Representative Hillslopes in the Community Terrestrial Systems Model

Sean Swenson, Martyn Clark, Ying Fan, David Lawrence

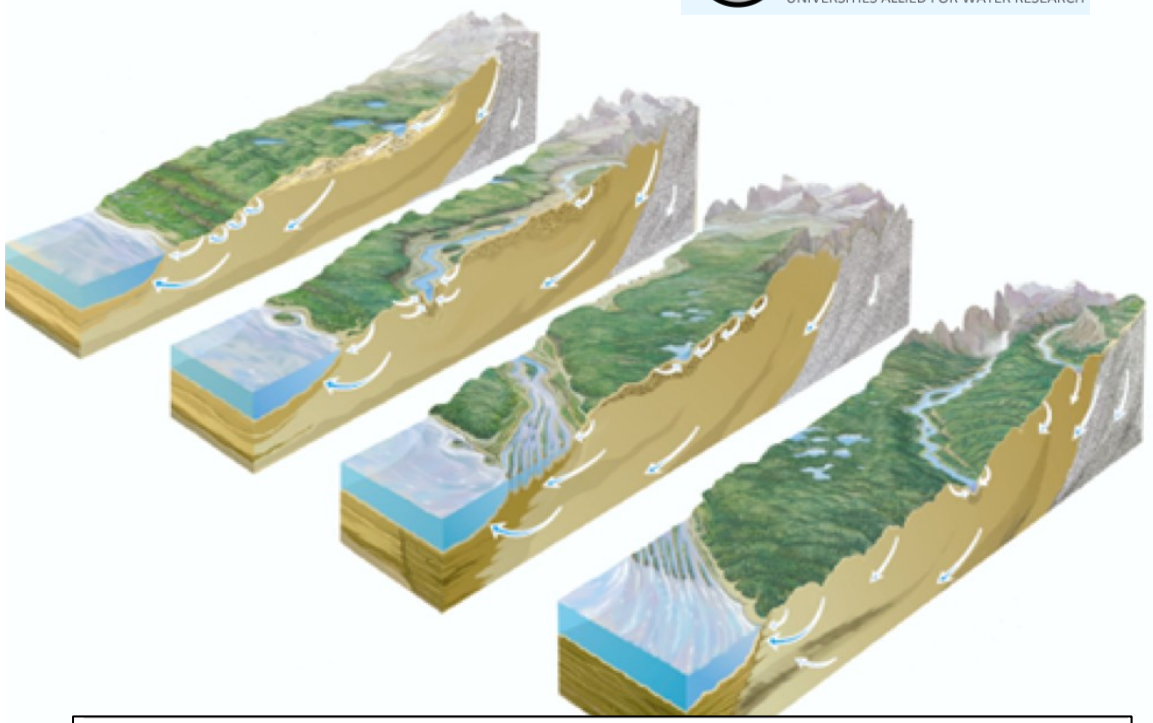
CUAHSI / NCAR Collaboration

- **CUAHSI** (Consortium of Universities for the Advancement of Hydrologic Science, Inc.) supports and enables community activities to advance hydrologic science

- **NCAR** (National Center for Atmospheric Research) supports and enables community activities to advance atmospheric and related sciences

- CUAHSI / NSF initiative to improve the representation of hydrologic processes in ESMs
  - Accelerate implementation of state-of-the-art hydrologic understanding into large-scale land models
  - Emphasis on model evaluation / benchmarking utilizing catchment-scale observations
  - Initial focus on implementation of hillslope hydrology into CLM

CUAHSI
UNIVERSITIES ALLIED FOR WATER RESEARCH



Water Resources Research

REVIEW ARTICLE
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Special Section:
The 50th Anniversary of Water Resources Research

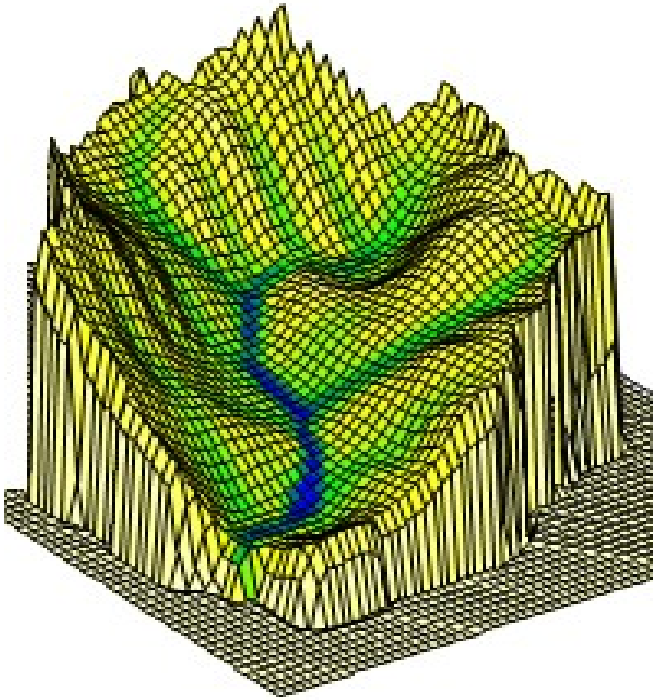
Improving the representation of hydrologic processes in Earth System Models

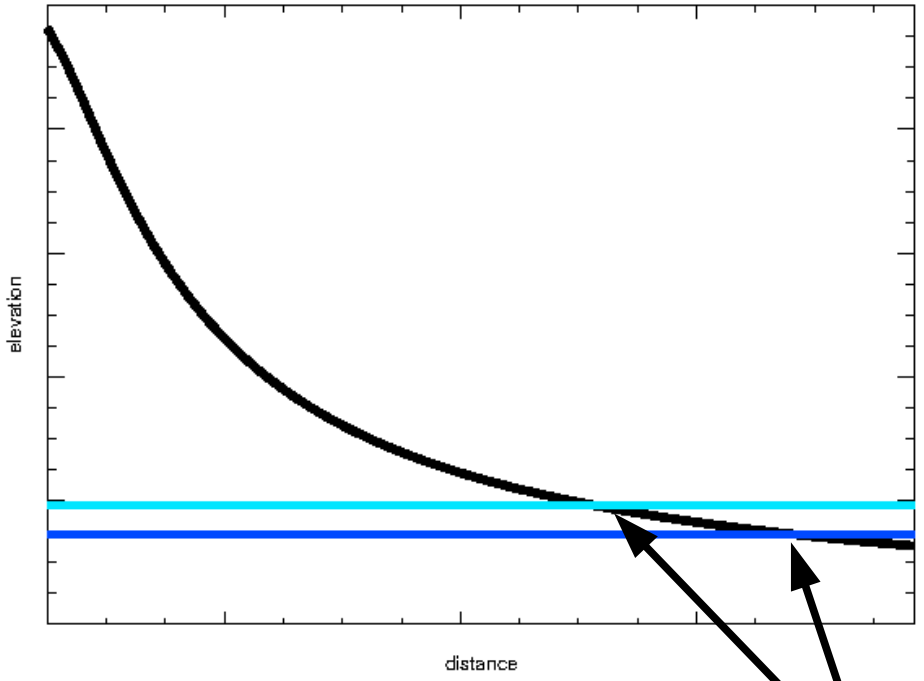
Martyn P. Clark[1], Ying Fan[2], David M. Lawrence[1], Jennifer C. Adam[3], Diogo Bolster[4], David J. Gochis[1], Richard P. Hooper[5], Mukesh Kumar[6], L. Ruby Leung[7], D. Scott Mackay[8], Reed M. Maxwell[9], Chaopeng Shen[10], Sean C. Swenson[1], and Xubin Zeng[11]

