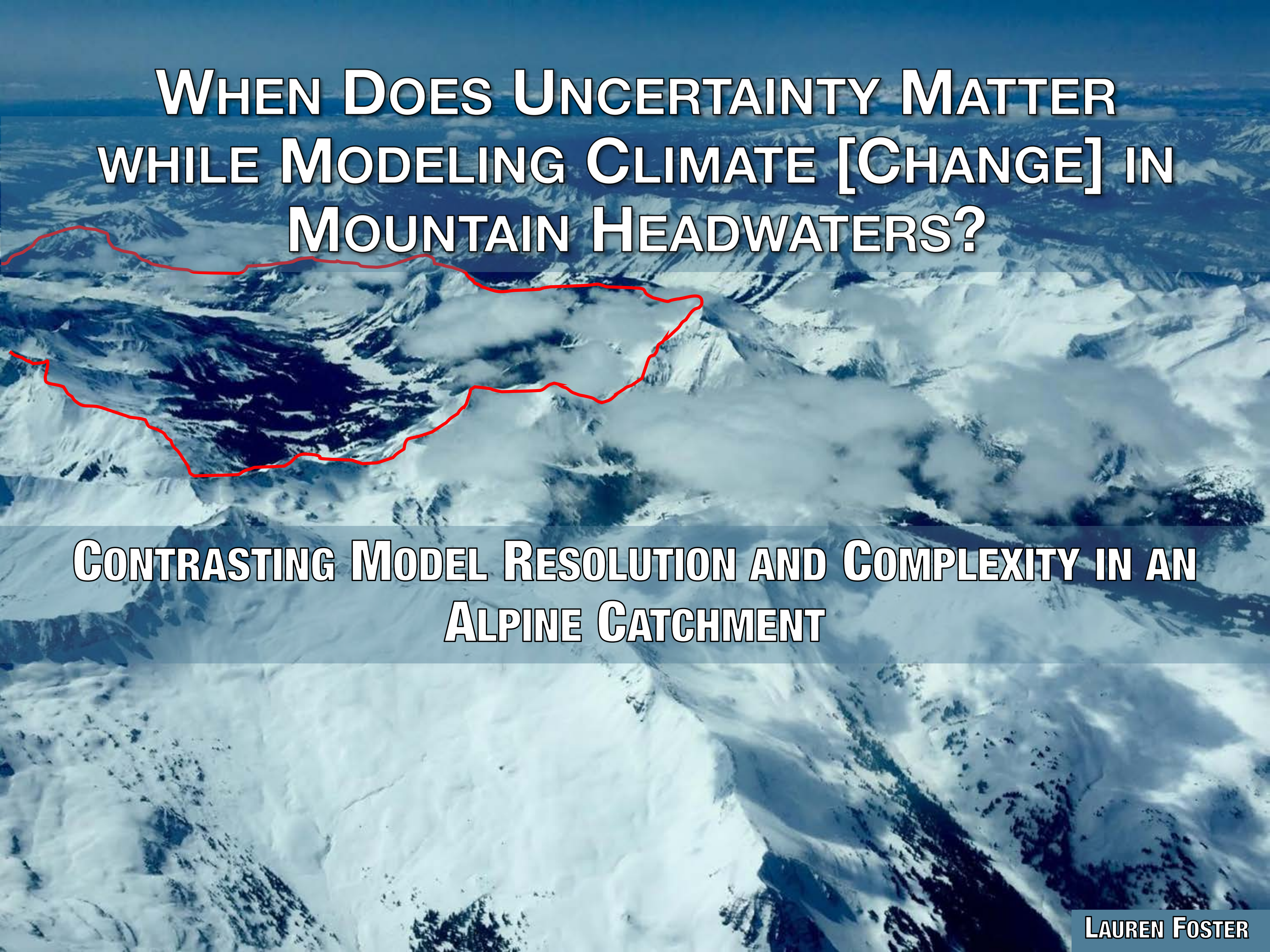


When Does Uncertainty Matter while Modeling Climate [Change] in Mountain Headwaters?

Contrasting Model Resolution and Complexity in an Alpine Catchment

Lauren Foster

Background - Parameter Scaling - Climate Change and Resolution - Conclusions

Bulk of talk

Brief summary of poster

CLIMATE CHANGE = ↑ Temp, ↓ Snowpack

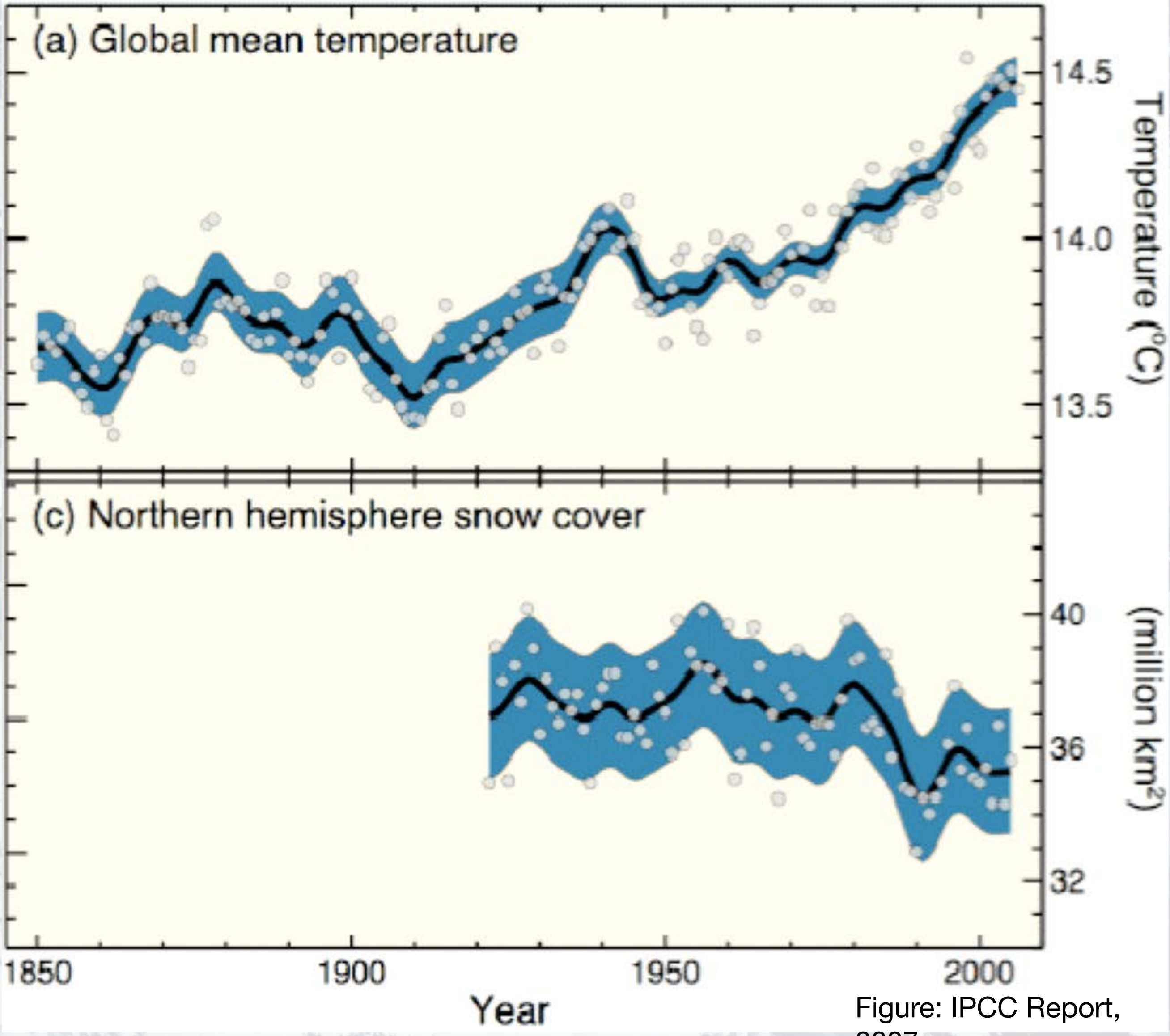


Figure: IPCC Report, 2007

MOUNTAIN SNOWPACK CRITICAL FOR WATER SUPPLIES

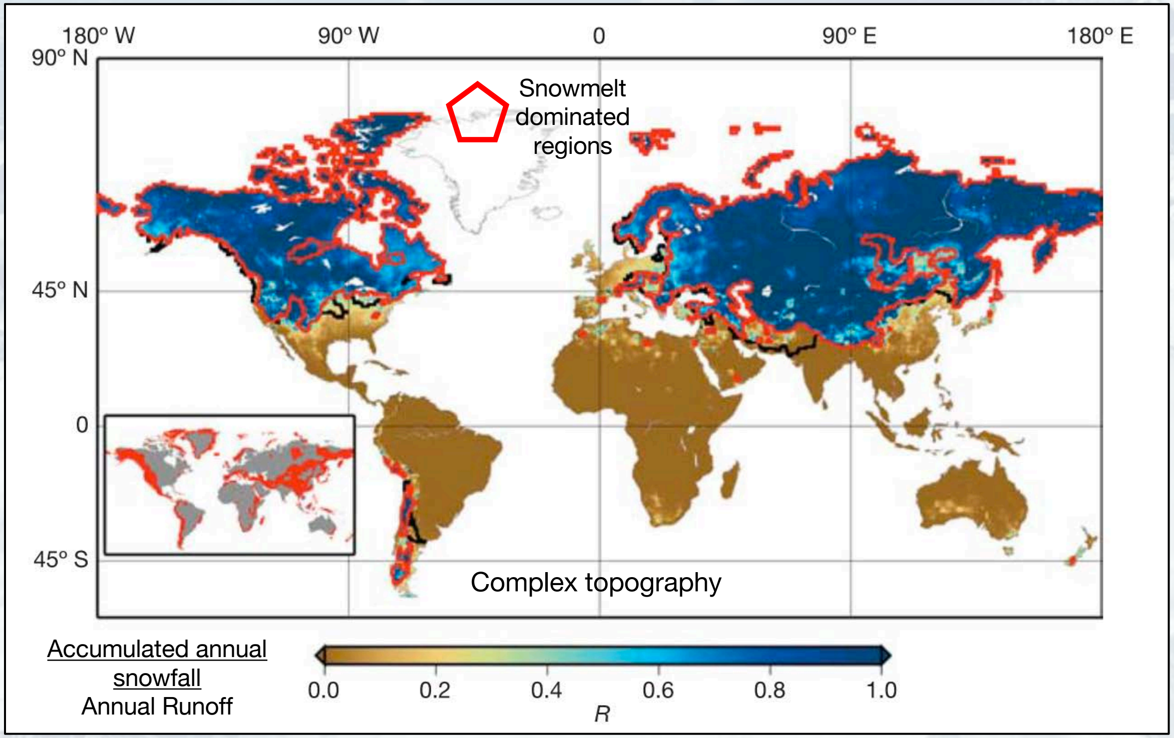


Figure (Barnett et al 2005): More than 1/6th population depends on surface water supplies from snowmelt-dominated systems.

MOUNTAIN SNOWPACK CRITICAL FOR WATER SUPPLIES

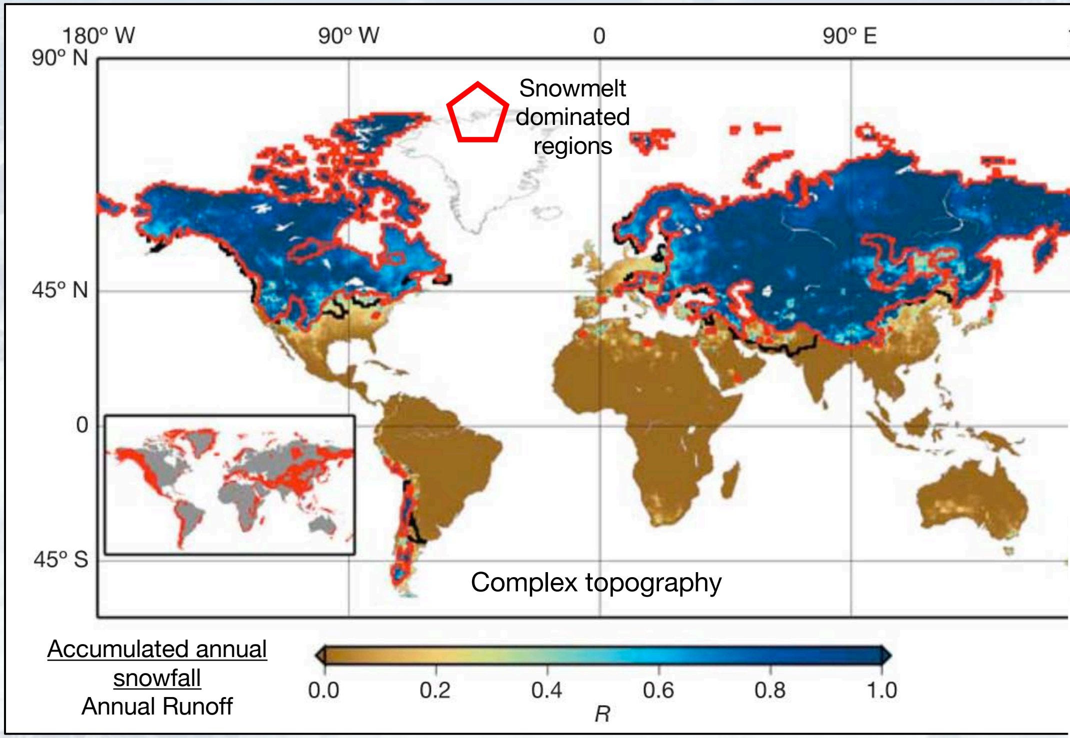


Figure (Barnett et al 2005): More than 1/6th population depends on surface water supplies from snowmelt-dominated systems.

