Scalability of Grid- and Subbasin-Based Land Surface Modeling Frameworks for Hydrologic Simulations

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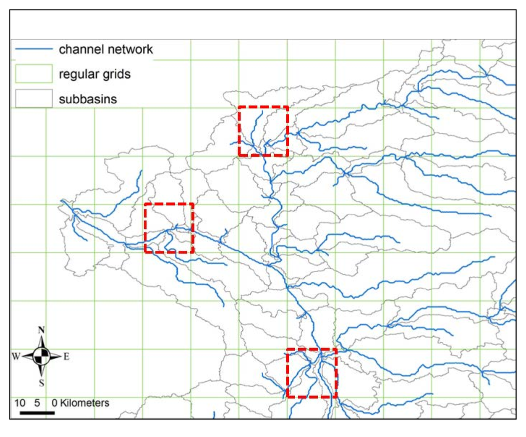
Introduction

Land surface models are typically configured to run on regular rectangular grids at uniform and relatively coarse spatial scales for coupling with atmospheric models to simulate climate and earth system processes. However, subbasin-based modeling framework (dividing a study domain into subbasins) offers distinct advantages, including:

- ▶Subbasins follow the natural topographic divides and river network structure that strongly govern hydrological processes such as runoff and streamflow; and
- ▶In grid-based approach, a grid cell often encompasses areas from several subbasins challenging the conceptual basis of runoff generation schemes in which topographic variation is of primary importance (e. g., TOPMODEL).



Subbasins overlaid with grids at 0.125° (highlighted with red dashed line are examples of grids containing areas from multiple river channels and subbasins).

Despite these advantages, the two modeling approaches have not been systematically compared to evaluate their relative merits in land surface modeling.

Objectives

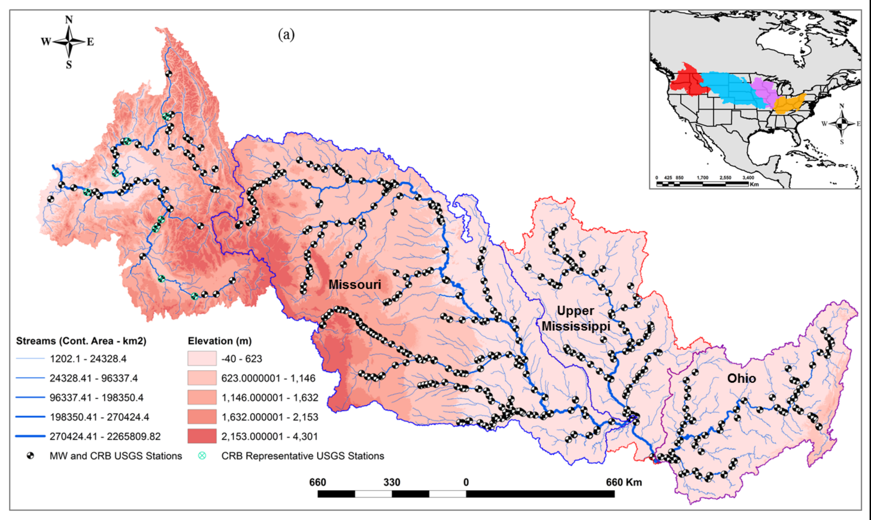
As a step towards understanding their relative merits, the two modeling frameworks are compared from scalability (ability to perform consistently across multiple spatial scales) perspective on runoff generation and streamflow simulation across multiple spatial scales.

Model development and experimental design

▶A subbasin-based modeling approach (SCLM) is introduced in the Community Land Modeling(CLM), the land component of the Community Earth System Model (CESM).

▶Both, SCLM and the grid-based (CLM) are coupled with a physically based routing model, Model for Scale Adaptive River Transport (MOSART).

▶Both modeling frameworks are applied at four spatial resolutions (0.125°, 0.25 °, 0.5°, and 1 °) over the Columbia River Baisn (CRB) and U.S. Midwest region (MW).



