Investigating soil moisture spatial scaling using Reduced Order Models and analysis of fractal temporal evolution patterns

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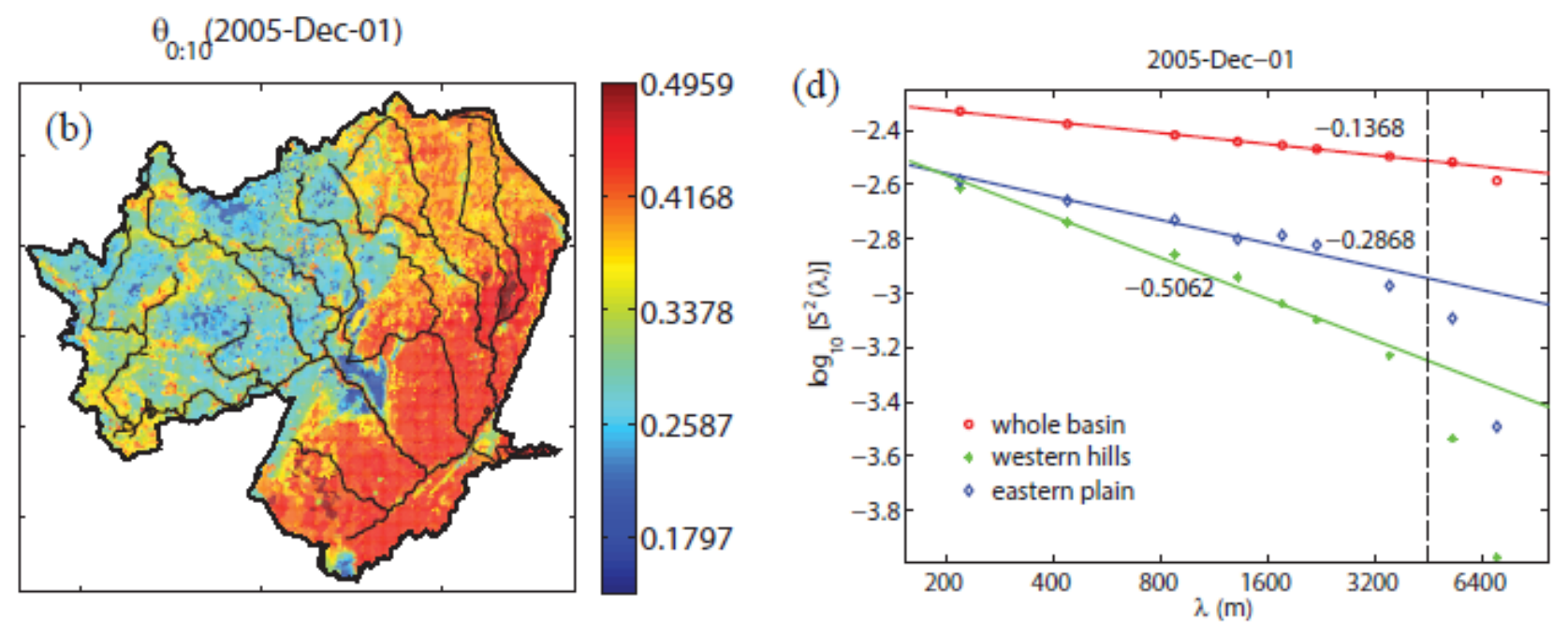
Motivations

Hydrologic spatial scaling and subgrid heterogeneity have been recognized as among the most significant challenges in hydrologic modeling. Soil moisture is the key variable that control hydrologic fluxes such as ET, infiltration and runoff. Watershed-scale hydrological and biogeochemical models are usually discretized at resolutions coarser than where significant heterogeneities exist. We explore two avenues to reduce the impact of subgrid heterogeneity in soil moisture:

- Avenue 1 (moments fitting): Can sub-grid distribution of soil moisture, represented by 2nd and higher order moments, be predicted by mean and environmental factors?
- Avenue 2 (fractal scaling): Can we find a predictive formula for the scaling exponents of the soil moisture spatial fractal*, which allows us to estimate 2nd and higher order moments from coarse-grid spatial pattern?

* It was discovered 2 decades ago that spatial variance of the soil moisture field show exponential decay as a function of observation window size (or support scale).