Soil Moisture Heterogeneity

Observed vegetation patterns imply variations in soil moisture

CLM Treatment of Soil Moisture Heterogeneity





Saturated fraction = 0.36

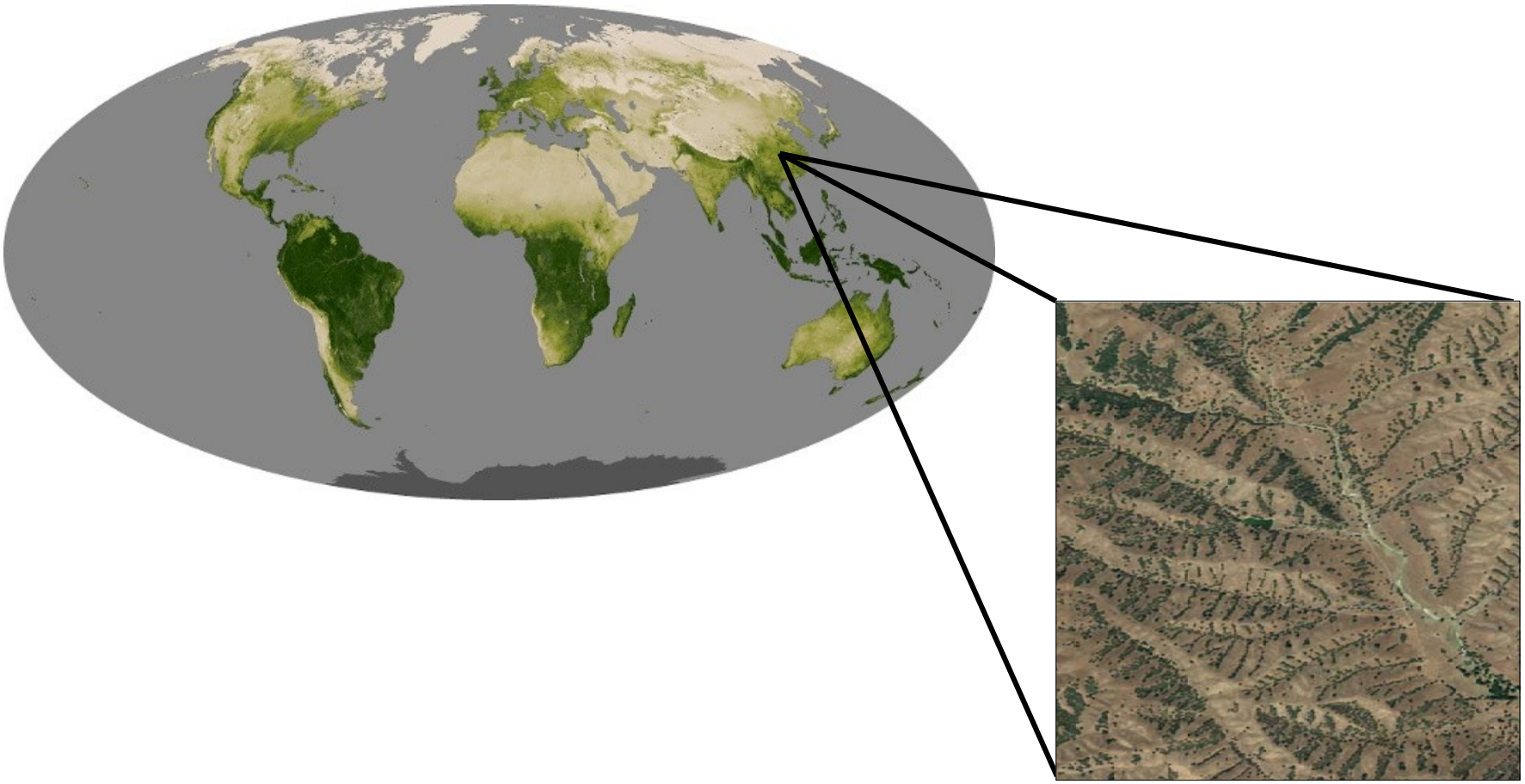
Saturated fraction = 0.14

TOPMODEL based expression used to parameterize saturated fraction based on column water table depth

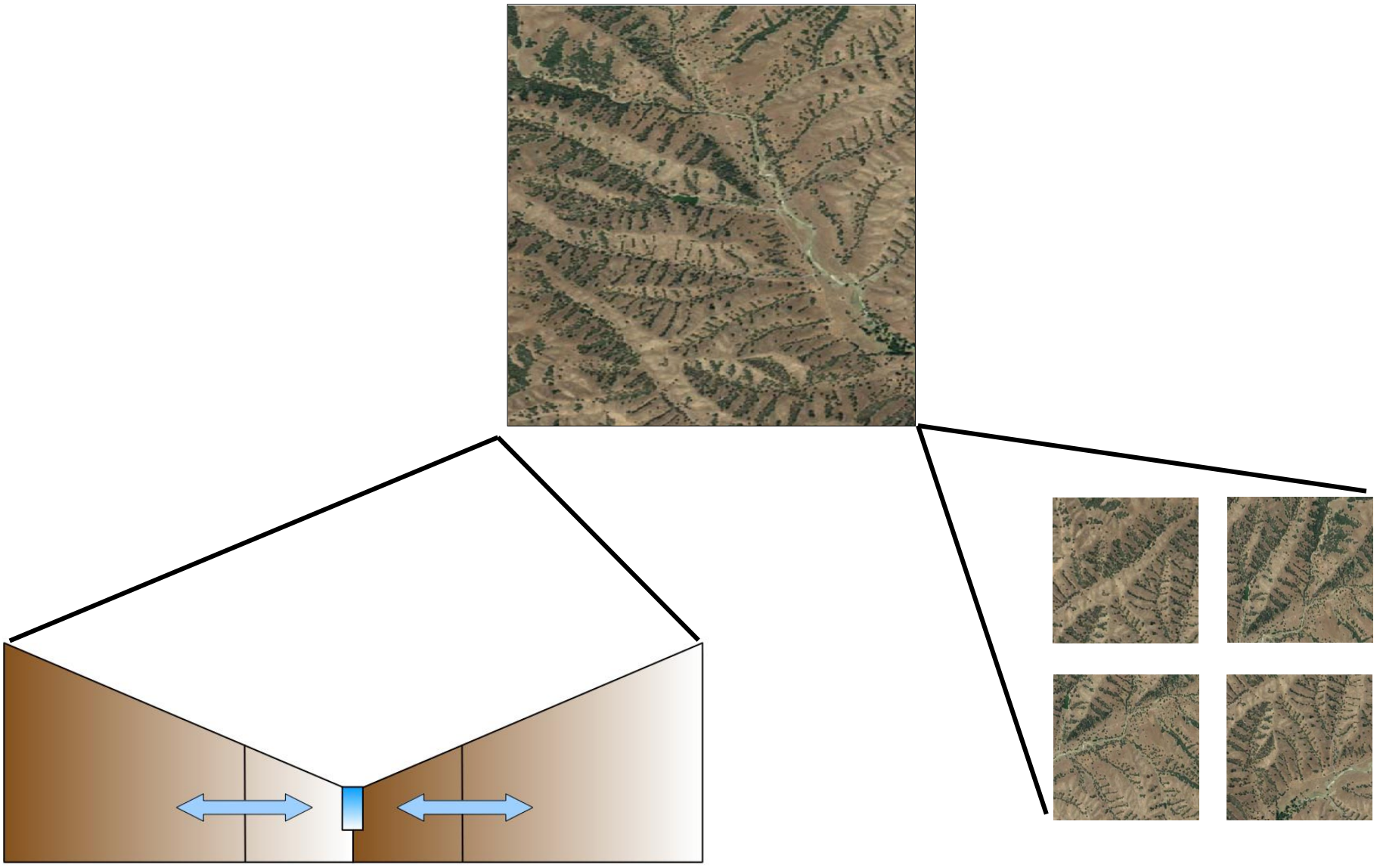
Point at which water table intersects surface determines saturated fraction

Saturated fraction only affects runoff; other processes experience a *single* soil moisture profile