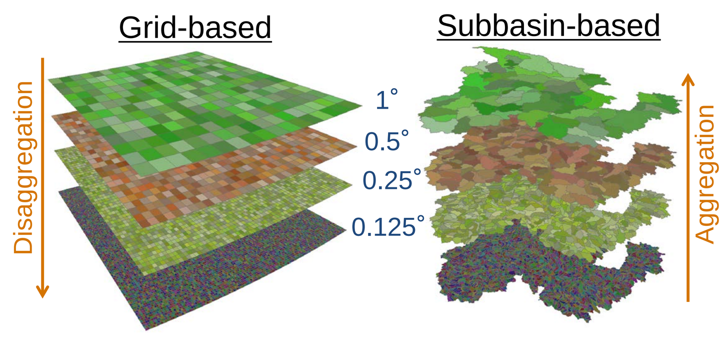
The Columbia River Basin (CRB) and U.S. Midwest (MW), elevation, stream networks, MW major basins, USGS streamflow gauging stations with drainage area greater than 15000 Km² and the stations selected for detailed analysis in CRB.

▶Both, grid- and subbasin-based models are driven by the same meteorological forcing (NLDAS-2 1979-2008) and land surface parameters generated using the same methods, and spun up until the state variables reached equilibrium.

Methods of analyses

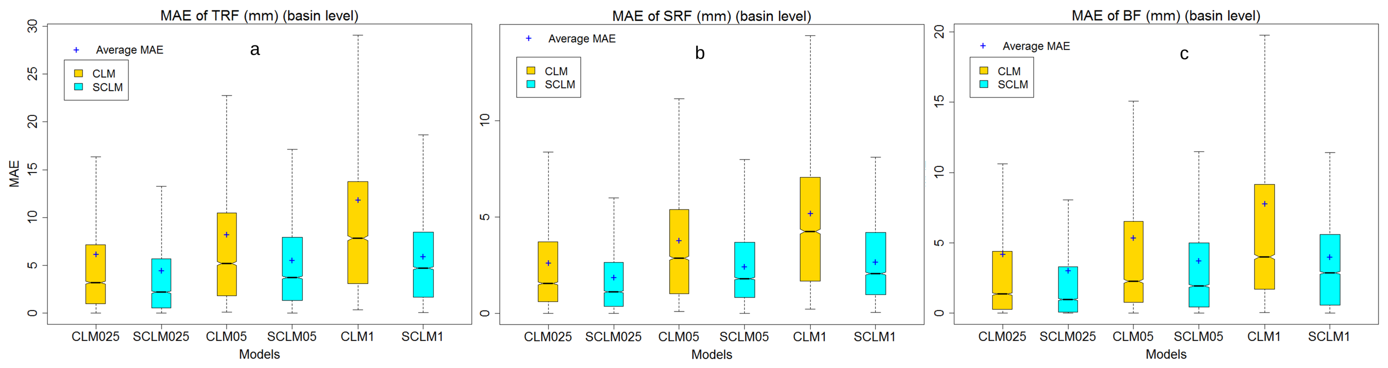
▶Using simulations at 0.125° as a reference, runoff simulated by the two modeling frameworks at each coarse resolution (0.25 °, 0.5°, and 1 °) are compared with the reference solutions using aggregated and disaggregated approaches at CRB (basin) and topographic region levels.

▶Major meteorological and land surface parameters are investigated over various topographic regions to provide insights on the factors that influence scalability on runoff generation.



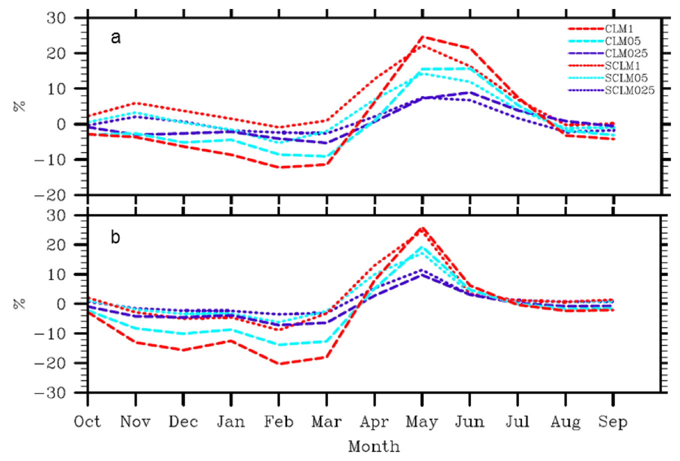
▶Using simulations at 0.125° as a reference solution, model scalability in streamflow simulation is investigated using absolute difference in specific peak flows (results not shown) at CRB gauges and Nash Sutcliffe Efficiency (NSE) at both CRB and MW stream gauges across multiple scales and various climate regimes.

