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Scaling of hydrologic flows in polygonal ground within an Arctic ecosystem

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ABSTRACT

Arctic and sub-Arctic soils currently contain approximately 1700 billion metric tones of frozen organic carbon, approximately 200 times current annual anthropogenic. This carbon is vulnerable to release to the atmosphere as CO_2 and CH_4 as high-latitude temperatures warm. Polygonal ground, with a characteristic length scale of $\approx$15 m, is a common landscape type that occurs over large parts of Arctic tundra. These ground structures, with high or low centers, dominate the local hydrologic environment, thereby impacting the energy balance, biogeochemical dynamics, vegetation communities, and carbon releases from the subsurface. A recent simulation study by Liljedahl et al. (2012) has shown the importance of low- and high-centered microtropgraphic features on Arctic basin water balance. In spite of their importance to local hydrologic processes, the impact of these microtopographic features at larger spatial scales is not well understood.

OBJECTIVES

We investigate spatial scaling of soil moisture in the presence of polygonal ground features for Arctic ecosystems by performing subsurface simulations at different model resolutions using PFLOTRAN, a parallel, multi-phase, multi-component reactive flow and transport model.

The Open-Source, Parallel Flow and Reactive Transport Code: PFLOTRAN

- PFLOTRAN is a multiphase flow and multicomponent geochemical transport simulator developed under the DOE SciDAC-2 Program.
- Key PFLOTRAN features/capabilities either implemented or currently being implemented(*) include:
  - Object-oriented data structures
  - PETSc solvers and preconditioners
  - Modular linkage to physicochemical processes
  - Unstructured Grids
    - Hexahedron
    - Prismatic
    - Tetrahedron
  - Multicontinuum subgrid model*
  - Multiphase flow, Nonisothermal transport
  - Multicomponent reactive transport
  - Biogeochemistry
  - Equilibrium and multirate sorption models
  - Surface complexation and ion exchange
  - Colloid-facilitated transport with mechanistic surface complexation model
  - Surface flow model*

STUDY AREA & DATA SOURCES

The study site is located near Barrow, Alaska (71.3225° N, −156.626° W; Figure 1). LIDAR digital elevation model (DEM) data with a horizontal resolution and spatial extent of 0.5 m and 500 m, respectively, are used in this study. Study domain encompasses four plots identified by the Next-Generation Ecosystem Experiments (NGEE)–Arctic project which have different geomorphic and hydrological conditions (Table 1).

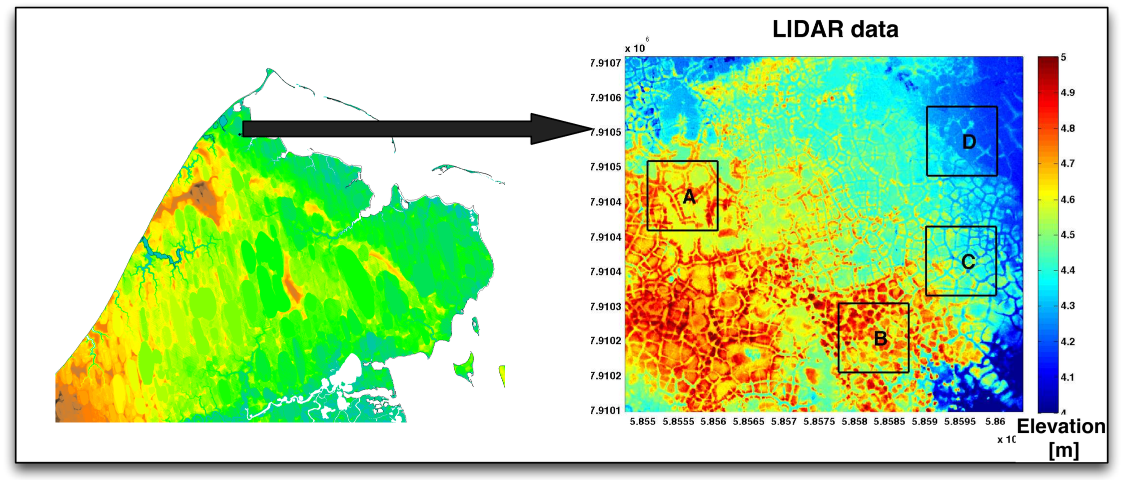

Figure 1 : (a) Location of study site near Barrow, AK. (b) LIDAR DEM data at 0.5 m resolution