Left Figures: numerical evidence of scale invariance in soil moisture field

Modeling Approach

We employ the Process-based Adaptive Watershed Simulator (PAWS), a physically-based, well-tested computationally efficient model, coupled with CLM. We apply this model to two basins, a 1800 km^2 Clinton River Basin (CRB) and the Upper Grand (UG). We run the model at a range of resolutions, from 220m to 7040m. The models are calibrated to streamflows, and show good performance with respect to various observations.

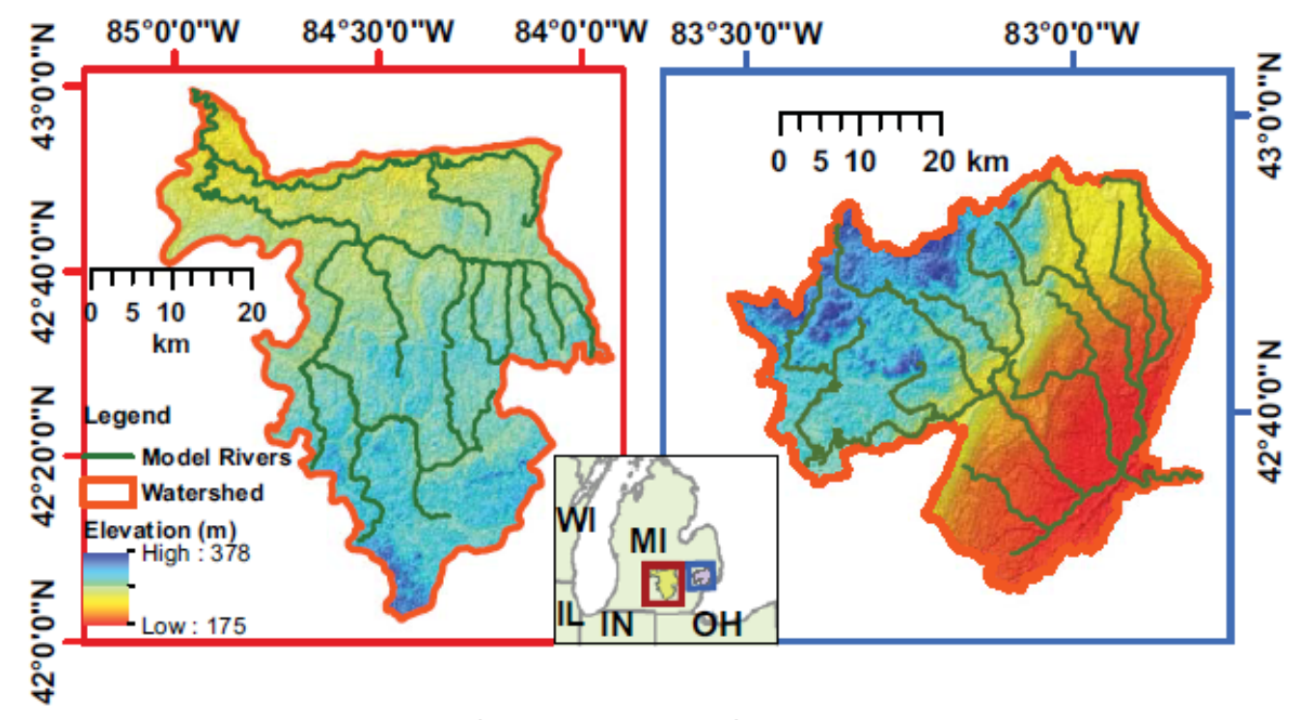


Figure: maps of UG (left) and CRB (right)