Results on runoff scalability



Scalability in (a) total, (b) surface and (c) subsurface runoff simulations based on mean absolute error (MAE) of the coarser scales in comparison to the reference solution aggregated to each coarse resolution.

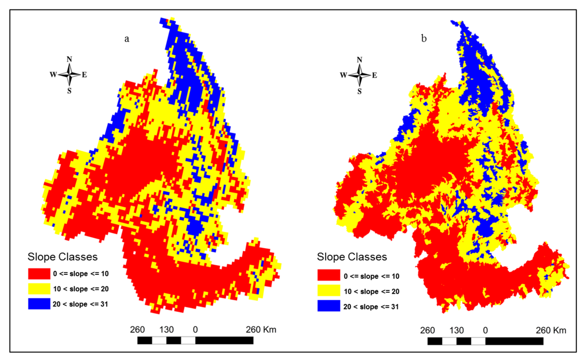
▶SCLM MAEs are much smaller than that of CLM at all coarse resolutions for total runoff, surface runoff, and subsurface runoff showing a clear scalability advantage for SCLM over CLM in runoff generation.



Relative error in long-term monthly mean (a) total and (b) surface runoff simulated by each coarse resolution as compared to the corresponding reference solution over the whole CR.

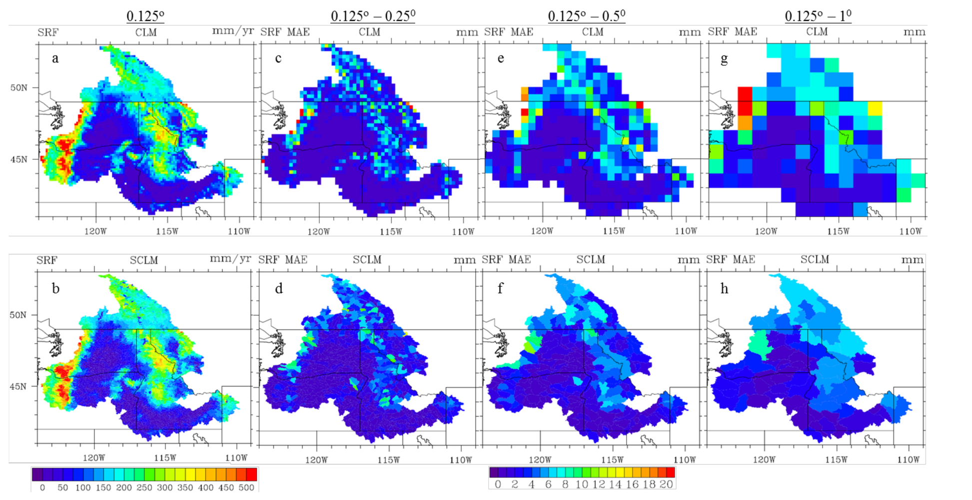
▶SCLM has better scalability in both total runoff and surface runoff than CLM.

▶Scalability advantage is more pronounced during winter months.



Topographic regions of CRB: (red) gentle, (yellow) moderately steep and (blue) steep gradients (a) grid-based and (b) subbasin-based.

▶Both, grid- and subbasin-based topographic regions have similar spatial distribution.