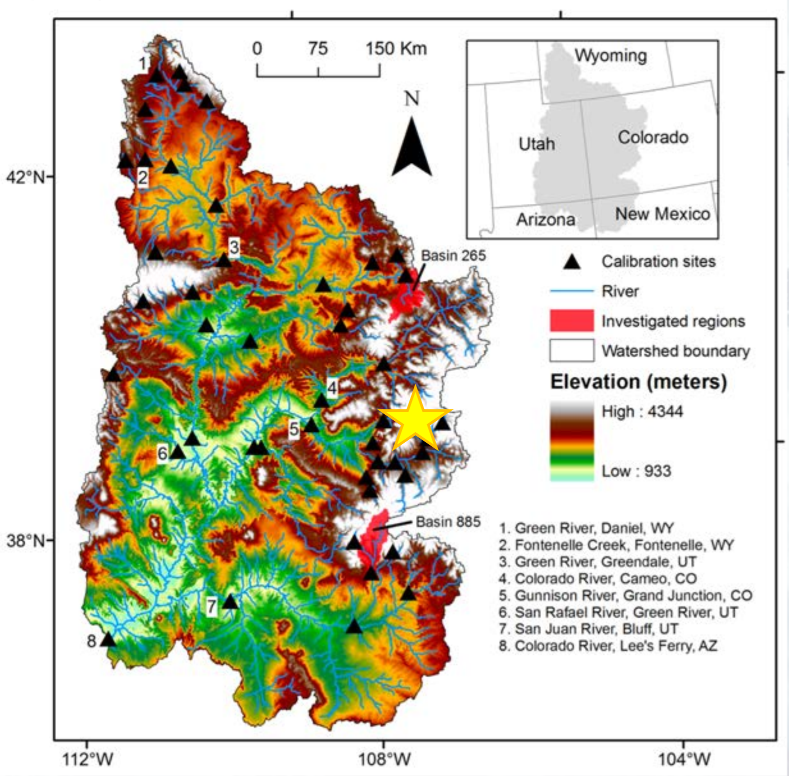
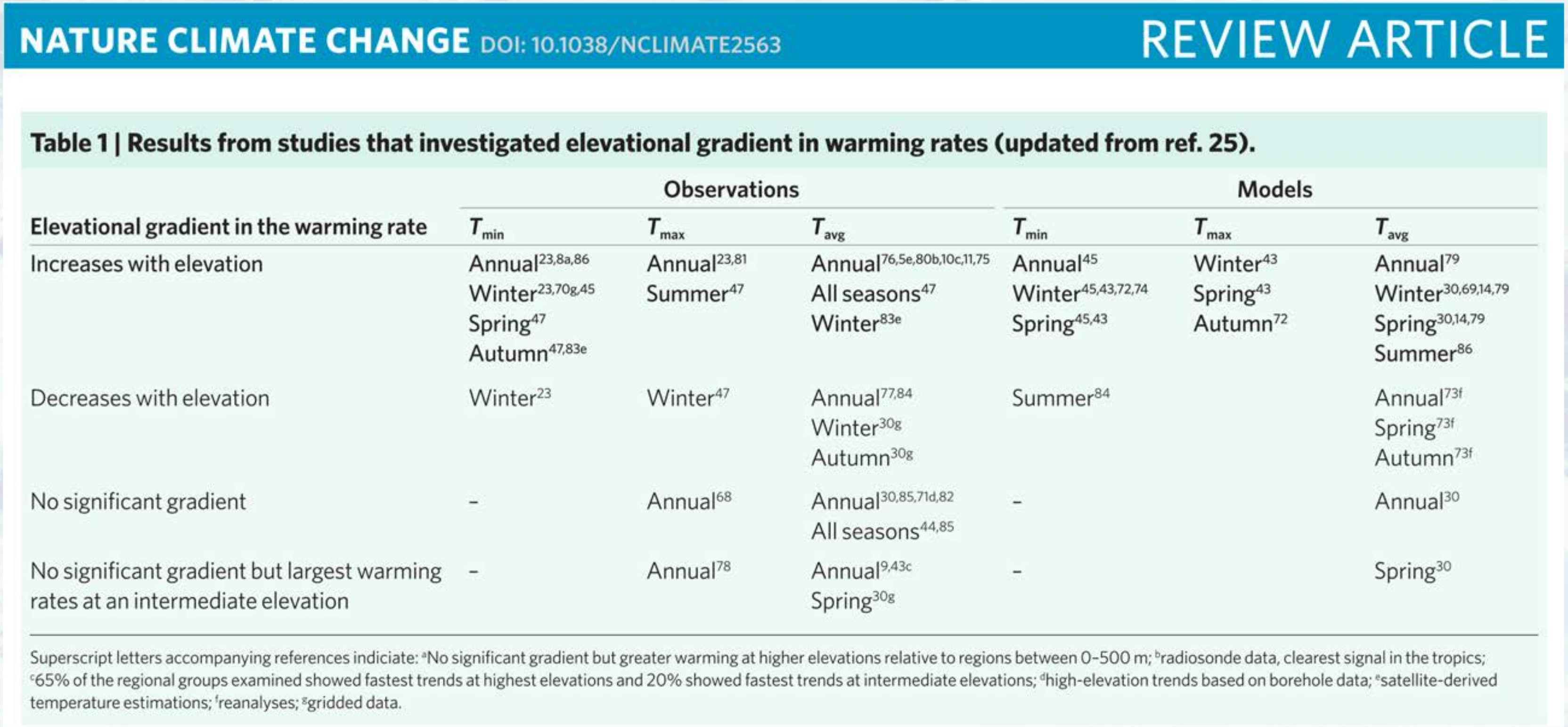


Figure (Ficklin et al 2013): More than 85% of upper Colorado R. Streamflow (main supply for Southwestern United States) generated from snowmelt in Rocky Mountain Headwaters.

Mountains to warm more quickly (NCC 2017)



NATURE CLIMATE CHANGE DOI: 10.1038/NCLIMATE2563 **REVIEW ARTICLE**

Table 1 | Results from studies that investigated elevational gradient in warming rates (updated from ref. 25).

	Observations			Models		
Elevational gradient in the warming rate	***T*$_{\mathrm{min}}$**	***T*$_{\mathrm{max}}$**	***T*$_{\mathrm{avg}}$**	***T*$_{\mathrm{min}}$**	***T*$_{\mathrm{max}}$**	***T*$_{\mathrm{avg}}$**
Increases with elevation	Annual[23,8a,86] Winter[23,70g,45] Spring[47] Autumn[47,83e]	Annual[23,81] Summer[47]	Annual[76,5e,80b,10c,11,75] All seasons[47] Winter[83e]	Annual[45] Winter[45,43,72,74] Spring[45,43]	Winter[43] Spring[43] Autumn[72]	Annual[79] Winter[30,69,14,79] Spring[30,14,79] Summer[86]
Decreases with elevation	Winter[23]	Winter[47]	Annual[77,84] Winter[30g] Autumn[30g]	Summer[84]		Annual[73f] Spring[73f] Autumn[73f]
No significant gradient	-	Annual[68]	Annual[30,85,71d,82] All seasons[44,85]	-		Annual[30]
No significant gradient but largest warming rates at an intermediate elevation	-	Annual[78]	Annual[9,43c] Spring[30g]	-		Spring[30]

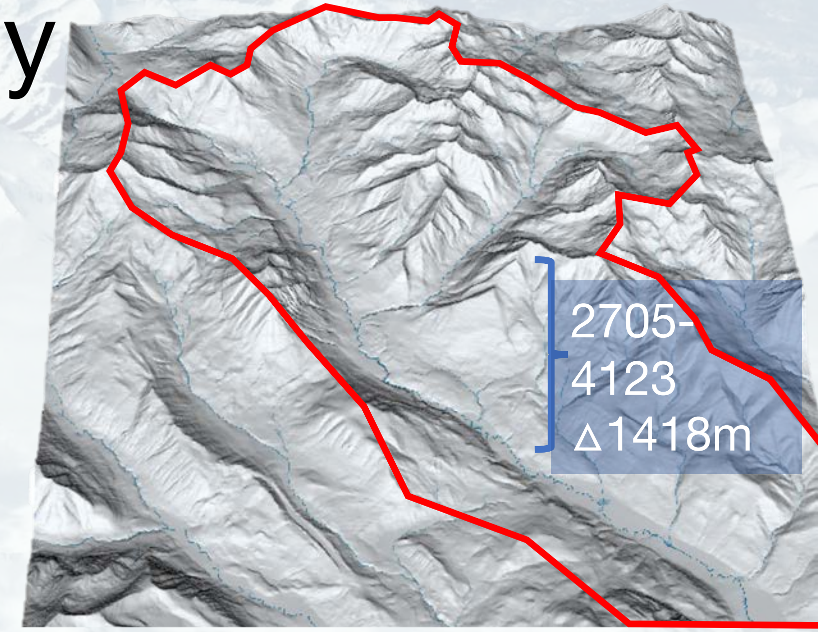
Superscript letters accompanying references indiciate: [a]No significant gradient but greater warming at higher elevations relative to regions between 0–500 m; [b]radiosonde data, clearest signal in the tropics; [c]65% of the regional groups examined showed fastest trends at highest elevations and 20% showed fastest trends at intermediate elevations; [d]high-elevation trends based on borehole data; [e]satellite-derived temperature estimations; [f]reanalyses; [g]gridded data.

Mountains are sensitive but process-based understanding is limited by complexity

Range of elevations

Steep Temperature Gradients

Variable Precipitation



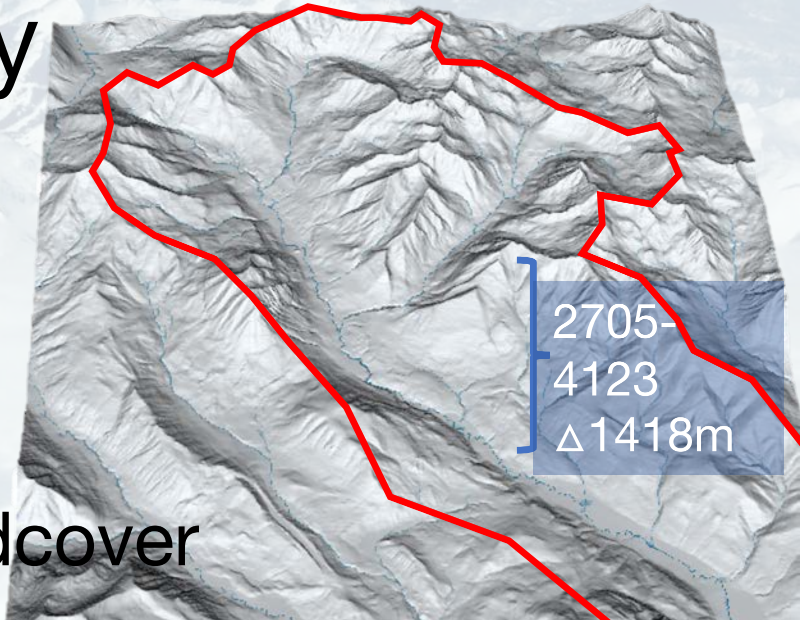
Mountains are sensitive but process-based understanding is limited by complexity