Table 1 : Characteristics of representative study plots within study site

Plot	Polygonal characteristics	Relative elevation	Moisture conditions	Estimated Carbon conditions	Relative age
A	Transitional low center	High	Inundated	High	Old
B	High low center	High	Desiccated	Low	Old-ancient
C	Transitional low center	High	Moderately dry	Moderate	Old
D	Low center	High	Moderately wet	High	Young

BOUNDARY CONDITIONS & SOIL PROPERTIES

Boundary conditions (BCs) for PFLOTRAN simulations are obtained by performing offline simulations with the Community Land Model (CLM). A 3000 years CLM spinup is performed using meteorological forcing data from AmeriFlux network from 1998–2006 and hourly simulated infiltration and evaptranspiration (ET) fluxes (Figure 2) at the end of spinup, serve as BCs for PFLOTRAN simulations at various model resolution.

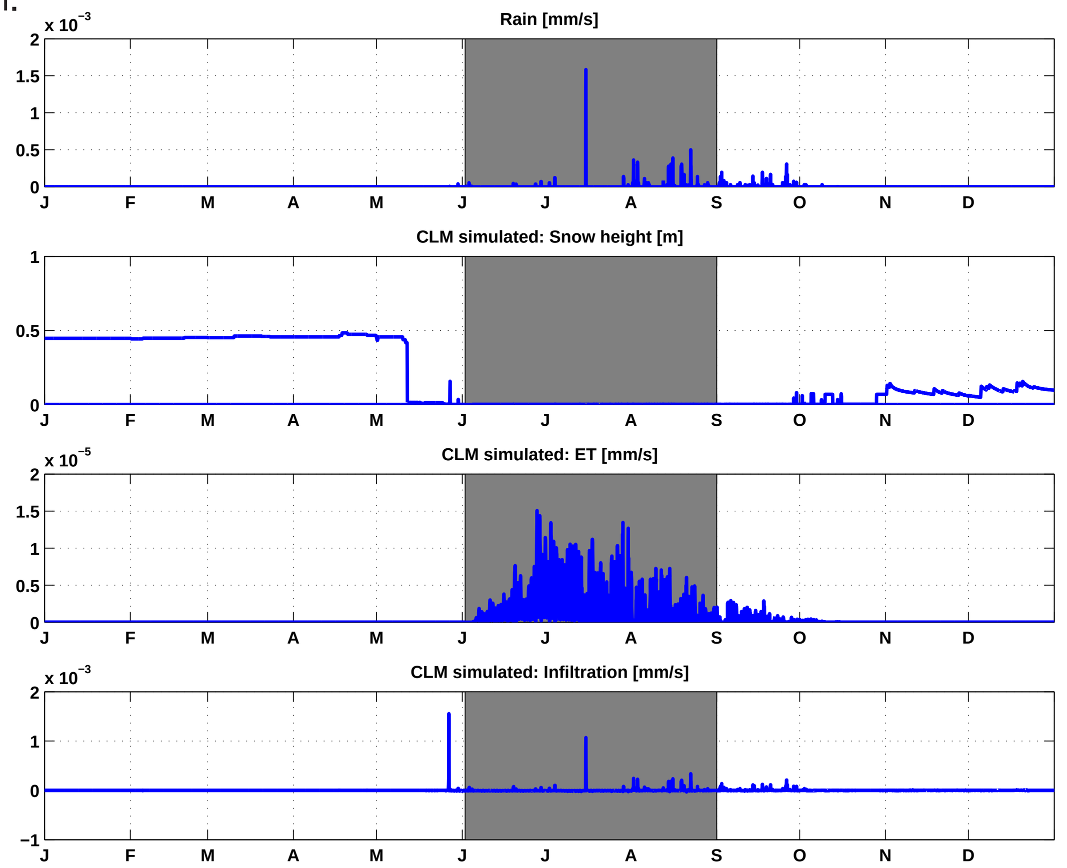

Figure 2 : (a) Observed rainfall forcing at US-Brw AmeriFlux station; CLM simulated: (b) Snow height; (c) ET; and (d) Infiltration fluxes

The van Genuchten model is fitted to soil water retention curves and unsaturated hydraulic conductivity as reported by Hinzmann et al. (1991).