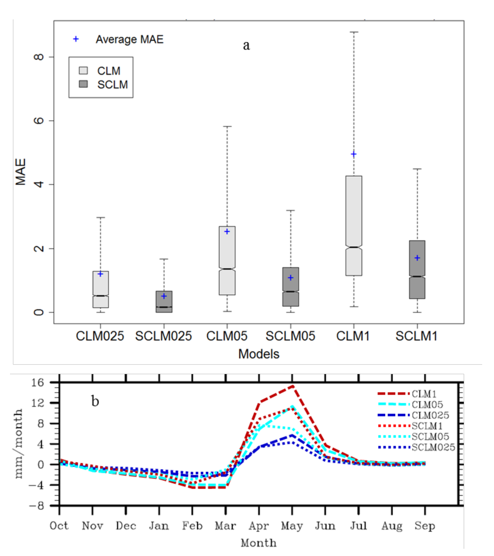


Spatial distribution of long-term average surface runoff in mm/year for (a) grid-based 0.125°, (b) subbasin-based 0.125° and the corresponding coarse resolutions.

▶Despite almost no discernible difference in spatial distribution at 0.125°, there is clear difference in MAEs at the coarse resolutions.

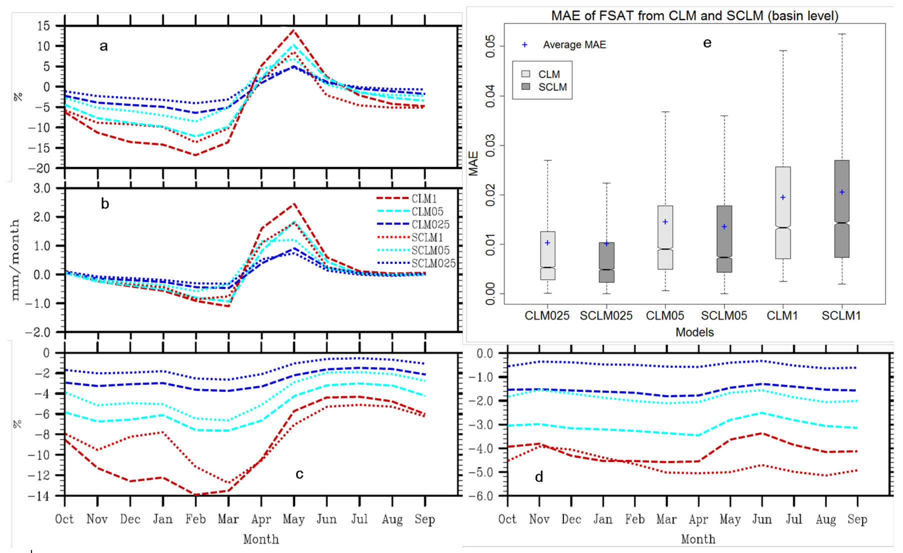
▶Differences are more pronounced over the moderately steep and steep regions.

Sources of differences on runoff scalability



Differences between SCLM and CLM on (a) MAEs (mm) of snowfall and (b) bias in long-term monthly average snowmelt (mm/month) at basin level.

▶Clear scalability advantage in snowfall and seasonal snowmelt, for SCLM, resulted from better consistency in surface temperature/elevation.

