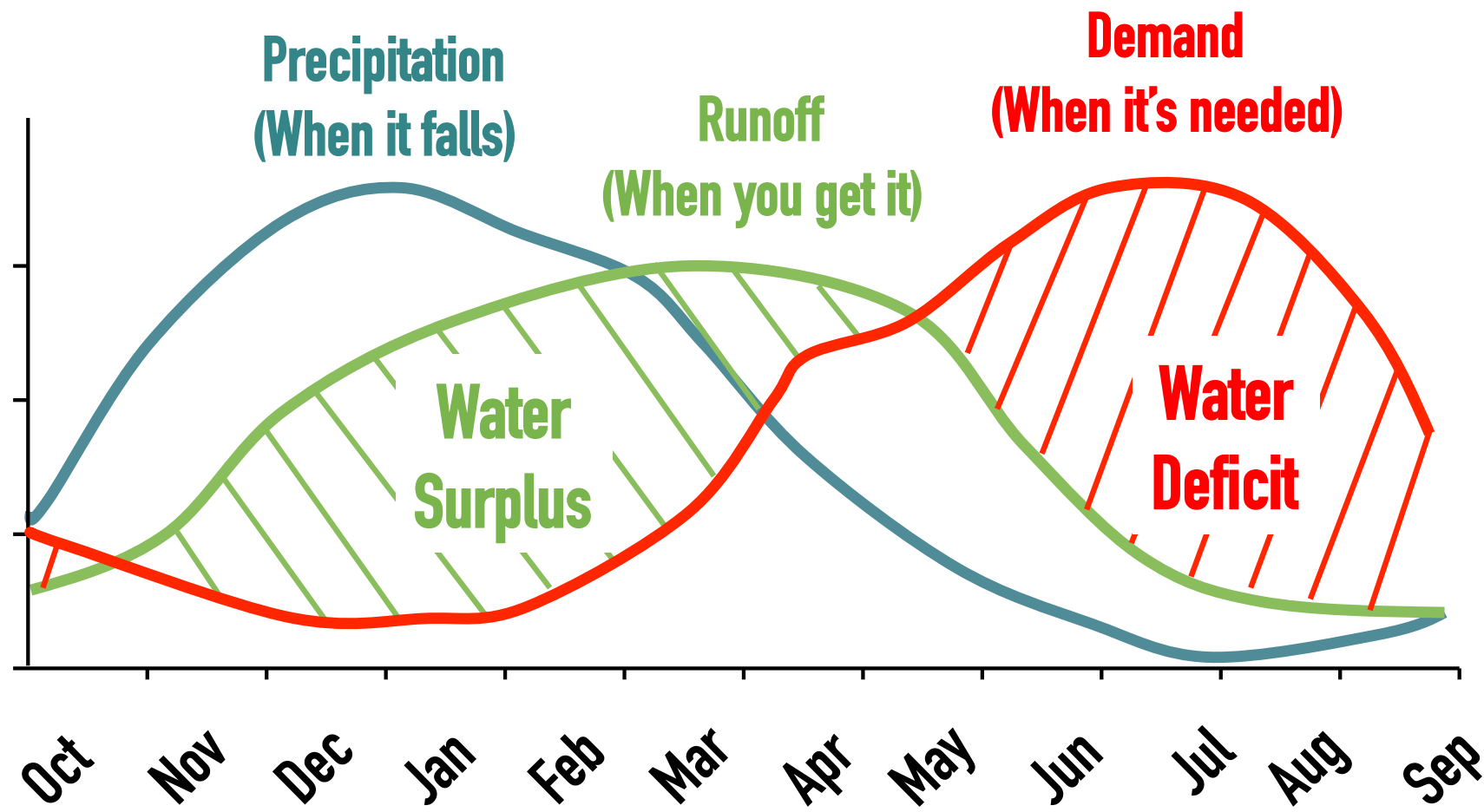
Number of Snow Days



Rain to Snow Ratio

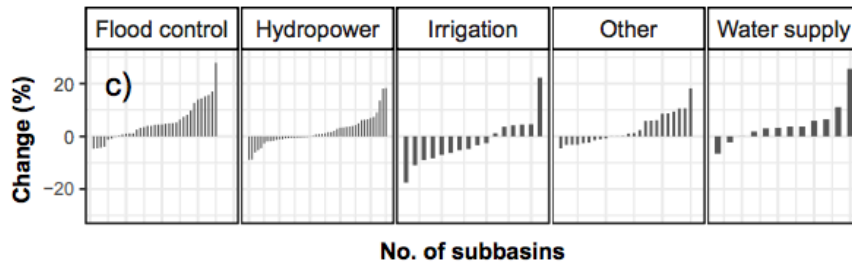
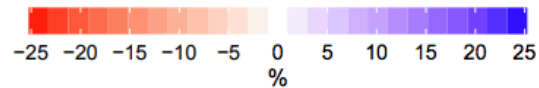
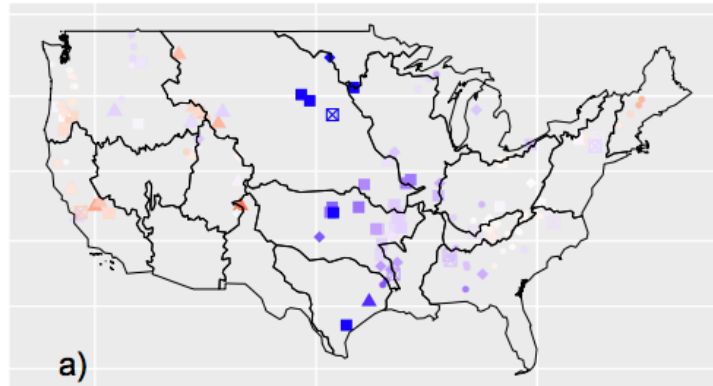