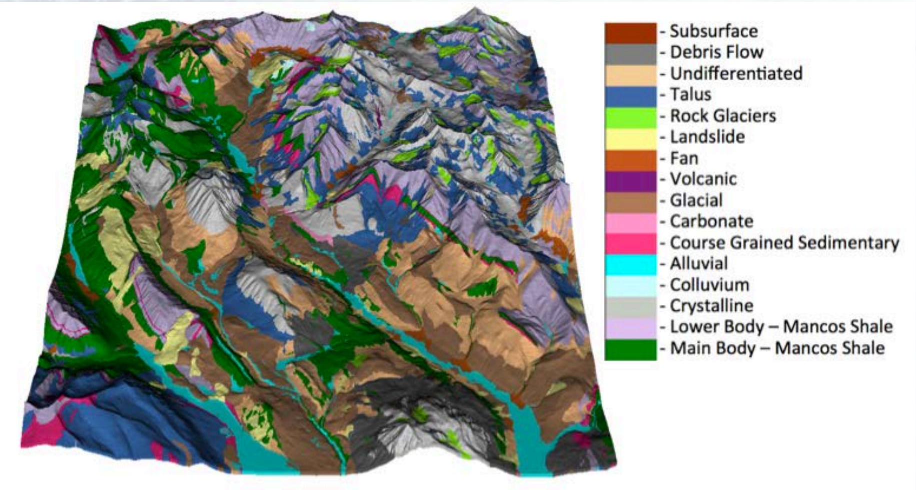
Range of elevations

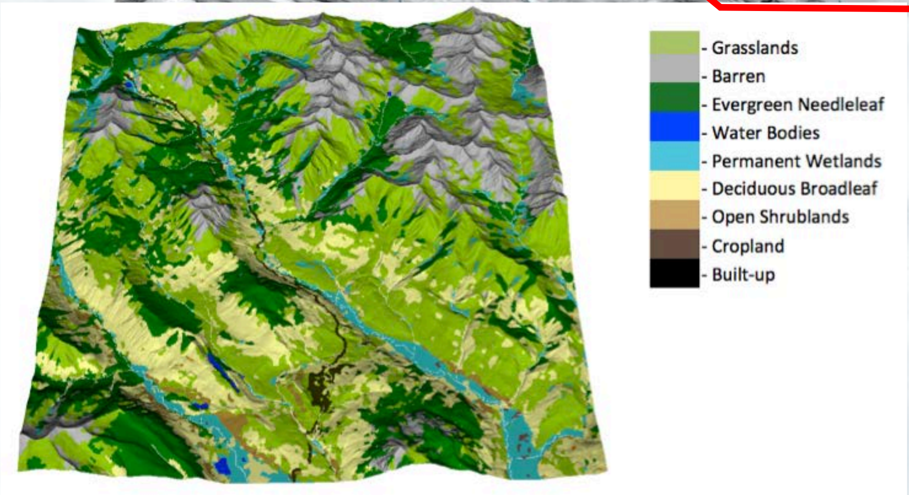
Steep Temperature Gradients

Variable Precipitation

Heterogeneous Geology & Landcover







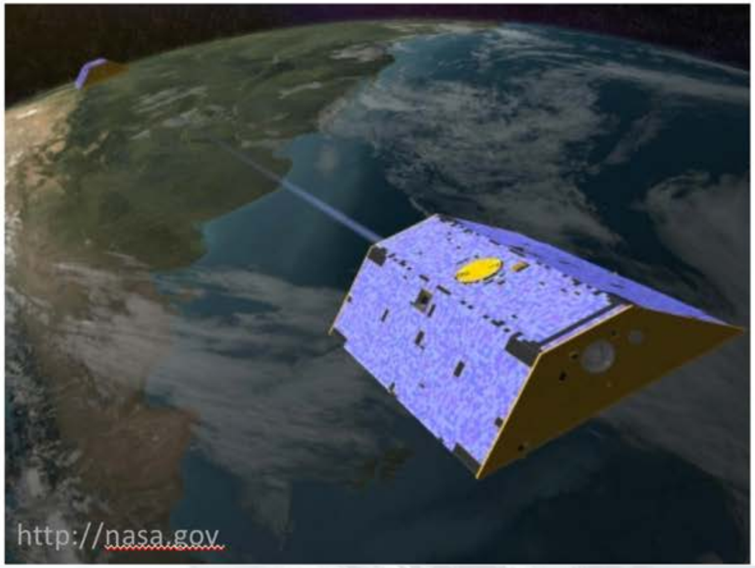
All methodologies simplify the real world…

- Observations:

Local measurements are difficult to scale

http://triplemlandfarms.com/

Remote sensing can't see everything



http://nasa.gov

All methodologies simplify the real world…

- Models
  - Coarse resolution models to make decisions/predictions -> run quickly, missing feedbacks

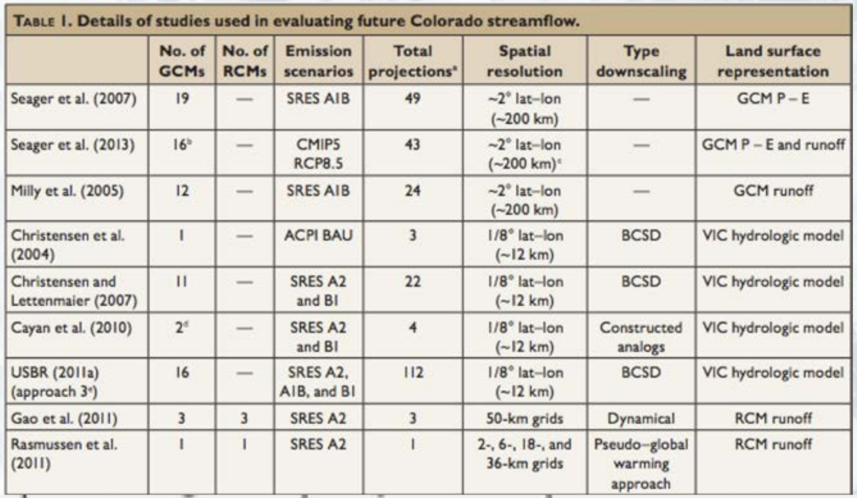
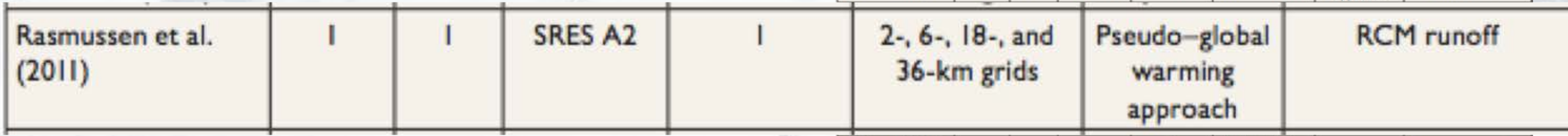
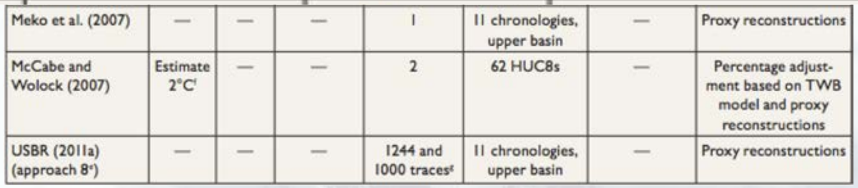


TABLE 1. Details of studies used in evaluating future Colorado streamflow.

	No. of GCMs	No. of RCMs	Emission scenarios	Total projections^a	Spatial resolution	Type downscaling	Land surface representation
Seager et al. (2007)	19	—	SRES A1B	49	~2° lat–lon (~200 km)	—	GCM P – E
Seager et al. (2013)	16^b	—	CMIP5 RCP8.5	43	~2° lat–lon (~200 km)^c	—	GCM P – E and runoff
Milly et al. (2005)	12	—	SRES A1B	24	~2° lat–lon (~200 km)	—	GCM runoff
Christensen et al. (2004)	1	—	ACPI BAU	3	1/8° lat–lon (~12 km)	BCSD	VIC hydrologic model
Christensen and Lettenmaier (2007)	11	—	SRES A2 and B1	22	1/8° lat–lon (~12 km)	BCSD	VIC hydrologic model
Cayan et al. (2010)	2^d	—	SRES A2 and B1	4	1/8° lat–lon (~12 km)	Constructed analogs	VIC hydrologic model
USBR (2011a) (approach 3^e)	16	—	SRES A2, A1B, and B1	112	1/8° lat–lon (~12 km)	BCSD	VIC hydrologic model
Gao et al. (2011)	3	3	SRES A2	3	50-km grids	Dynamical	RCM runoff
Rasmussen et al. (2011)	1	1	SRES A2	1	2-, 6-, 18-, and 36-km grids	Pseudo–global warming approach	RCM runoff
Meko et al. (2007)	—	—	—	1	11 chronologies, upper basin	—	Proxy reconstructions
McCabe and Wolock (2007)	Estimate 2°C^f	—	—	2	62 HUC8s	—	Percentage adjustment based on TWB model and proxy reconstructions
USBR (2011a) (approach 8^e)	—	—	—	1244 and 1000 traces^g	11 chronologies, upper basin	—	Proxy reconstructions



| Rasmussen et al. (2011) | 1 | 1 | SRES A2 | 1 | 2-, 6-, 18-, and 36-km grids | Pseudo–global warming approach | RCM runoff |

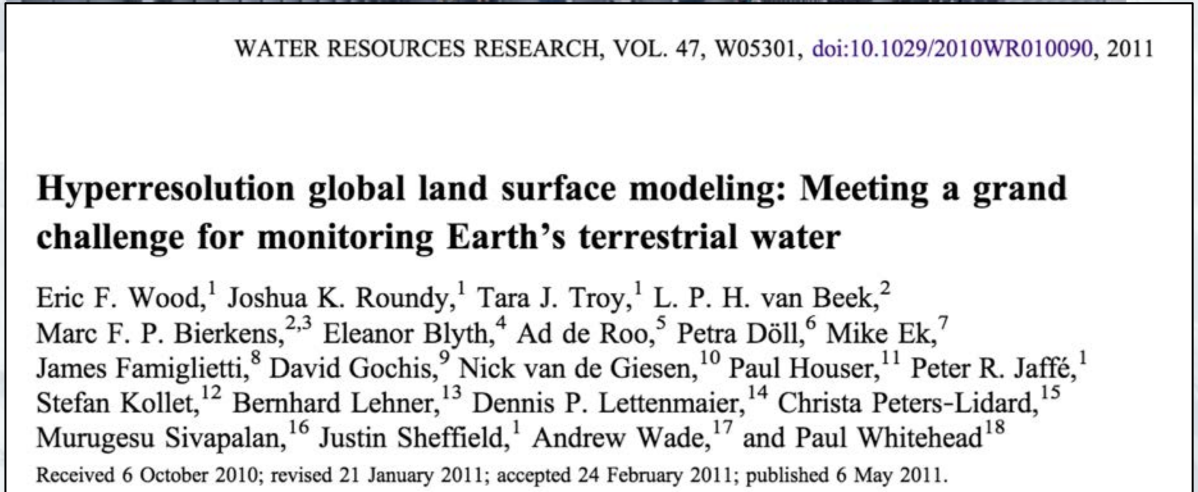


- Fine resolution models are computationally expensive

… but when does it matter?

Using high resolution enabled by super computing to inform low resolution models… bridge the gap

1. High resolution in both SPACE and TIME can bridge observational gaps
2. Insight into physical mechanisms driving changes
3. Inform predictive and decision-making models



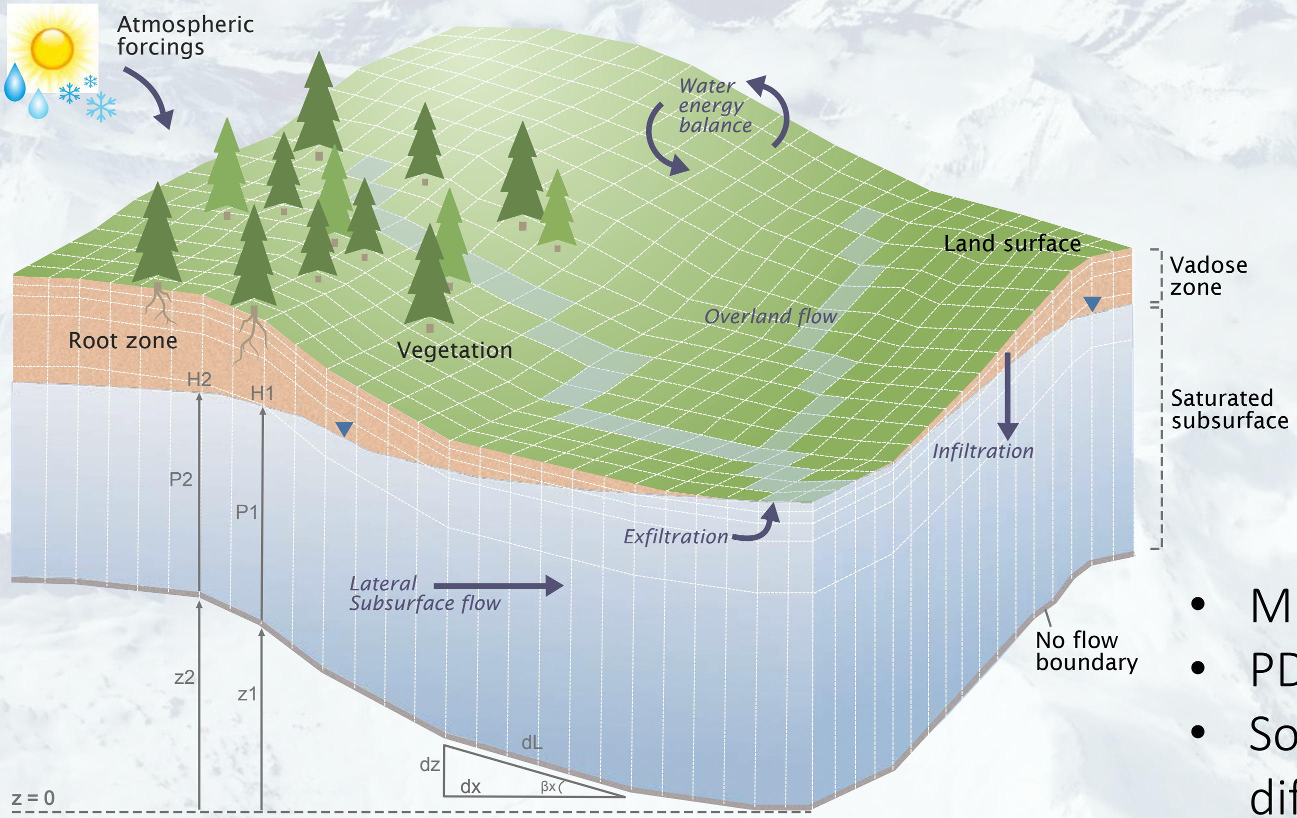
WATER RESOURCES RESEARCH, VOL. 47, W05301, doi:10.1029/2010WR010090, 2011

Hyperresolution global land surface modeling: Meeting a grand challenge for monitoring Earth's terrestrial water

Eric F. Wood,[1] Joshua K. Roundy,[1] Tara J. Troy,[1] L. P. H. van Beek,[2] Marc F. P. Bierkens,[2,3] Eleanor Blyth,[4] Ad de Roo,[5] Petra Döll,[6] Mike Ek,[7] James Famiglietti,[8] David Gochis,[9] Nick van de Giesen,[10] Paul Houser,[11] Peter R. Jaffé,[1] Stefan Kollet,[12] Bernhard Lehner,[13] Dennis P. Lettenmaier,[14] Christa Peters-Lidard,[15] Murugesu Sivapalan,[16] Justin Sheffield,[1] Andrew Wade,[17] and Paul Whitehead[18]

Received 6 October 2010; revised 21 January 2011; accepted 24 February 2011; published 6 May 2011.