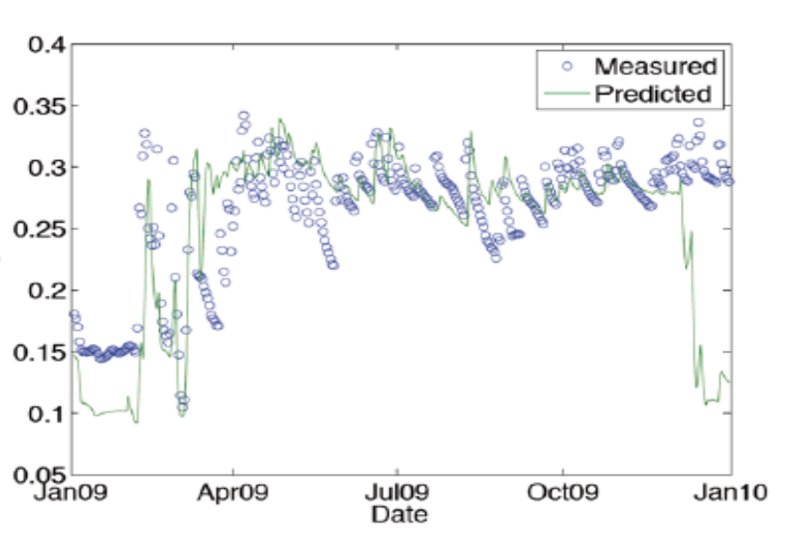


Figure: comparison with measured soil moisture

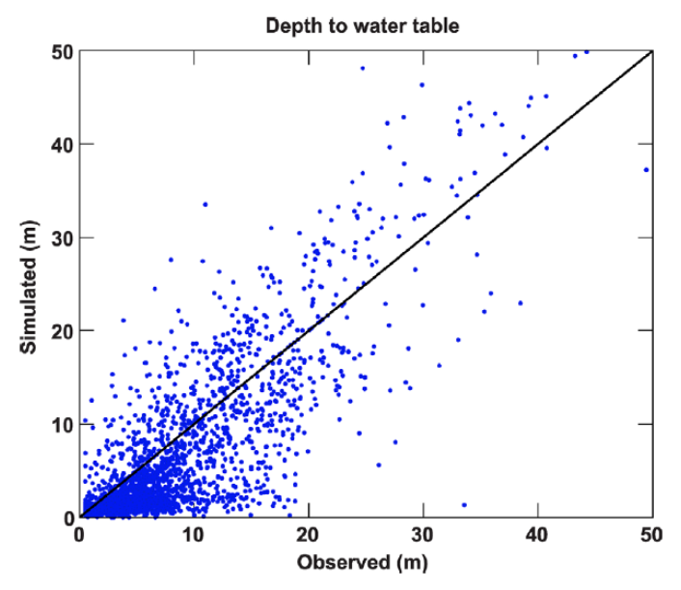


