Representiative Hillslopes in the Community Terrestrial Systems Model

Sean Swenson, Martyn Clark, Ying Fan, David Lawrence

NCAR
NATIONAL CENTER FOR ATMOSPHERIC RESEARCH

NSF

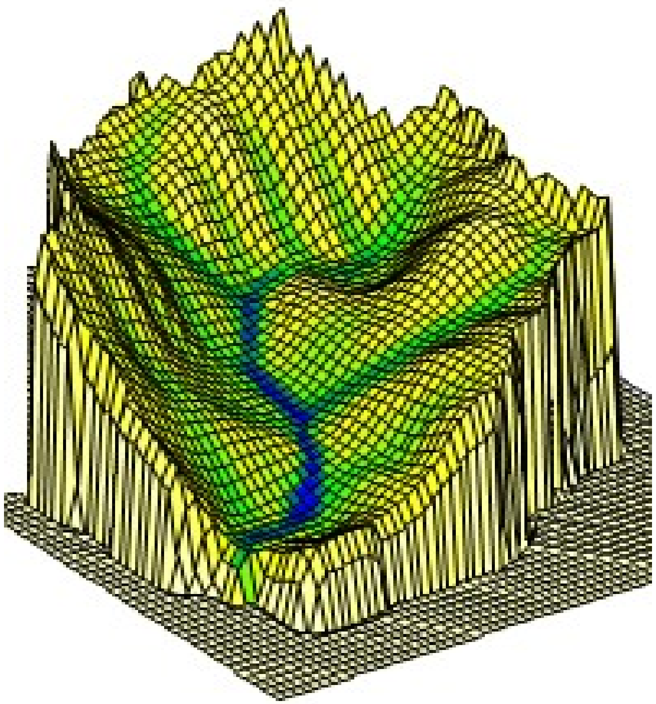
CUAHSI
UNIVERSITIES ALLIED FOR WATER RESEARCH

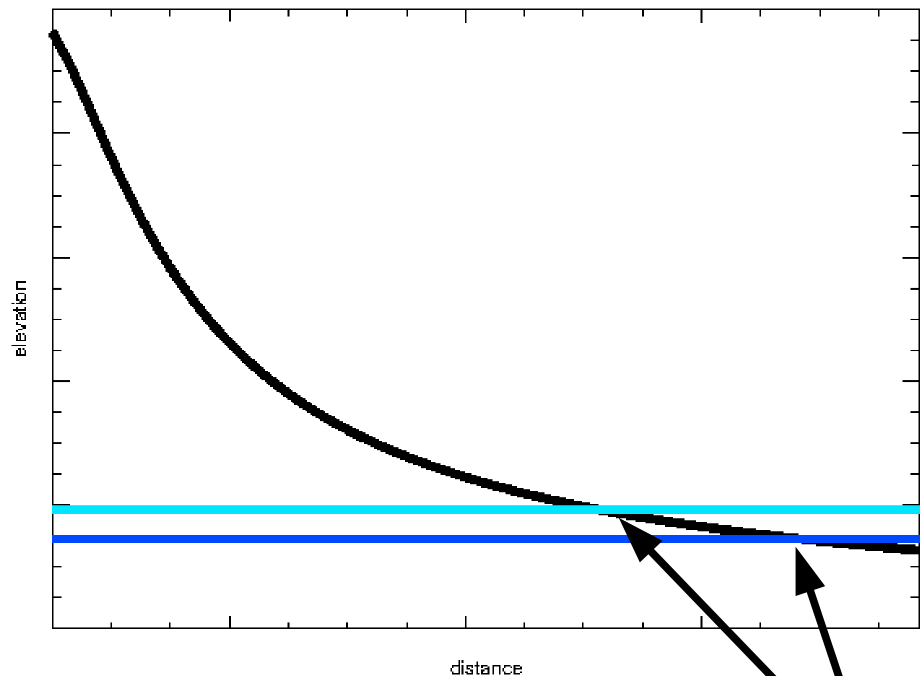
Soil Moisture Heterogeneity

Observed vegetation patterns imply variations in soil moisture




CLM Treatment of Soil Moisture Heterogeneity





Saturated fraction = 0.36

Saturated fraction = 0.14

Point at which water table intersects surface determines saturated fraction

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

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

Evolution of Process Representation in Land Models

Land as a lower boundary to the atmosphere → **Land as an integral component of the Earth System**

Focus on land-atmosphere energy fluxes

Limited representation of land processes & feedbacks

→

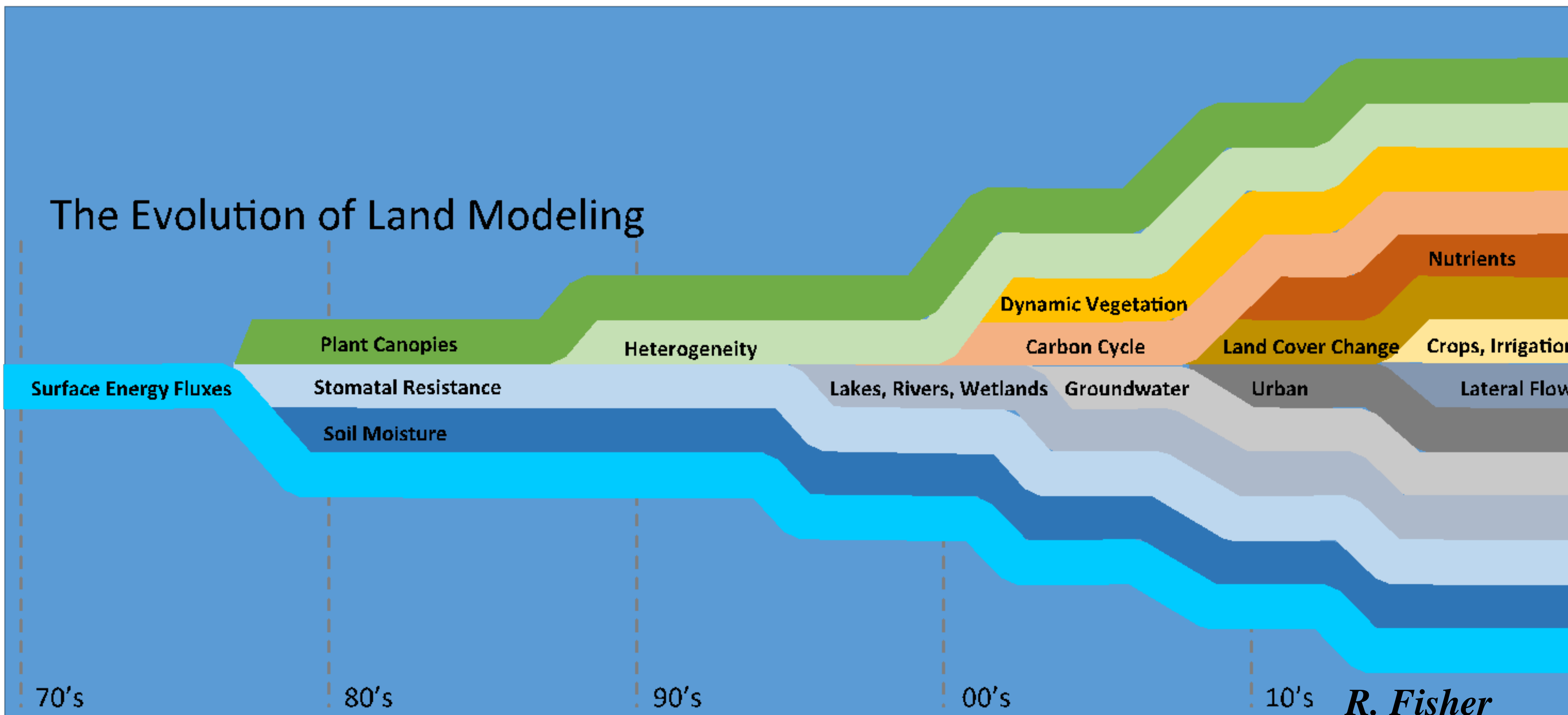
Mechanistic modeling of land processes

Properties define processes (focus on short-term fluxes)

→

Simulate the dynamics of change (e.g., dynamic vegetation)

Processes define properties (feedbacks and interactions across time scales)