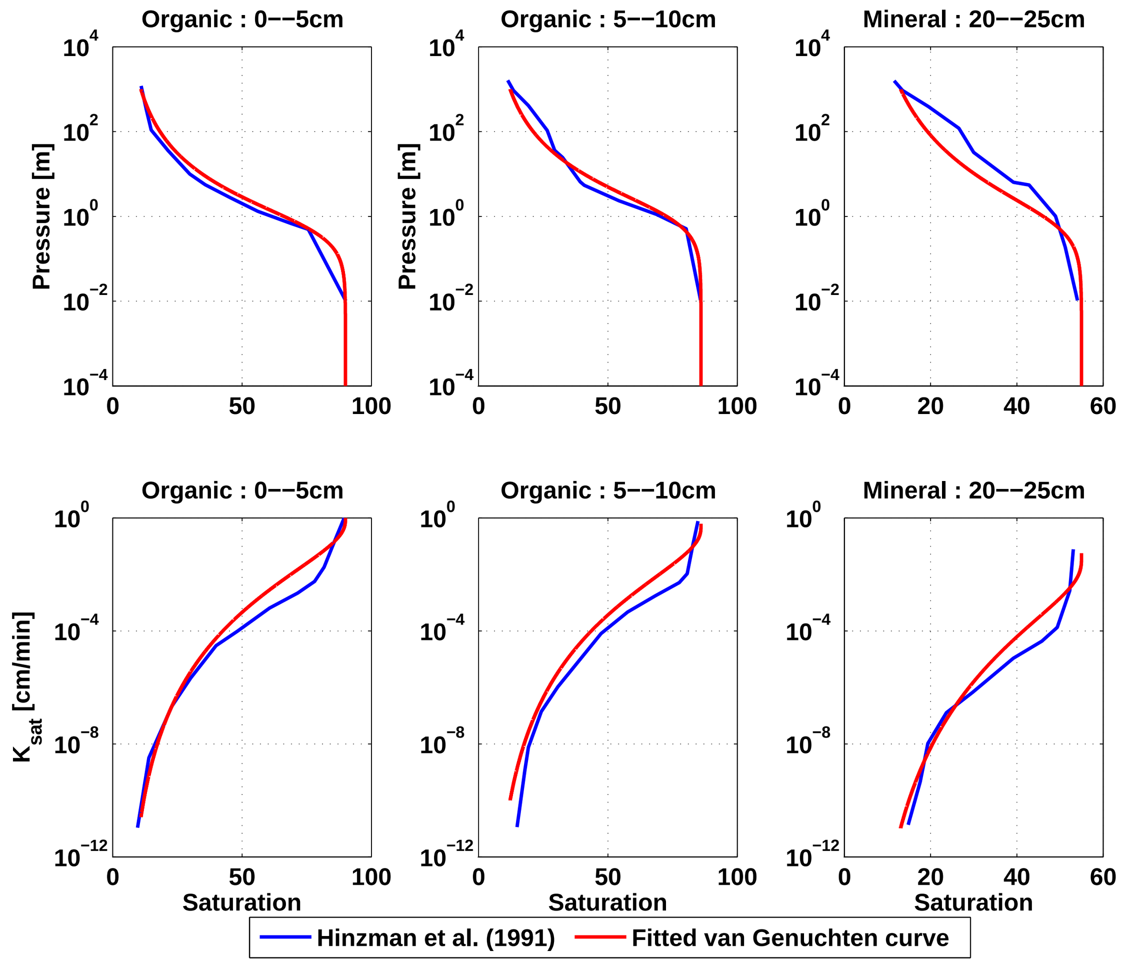

Figure 3 : Fitted van Genuchten model to data reported by Hinzmann et al. (1991).

PFLOTRAN SIMULATIONS

- Simulation length: 90-days during summer months.
- Vertical grid resolution: 8 soil layers with exponentially varying soil thickness (same as used in CLM) reaching a depth of 100 cm.
- Horizontal grid resolution: 0.5, 1, 2, 5, and 10 m.
- PFLOTRAN mesh comprises of unstructured prismatic elements: 16×10^6, 4×10^6, 1×10^6, 160×10^3, and 40×10^3, respectively.
- Isothermal 3-dimensional subsurface flow.

RESULTS

For the first half of the 90-days simulation period, the soil moisture decreases because of draw down due to ET (Figure 4); and rainfall events occur in the later half of the simulation period corresponding to sharp increase in soil moisture. The results in this study focus on days before and after the large rainfall event (shown with a dashed line).