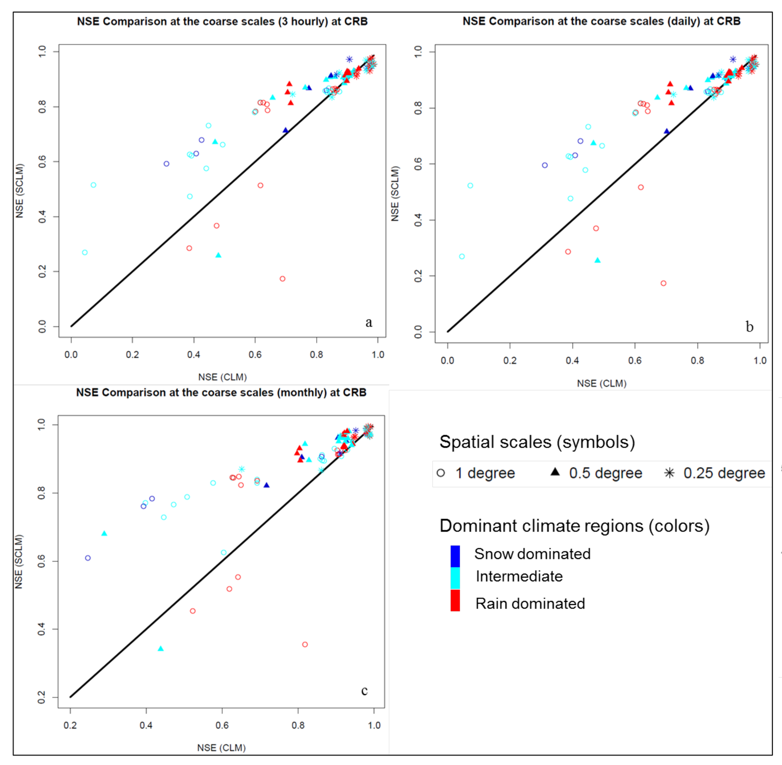


Difference between the coarse scale CLM and SCLM compared to the 0.125° aggregated to the coarse resolutions for the (a) saturated fraction of surface runoff (%), (b) snowmelt component of saturated surface runoff (mm/month), (c) rain component of saturated surface runoff of the seasonal saturated fraction (%), and (d) F_{sat} (%). The MAEs (fraction) of saturated fraction, F_{sat}, are shown in Figure 11e.

▶Scalability difference between SCLM and CLM in the rain-driven saturated runoff is caused by F_{sat}.

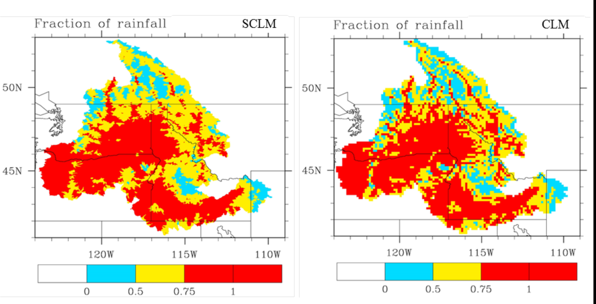
▶Topography contributes to SCLM scalability advantage.

Results on streamflow scalability

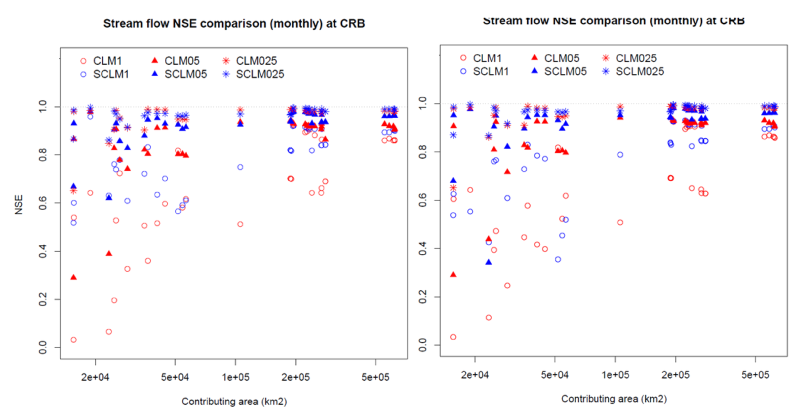


Scalability comparison using Nash Sutcliffe Efficiency (NSE) of streamflow at 3 hourly (a), daily (b) and monthly (c) calculated between each coarse scale and the corresponding fine scale in each modeling framework at the USGS stations with contributing area larger than 15000 km².

▶SCLM-MOSART resulted in superior scalability, especially in snow dominated regions.