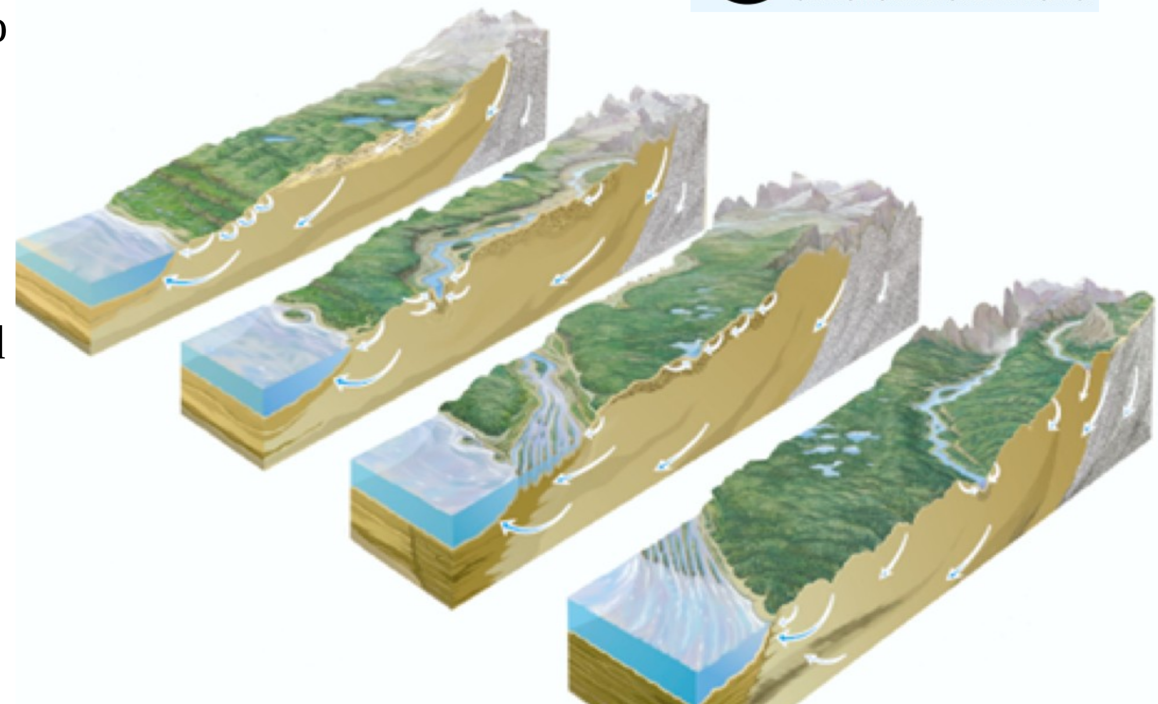
CUAHSI / NCAR Collaboration

- **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

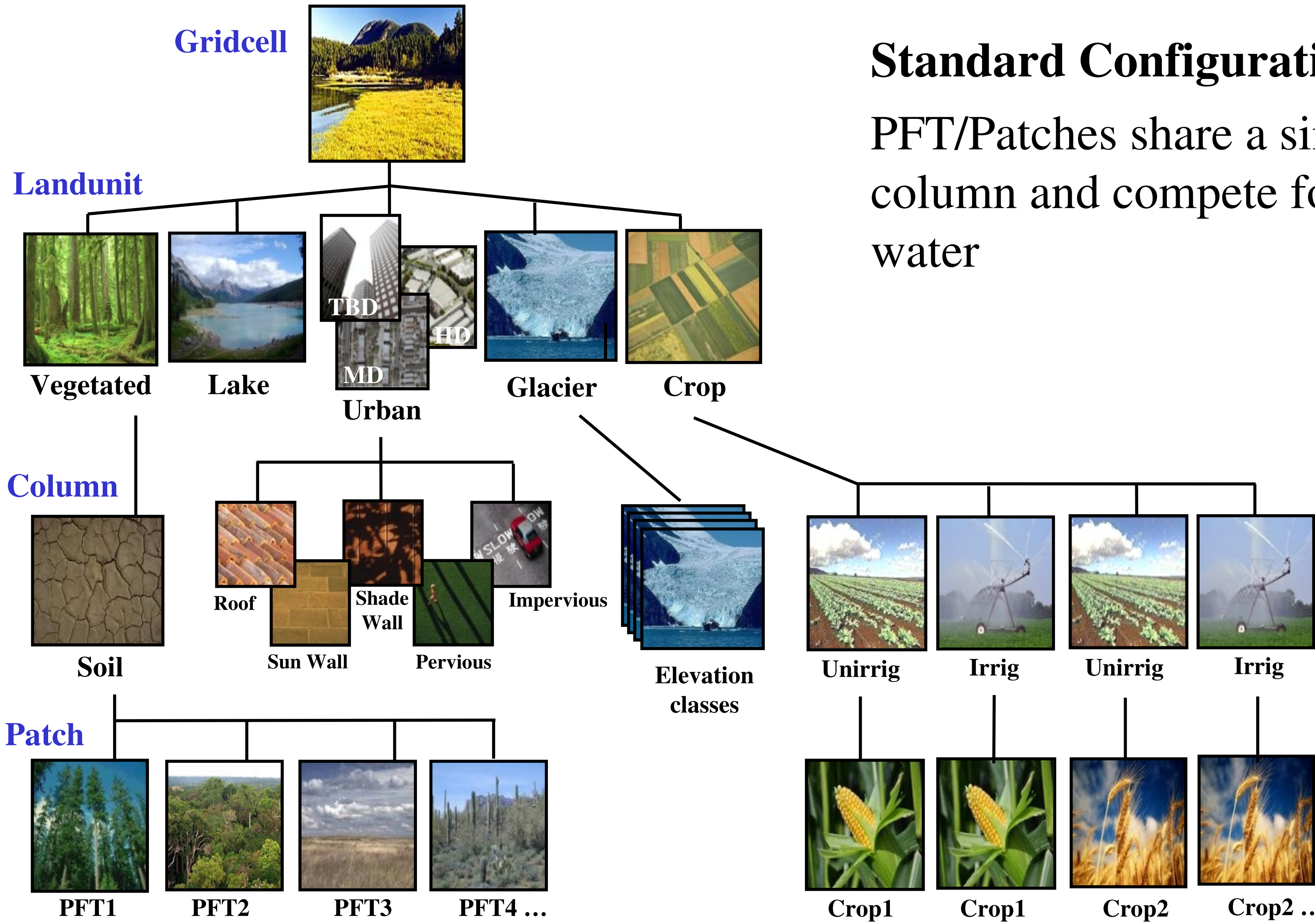
REVIEW ARTICLE
10.1002/2015WR017096

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]

CLM Subgrid Tiling Structure



Standard Configuration:

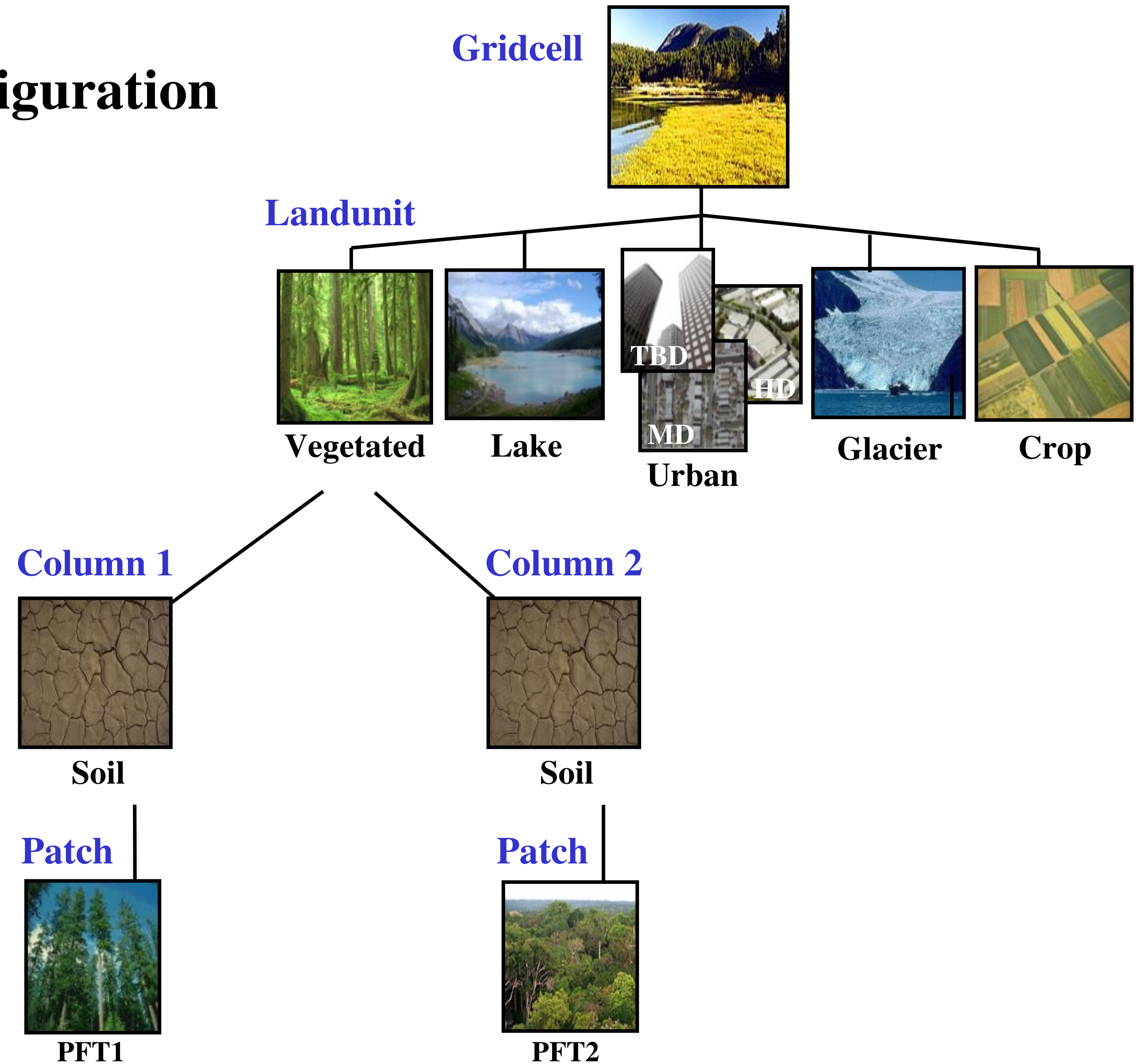
PFT/Patches share a single column and compete for water

CLM Subgrid Tiling Structure

Multicolumn Configuration

(1 pft per col):