Expected future **changes** in **snowmelt driven** water resources

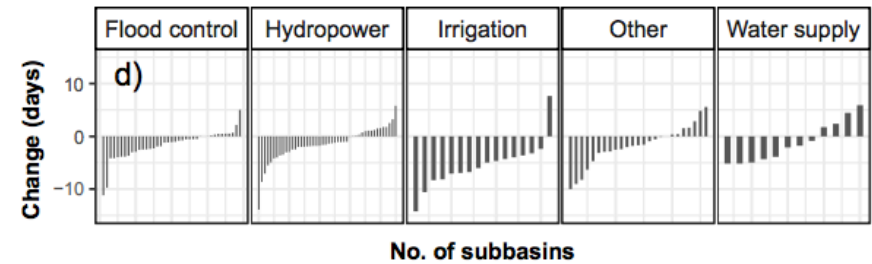
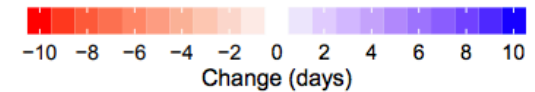
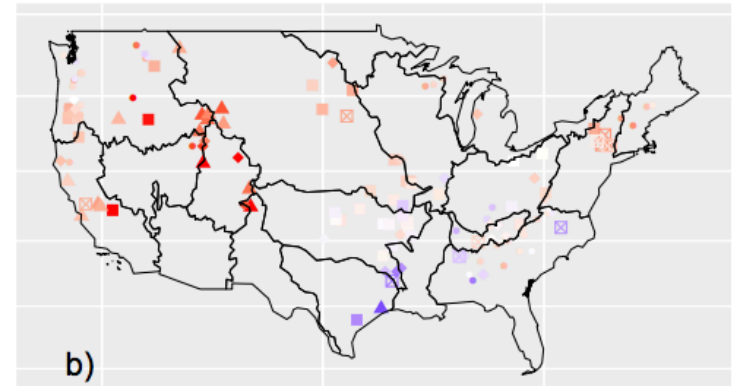