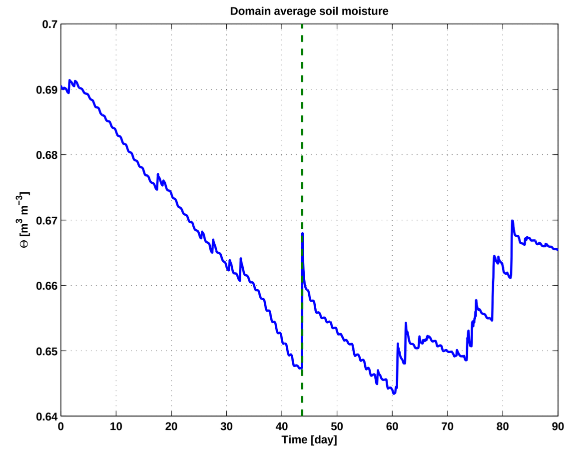

Figure 4 : PFLOTRAN simulated soil moisture

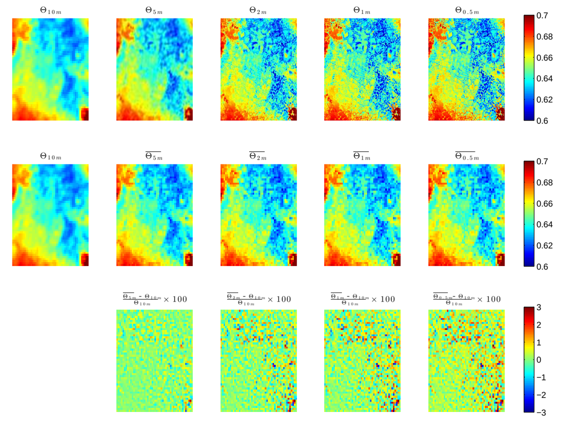

Figure 5 : Simulated θ fields at multiple resolutions; spatially average $\bar{\theta}$ at 10 m; percentage difference between $\bar{\theta}$ and model simulation at 10 m for the day before the rainfall event.

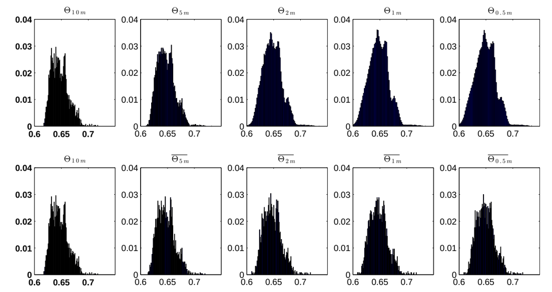

Figure 6 : Histograms of θ and $\bar{\theta}$ as shown in Figure 5.

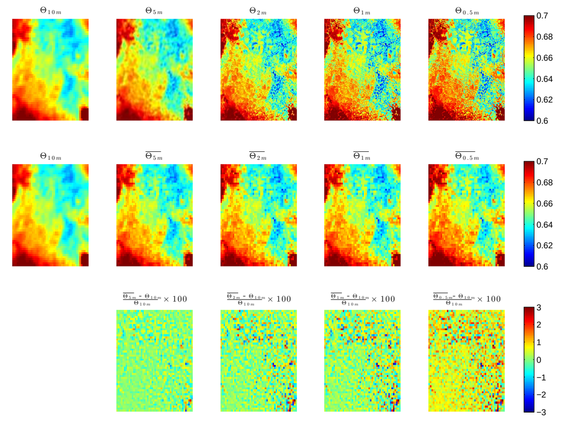

Figure 7 : Same as Figure 6 except after rainfall event.

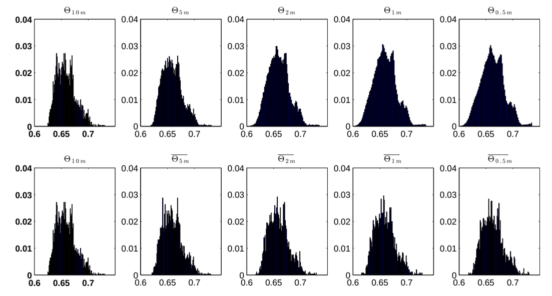

Figure 8 : Same as Figure 6 except after rainfall event.

Numerous studies have applied statistical self-similarity to the scaling of soil moisture (Rodrigues-Iturbe et al., (1995), Dubayah et al. (1996)) as

$$\mathbb{E}[\theta^q(A_i)] = \left(\frac{A_j}{A_i}\right)^{K(q)} \mathbb{E}[\theta^q(A_j)] \tag{1}$$

where q is the order moment, $K(q)$ is a s set of scaling exponents associated with the moments, and the ratio A_j/A_i is the scale parameter λ. If the spatial scale A_j corresponds to the coarsest scale, then finer scales corresponding to scale A_i will have scale parameters going from $\lambda = 1$ (for coarsest scale) to $\lambda = \frac{1}{2}, \frac{1}{4} \ldots$ as spatial resolution is increased. The process is said to have simple scaling if the scaling exponents are linearly related to the moment order q; otherwise it is termed multiscaling (Wood (1998)). Soil moisture variance at multiple spatial scales using 0.5 m PFLOTRAN simulation are computed via Equation 1 for top 20 cm and 100 cm soil column before and after the rainfall event (Figure 9).