Figure: Depth to water table comparisons

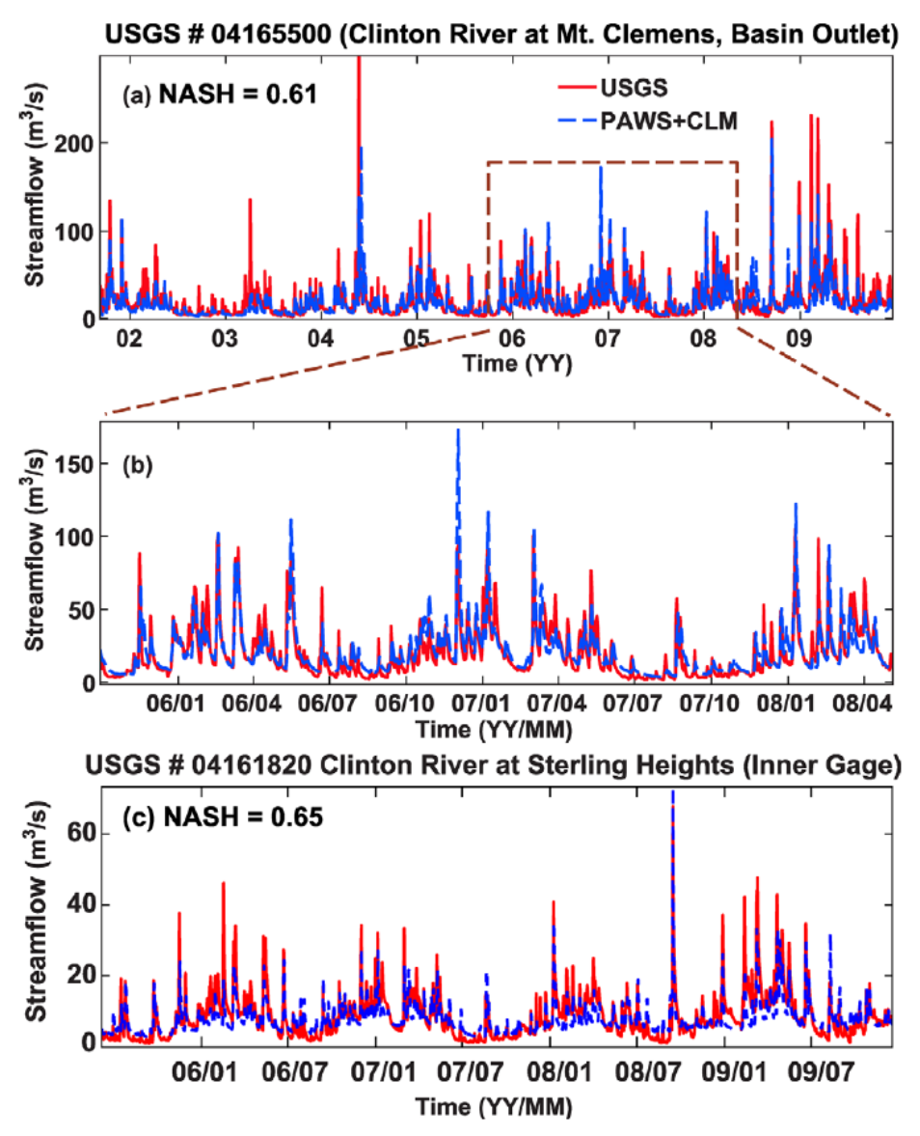
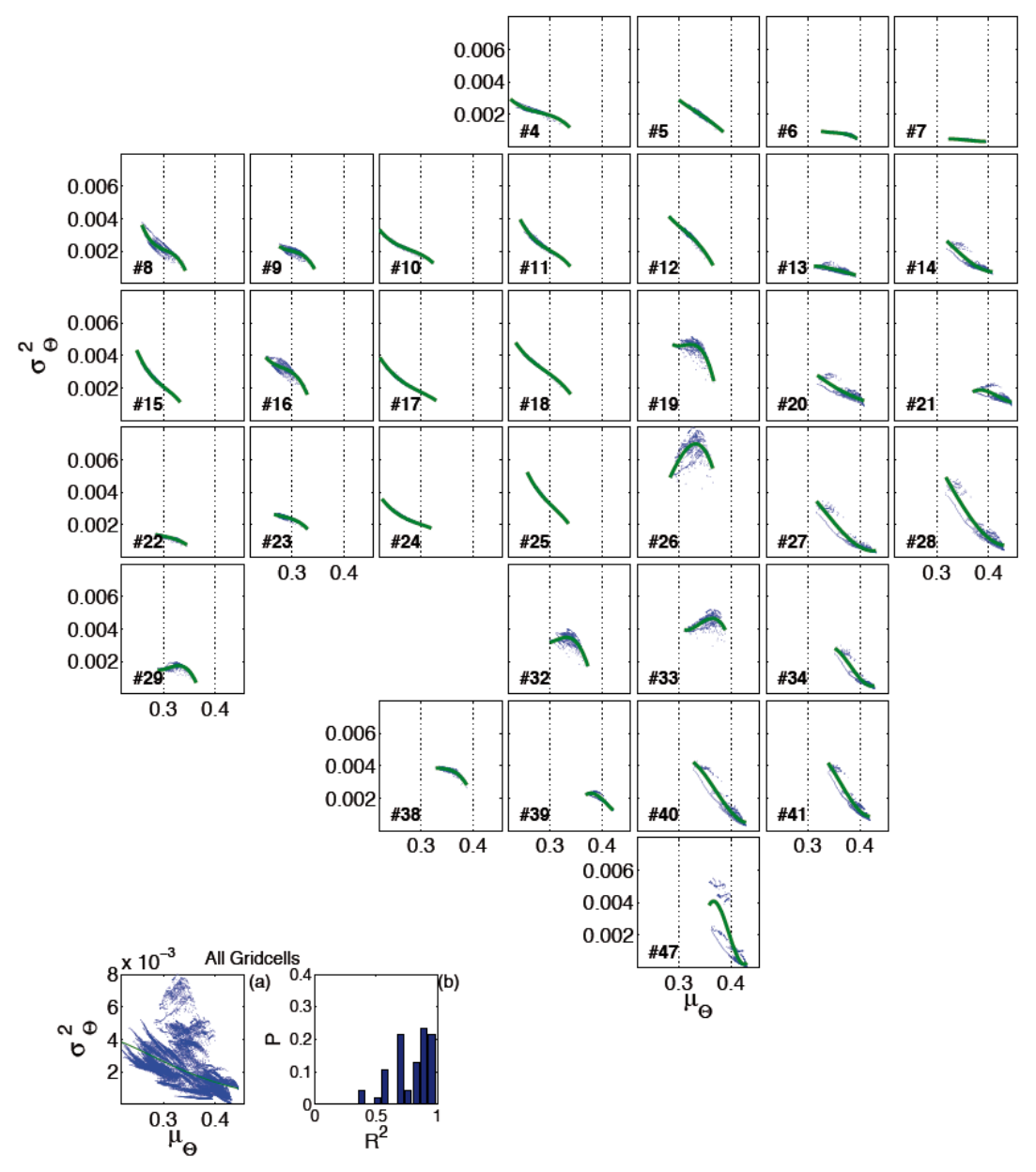