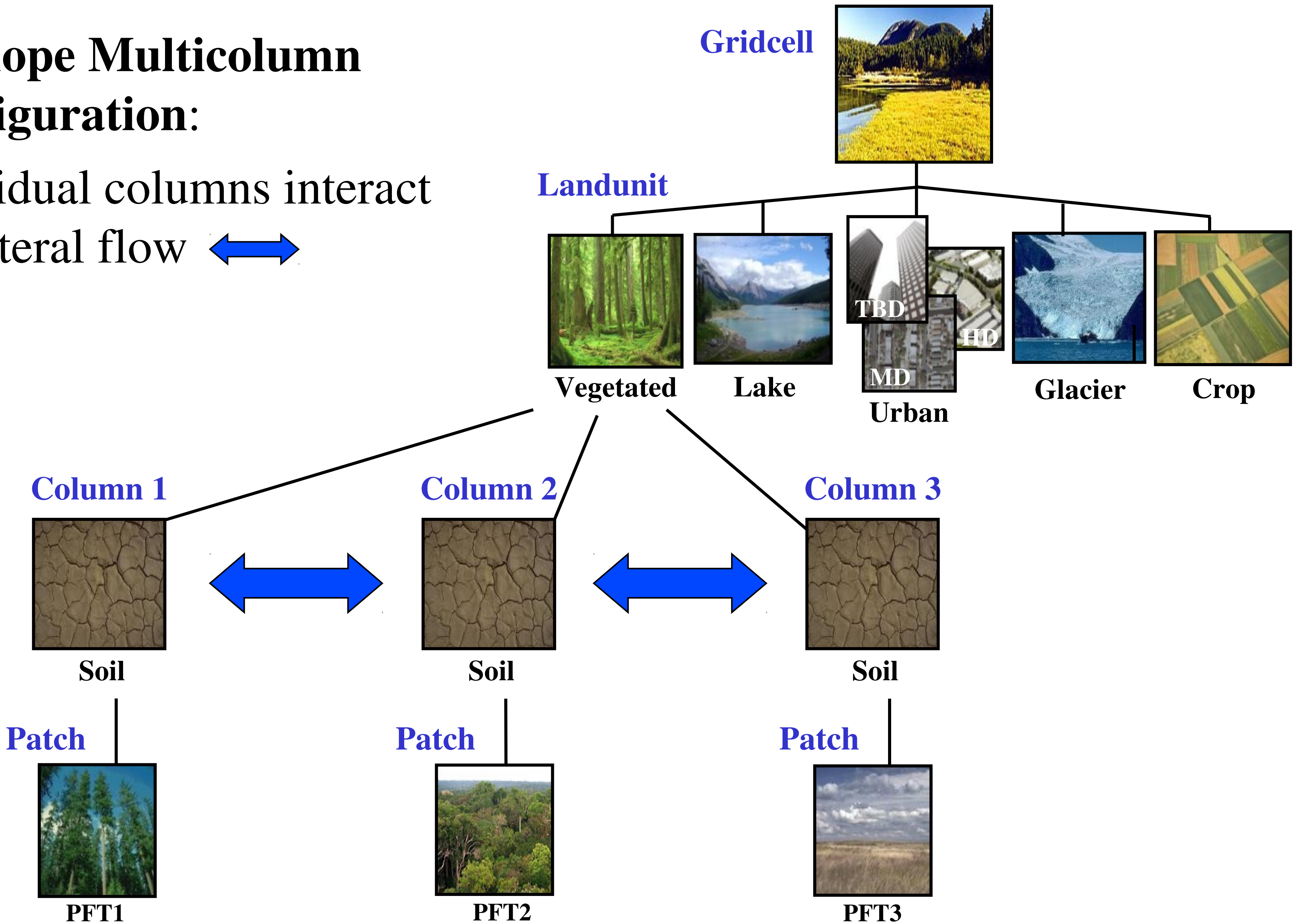
PFT/Patches occupy individual columns



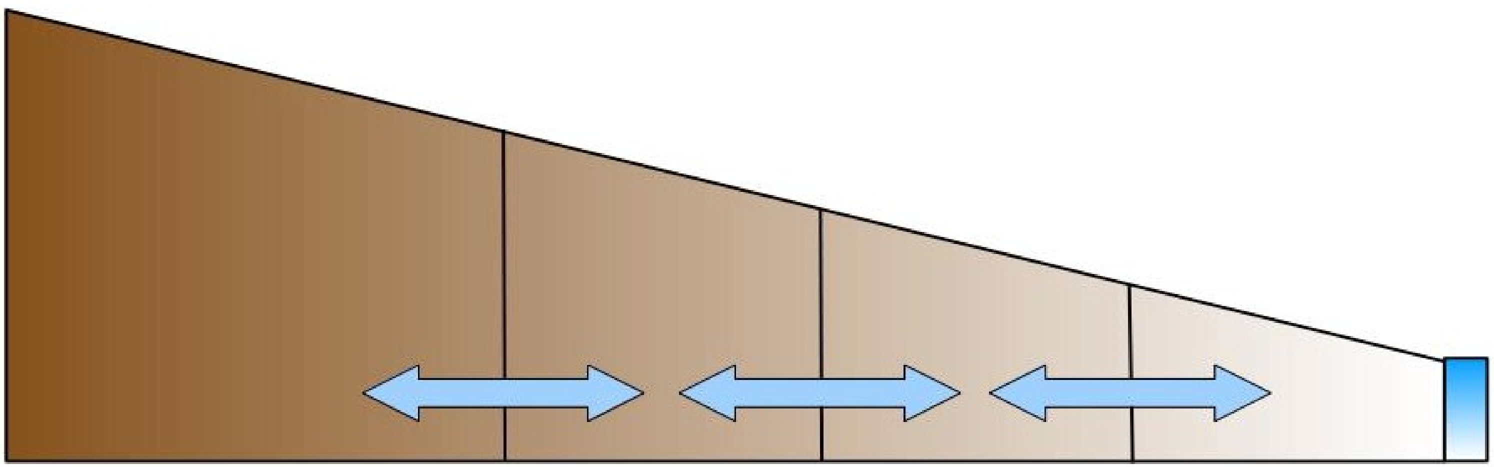
CLM Subgrid Tiling Structure

Hillslope Multicolumn Configuration:

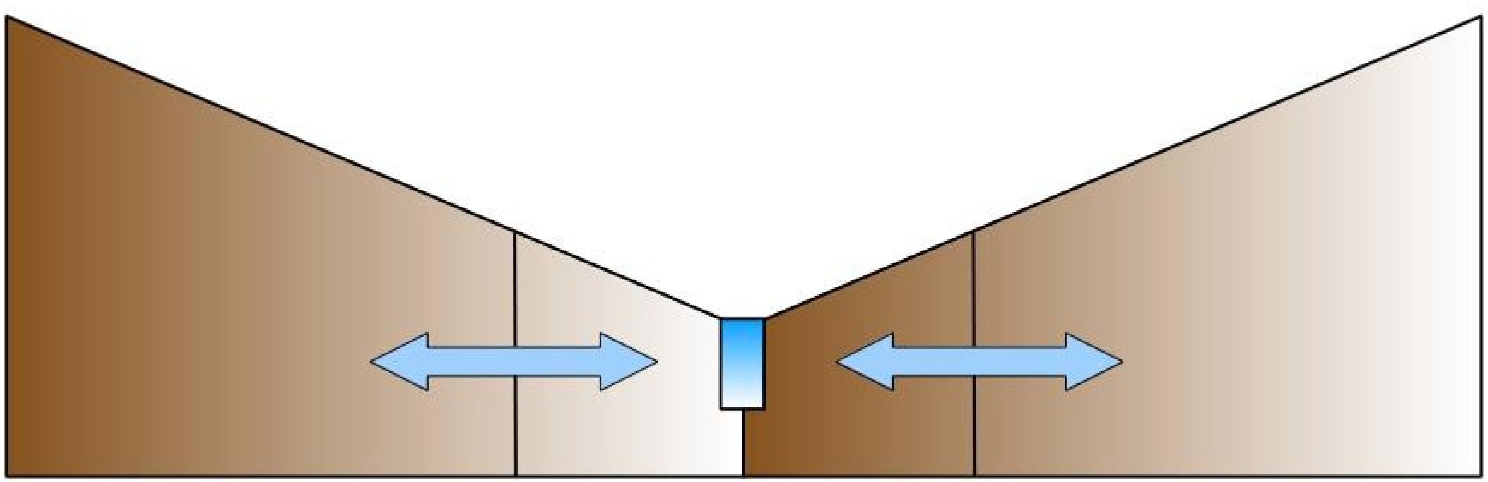
Individual columns interact via lateral flow ⟺



Conceptual Hillslopes

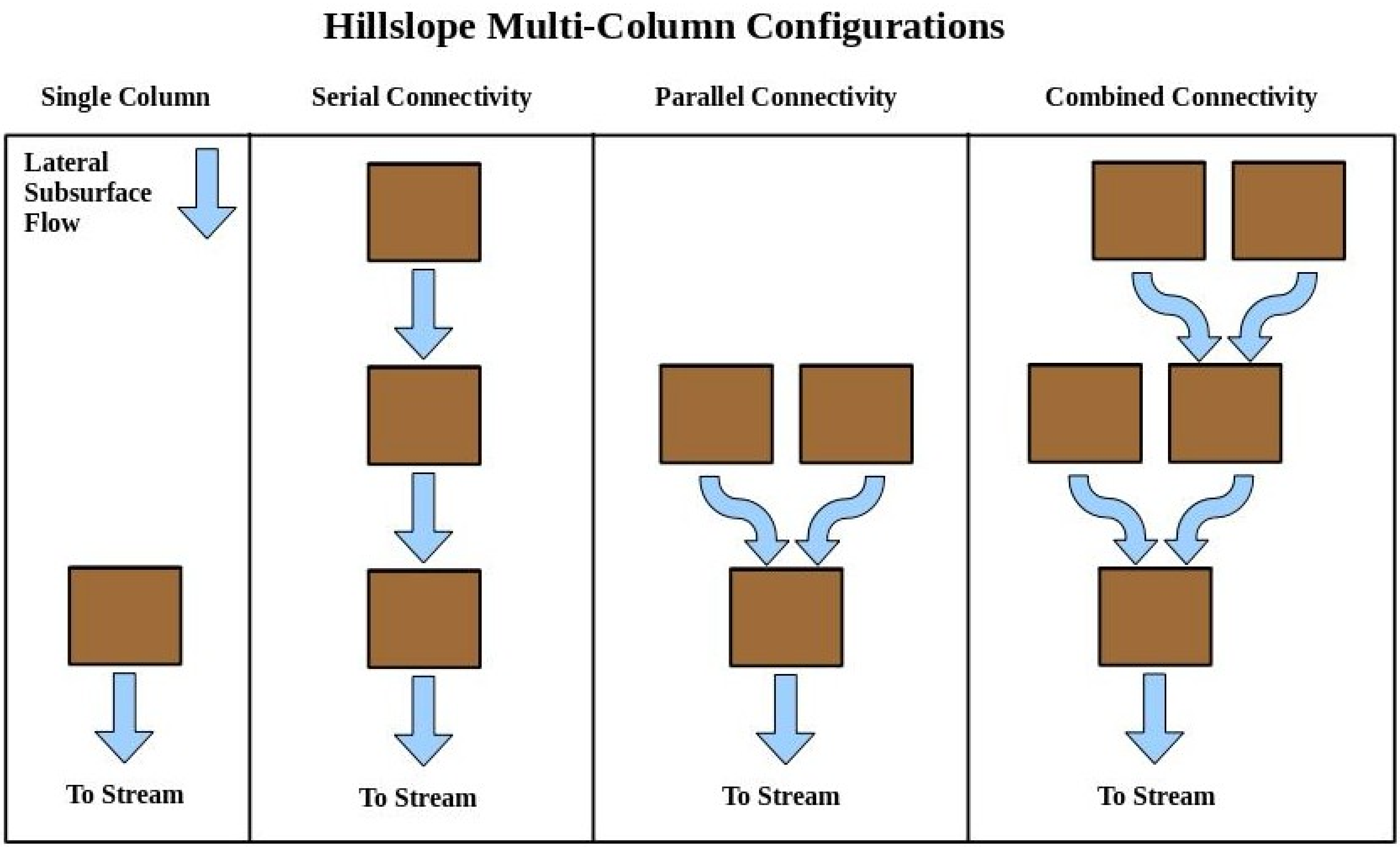


Serial subsurface flow inputs to riparian zone



Independent (parallel) subsurface flow inputs to riparian zone

Hillslope Connectivity



Characterizing Hillslopes
1. Analytical Landform Equations

Divergent

Convergent

Uniform

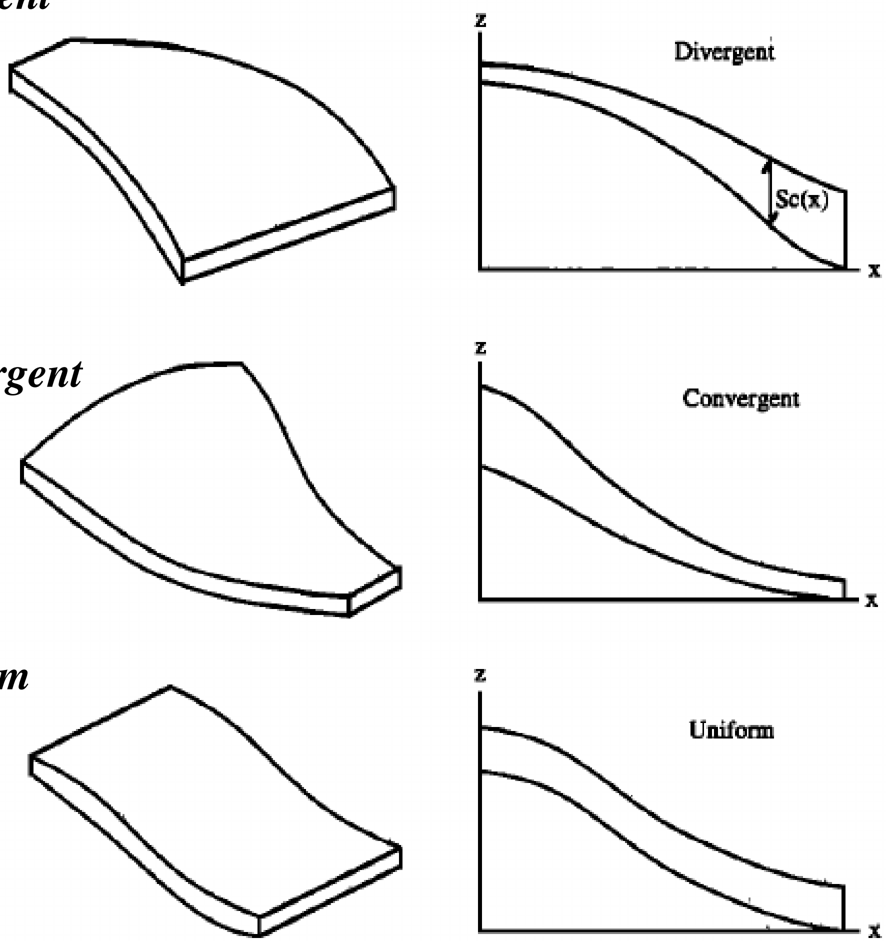


Figure 2. Schematic illustration of the three characteristic hillslope types.