Projected **Changes** in Streamflows

Changes in Q



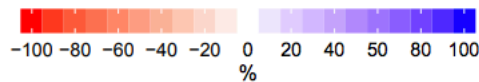
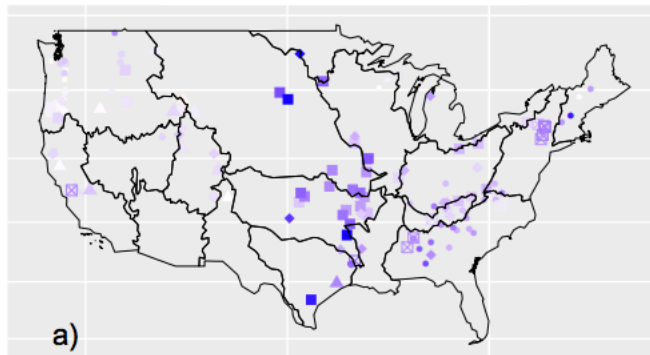
Changes in CT*



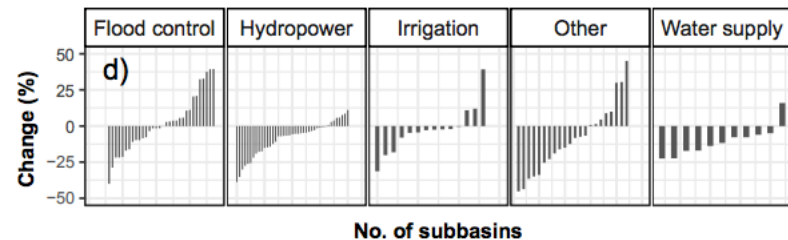
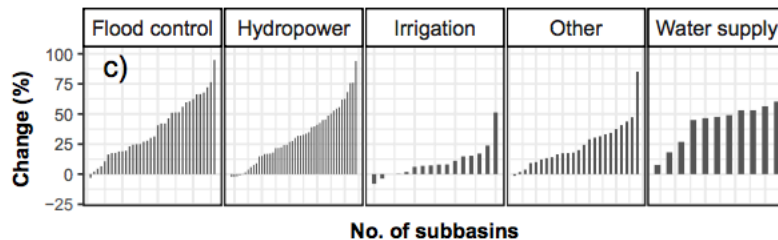
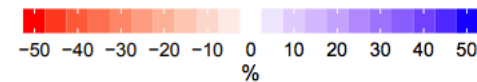
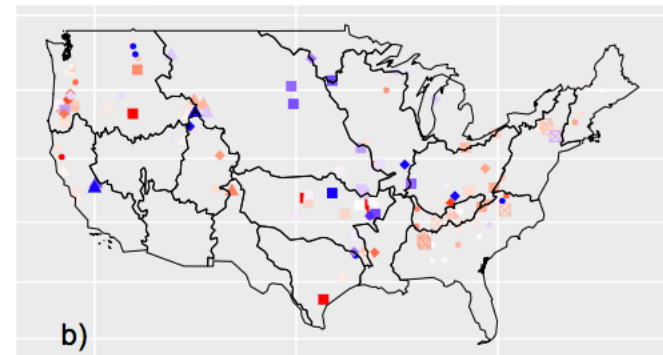
*CT is the date since October 1st when 50% of the total streamflow occurs

Projected **Changes** in Extreme Streamflows

Change in Q100



Change in 7Q10

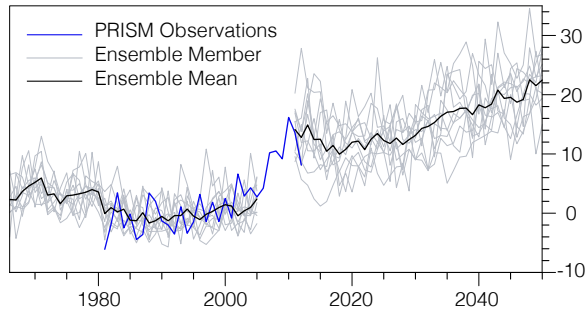


Q100 is the 100-year return level of daily high streamflow, used as a proxy for the likelihood of floods