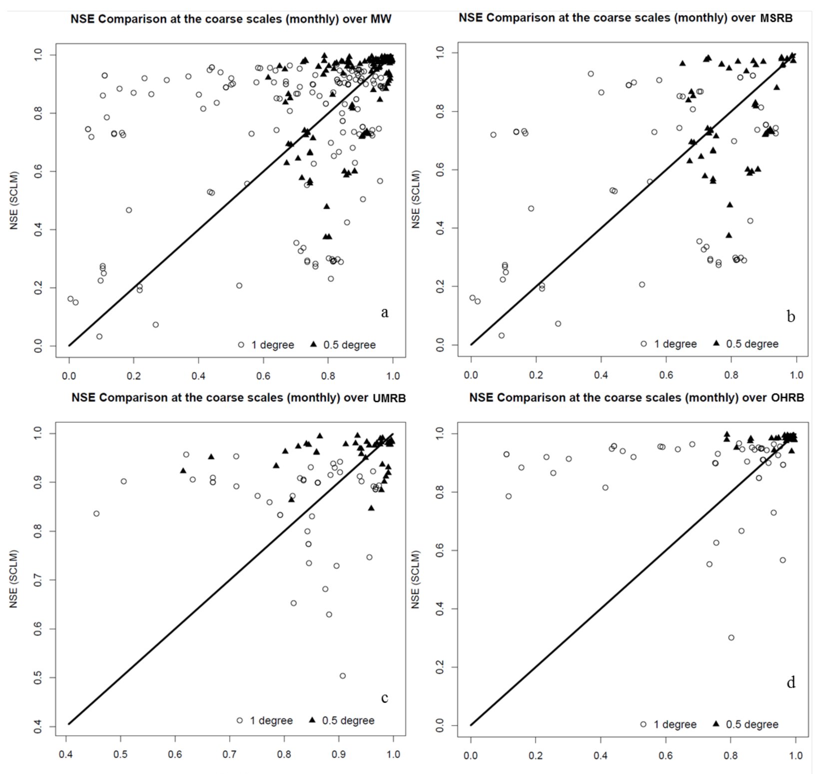
Climate regions based on model simulated rainfall/snowfall partitioning.



NSEs of monthly streamflow across spatial scale over USGS stations with drainage area greater than 15000 km² over CRB.

▶Both frameworks have a threshold behavior with increasing spatial scale.

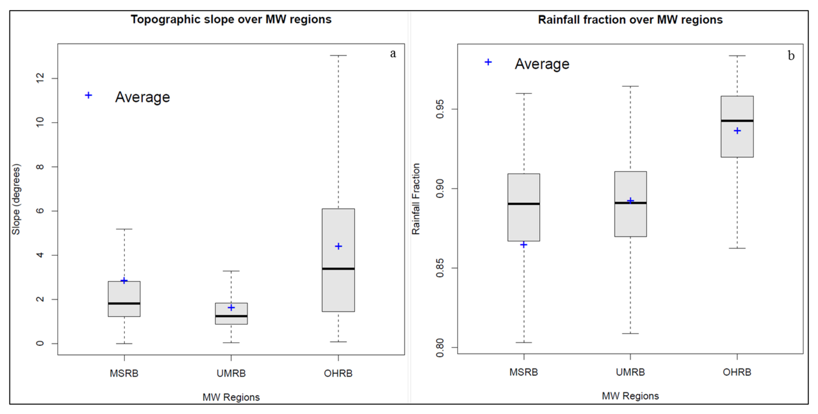
▶SCLM-MOSART converges to reference solution faster than CLM-MOSART.



NSE values from monthly streamflow compared at the USGS stations with contributing area larger than 15000 km² located in the whole Midwest (a), and Missouri (b), Upper Mississippi (c) and Ohio (d) regions.

▶There is minimal scalability differences between the two modeling frameworks over MW, MSRB and UMRB.

▶There is clear scalability advantage for SCLM-MOSART at the OHRB than for CLM-MOSART, which is related to the topographic complexity of OHRB.



Topographic slope and rainfall fraction over the Missouri (MSRB), Upper Mississippi (UMRB) and Ohio (OHRB) regions.

▶Topographic slope and rainfall fractions of OHRB are quite different from those of MSRB and UMRB regions.

Conclusions

- ▶SCLM is more consistent in simulating runoff generation than CLM across spatial scales.
- ▶Improved scalability in runoff simulation is related to better consistency in major meteorological and land surface parameters.
- ▶SCLM-MOSART also showed better scalability in streamflow simulation across spatial scales than CLM-MOSART.
- ▶Scalability advantages in stream flow simulation are driven by the combination of scalability advantages in runoff generation and routing processes.

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