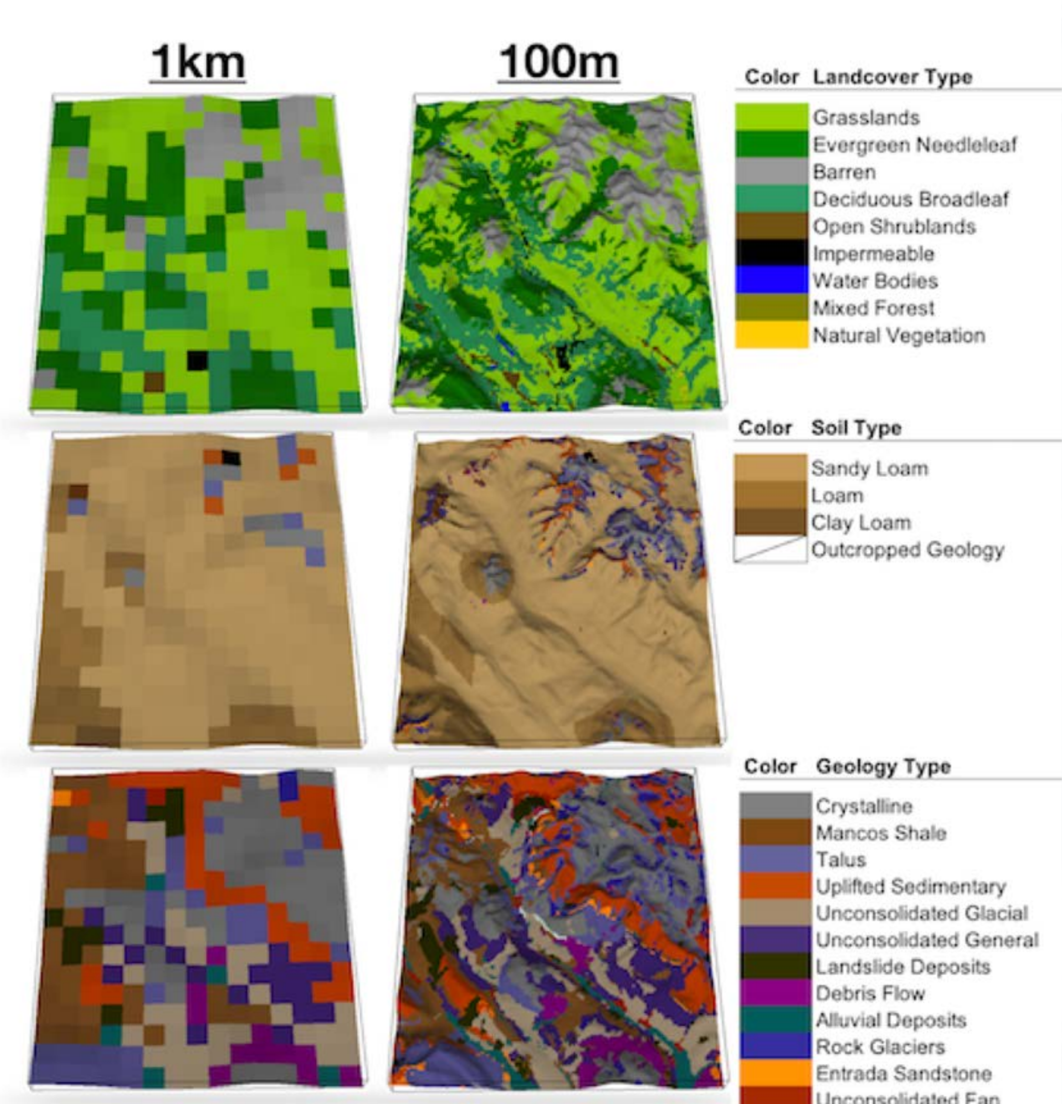
We use the integrated hydrologic model ParFlow, coupled to land surface model CLM



- Multi-physics
- PDE-based system
- Solving the nonlinear diffusion and wave equations
  - Globally
  - Implicitly
  - In parallel

Maxwell (2013); Kollet and Maxwell (2008); Kollet and Maxwell (2006);Maxwell and Miller (2005); Dai et al. (2003); Jones and Woodward (2001); Ashby and Falgout (1996)

At 1km patterns of landcover, elevation, geology, and soils are decimated

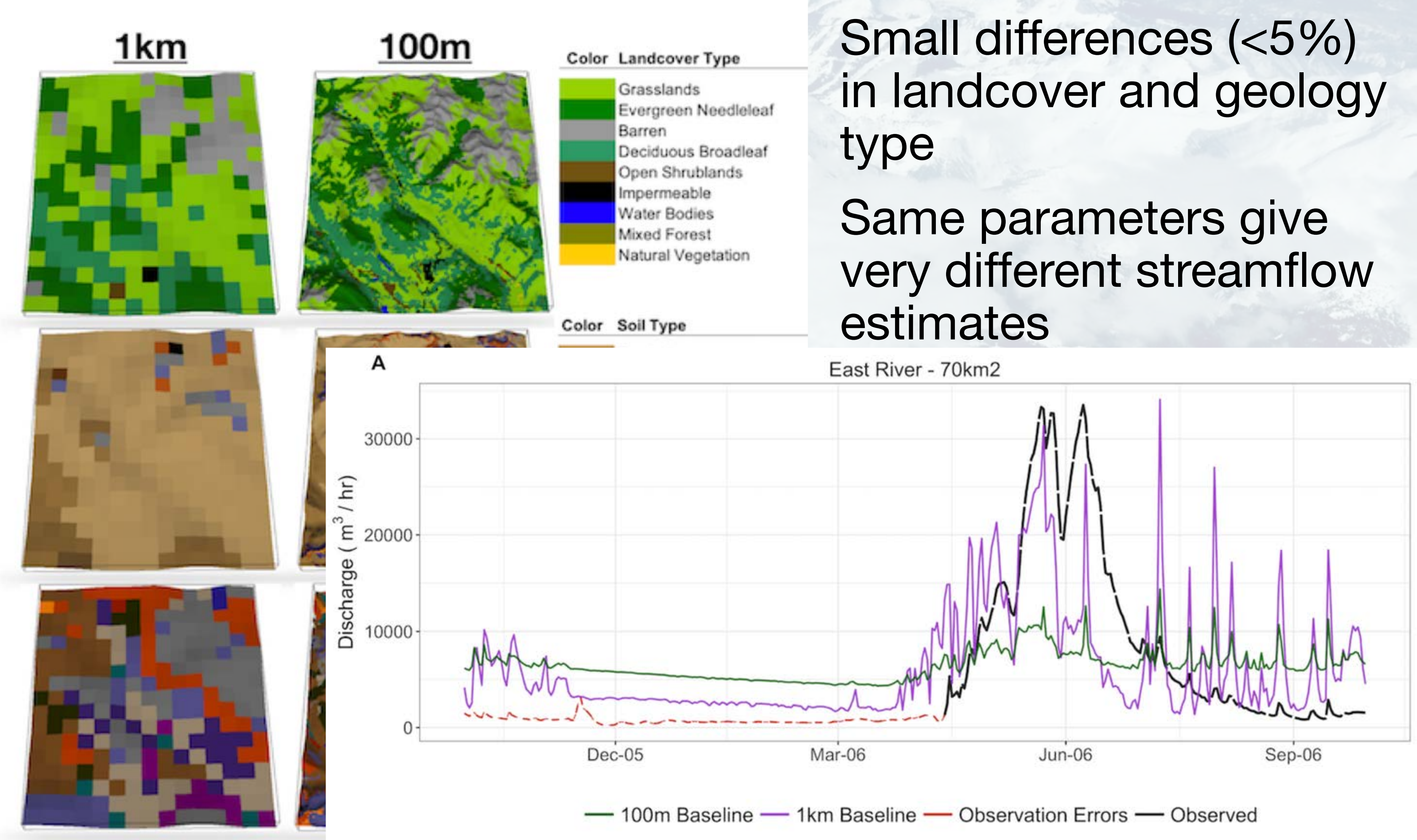


Small differences (<5%) in landcover and geology type

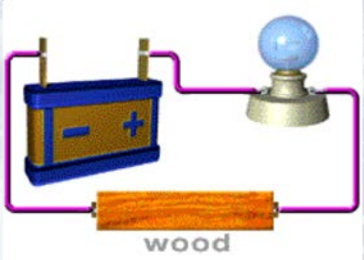
At 1km patterns of landcover, elevation, geology, and soils are decimated

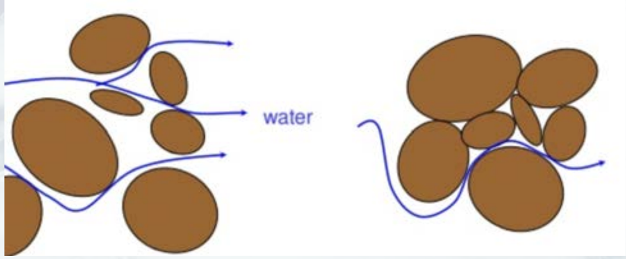
Small differences (<5%) in landcover and geology type

Same parameters give very different streamflow estimates



Hydraulic conductivity- critical parameter for estimating streamflow

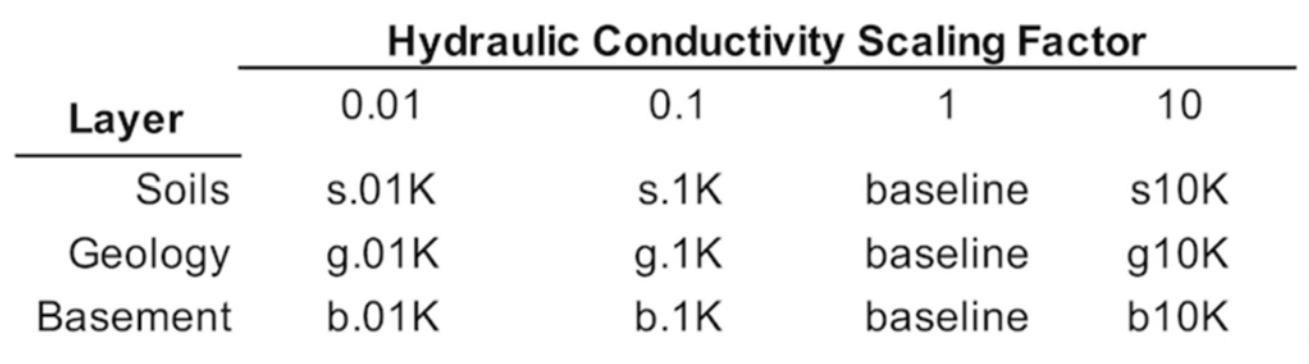




Electrical Conductivity: inherent property of substance explaining how conducive to FLOW

