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

Contrasting Model Resolution and Complexity in an Alpine Catchment
CLIMATE CHANGE = ⬆ Temp, ⬇ Snowpack
Figure (Barnett et al 2005): More than 1/6th population depends on surface water supplies from snowmelt-dominat es systems.
MOUNTAIN SNOWPACK CRITICAL FOR WATER SUPPLIES

Figure (Barnett et al 2005): More than $1/6$th 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)

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

<table>
<thead>
<tr>
<th>Elevational gradient in the warming rate</th>
<th>Observations</th>
<th>Models</th>
</tr>
</thead>
<tbody>
<tr>
<td>Increases with elevation</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Annual(^{23,8a,86})</td>
<td>Annual(^{23,81})</td>
<td>Annual(^{76,5e,80b,10c,11,75})</td>
</tr>
<tr>
<td>Winter(^{23,70g,45})</td>
<td>Winter(^{47})</td>
<td>Winter(^{45,43,72,74})</td>
</tr>
<tr>
<td>Spring(^{47})</td>
<td>Summer(^{47})</td>
<td>Spring(^{45,43})</td>
</tr>
<tr>
<td>Autumn(^{62,83c})</td>
<td></td>
<td>Autumn(^{72})</td>
</tr>
<tr>
<td>Decreases with elevation</td>
<td>Winter(^{23})</td>
<td>Winter(^{130})</td>
</tr>
<tr>
<td>Annual(^{68})</td>
<td>Annual(^{77,84})</td>
<td>Annual(^{30,13c,14,82})</td>
</tr>
<tr>
<td>Winter(^{30g})</td>
<td>Winter(^{30g})</td>
<td>All seasons(^{44,85})</td>
</tr>
<tr>
<td>Autumn(^{30g})</td>
<td>Autumn(^{30g})</td>
<td></td>
</tr>
<tr>
<td>No significant gradient</td>
<td>Annual(^{78})</td>
<td>Annual(^{30})</td>
</tr>
<tr>
<td>Annual(^{9,43c})</td>
<td>Annual(^{9,43c})</td>
<td></td>
</tr>
<tr>
<td>Spring(^{30g})</td>
<td>Spring(^{30g})</td>
<td></td>
</tr>
<tr>
<td>No significant gradient but largest warming rates at an intermediate elevation</td>
<td>Annual(^{78})</td>
<td>Annual(^{30})</td>
</tr>
</tbody>
</table>

Superscript letters accompanying references indicate: ‘No significant gradient but greater warming at higher elevations relative to regions between 0-500 m; `radiosonde data, clearest signal in the tropics; 65% of the regional groups examined showed fastest trends at highest elevations and 20% showed fastest trends at intermediate elevations; *high-elevation trends based on borehole data; †satellite-derived temperature estimations; ‡reanalyses; §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
  * Remote sensing can’t see everything
All methodologies simplify the real world…

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

- 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
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.

<table>
<thead>
<tr>
<th>Layer</th>
<th>Hydraulic Conductivity Scaling Factor</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0.01</td>
</tr>
<tr>
<td>Soils</td>
<td>s.01K</td>
</tr>
<tr>
<td>Geology</td>
<td>g.01K</td>
</tr>
<tr>
<td>Basement</td>
<td>b.01K</td>
</tr>
</tbody>
</table>
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): $3.6E-11 < K < 1.08$

- 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 $K_{\text{eff}}$ ratio

White color means $K_{\text{eff}}$ 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.

Now we have matching fine and coarse-scale models to examine climate change impacts...
Global climate models and regional hydrologic models are known to perform poorly in the Rockies.

- 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
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, Kenneth Williams, Reed Maxwell

MODEL SETUP

The Common Land Model (CLM) solves the surface energy budget including snow, evaporation, and transpiration.

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

EXPERIMENT TO ANSWER THESE QUESTIONS:

- Over 50 simulations were developed covering 27 climate projections for the Colorado Rocky Mountains at 1km and 100m resolution.
- Each simulation was run for 2-4 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 on a linear scale, with the variation due to precipitation plotted as shading.

ARE CLIMATE IMPACTS CONSISTENT AT DIFFERENT RESOLUTIONS?

- Finer resolution shows more sensitivity to change...but why?
- SVM is driven mostly by temperature and precipitation. The forcing was developed to be equivalent.
- ET shows the largest change between resolutions, and is likely a driver of streamflow change. This could be due to availability from more finely resolved lateral flow, or greater landslides 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.

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 (2-4 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 overpredict future water supply.
Why systems like BW? Computational Demand...

Parameter scaling study:
- 36 simulations
- 60,000 core hours

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.
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- Model interrogation and development are critical to getting the right answers for the right reasons... i.e. model sensitivity and parameter estimation!
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• 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!!
Climate [change]?

My desire to be well-informed is currently at odds with my desire to remain sane.

Questions?