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
1. Analytical Landform Equations

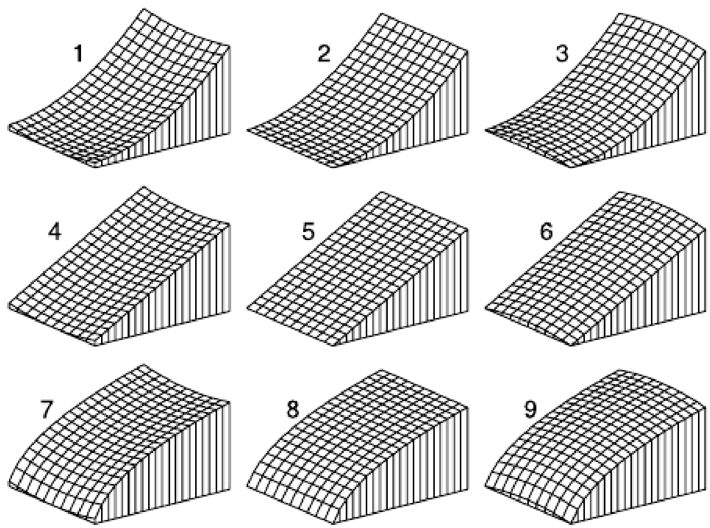


Fig. 5. Three-dimensional view of the nine different hillslopes used in this study. The numbers in the figure refer to Table 1.

Unfortunately, integrable expressions are limited and often lead to unrealistic flowpaths

642 *P. Troch et al. / Advances in Water Resources 25 (2002) 637–649*

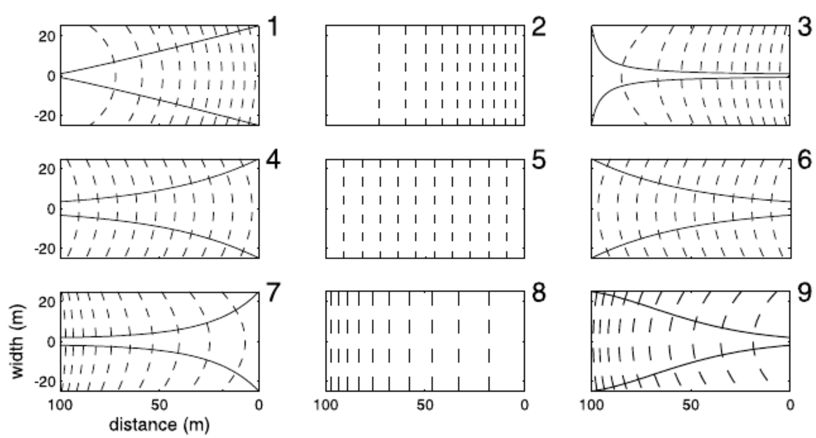


Fig. 6. Plan view of drainage divides (solid lines) and contour lines (dashed lines) of nine hillslopes. The upslope divide of each hillslope is at $x = 0$.

Troch et al., 2002, Analytical solutions to a hillslope-storage kinematic wave equation for subsurface flow, AWR.

Characterizing Hillslopes
2. DEM Analysis

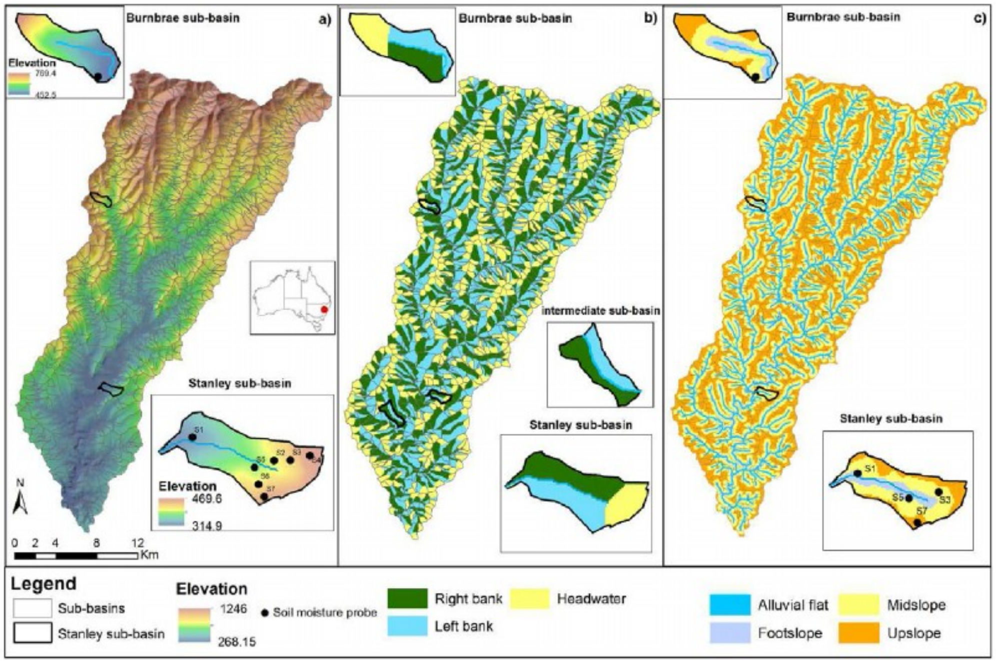
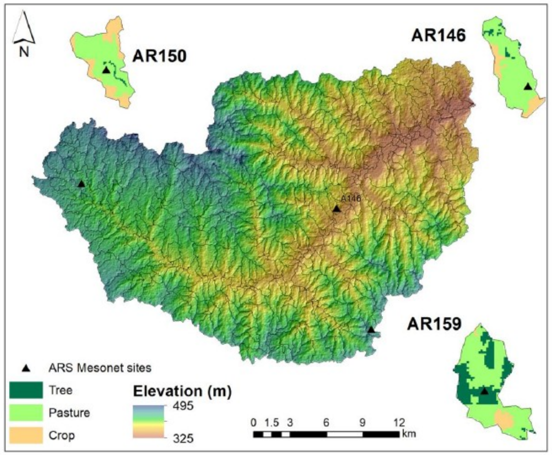


Fig. 4. Krui River catchment and the Stanley and Burnbrae sub-basins in Australia. SMART delineates (a) first order sub-basins (b) hillslopes and (c) landforms of the catchment. Soil moisture probes in (c) are used for model comparison.

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.

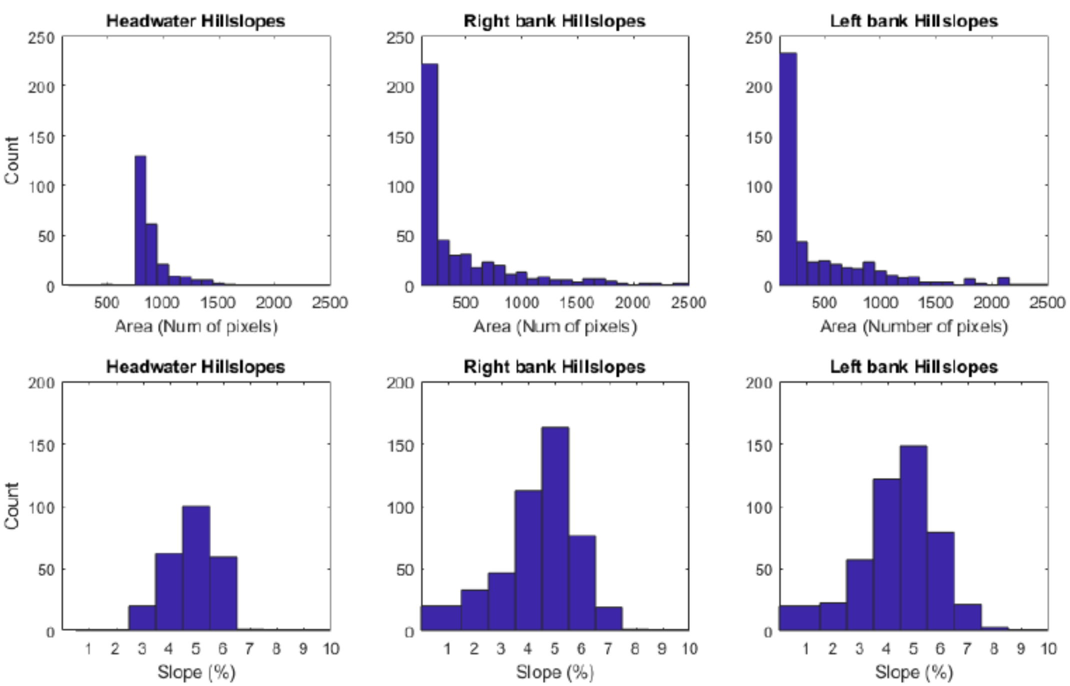
Characterizing Hillslopes
2. DEM Analysis

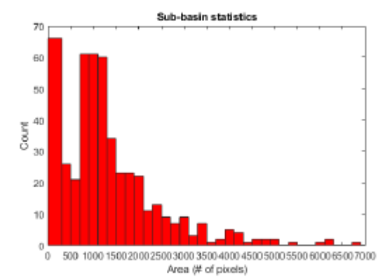


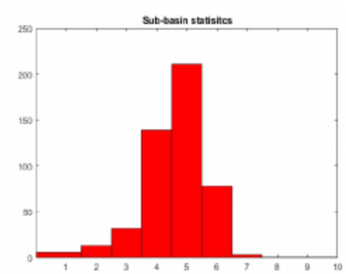
Little Washita catchment: Hillslope Scale Statistics

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

This work is ongoing at this time...

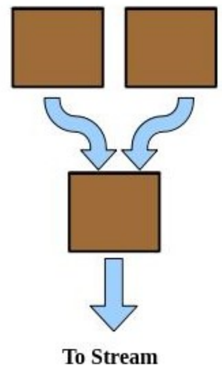






Hoori Ajami (personal communication), 2018.