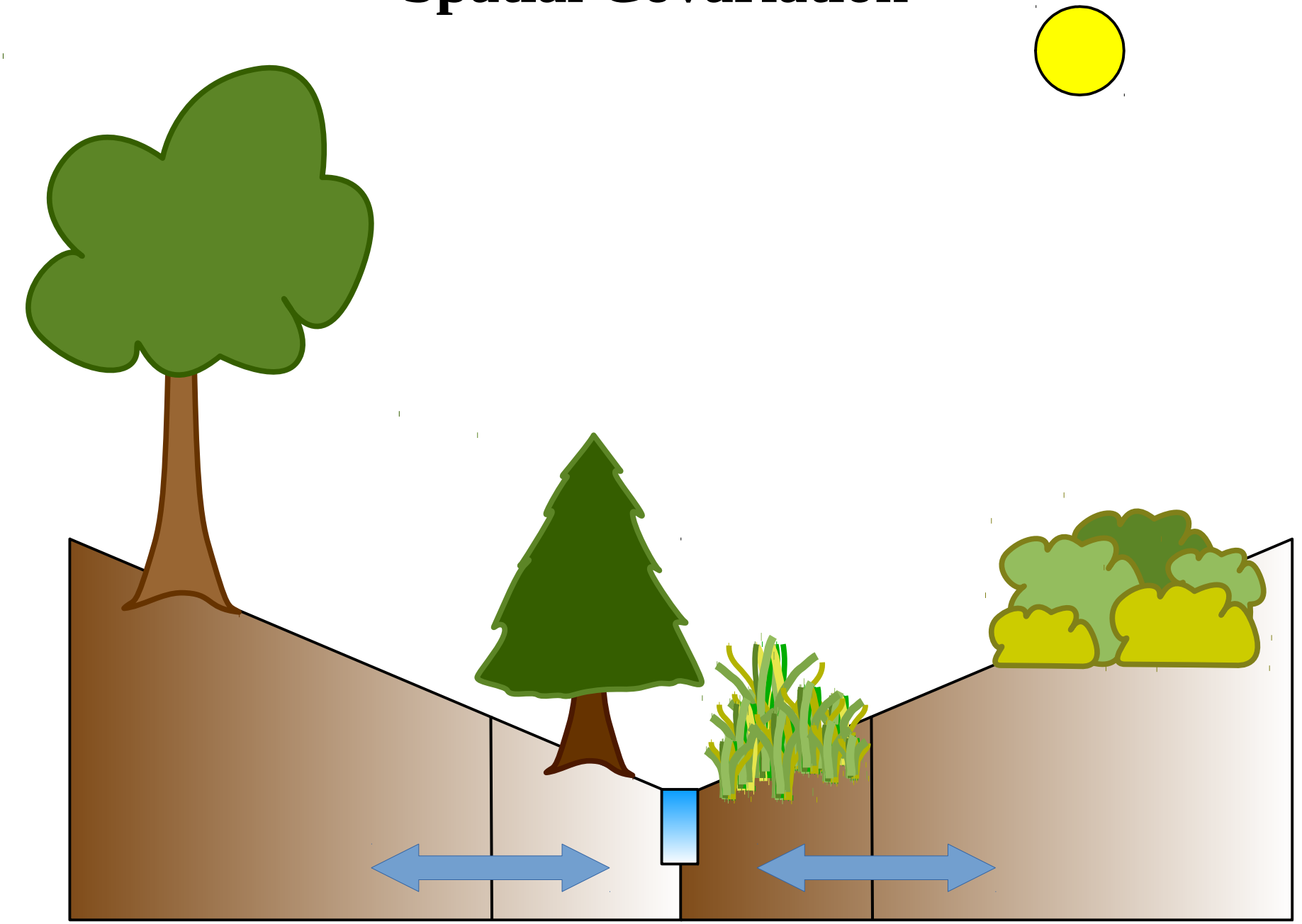
Representing Spatial Heterogeneity



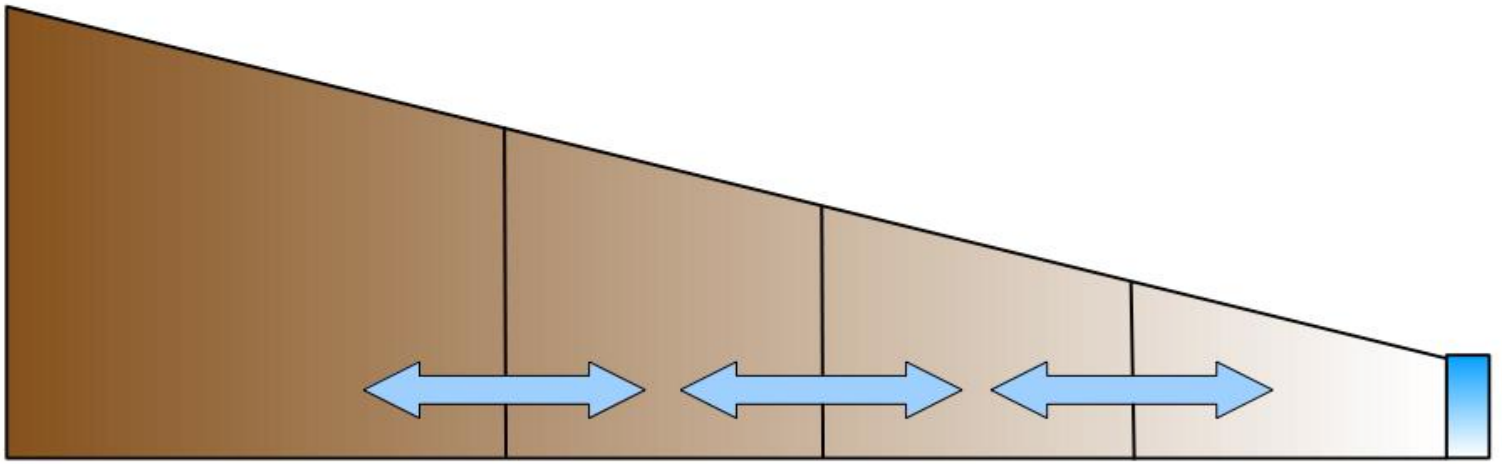
Representative Hillslopes



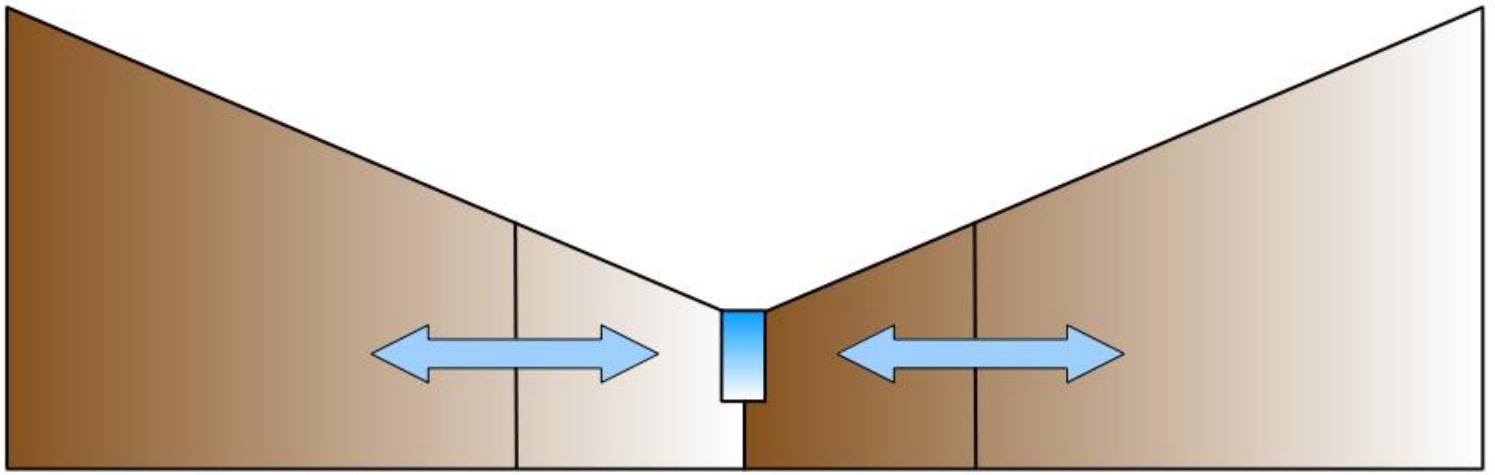
Spatial Covariation



Conceptual Hillslopes

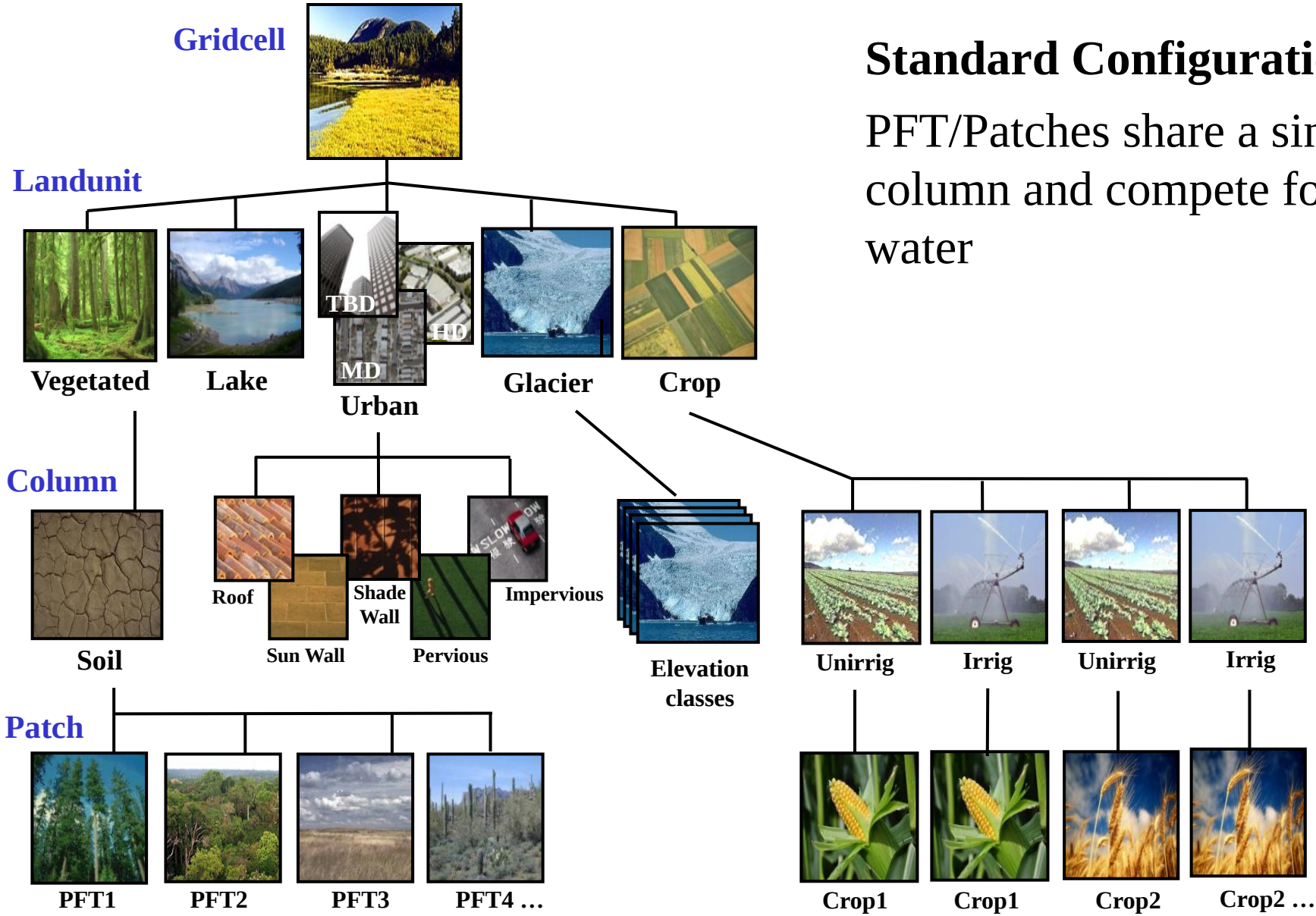


Serial subsurface flow inputs to riparian zone



Independent (parallel) subsurface flow inputs to riparian zone

CLM Subgrid Tiling Structure



Standard Configuration:

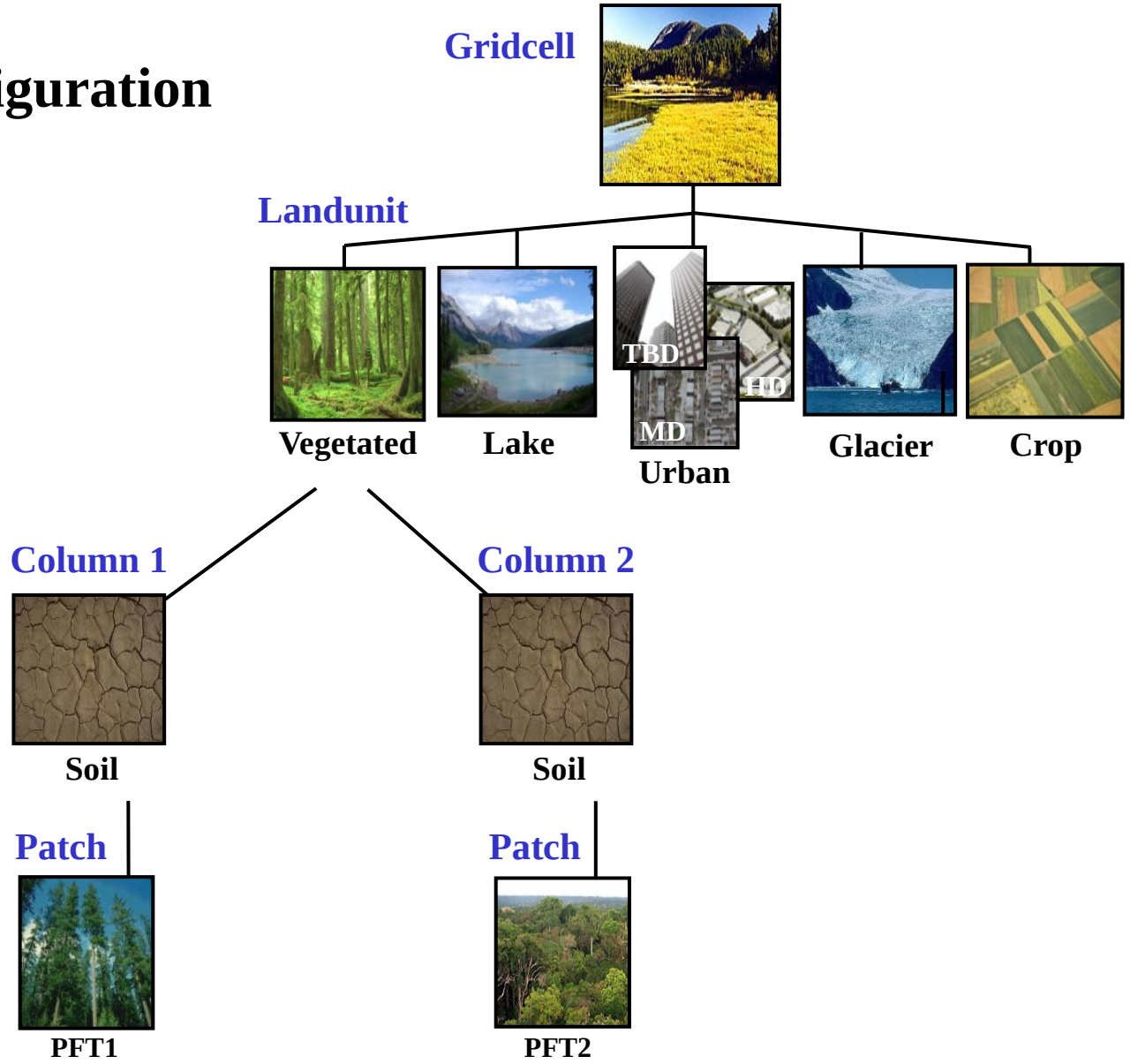
PFT/Patches share a single column and compete for water

CLM Subgrid Tiling Structure

Multicolumn Configuration

(1 pft per col):

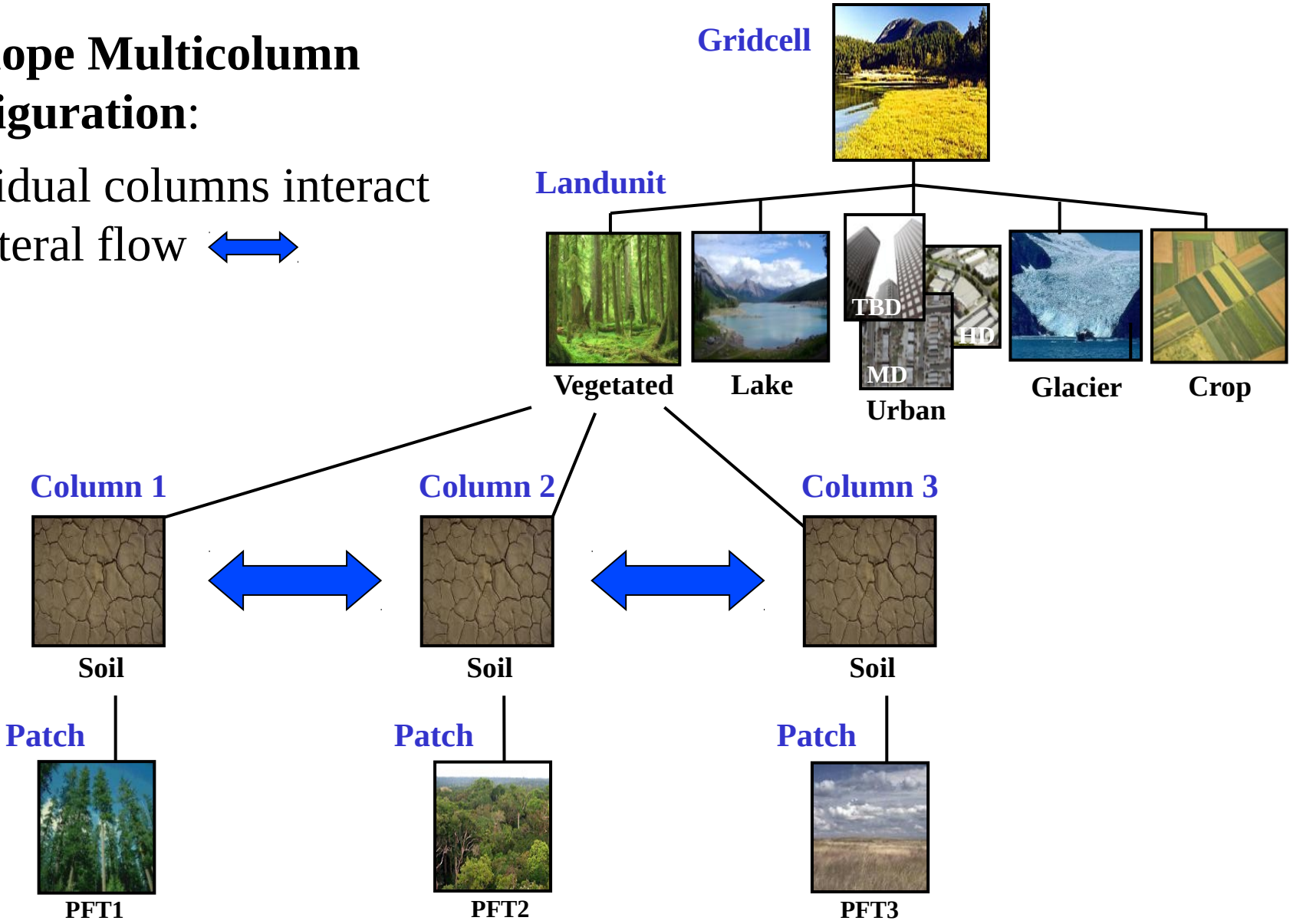
PFT/Patches occupy individual columns



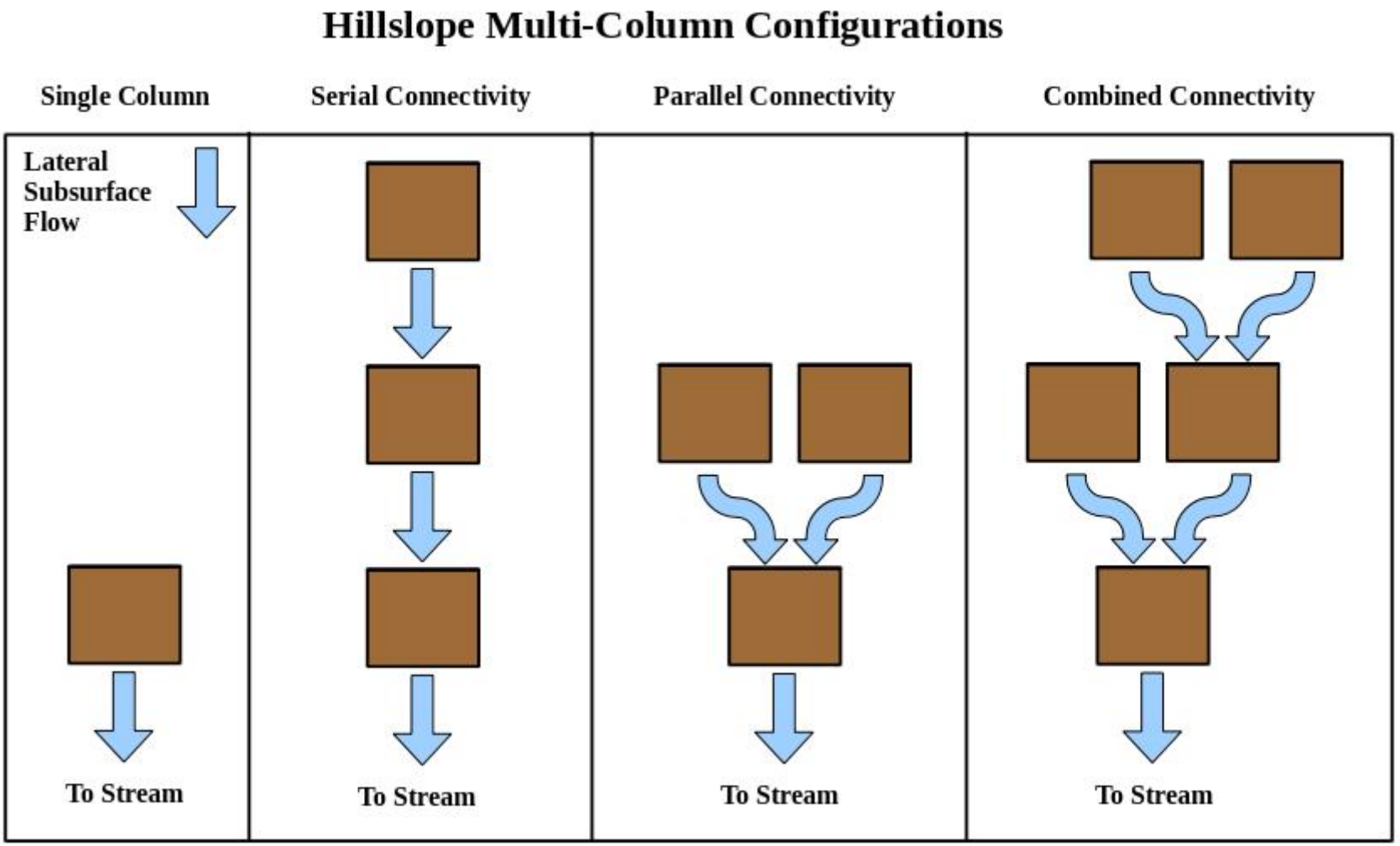
CLM Subgrid Tiling Structure

Hillslope Multicolumn Configuration:

Individual columns interact via lateral flow ⟺

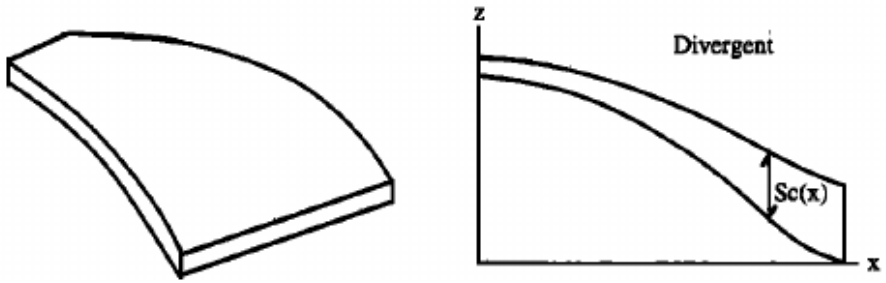


Hillslope Connectivity

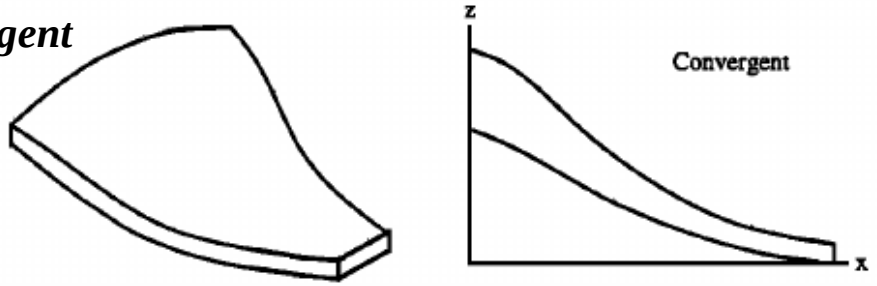


Characterizing Hillslopes
1. Analytical Landform Equations

Divergent



Convergent



Uniform

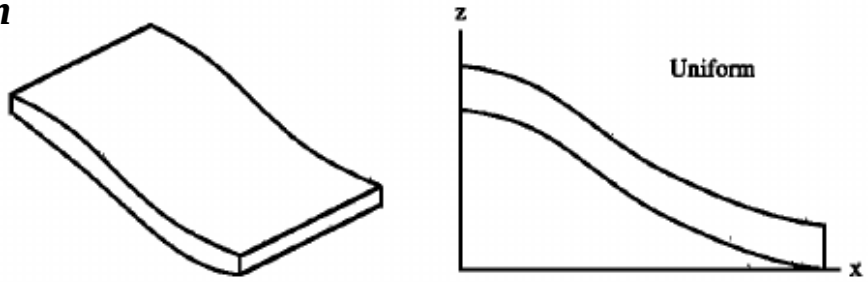


Figure 2. Schematic illustration of the three characteristic hillslope types.

Basic hillslope forms, e.g. convergent, uniform, and divergent, can be expressed with parametric equations

Key features include: *elevation*, *slope*, *width*, and *area* as functions of distance from base of hillslope

Fan and Bras, 1998, Analytical solutions to hillslope subsurface storm flow and saturation overland flow, WRR.

Characterizing Hillslopes
2. DEM Analysis

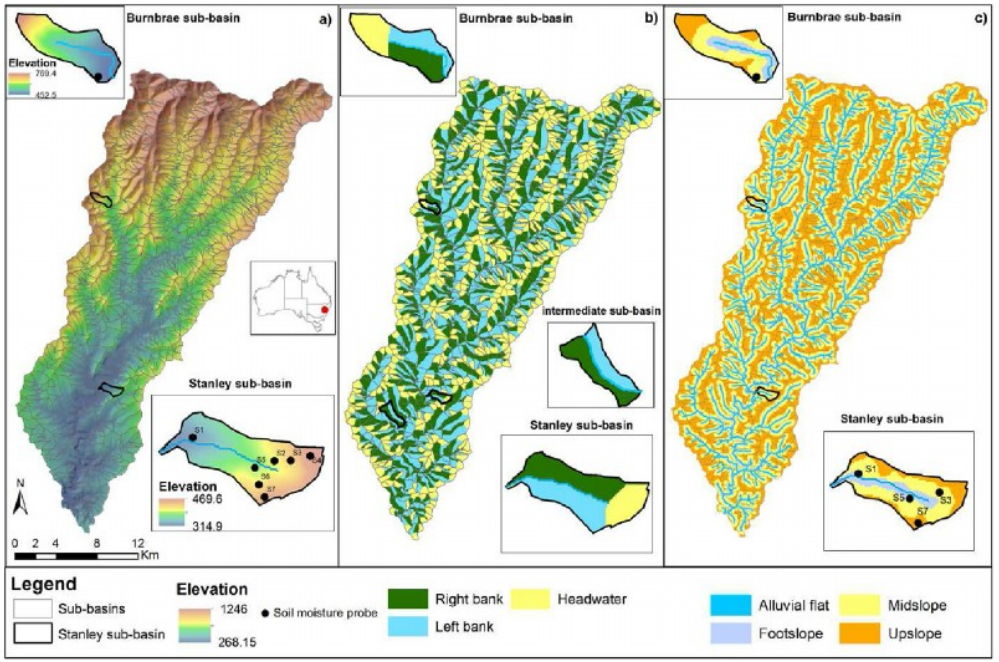
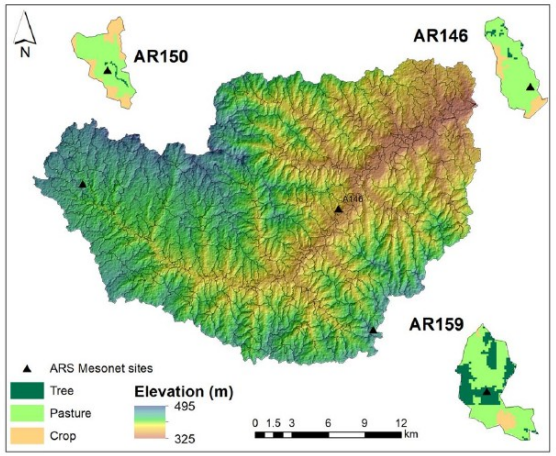


Fig. 4. Krui River catchment and the Stanley and Burnbrae sub-basins in Australia. SMART delineates (a) first order sub-basins (b) hillslopes and (c) landforms of the catchment. Soil moisture probes in (c) are used for model comparison.

Geospatial analysis of DEMs can be used to directly extract geomorphological information and generate representative hillslopes

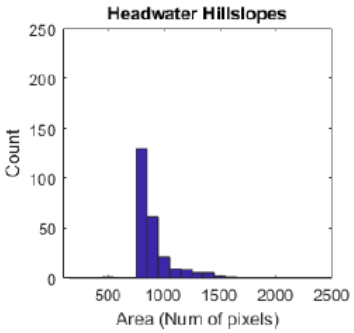
Ajami et al., 2016, Development of a computationally efficient semi-distributed hydrologic modeling application for soil moisture, lateral flow and runoff simulation, EMS.

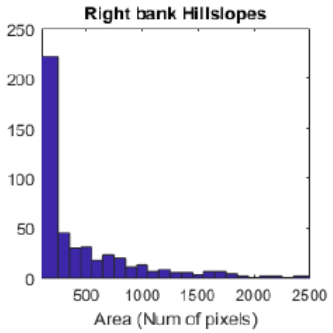
Characterizing Hillslopes
2. DEM Analysis

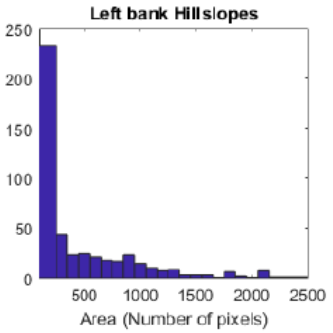


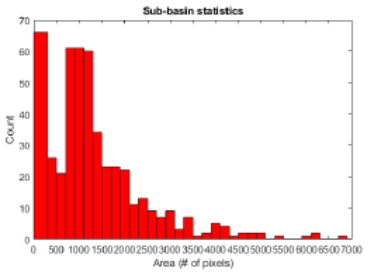
Little Washita catchment: Hillslope Scale Statistics

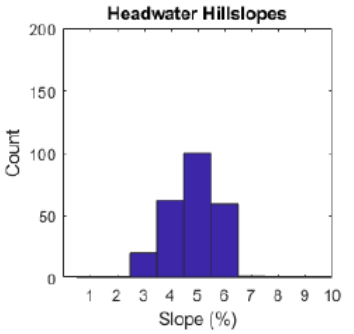
Statistical analysis provides information on distributions of hillslope characteristics within a region.