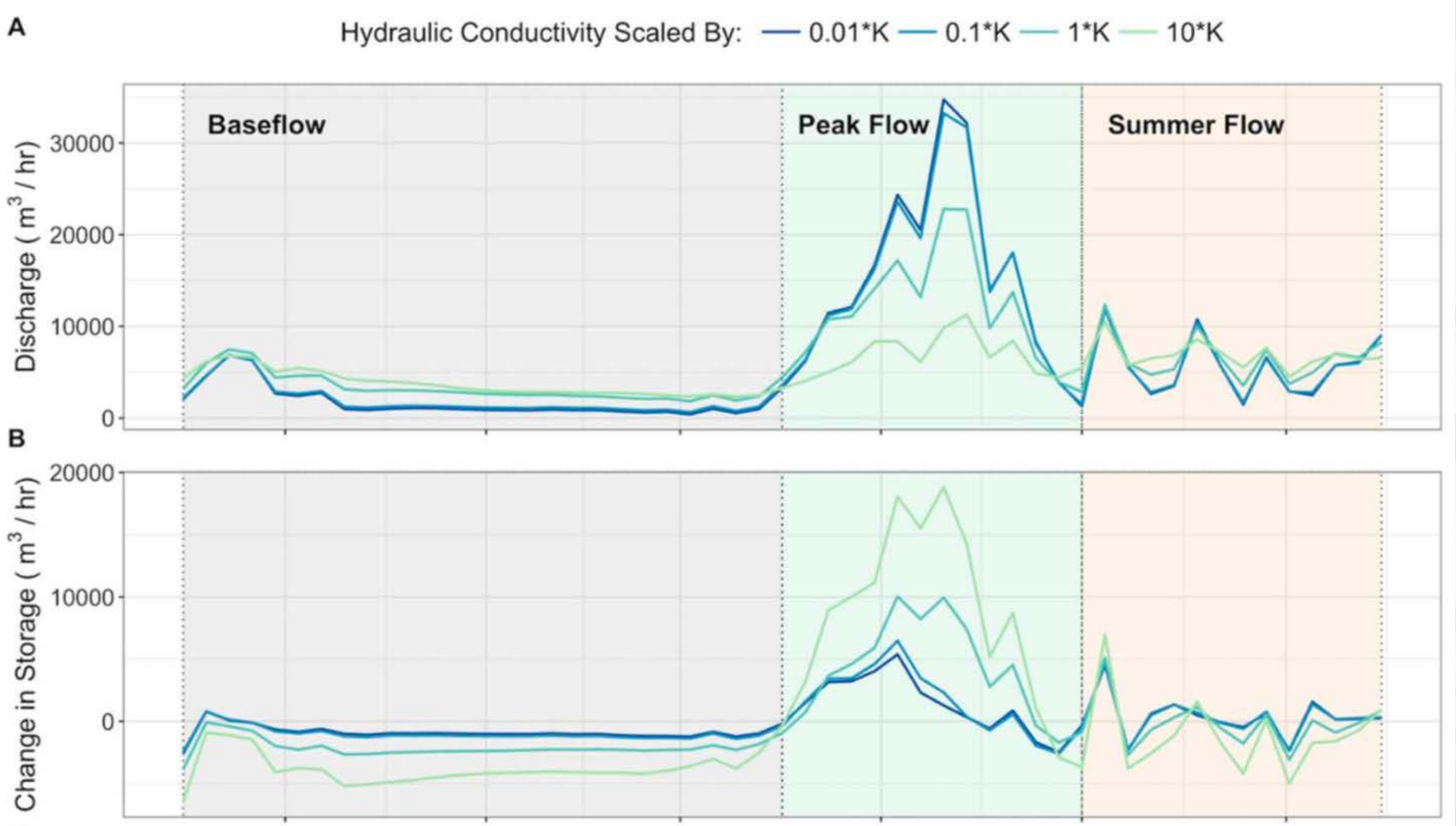
Hydraulic Conductivity: inherent property of rock explaining how easily water flows through it.

Sensitivity Experiment

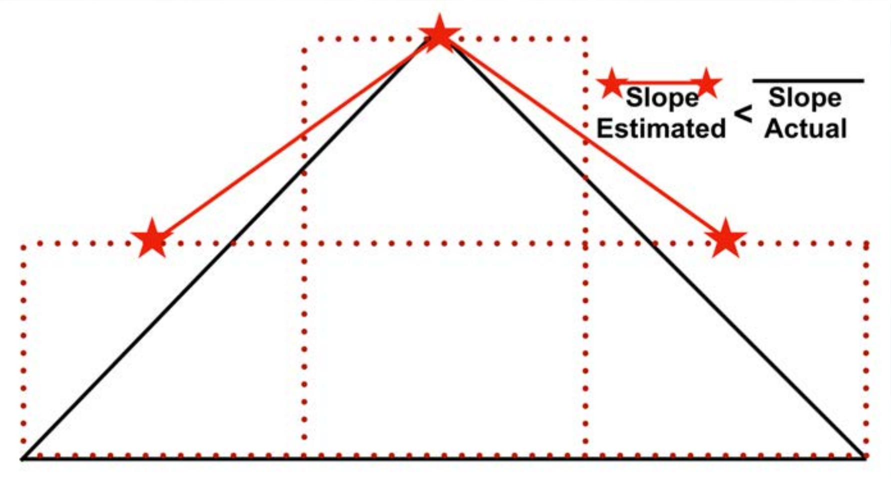


	Hydraulic Conductivity Scaling Factor			
Layer	0.01	0.1	1	10
Soils	s.01K	s.1K	baseline	s10K
Geology	g.01K	g.1K	baseline	g10K
Basement	b.01K	b.1K	baseline	b10K

Hydraulic conductivity acts as a moderator between streamflow and subsurface flow…

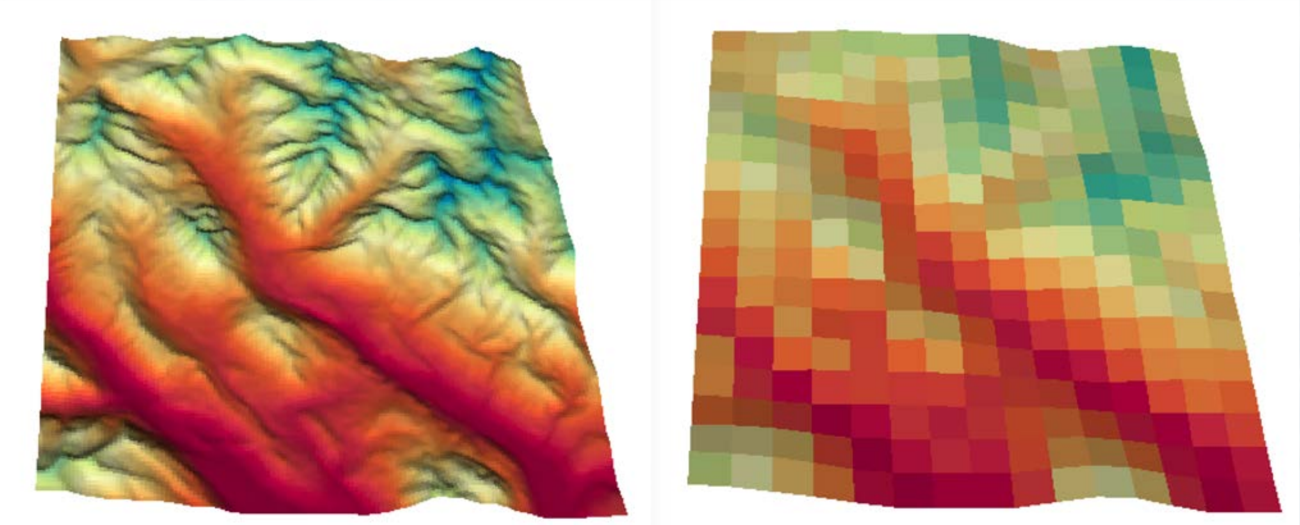


So then what changes between resolutions to cause different flow?



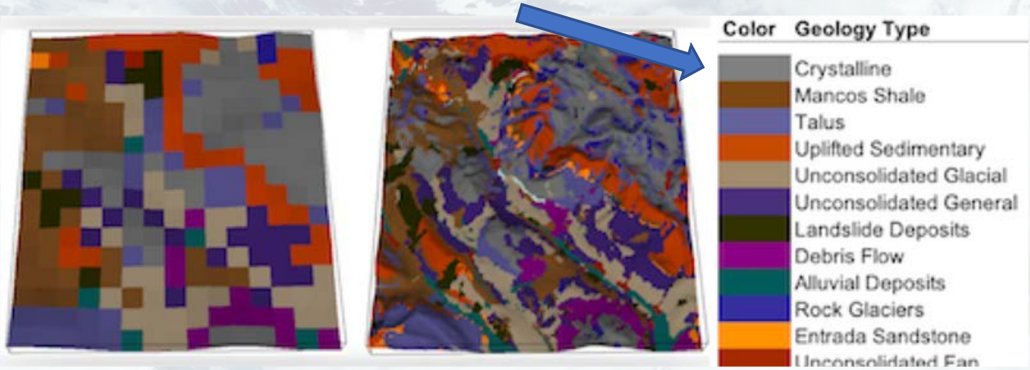
Simple Hydrology:

- Water flows downhill (GRAVITY)
- Resisted by friction (1/HYDRAULIC CONDUCTIVITY)



Combine uncertainty in *K* with loss of gradient to make *effective K*

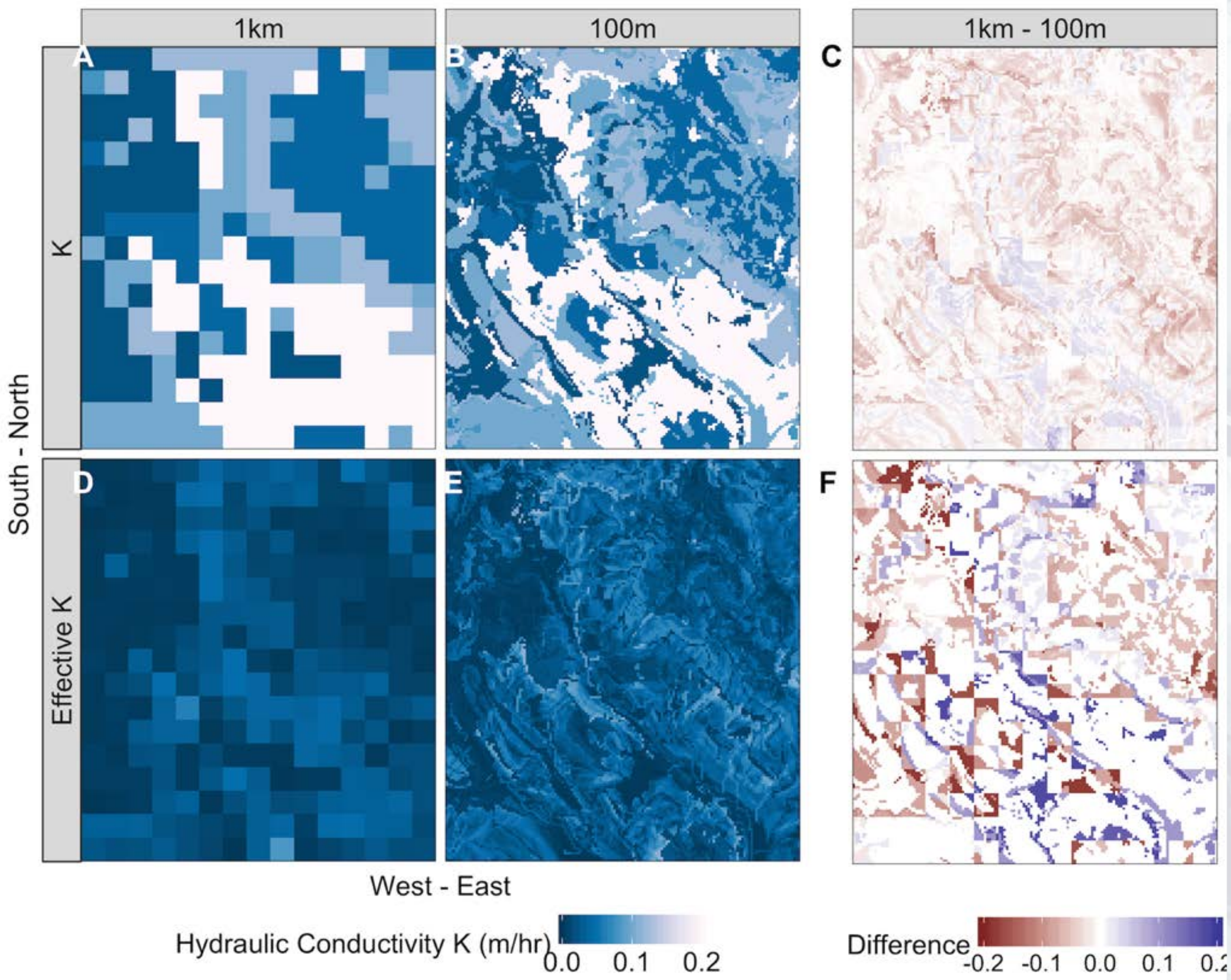
Measured Crystalline K (m/hr): $3.6\text{E-}11 < K < 1.08$