Simple Global Test Case



• One hillslope, three columns

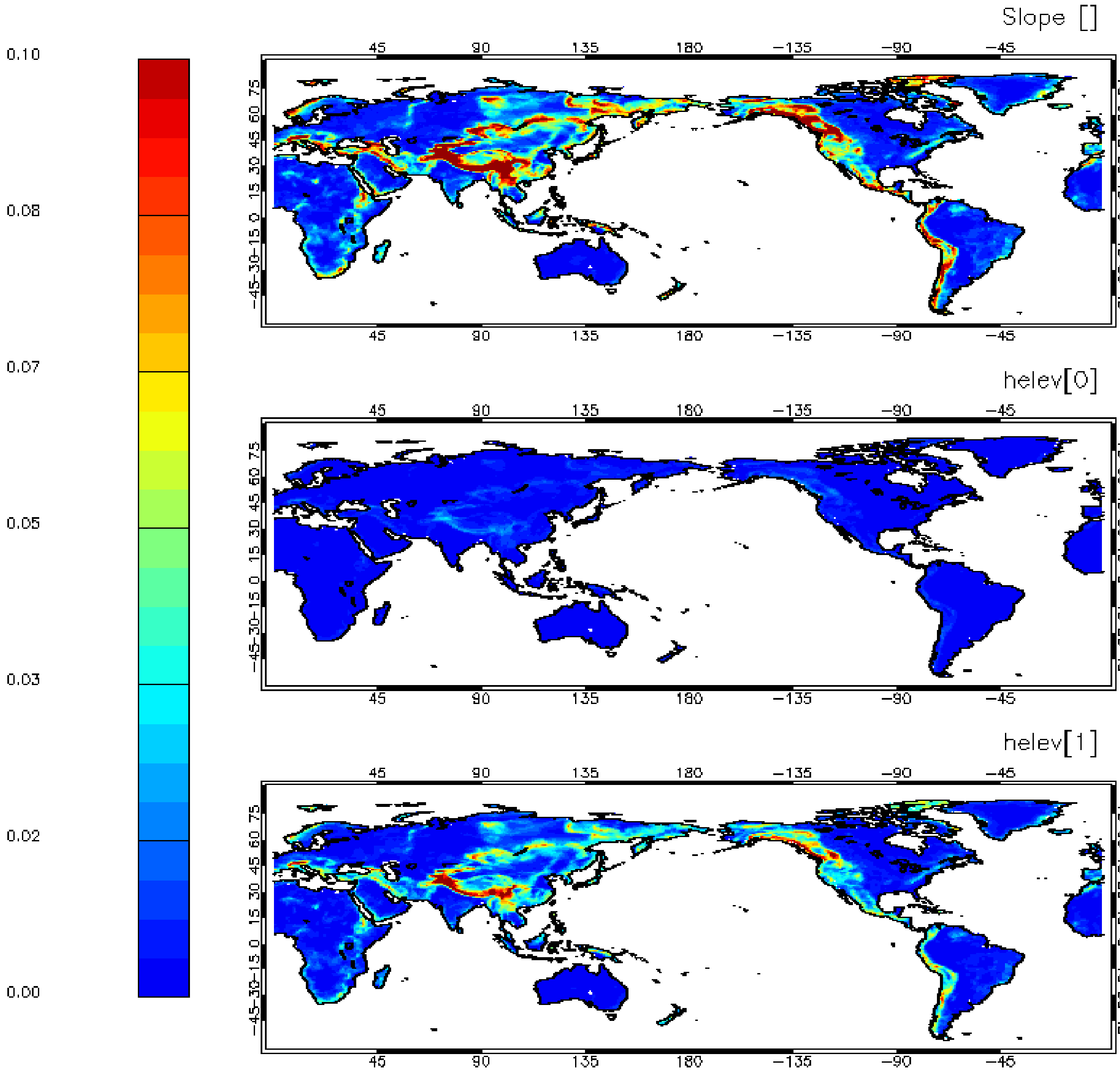
• Two upland columns are connected in parallel to one lowland column