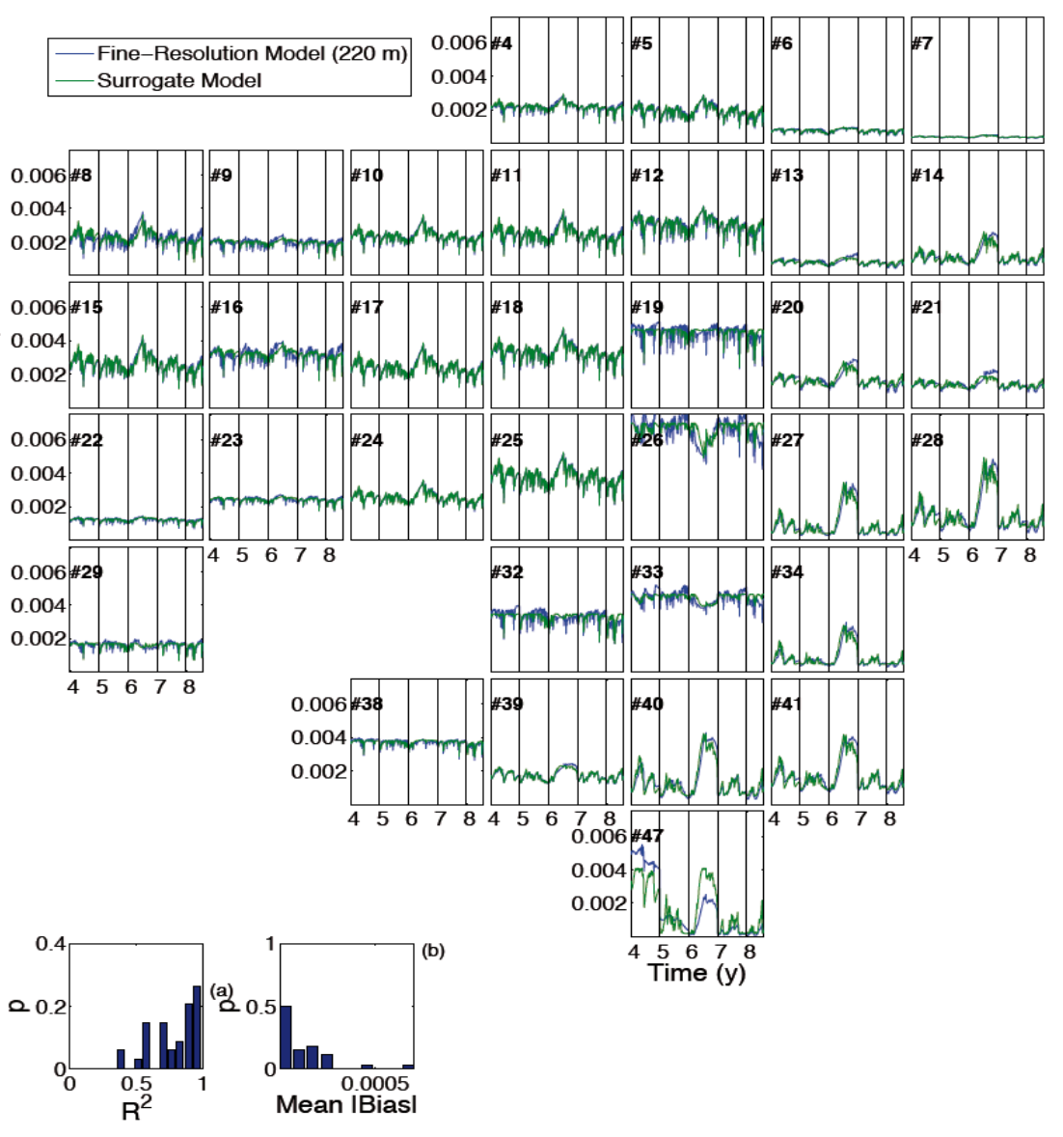
Figure: Stream hydrograph comparisons

Avenue 1: moment fitting

Using the 0-10 cm soil moisture predictions from the 220 m resolution simulation, we evaluated μ_θ, σ_θ^2, s_θ, and k_θ at every time point (daily for 5 years) for each of the thirty-four 7040 m × 7040 m coarse-resolution gridcells. We used these temporally resolved values to build 3rd order best-fit polynomial relationships. Overall, these surrogate models accurately captured the relationships between μ_θ and σ_θ^2, s_θ, and k_θ, with mean R^2 values of 0.73, 0.74, and 0.75, respectively.



Left Figure. In each subplot, variance (σ_θ^2) is plotted versus mean (μ_θ) for that coarse-resolution gridcell based on the fine-resolution (220 m) model predictions (blue dots) and the best-fit 3rd order polynomial fits (green line).



Right Figure. Comparison over time between the fine-resolution (220 m) simulated soil moisture variance (σ_θ^2) and that predicted by the surrogate model using the mean of the fine-resolution soil moisture (μ_θ).

In our predictions, ~80% of the coarse-resolution gridcells were relatively well characterized by a linear fit with a negative slope. About 20% of the gridcells were predicted to have a convex-up relationship

We investigated sixteen hypothesized controllers of this slope. six had independent linear best-fits with R^2 > 0.05: gradient (g; R^2 = 0.07), mean of evapotranspiration ((E_T; (Wm^{-2}); R^2 = 0.16), temporal mean of the spatial variance of evapotranspiration (R^2 = 0.05), porosity (R^2 = 0.08), mean of groundwater depth (R^2 = 0.06), and mean of stream density (R^2 = 0.05). Using a stepwise linear regression with these six variables and allowing for first order interactions, the best-fit model explained 59% of the variance in m and had the form: $C_1 + C_2 g\overline{E_T}$, where C_1 and C_2 are constants.

Avenue 2: fractal scaling

We first sought to understand how the fractal scaling exponents evolve in time, in response to seasonal climatic forcings and storm events. We calculated the time series of $\tau_{0:10}(2)$, the scaling exponents extracted from the top 10cm soil moisture field from a 220m resolution simulation. We only used scales below the fractal cutoff.