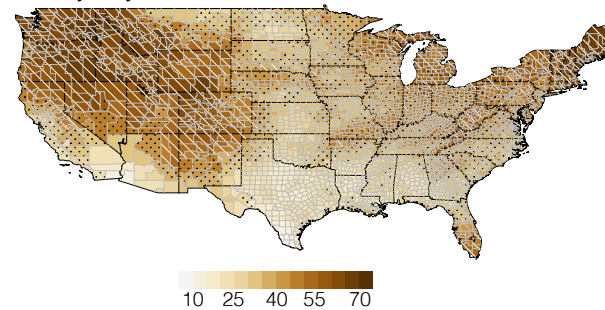
7Q10 is the 10-year return level of 7-day average streamflow, used as a proxy for droughts

Further **Intensification** of Hydrological Cycle

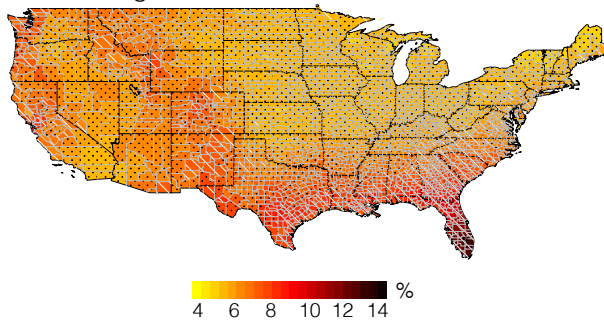
Climate Extreme Index



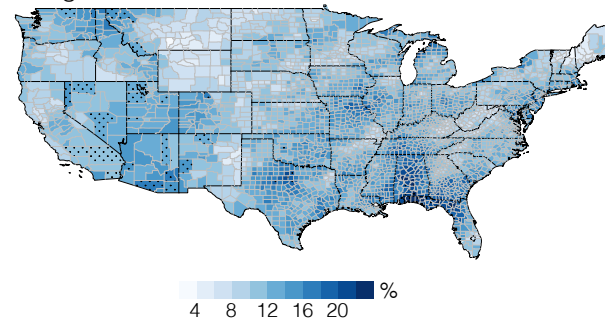
Very Dry Conditions



Warm Nights

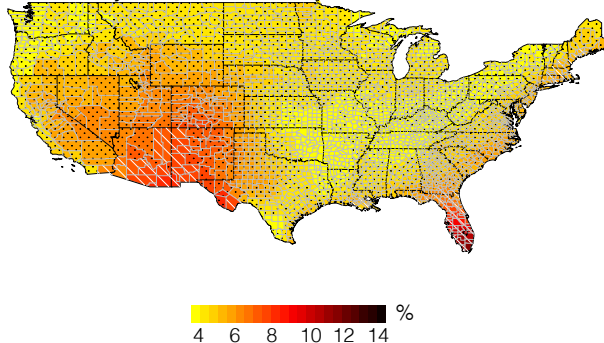


High Contribution from Intense Wet Events

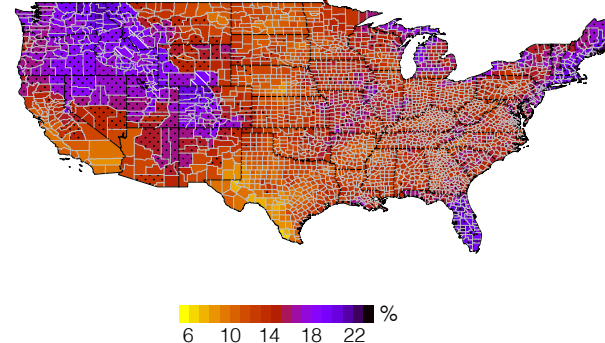


Simulated
Changes
By **2050**
w.r.t
1980 to 2005

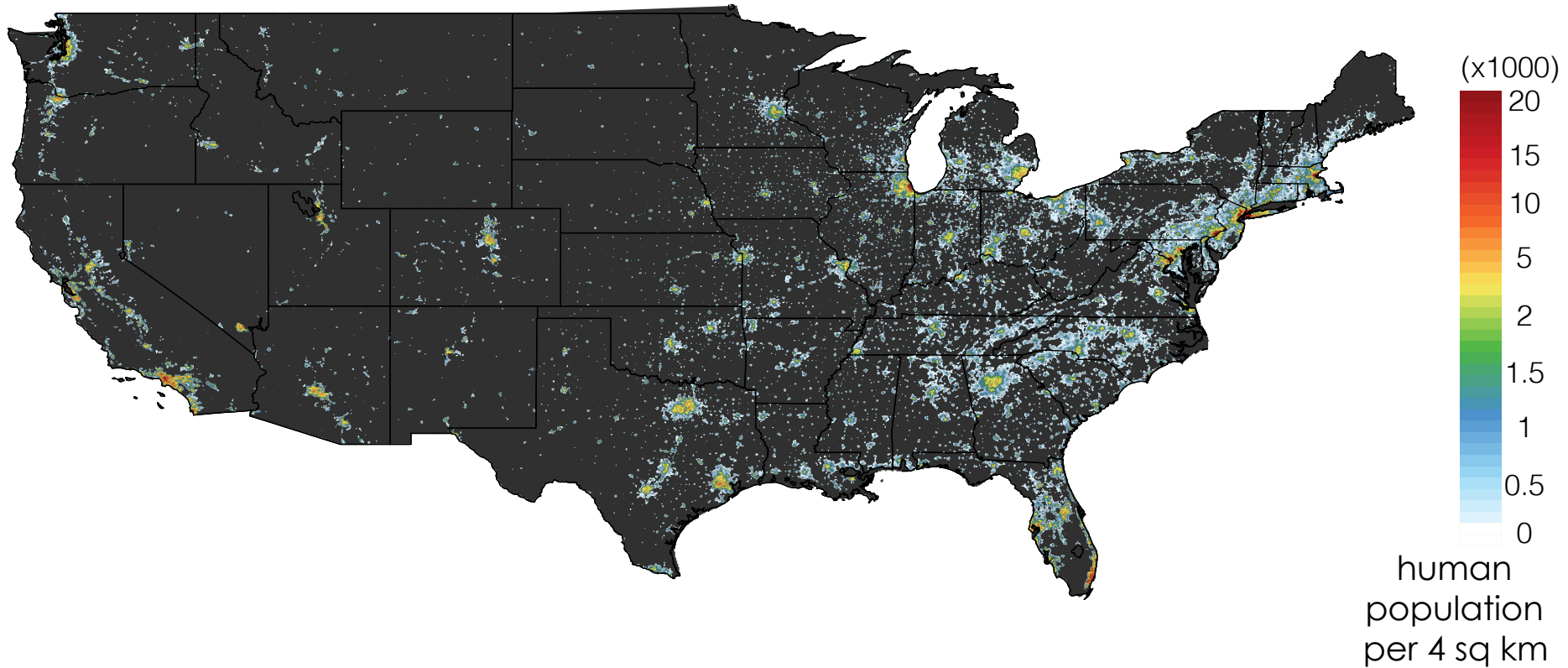
Hot Days



Climate Extreme Index



Changes in **human exposure** to climate **extremes** by **2050**



Summary

- Reliability of regional and local scale climate change impact assessments require **robust modeling strategies with high fidelity**
- Present-day Regional hydrological cycle over the U.S. **exhibits precursor of intensification**, and future projections suggest further **exacerbation of prevailing trends**
- Greatest future challenges are for those regions that presently **depend on snow-driven runoff**