• 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

Topographic Properties

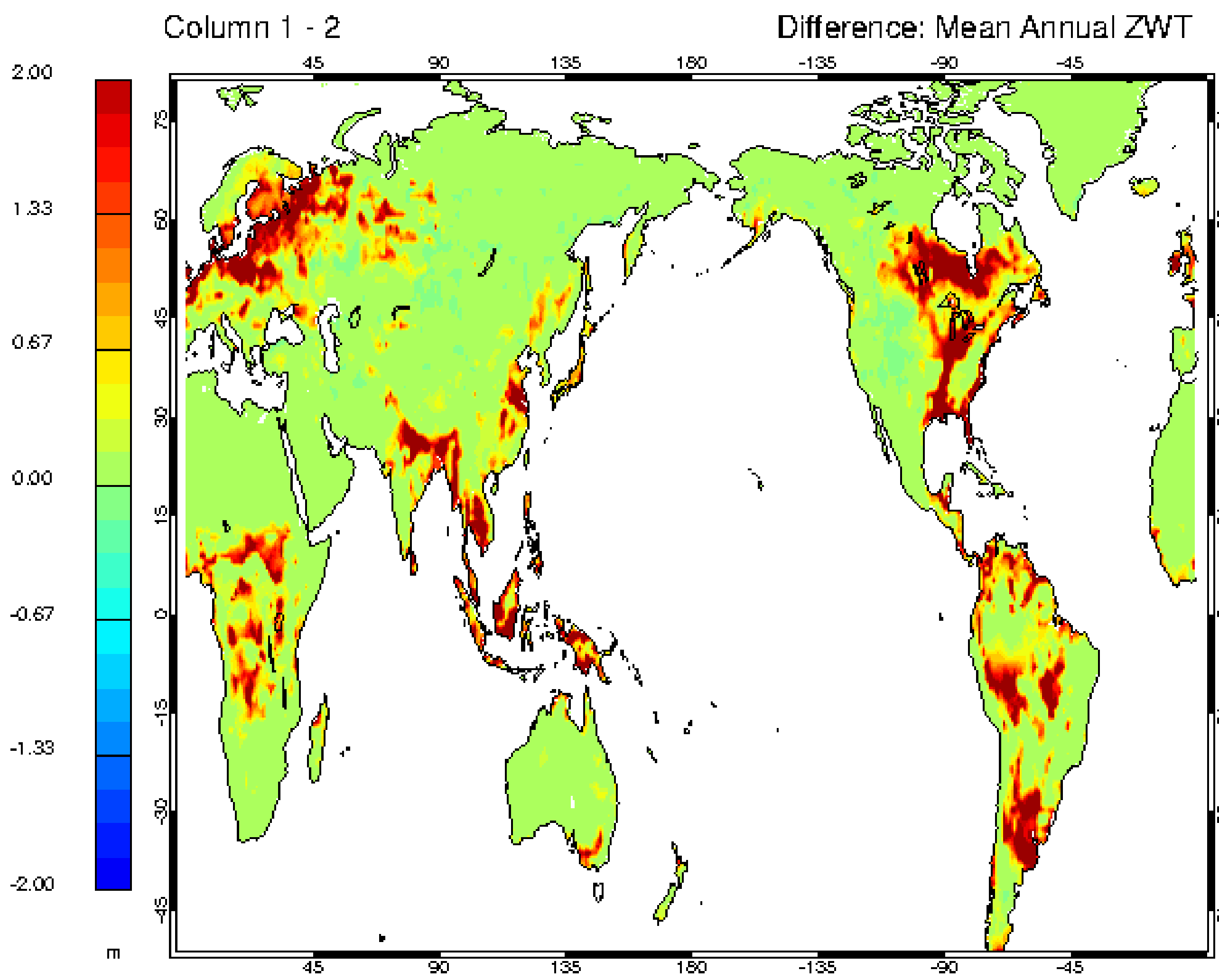


Gridcell Mean Slope

Lowland Elevation

Upland Elevation

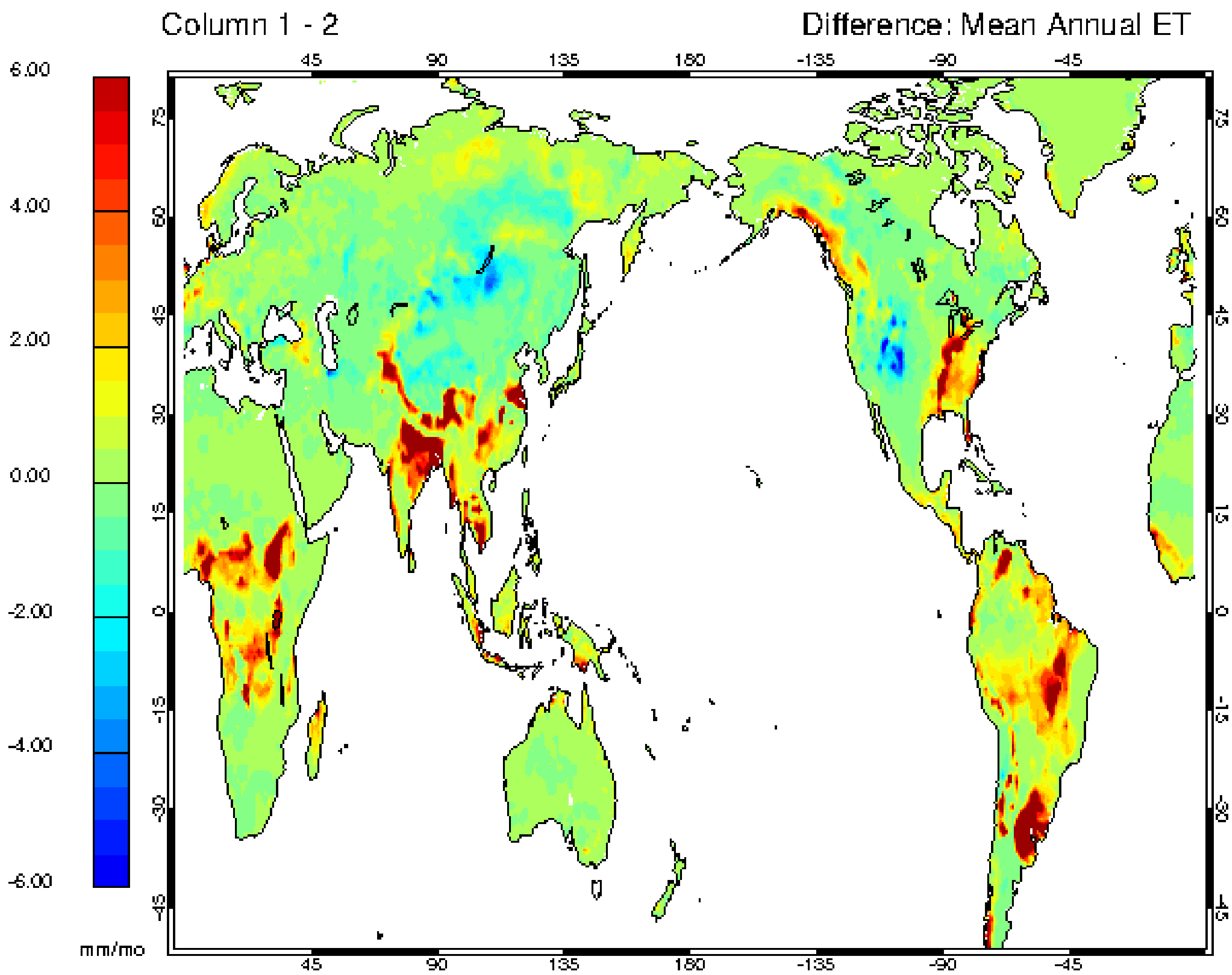
Impact of Subsurface Lateral Flow



Saturated Thickness greater in Lowland column relative to Upland column

Convergence leads to shallower water tables in transitional regions

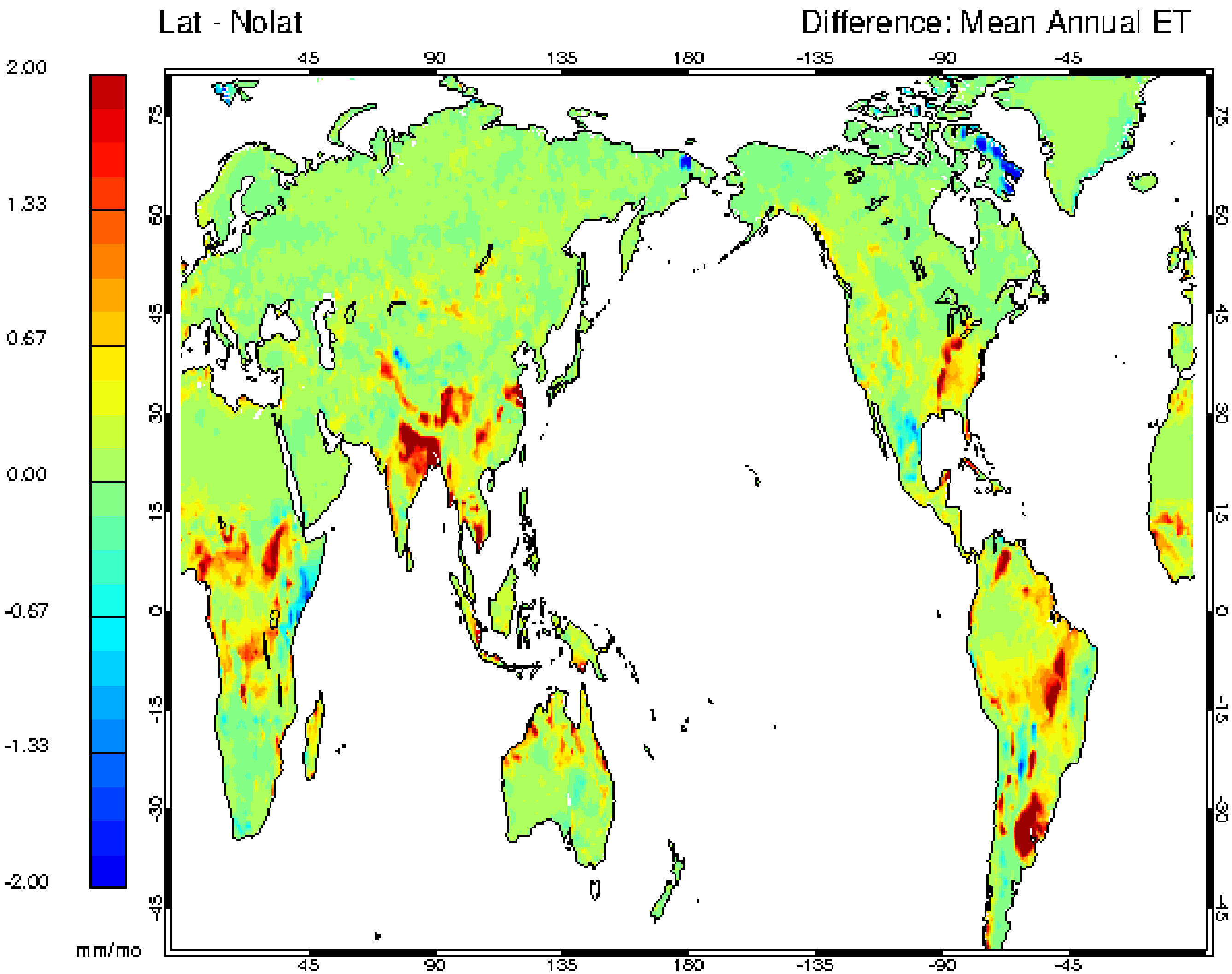
Impact of Subsurface Lateral Flow



Difference in ET:
Lowland minus Upland

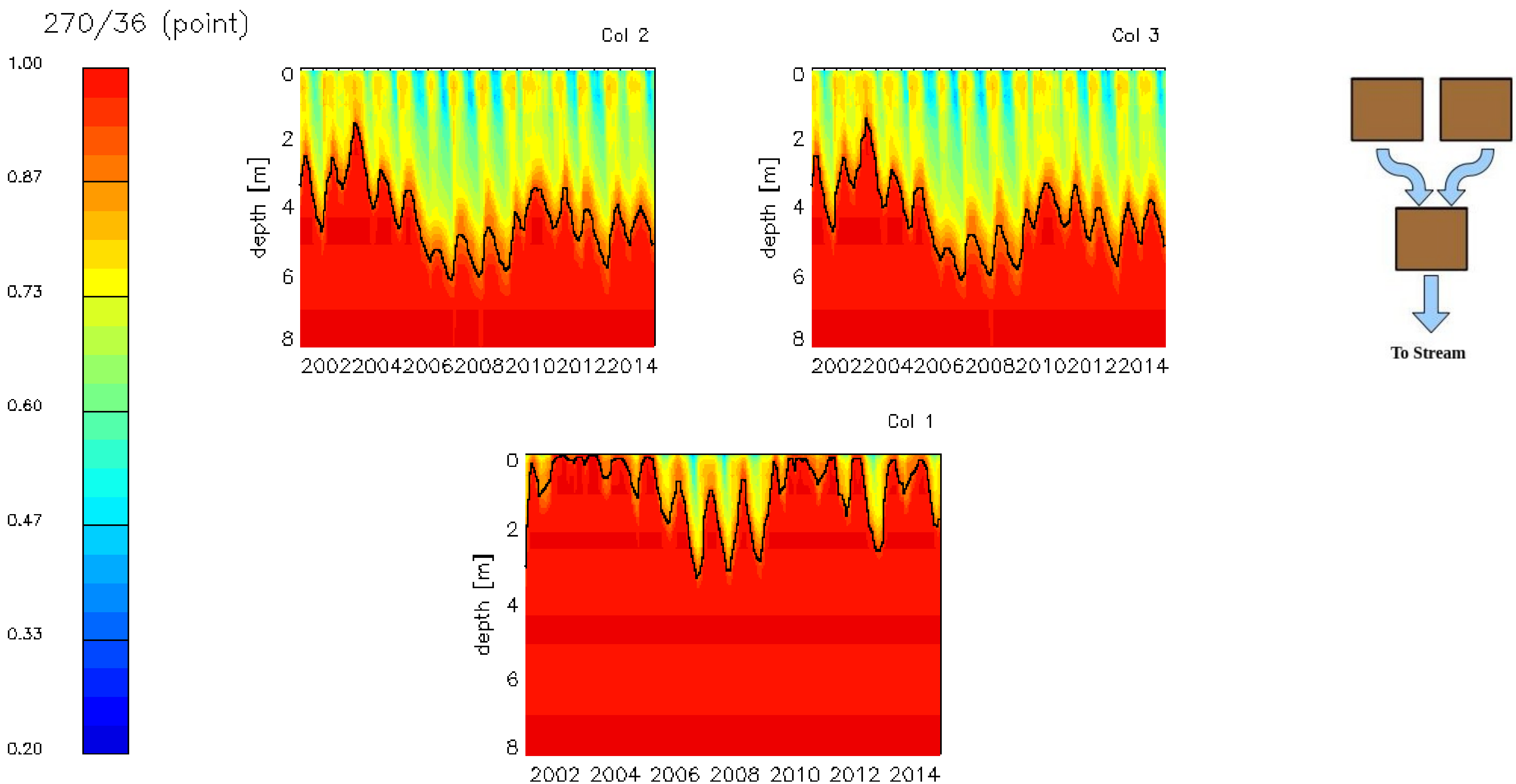
In water limited regions, higher latent heat fluxes are then possible

Gridcell Average ET



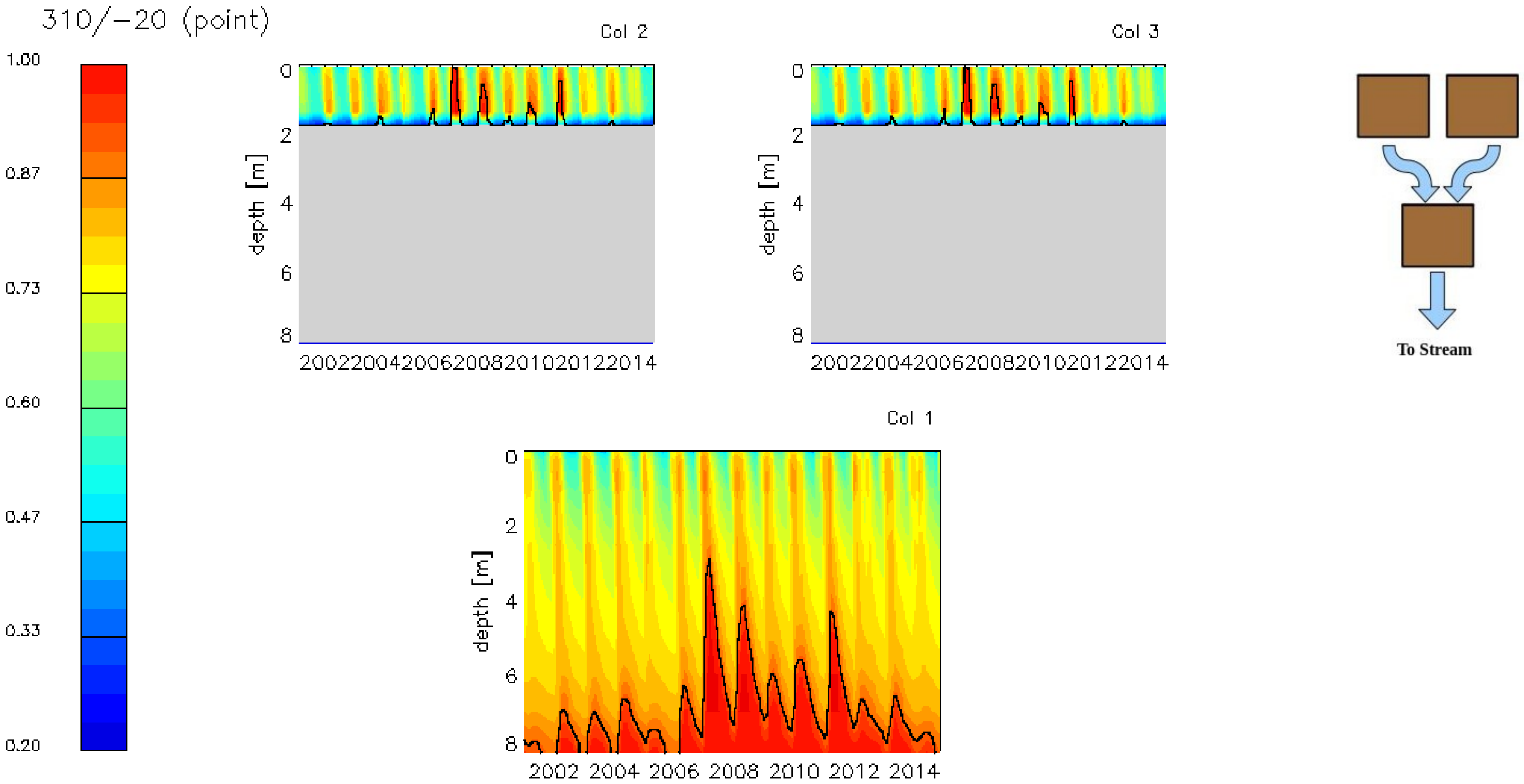
Difference in ET:
Lateral Flow minus No Lateral Flow