- Topographic loss of 191m of elevation… reduces gravity term in 1km model.
- Hydraulic Conductivity (K) is a highly variable (10 OM) measured parameter

$$K_{eff} = sin\theta K$$

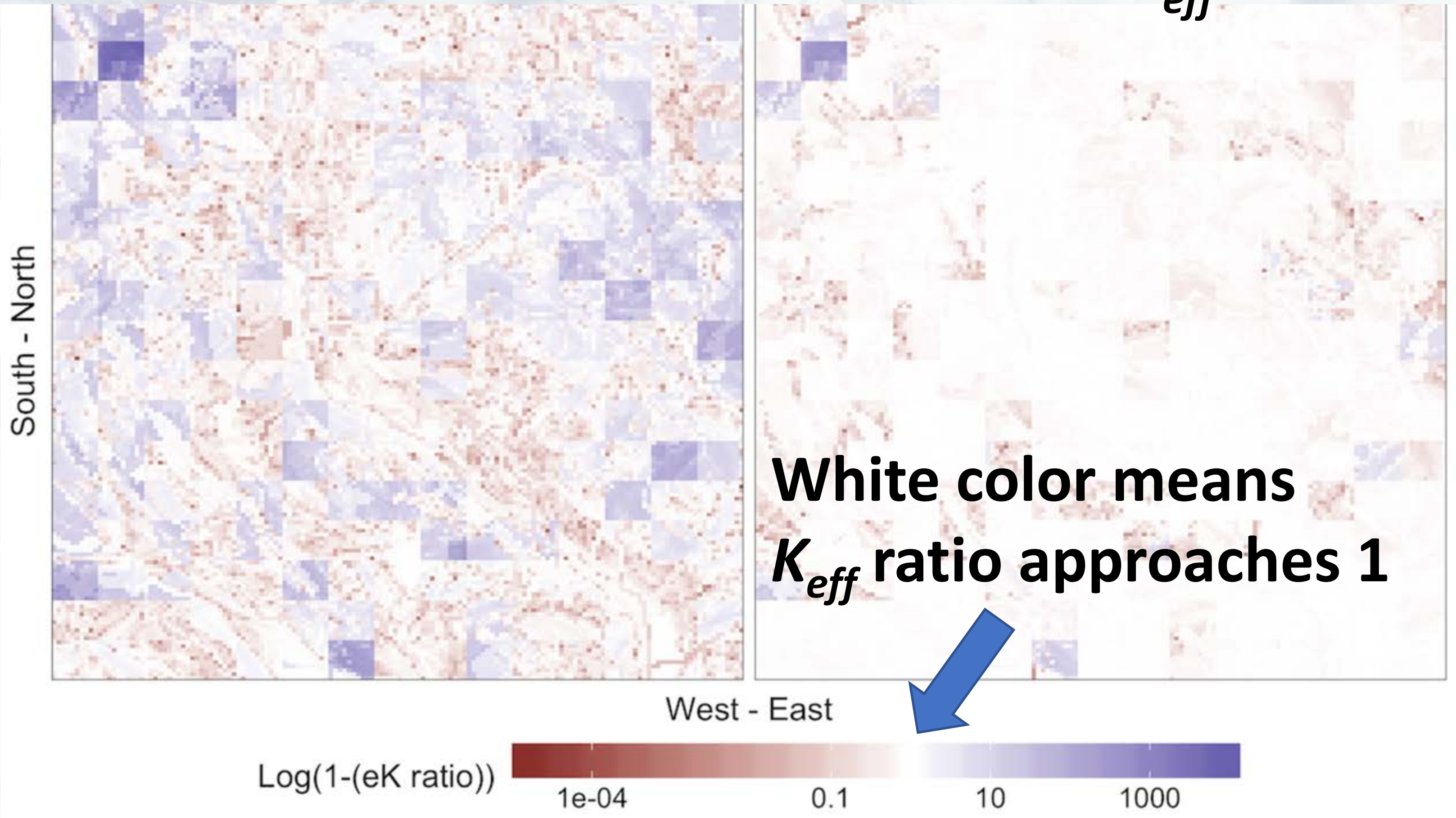
Much larger difference between 1km and 100m *effective K* than *K*



Next step to parameter matching is minimizing the *effective K* ratios between resolutions

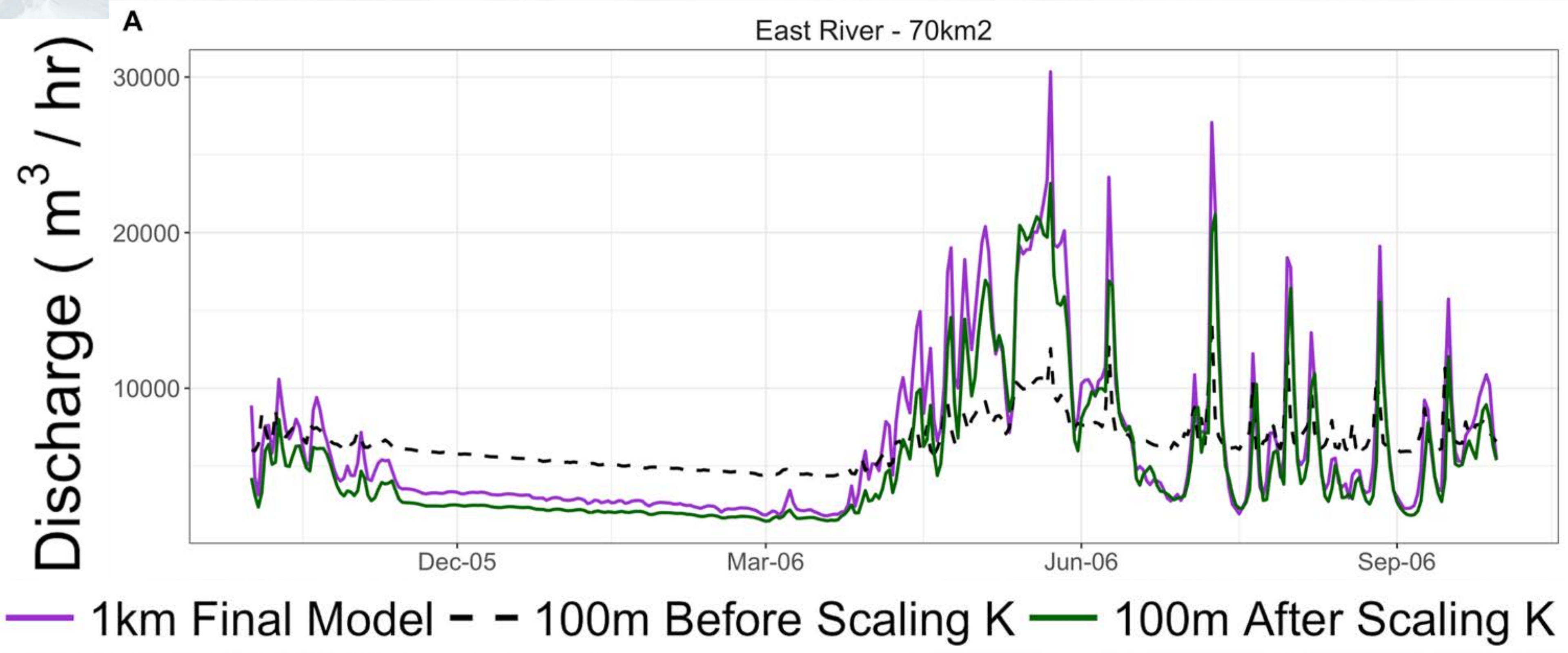
BEFORE SCALING

SCALING:
Minimize K_{eff} *ratio*



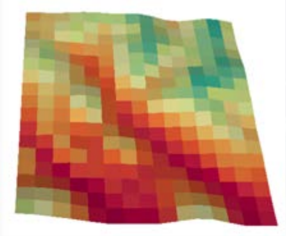
White color means K_{eff} ratio approaches 1

The improvement to matching streamflow between resolutions is dramatic

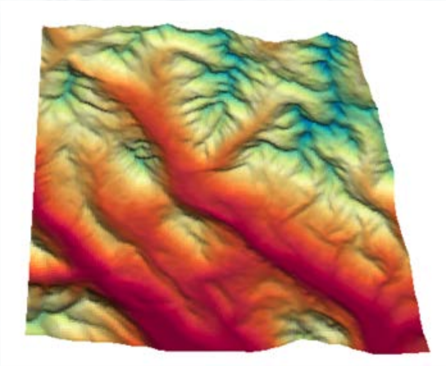


This method can help parameterize hyper-resolution models where traditional calibration procedures are limited by computational demand

Tune simple model parameters

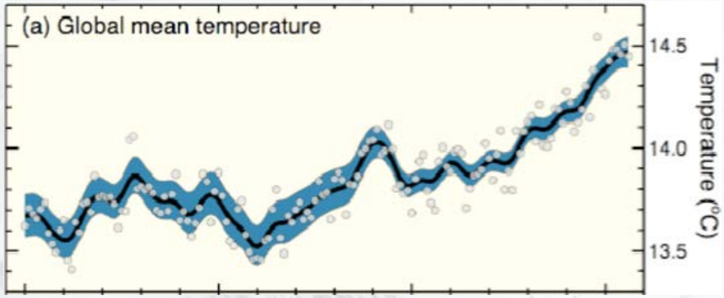


Parameter scaling method



Accurate fine to hyper scale model

Now we have matching fine and coarse-scale models to examine climate change impacts…



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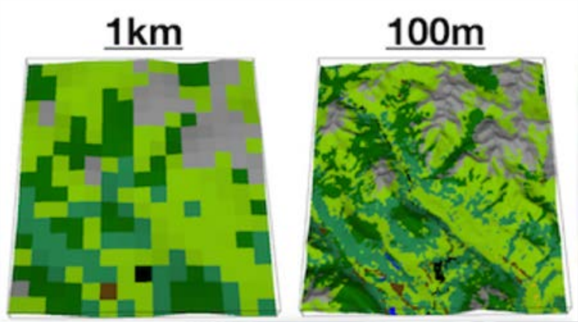


= ???

Global climate models and regional hydrologic models are known to perform poorly in the Rockies.

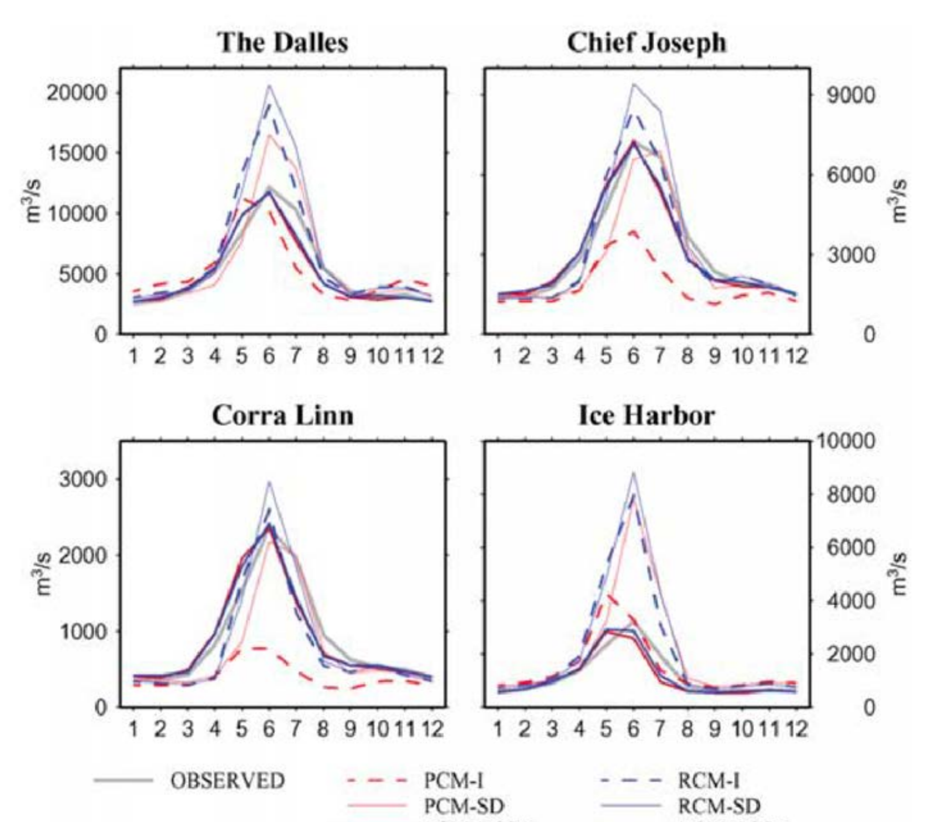
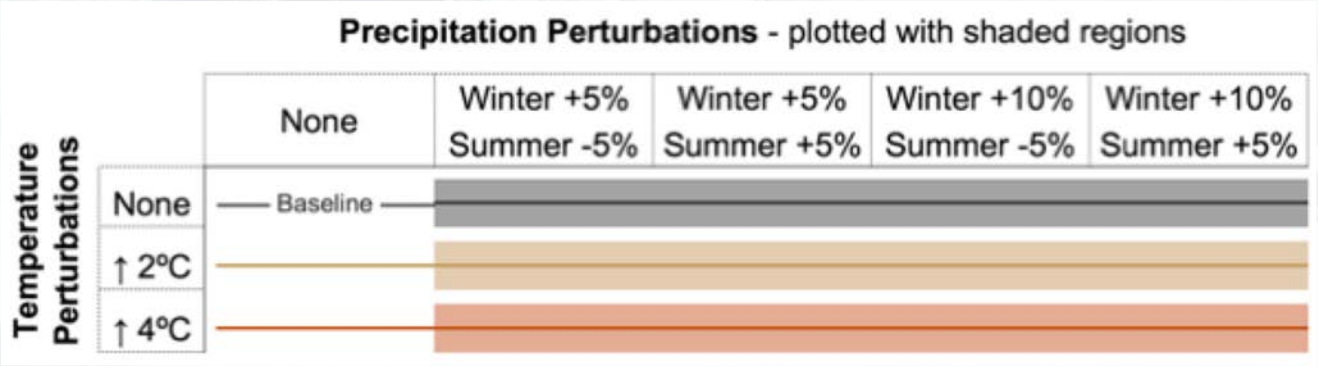


Figure 8

- Figure: simulated streamflow for different downscaling methods on PNW snowmelt driven rivers. (Wood et. al. 2003)
- Begs the question… if our models are more uncertain than climate change… are we able to predict climate impacts?