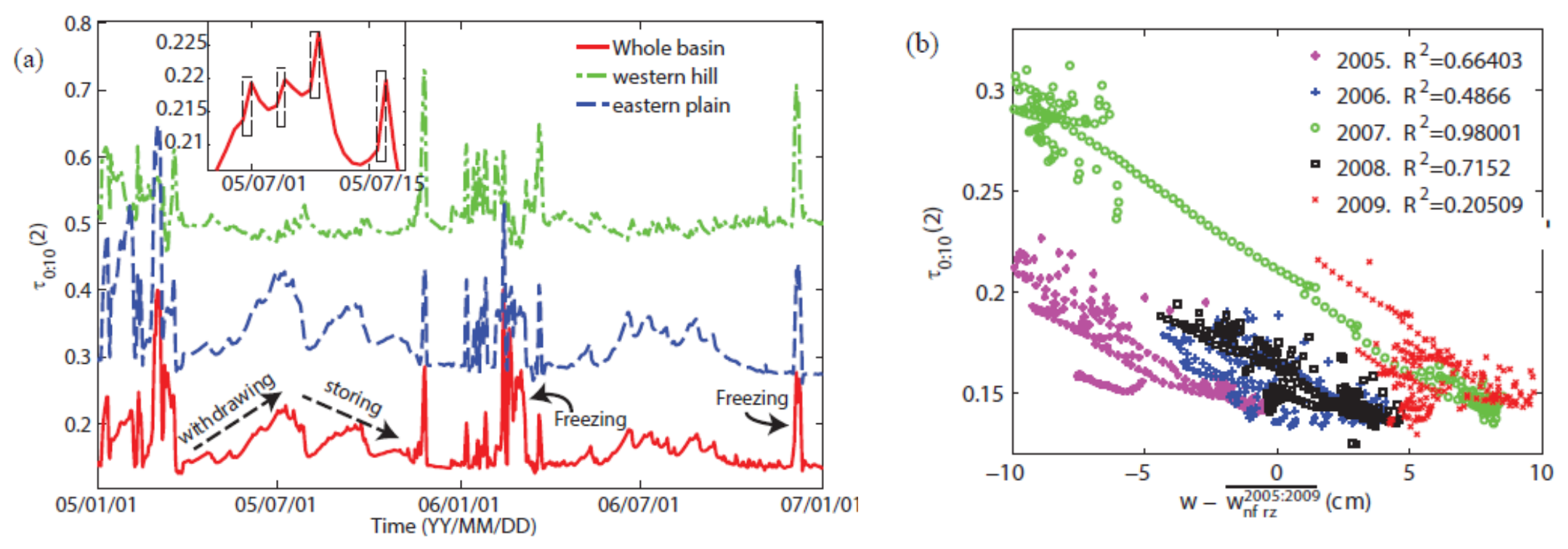


Figure (a) Time evolution of the scaling exponents in the CRB.; (b) Relationship between $\tau_{0:10}(2)$ and basin-average water storage anomaly during non-frozen period (April – Oct) in 2005-2009.

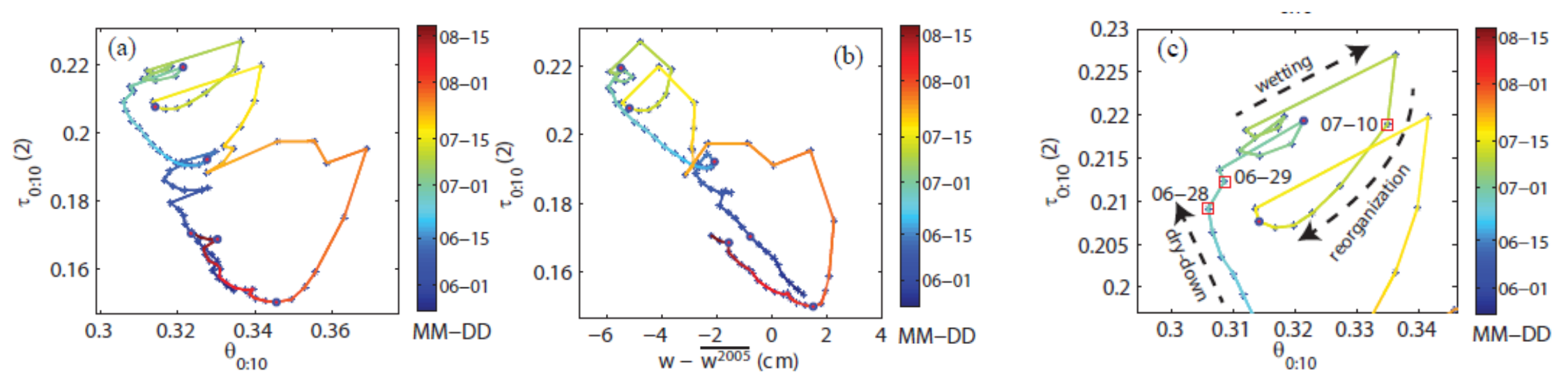


Figure (a) $\tau_{0:10}(2)$ vs. top 10 cm layer soil moisture from May 24th to Aug 18th, 2005; (b) $\tau_{0:10}(2)$ vs. subsurface water storage anomaly (with respect to 2005 mean); (c) Close-up of the upper half region of (a). The red Color of the lines in all panels indicates time (MM-DD)

Fractal scaling exponents display complex hysteresis and are not single-valued functions of mean moisture. We identified a seasonal mode that is related to seasonal variation in basin water storage, while storm events induce hysteretic excursion loops which can be divided into wetting, re-organization-dominated, and dry-down-dominated phases. Topography and groundwater flow play important roles in regulating the fractal evolution.

Summary

Progresses:

- We explored two avenues to predict soil moisture subgrid variability using coarse grid mean (moments fitting) and spatial pattern (fractal scaling)
- The moment-fitting method obtained promising accuracy, while the environmental controllers need to be further understood.
- We obtained a basic understanding of the temporal dynamics of the soil moisture fractal, which consists of an underlying seasonal mode, while storm events create hysteretic excursion loops.
- The results will help us create predictive formula for subgrid variability in soil moisture, which influence biogeochemical processes

References

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Earth System Modeling