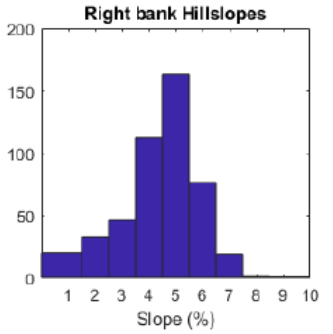


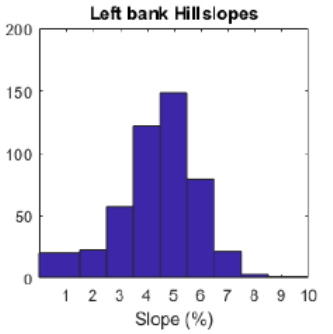


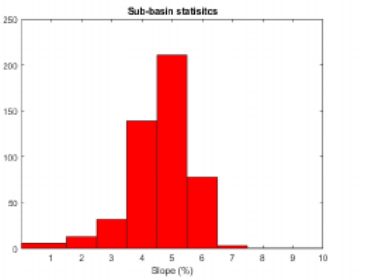






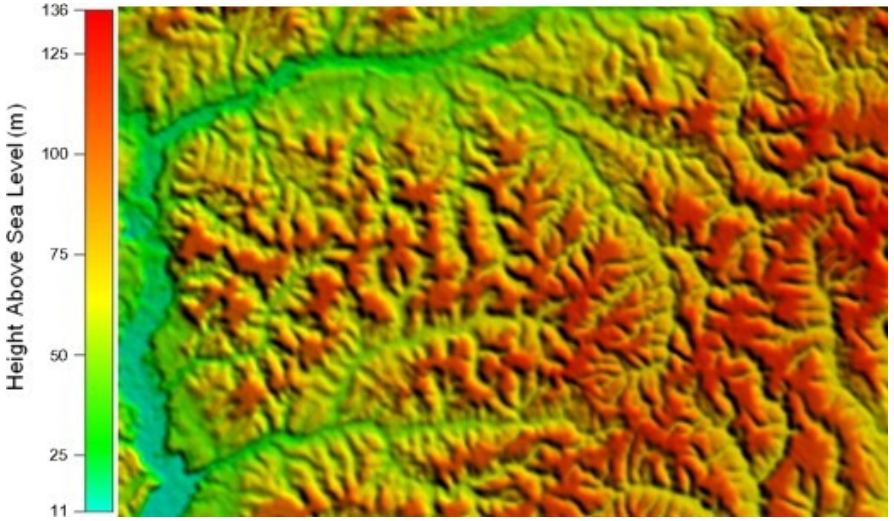




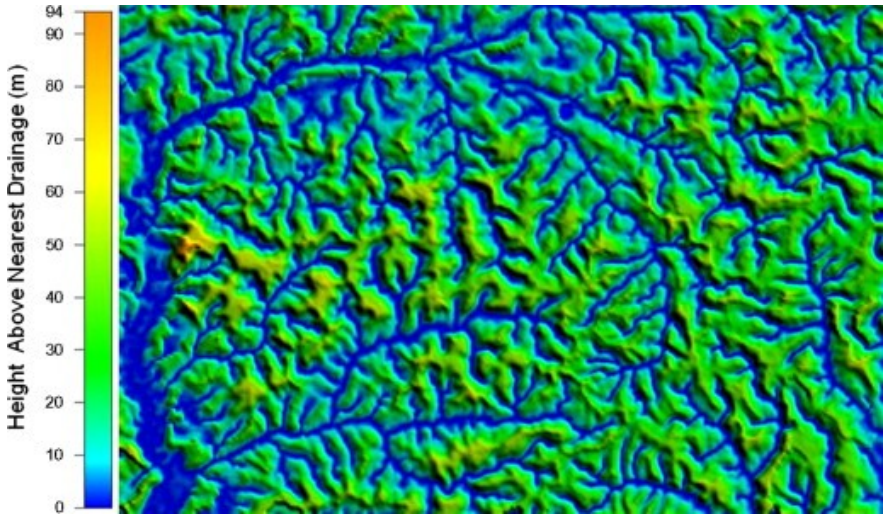


Hoori Ajami (personal communication), 2018.

Characterizing Hillslopes
3. HAND Analysis



Height Above Sea Level

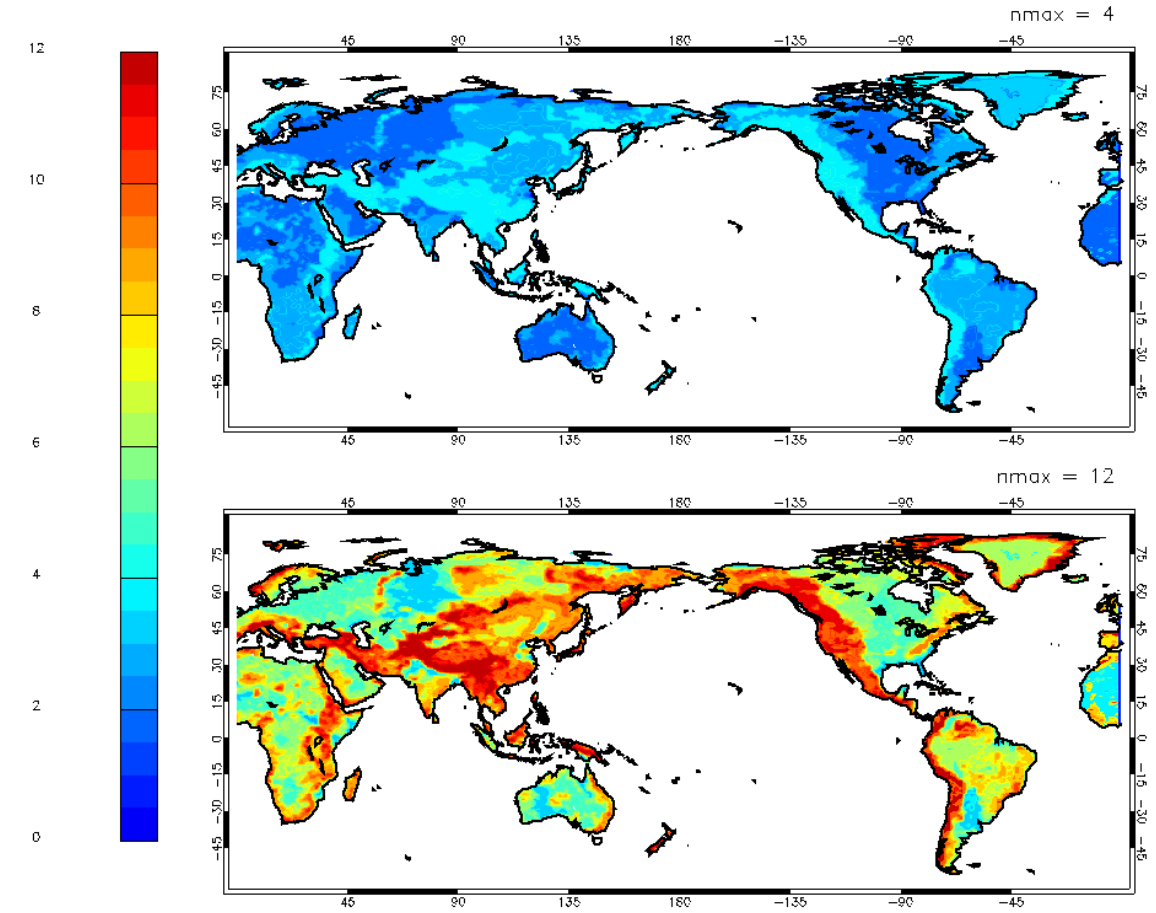


Height Above Nearest Drainage

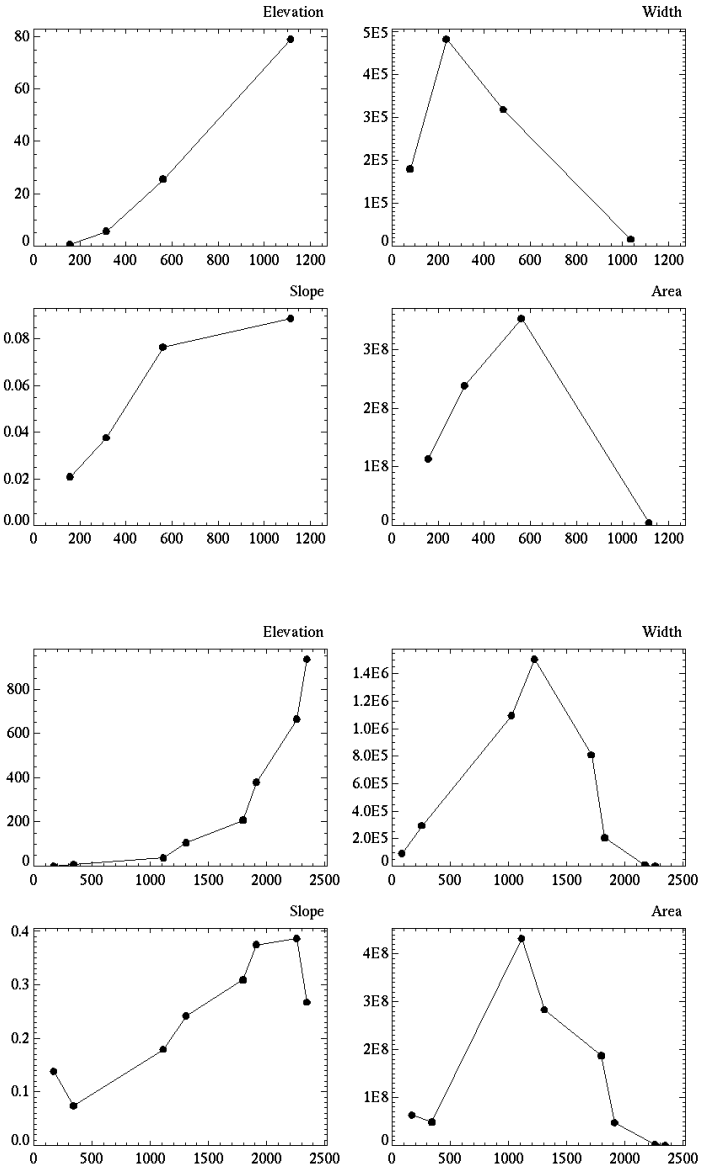
Nobre et al., J. Hydrology, 2011.