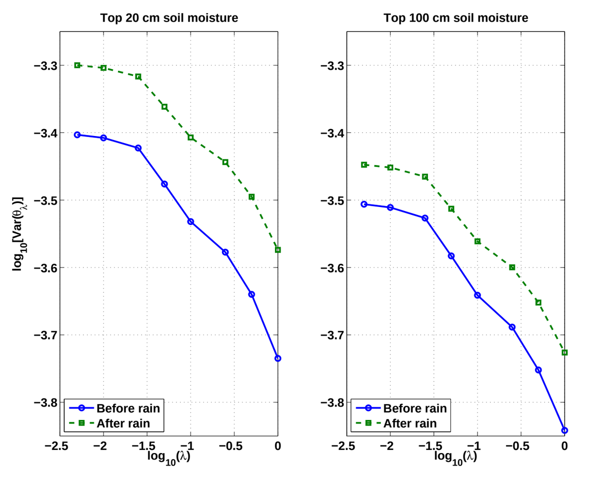

Figure 9 : σ_θ^2 for (a) 20 cm; and (b) 100 cm

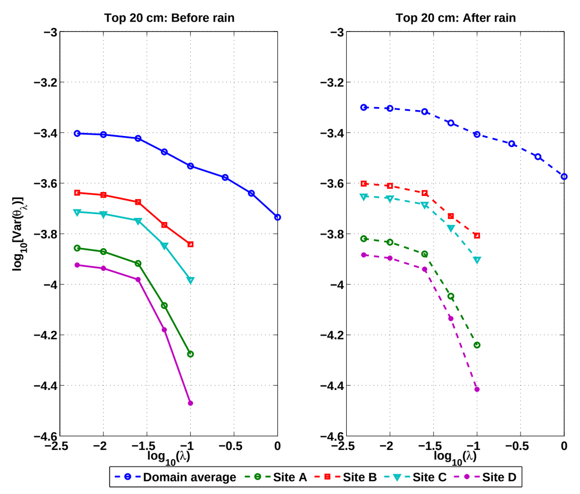

Figure 10 : σ_θ^2 for A, B, C, and D site

RESULTS (continued)

Figure 10 shows soil moisture variance for sites A, B, C, and D before and after the rainfall event. These results suggest that soil moisture variance demonstrates a multiscaling behavior, and various portions of the domain scale differently. Higher moments of soil moisture, computed using Equation 1, show similar multiscaling behavior (Figure 11); while time evolution of scaling exponent, $K(q)$, for different parts within the domain is presented in Figure 12.

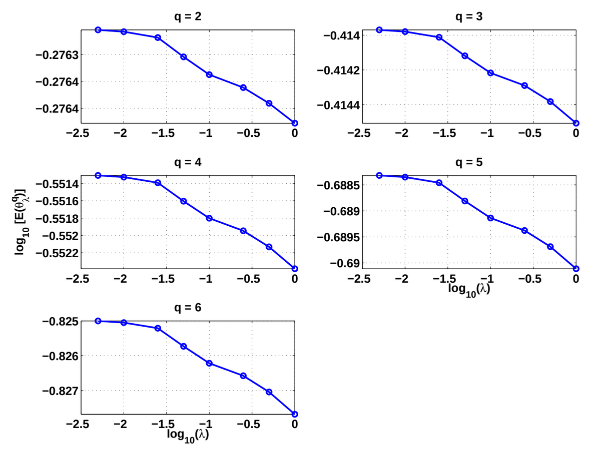

Figure 11 : Various moments of simulated soil moisture fields as a function of scale factor.