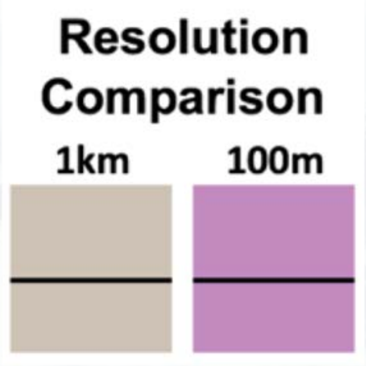
We compared climate variability with variation in model resolution

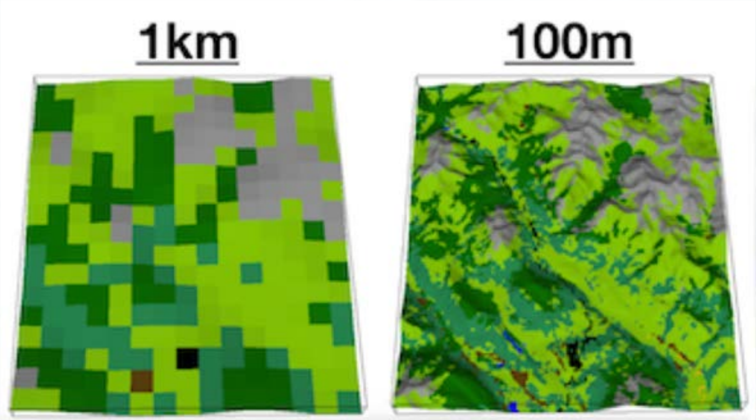
30 climate scenarios from Rocky Mountain projections



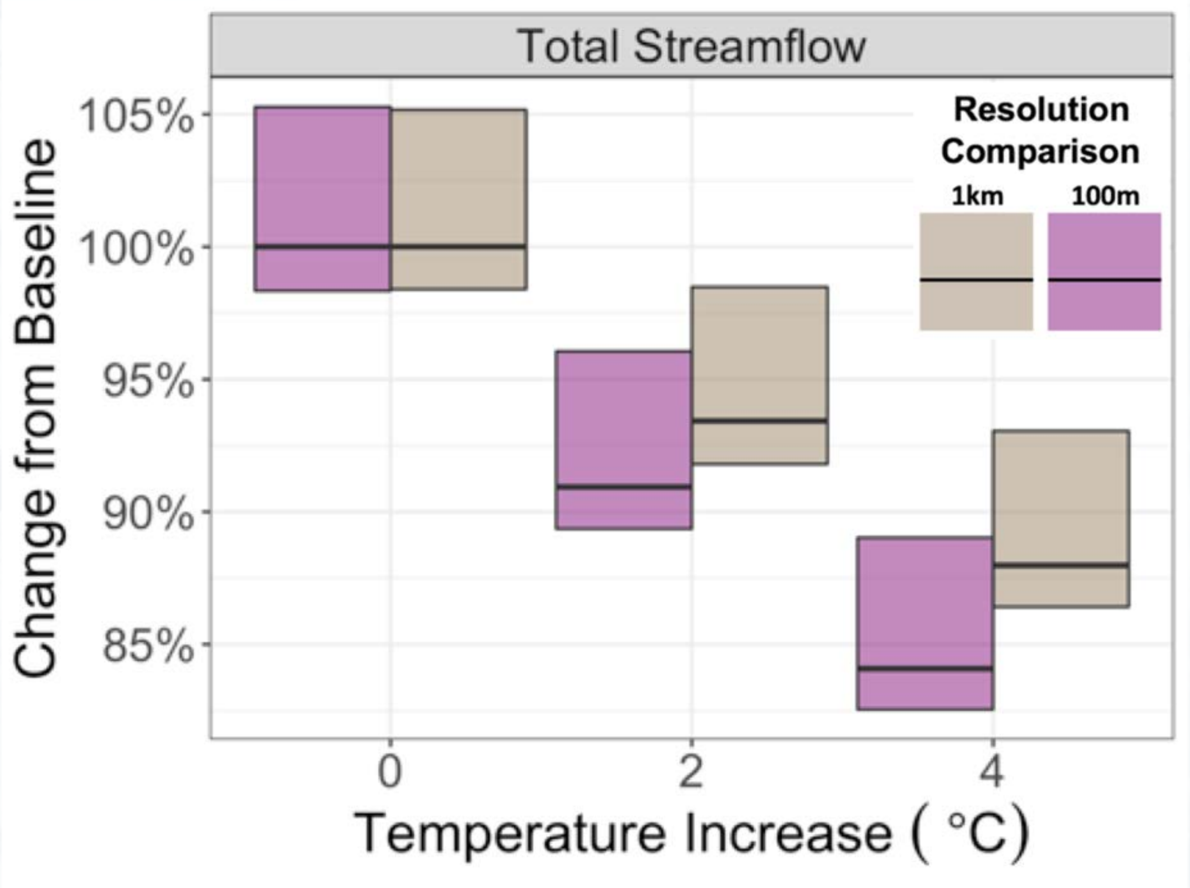
Precipitation Perturbations - plotted with shaded regions

Temperature Perturbations		None	Winter +5% Summer -5%	Winter +5% Summer +5%	Winter +10% Summer -5%	Winter +10% Summer +5%
	None	Baseline				
	↑ 2ºC					
	↑ 4ºC					



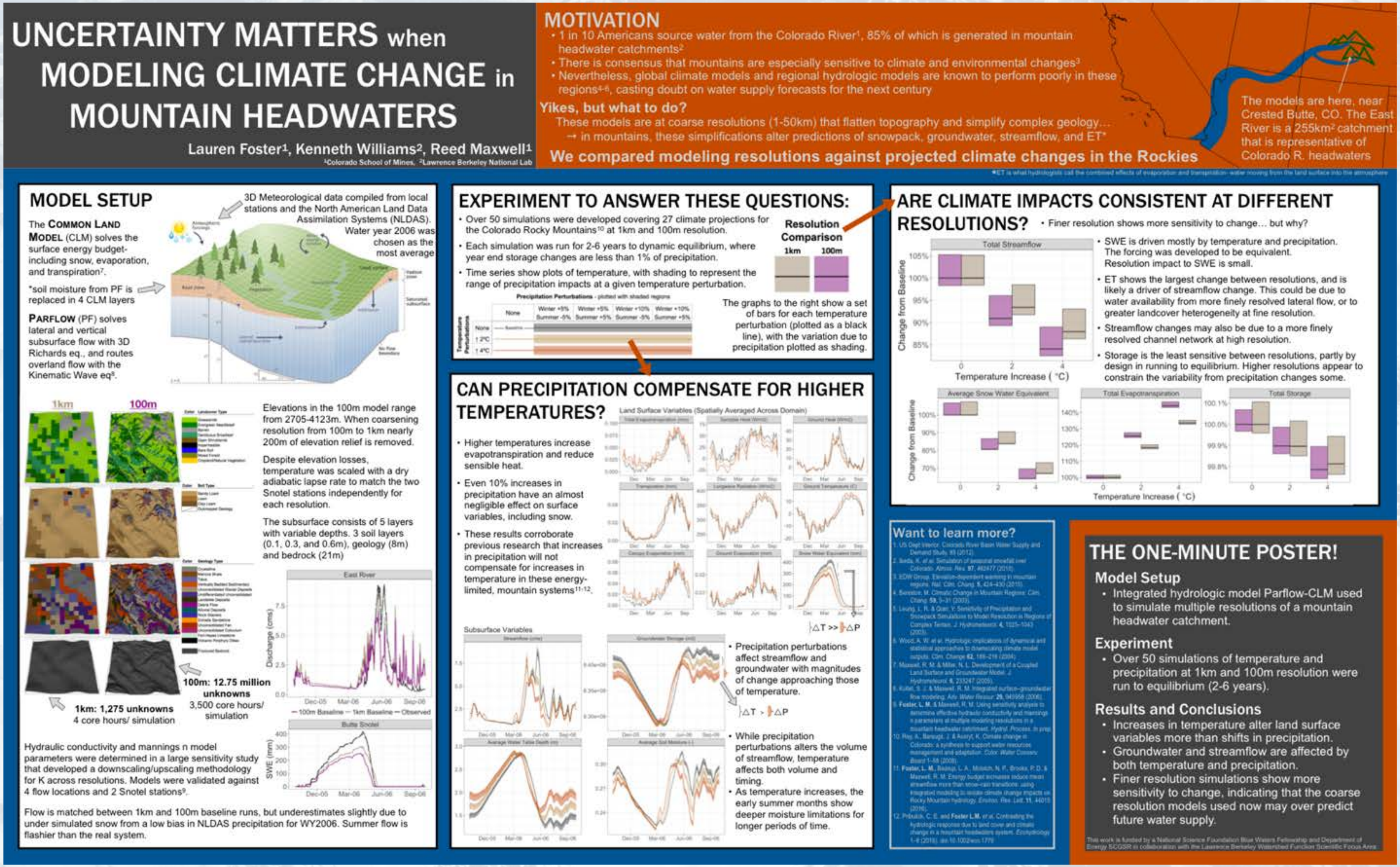


Results suggest that the coarse-resolution models used today may underestimate climate impacts



- 100m model predicts a 18% decrease in headwater streamflow after 4 degrees of warming… 1km model only predicts a 12%

To learn more…



UNCERTAINTY MATTERS when MODELING CLIMATE CHANGE in MOUNTAIN HEADWATERS

Lauren Foster[1], Kenneth Williams[2], Reed Maxwell[1]
[1]Colorado School of Mines, [2]Lawrence Berkeley National Lab

MOTIVATION

- 1 in 10 Americans source water from the Colorado River[1], 85% of which is generated in mountain headwater catchments[2]
- There is consensus that mountains are especially sensitive to climate and environmental changes[3]
- Nevertheless, global climate models and regional hydrologic models are known to perform poorly in these regions[4-6], casting doubt on water supply forecasts for the next century

Yikes, but what to do?

These models are at coarse resolutions (1-50km) that flatten topography and simplify complex geology…
→ in mountains, these simplifications alter predictions of snowpack, groundwater, streamflow, and ET*

We compared modeling resolutions against projected climate changes in the Rockies

The models are here, near Crested Butte, CO. The East River is a 255km² catchment that is representative of Colorado R. headwaters

*ET is what hydrologists call the combined effects of evaporation and transpiration- water moving from the land surface into the atmosphere

MODEL SETUP

3D Meteorological data compiled from local stations and the North American Land Data Assimilation Systems (NLDAS). Water year 2006 was chosen as the most average

The **COMMON LAND MODEL** (CLM) solves the surface energy budget- including snow, evaporation, and transpiration[7].

*soil moisture from PF is replaced in 4 CLM layers

PARFLOW (PF) solves lateral and vertical subsurface flow with 3D Richards eq., and routes overland flow with the Kinematic Wave eq[8].

Elevations in the 100m model range from 2705-4123m. When coarsening resolution from 100m to 1km nearly 200m of elevation relief is removed.

Despite elevation losses, temperature was scaled with a dry adiabatic lapse rate to match the two Snotel stations independently for each resolution.

The subsurface consists of 5 layers with variable depths. 3 soil layers (0.1, 0.3, and 0.6m), geology (8m) and bedrock (21m)

100m: 12.75 million unknowns
3,500 core hours/ simulation

1km: 1,275 unknowns
4 core hours/ simulation

Hydraulic conductivity and mannings n model parameters were determined in a large sensitivity study that developed a downscaling/upscaling methodology for K across resolutions. Models were validated against 4 flow locations and 2 Snotel stations[9].

Flow is matched between 1km and 100m baseline runs, but underestimates slightly due to under simulated snow from a low bias in NLDAS precipitation for WY2006. Summer flow is flashier than the real system.

EXPERIMENT TO ANSWER THESE QUESTIONS:

- Over 50 simulations were developed covering 27 climate projections for the Colorado Rocky Mountains[10] at 1km and 100m resolution.
- Each simulation was run for 2-6 years to dynamic equilibrium, where year end storage changes are less than 1% of precipitation.
- Time series show plots of temperature, with shading to represent the range of precipitation impacts at a given temperature perturbation.

The graphs to the right show a set of bars for each temperature perturbation (plotted as a black line), with the variation due to precipitation plotted as shading.

CAN PRECIPITATION COMPENSATE FOR HIGHER TEMPERATURES?