Moisture Convergence



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

Soil Thickness Variations



Test Case: Reynolds Mountain East Catchment
NSF Critical Zone Observatory

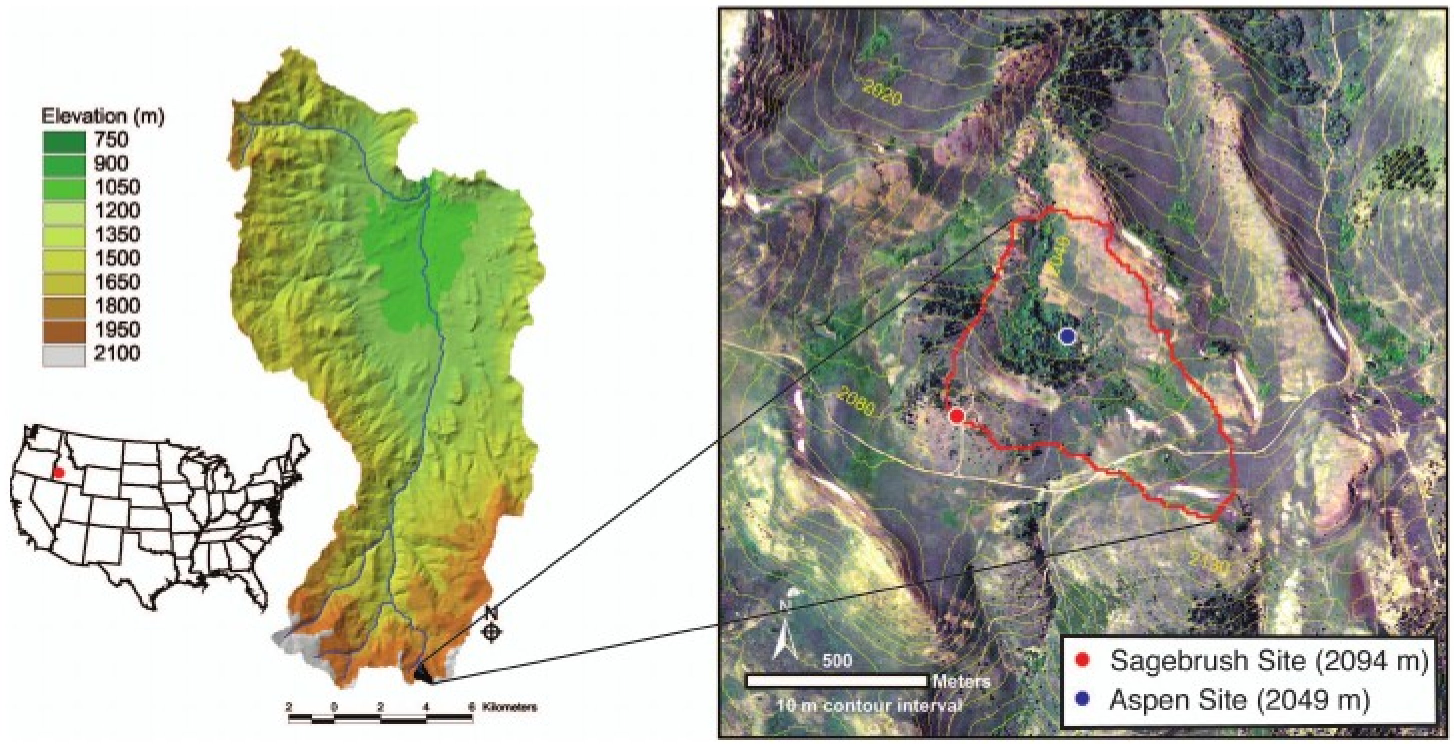


Fig. 1. Location map of Reynolds Mountain East Catchment.

Flerchinger, G., D. Marks, M. L. Reba, Q. Yu, and M. S. Seyfried, 2010: Surface fluxes and water balance of spatially varying vegetation within a small mountainous headwater catchment. Hydrol. Earth Syst. Sci., 14, 965–978.

Spatially Varying Snowpack

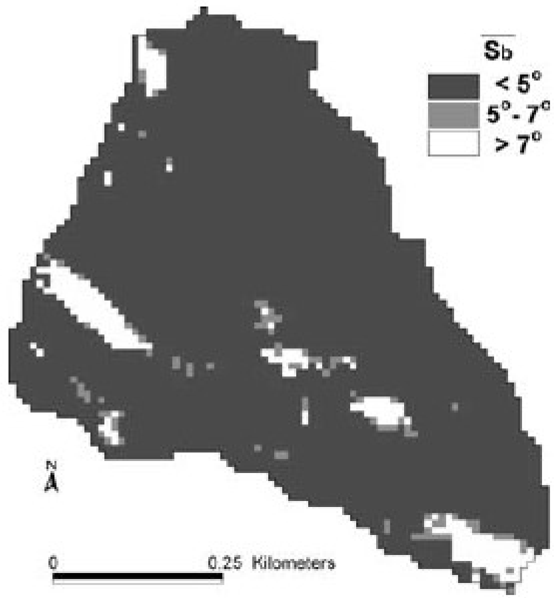


Figure 3. $\overline{Sb}$ calculated from the DEM for the resultant mean wintertime wind direction of 230°. Decreasing the $\overline{Sb}$ threshold for determining drift zones from 7° to 5° resulted in a 46% increase in delineated drift cells.

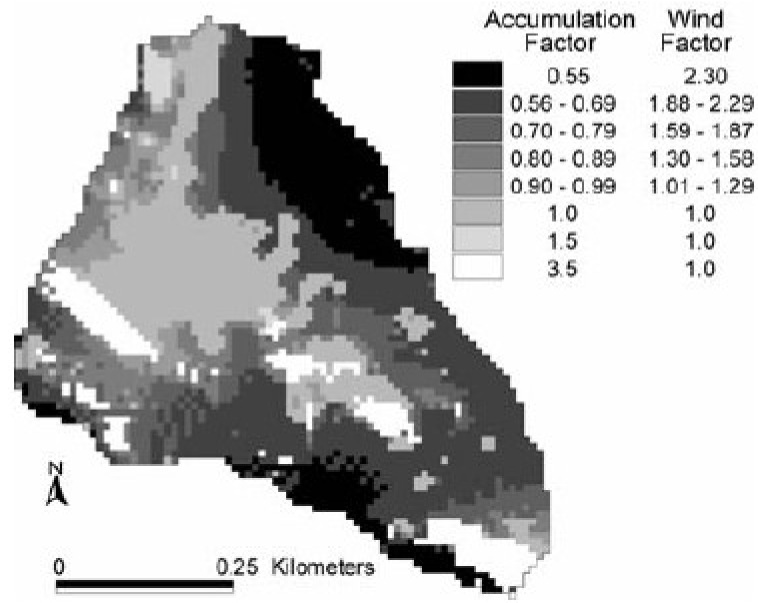
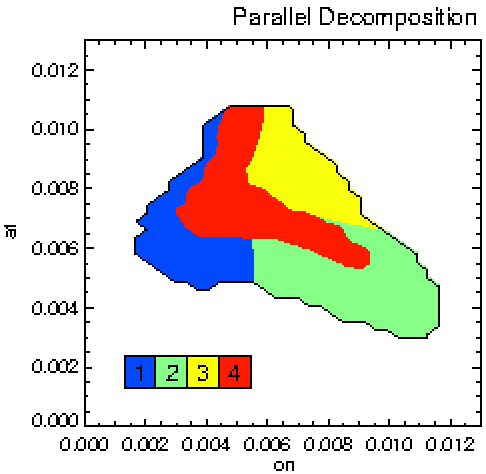


Figure 4. Snow accumulation and wind factors calculated for 230° winds with no snow on the ground. Accumulation and wind factors were derived for all possible wind directions with observations interpolated over the appropriate image.

Winstral, Adam & Marks, Danny, 2002, Simulating wind fields and snow redistribution using terrain-based parameters to model snow accumulation and melt over a mountain catchment. Hydrological Processes. 16. 3585 - 3603. 10.1002/hyp.1238.

Model Configuration



- One hillslope, four columns

- Three upland columns are connected in parallel to one lowland column

- All columns forced with identical meteorological data

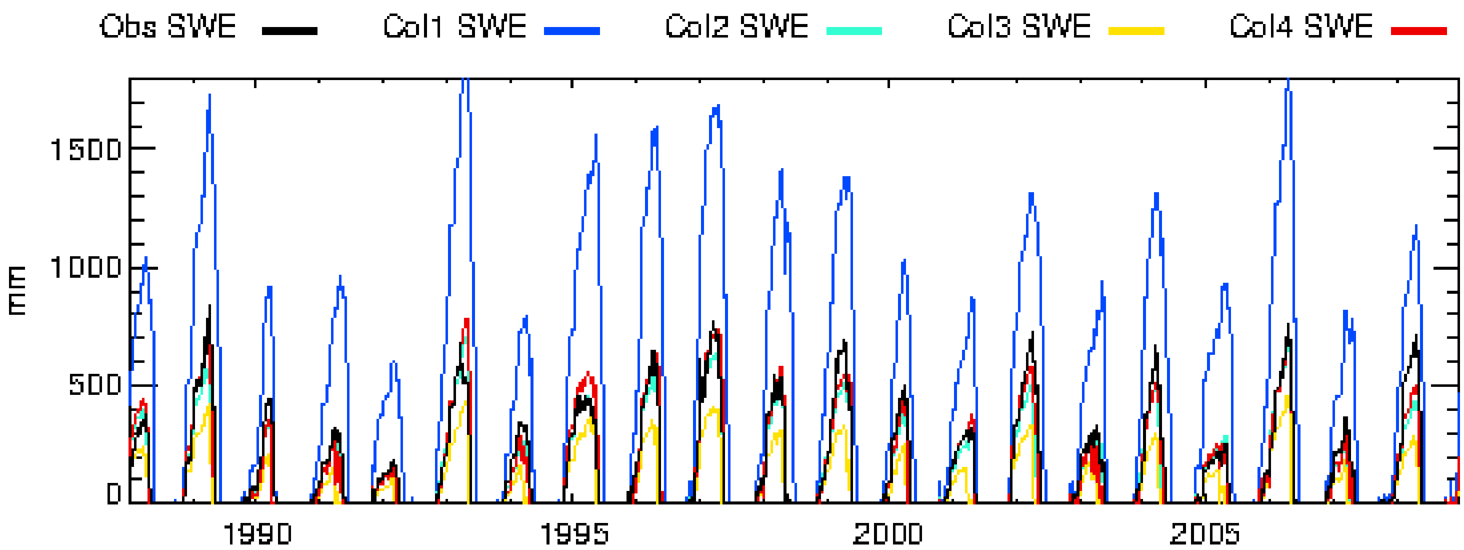
- Snowfall is transferred from a 'wind-scoured' column to a 'wind-drifted' column

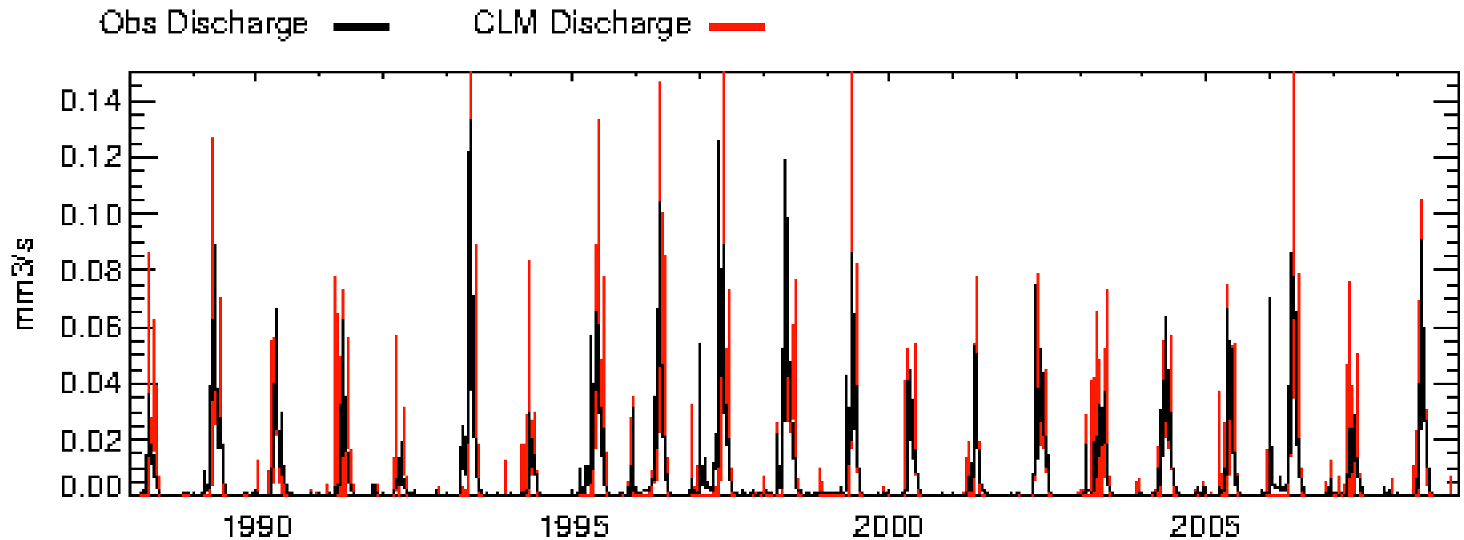
- Vegetation distribution approximates observed distribution