Characterizing Hillslopes
3. HAND Analysis

Number of columns per hillslope

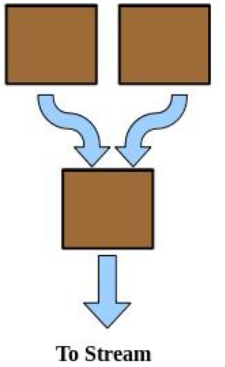


Hillslope geomorphology



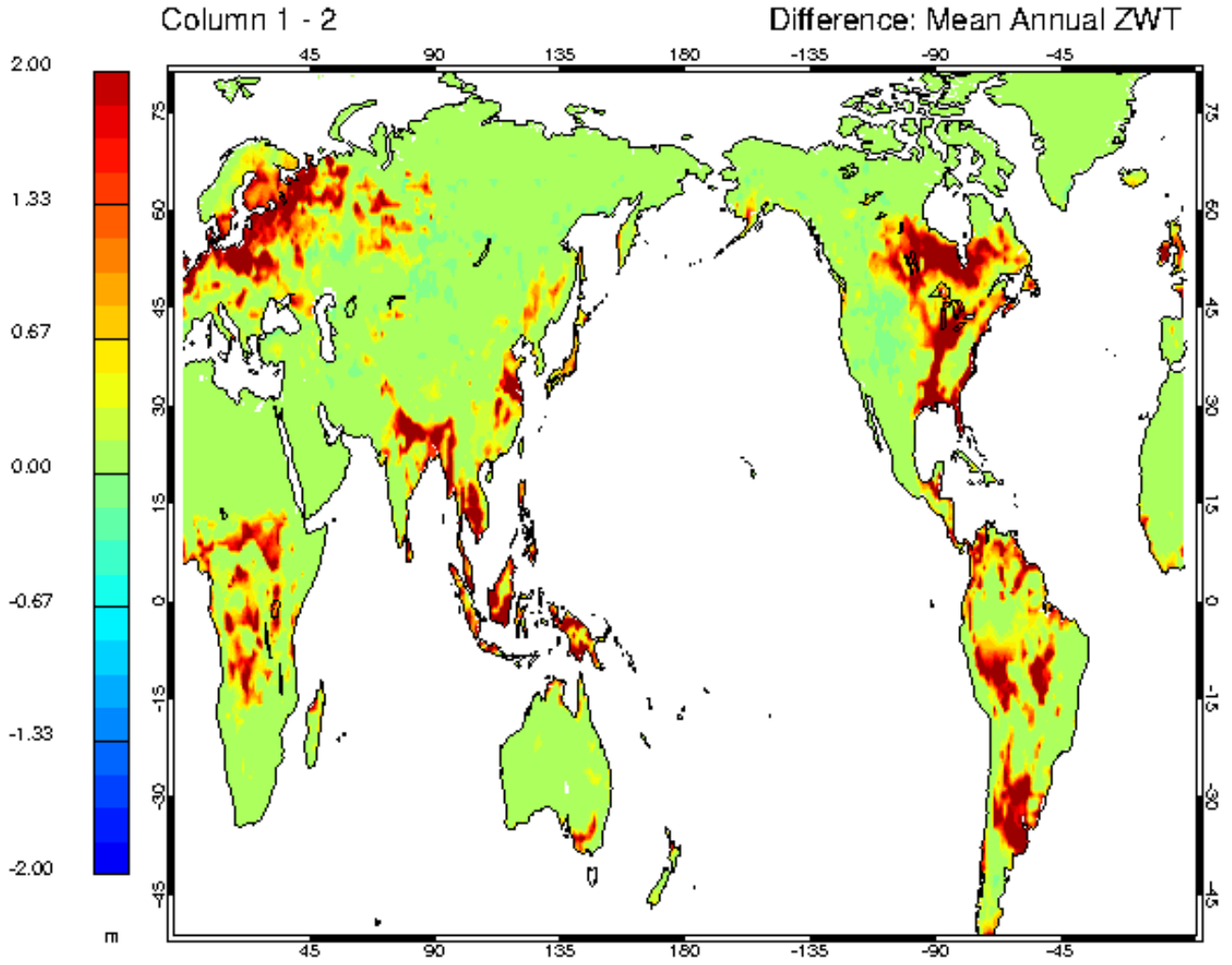
Aaron Potkay (personal communication), 2018.

Simple Global Test Case



- One hillslope, three columns
- Two upland columns are connected in parallel to one lowland column
- Identical column width and area, spatially varying elevation and slope derived from global topographic dataset
- Atmospheric forcing from global reanalysis-based dataset
- Spatially varying vegetation and soil properties

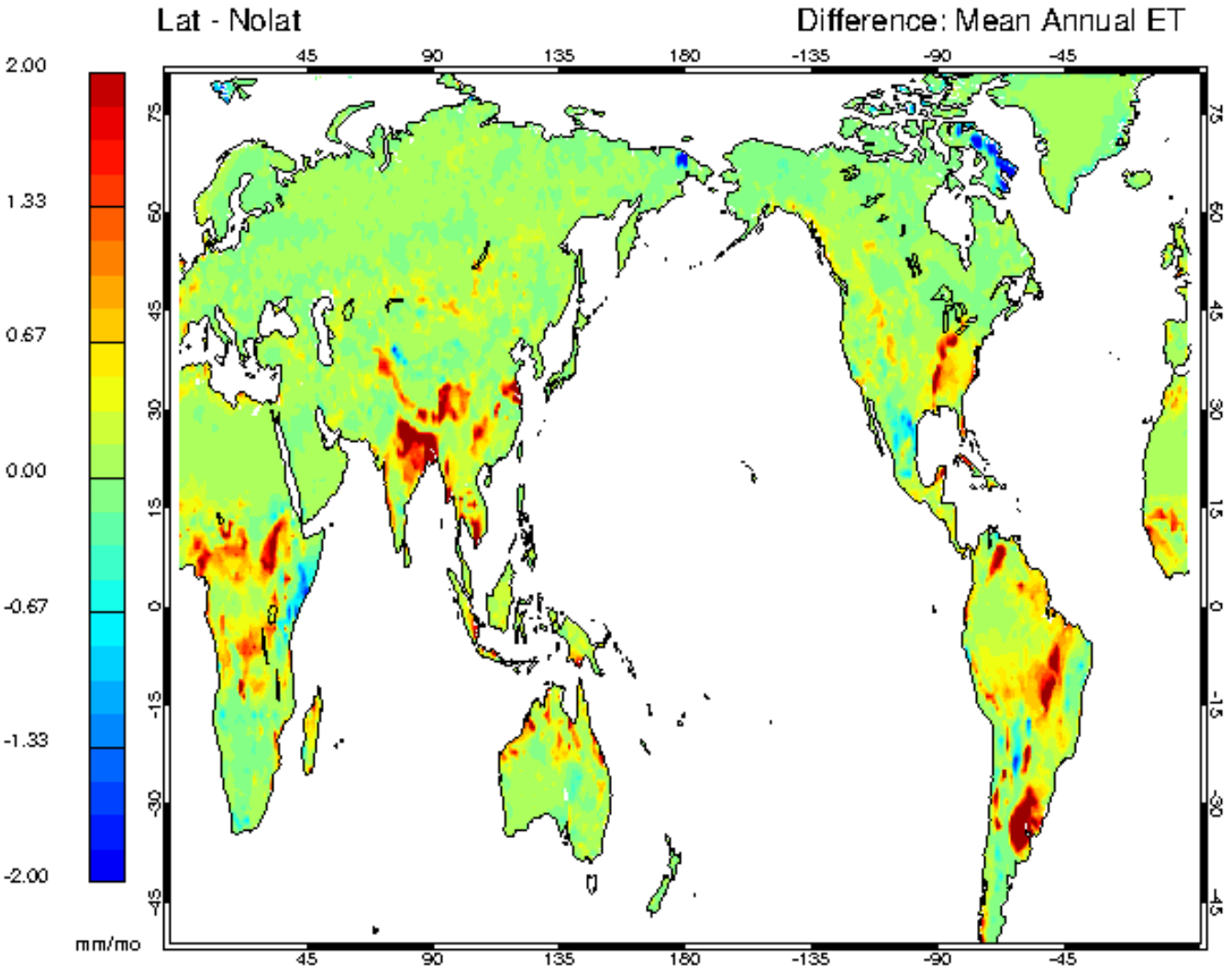
Impact of Subsurface Lateral Flow



Saturated Thickness greater in Lowland column relative to Upland column

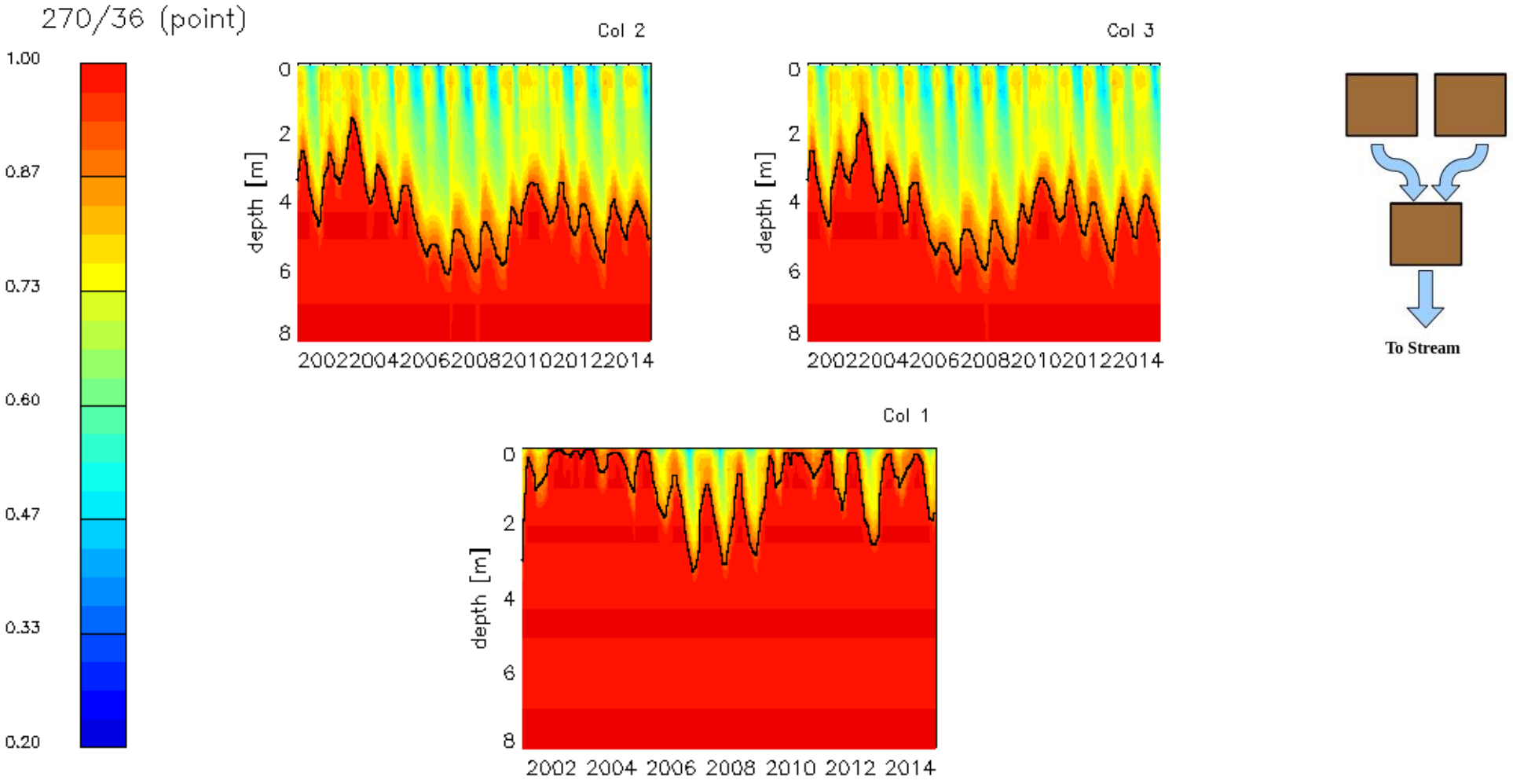
Convergence leads to shallower water tables in transitional regions