- Higher temperatures increase evapotranspiration and reduce sensible heat.
- Even 10% increases in precipitation have an almost negligible effect on surface variables, including snow.
- These results corroborate previous research that increases in precipitation will not compensate for increases in temperature in these energy-limited, mountain systems[11,12].

- Precipitation perturbations affect streamflow and groundwater with magnitudes of change approaching those of temperature.

- While precipitation perturbations alters the volume of streamflow, temperature affects both volume and timing.
- As temperature increases, the early summer months show deeper moisture limitations for longer periods of time.

ARE CLIMATE IMPACTS CONSISTENT AT DIFFERENT RESOLUTIONS?

- Finer resolution shows more sensitivity to change… but why?

- SWE is driven mostly by temperature and precipitation. The forcing was developed to be equivalent. Resolution impact to SWE is small.
- ET shows the largest change between resolutions, and is likely a driver of streamflow change. This could be due to water availability from more finely resolved lateral flow, or to greater landcover heterogeneity at fine resolution.
- Streamflow changes may also be due to a more finely resolved channel network at high resolution.
- Storage is the least sensitive between resolutions, partly by design in running to equilibrium. Higher resolutions appear to constrain the variability from precipitation changes some.

Want to learn more?

THE ONE-MINUTE POSTER!

Model Setup

- Integrated hydrologic model Parflow-CLM used to simulate multiple resolutions of a mountain headwater catchment.

Experiment

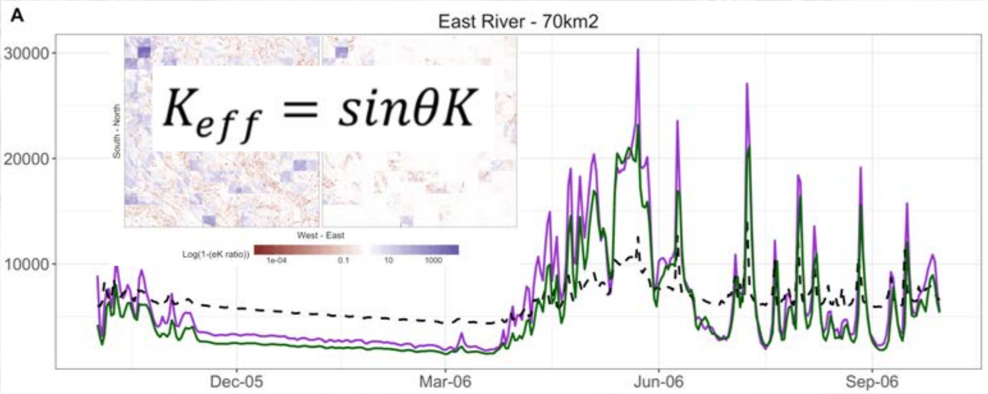
- Over 50 simulations of temperature and precipitation at 1km and 100m resolution were run to equilibrium (2-6 years).

Results and Conclusions

- Increases in temperature alter land surface variables more than shifts in precipitation.
- Groundwater and streamflow are affected by both temperature and precipitation.
- Finer resolution simulations show more sensitivity to change, indicating that the coarse resolution models used now may over predict future water supply.

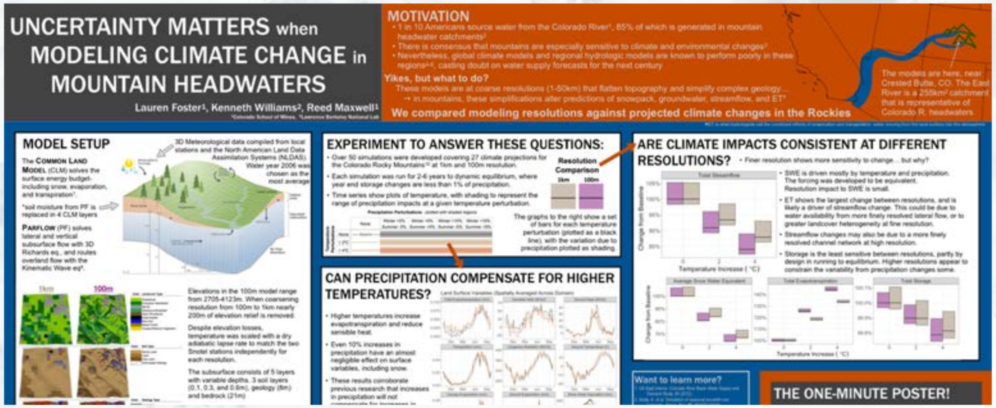
This work is funded by a National Science Foundation Blue Waters Fellowship and Department of Energy SCGSR in collaboration with the Lawrence Berkeley Watershed Function Scientific Focus Area

Why systems like BW? Computational Demand…



Parameter scaling study:

- 36 simulations
- 60,000 core hours



UNCERTAINTY MATTERS when MODELING CLIMATE CHANGE in MOUNTAIN HEADWATERS

Lauren Foster[1], Kenneth Williams[2], Reed Maxwell[1]

MOTIVATION

- 1 in 10 Americans source water from the Colorado River[1], 85% of which is generated in mountain headwater catchments[2]
- There is consensus that mountains are especially sensitive to climate and environmental changes[3]
- Nevertheless, global climate models and regional hydrologic models are known to perform poorly in these regions[4], casting doubt on water supply forecasts for the next century

Yikes, but what to do?

These models are at coarse resolutions (1-50km) that flatten topography and simplify complex geology…
→ in mountains, these simplifications alter predictions of snowpack, groundwater, streamflow, and ET*

We compared modeling resolutions against projected climate changes in the Rockies

The models are here, near Crested Butte, CO. The East River is a 255km² catchment that is representative of Colorado R. headwaters

MODEL SETUP

EXPERIMENT TO ANSWER THESE QUESTIONS:

ARE CLIMATE IMPACTS CONSISTENT AT DIFFERENT RESOLUTIONS? • Finer resolution shows more sensitivity to change… but why?

CAN PRECIPITATION COMPENSATE FOR HIGHER TEMPERATURES?

Want to learn more?

THE ONE-MINUTE POSTER!

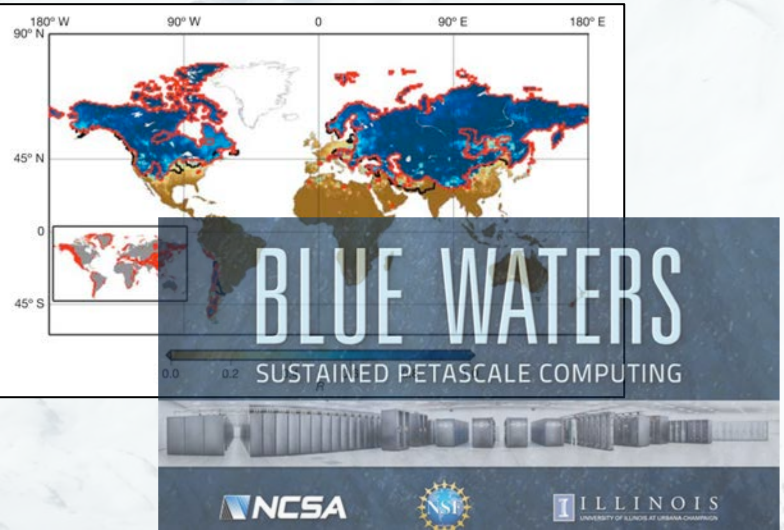
Climate uncertainty study:

- 54 simulations
- 90,000 core hours

Total: 150,000 hours (not counting mistakes or experiments that were not included in papers)

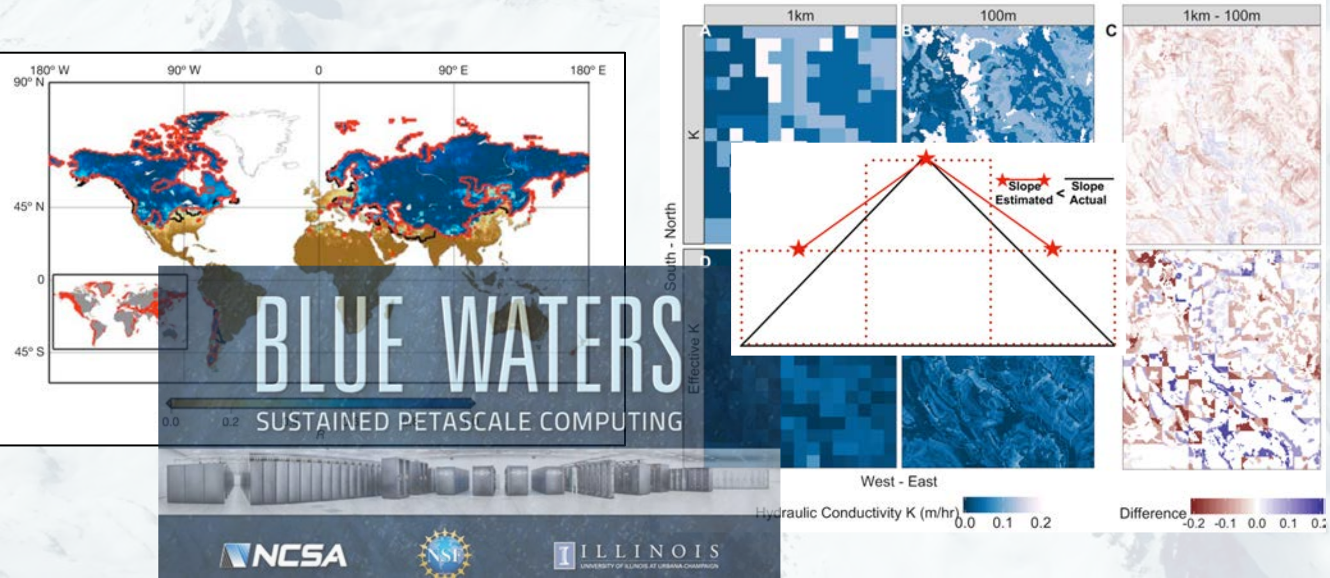
Conclusions

- Hyper-resolution models and HPC systems can help us understand important, complex systems like mountains



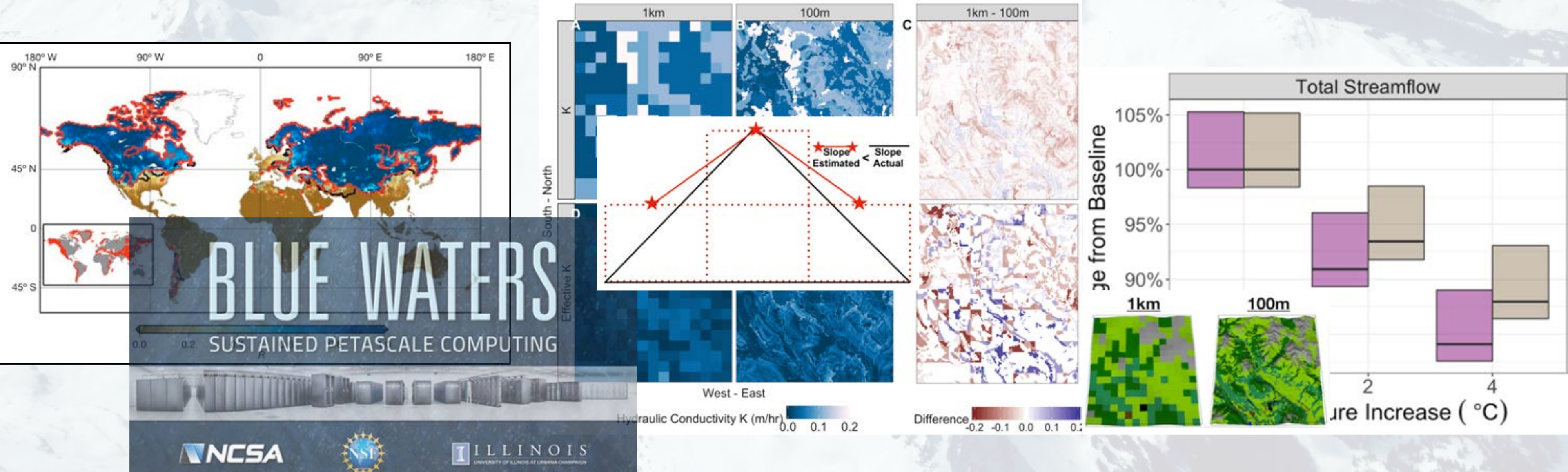
Conclusions

- Hyper-resolution models and HPC systems can help us understand important, complex systems like mountains
- Model interrogation and development are critical to getting the right answers for the right reasons… i.e. model sensitivity and parameter estimation!



Conclusions

- Hyper-resolution models and HPC systems can help us understand important, complex systems like mountains
- Model interrogation and development are critical to getting the right answers for the right reasons… i.e. model sensitivity and parameter estimation!
- How we build and use our models is as important as the climate changes they are built to detect, so we must be thoughtful about our results and their implications.



Thank you!!

BLUE WATERS

SUSTAINED PETASCALE COMPUTING

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COLORADO SCHOOL OF MINES

EARTH • ENERGY • ENVIRONMENT

Climate [change]?

Questions?