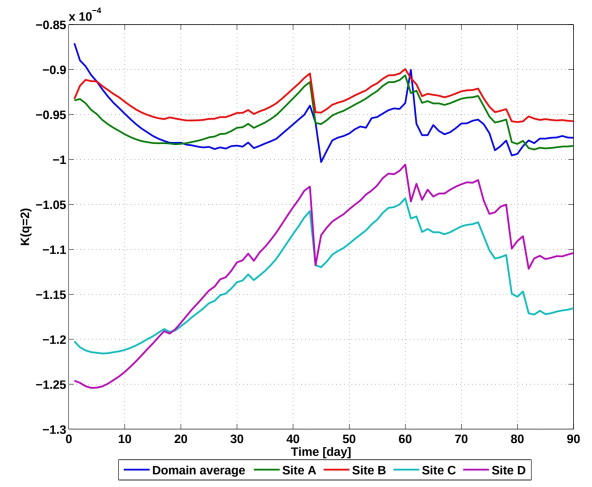

Figure 12 : Time series of scaling exponent

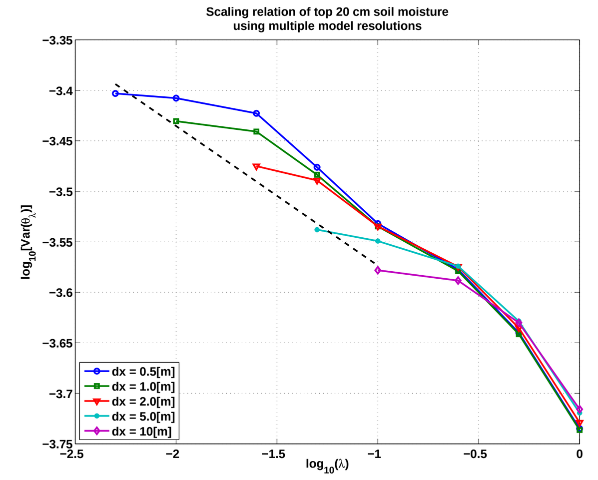

Figure 13 : Same as Figure 9, except starting with PFLOTRAN simulation at multiple resolutions

Variance of simulated top 20 cm soil moisture fields as a function of scale factor using PFLOTRAN simulations at different spatial resolution is shown in Figure 13. The results show that soil moisture variance exhibits multiscaling behavior irrespective of starting grid resolution. Additionally, at larger scale factors (i.e., coarse spatial resolution), the variance of soil moisture shows linear scaling.

FUTURE DIRECTIONS

PFLOTRAN simulations in this study are limited to subsurface flow with prescribed ET boundary conditions. We plan to extend the present study by including coupled surface–subsurface flows and utilize the coupled PFLOTRAN–CLM model to account for soil moisture – ET feedbacks.

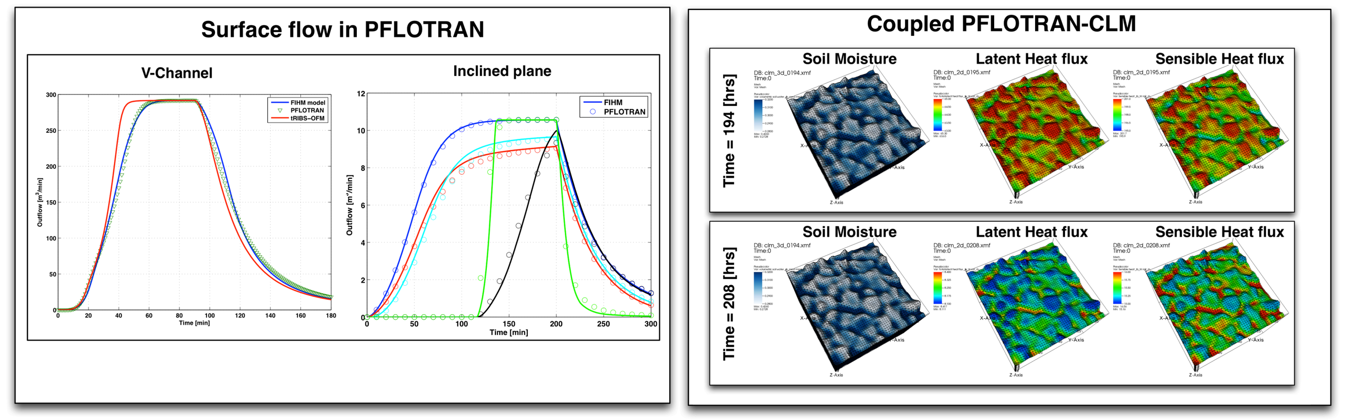

Figure 14 : (a) Comparison of simulated hydrography by the surface flow model in PFLOTRAN against other models for V-channel and inclined plane geometries. (b) Simulated soil moisture, latent heat flux, and sensible heat flux for site B during day and night by the PFLOTRAN–CLM model.

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