Gridcell Average ET



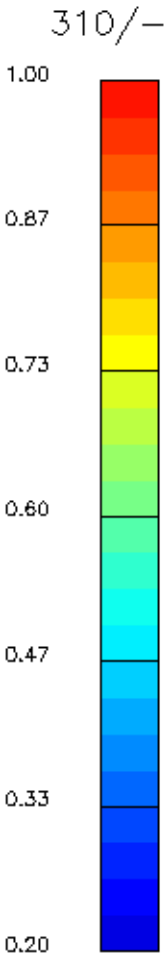
Difference in ET:
Lateral Flow minus No Lateral Flow

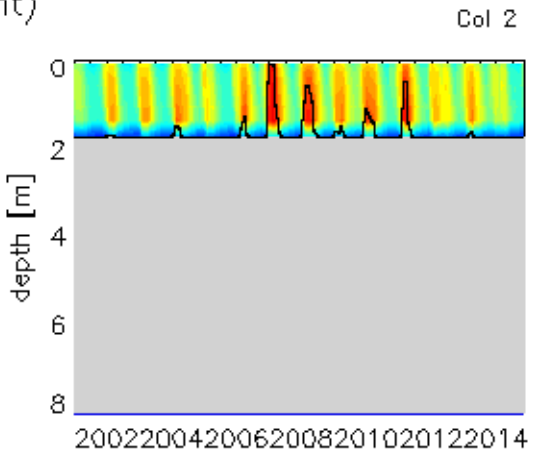
Moisture Convergence

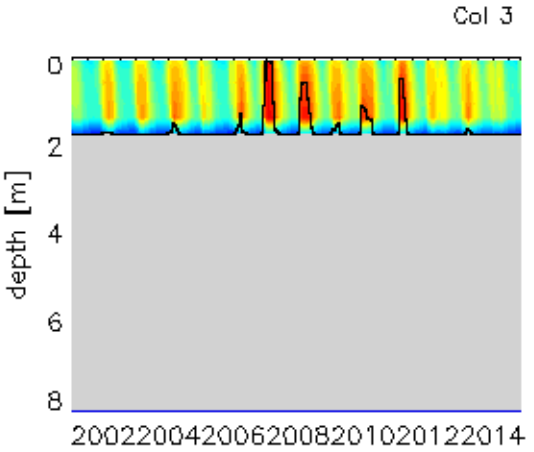


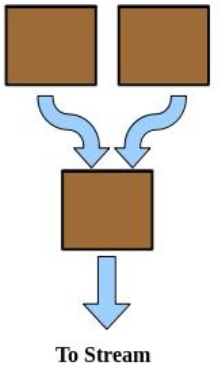
Lowland column (bottom) has higher saturation level than upland columns (top).

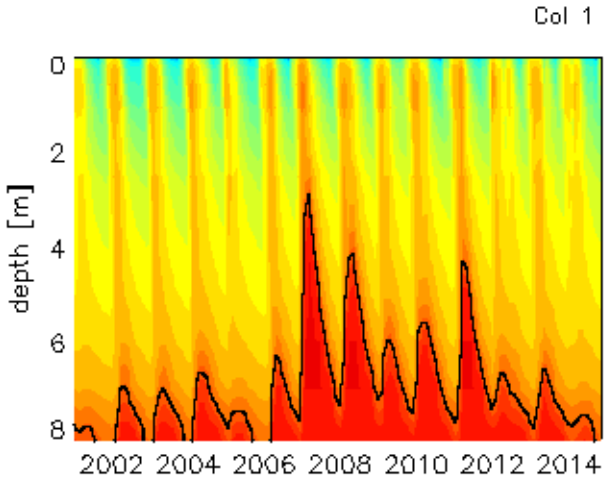
Soil Thickness Variations



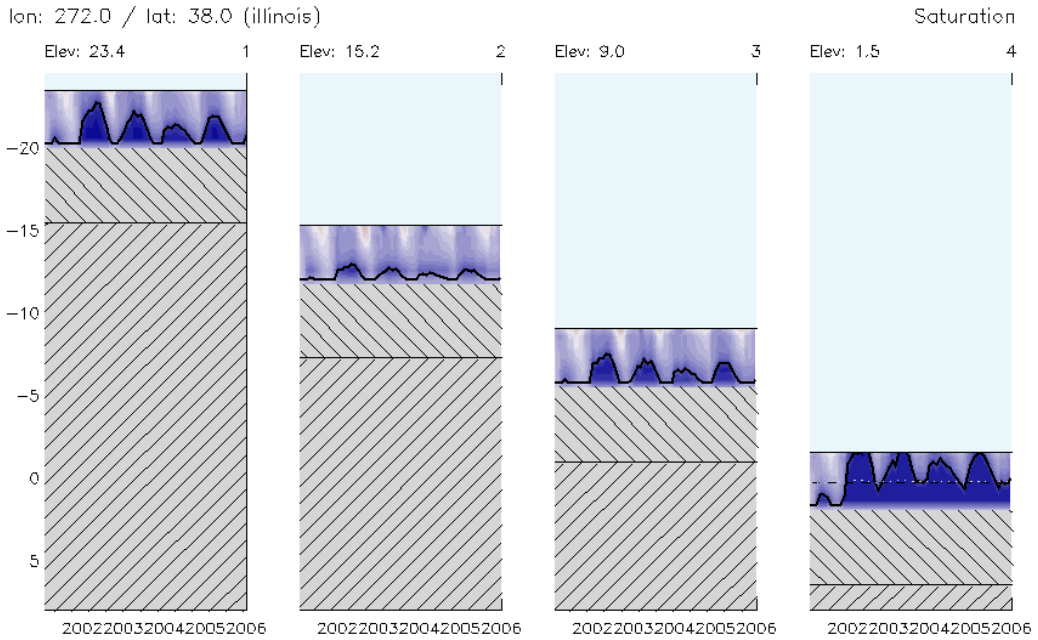


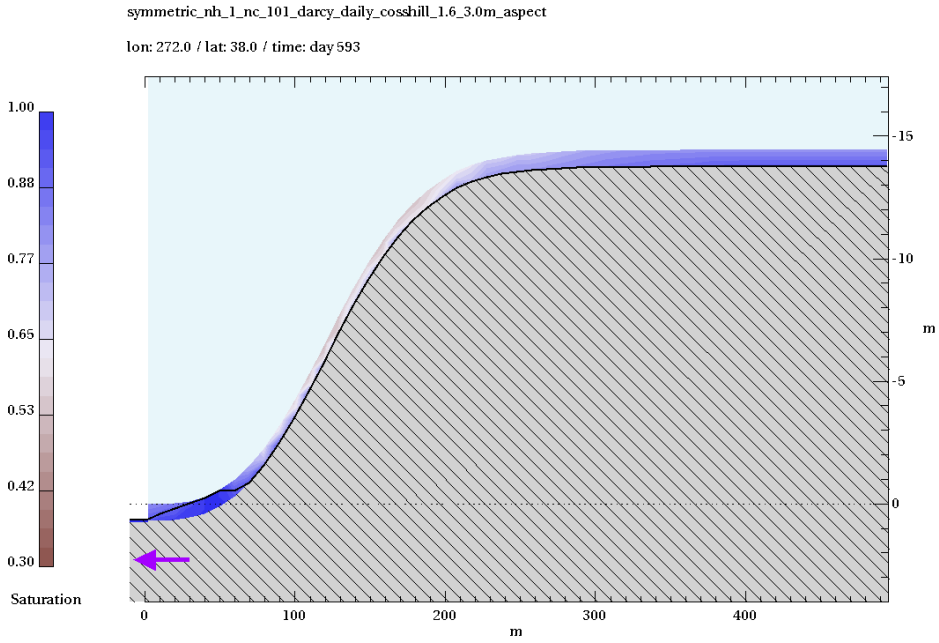


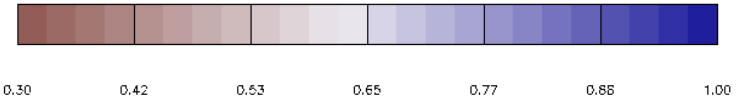




High Resolution Test







Summary

- CTSM-Hillslope model infrastructure in place
- Covariation of landscape quantities important
- Global simulation shows interaction of hydrology with climate
- “Hillslope Hydrology” model will be available via Github with upcoming versions of CTSM

Applications

- Soil moisture heterogeneity impacts on:
  - prognostic vegetation and ecosystem cycling
  - permafrost distribution
  - boundary layer formation

- Saturation heterogeneity impacts on:
  - soil carbon decomposition
  - methane production and oxidation
  - runoff production

Research Opportunities

- Terrain analysis
- Catchment decomposition
- Radiation partitioning due to varying slope and aspect
- Downscaling of meteorological forcing
- Sensitivity analyses
- Parameterization formulation

Open Question

Does vegetation in CLM respond to soil moisture realistically?