- Soil thicknesses are ~1 m

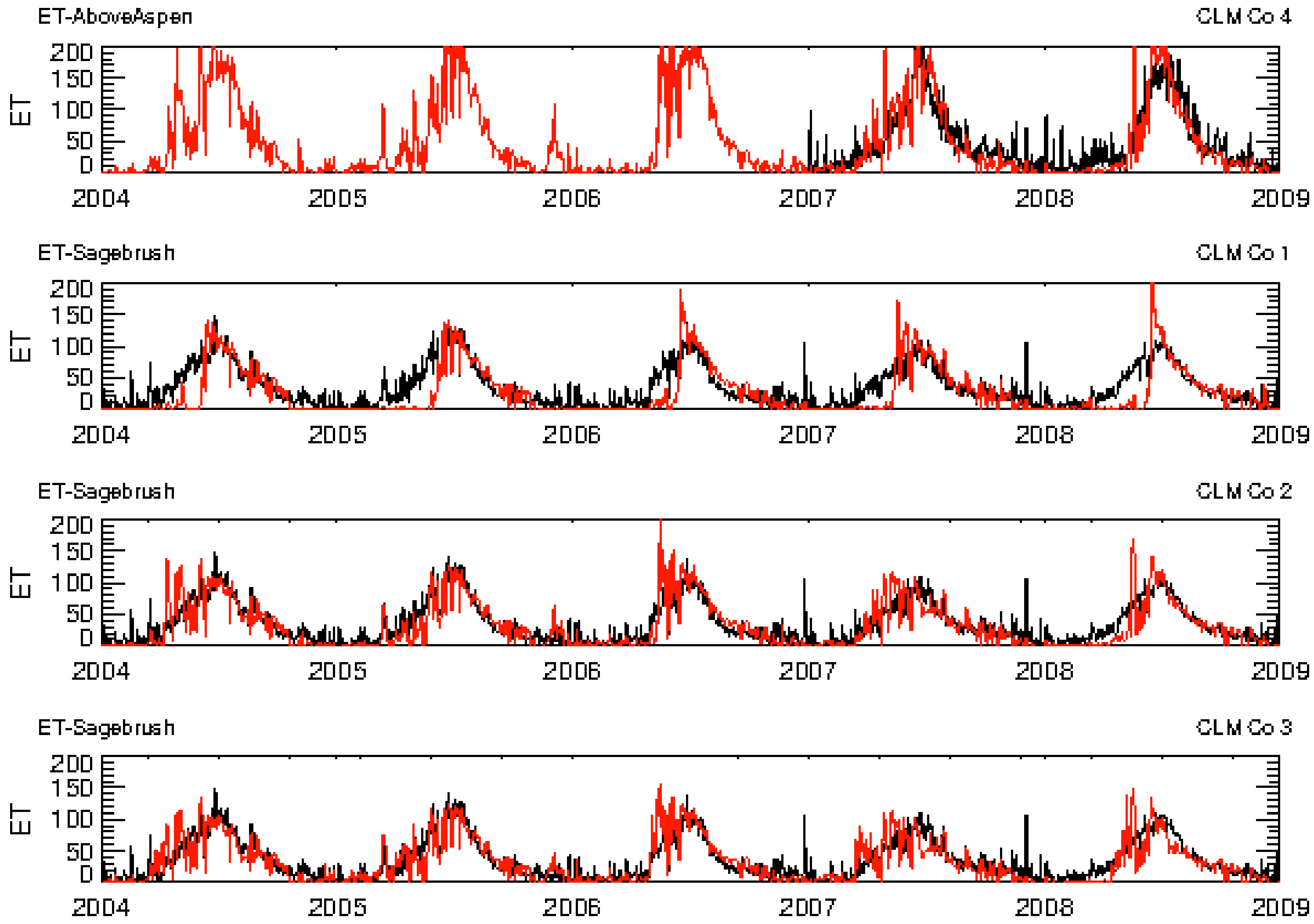
- Kinematic wave lateral flow approximation

Snowpack & Streamflow Comparison

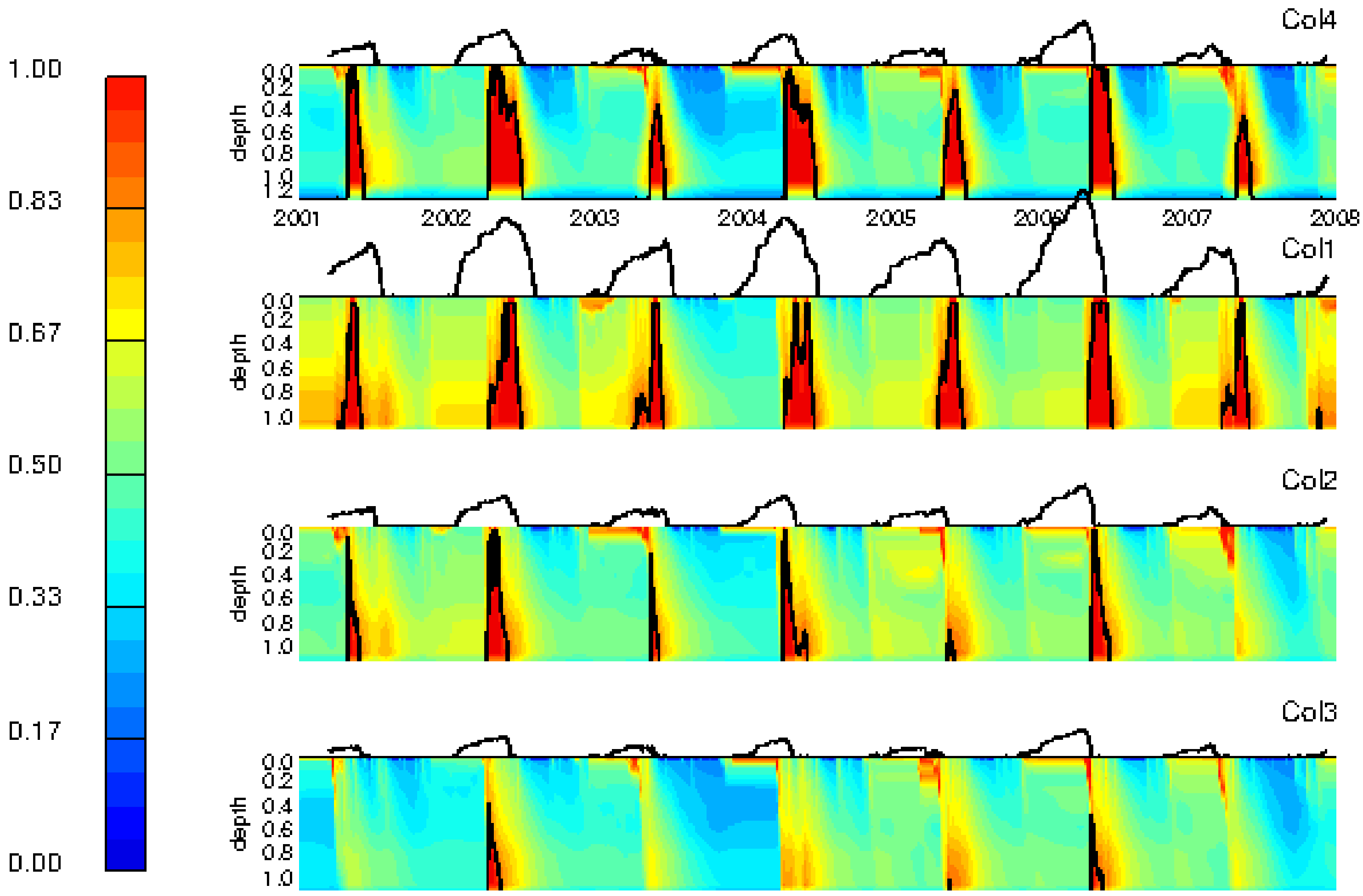




Latent Heat Flux Comparison



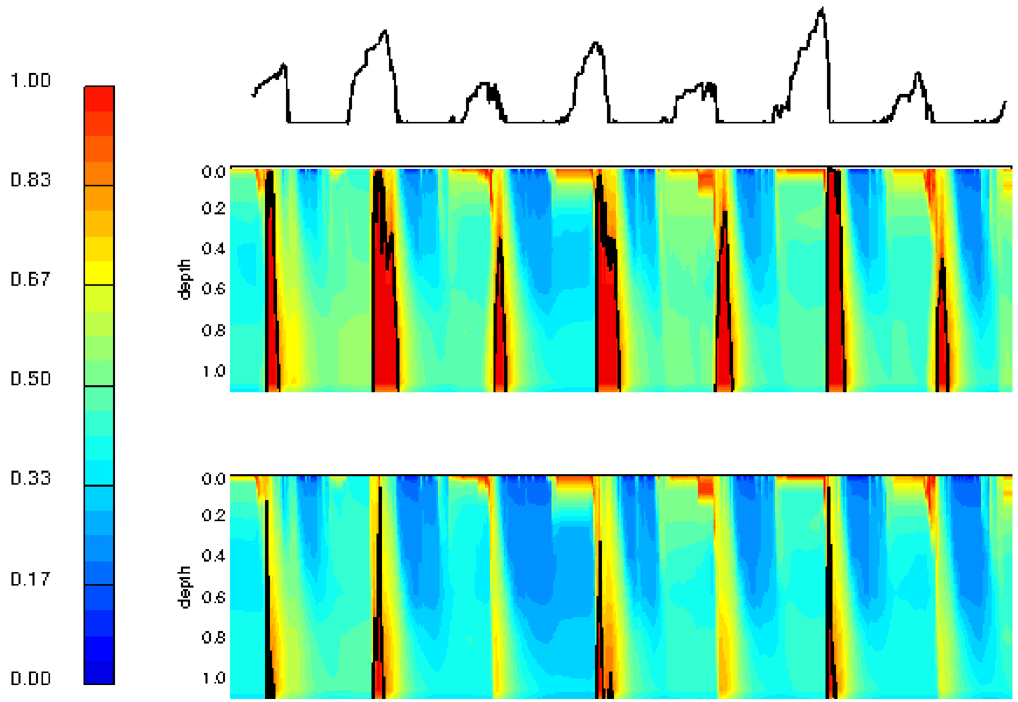
Soil Moisture



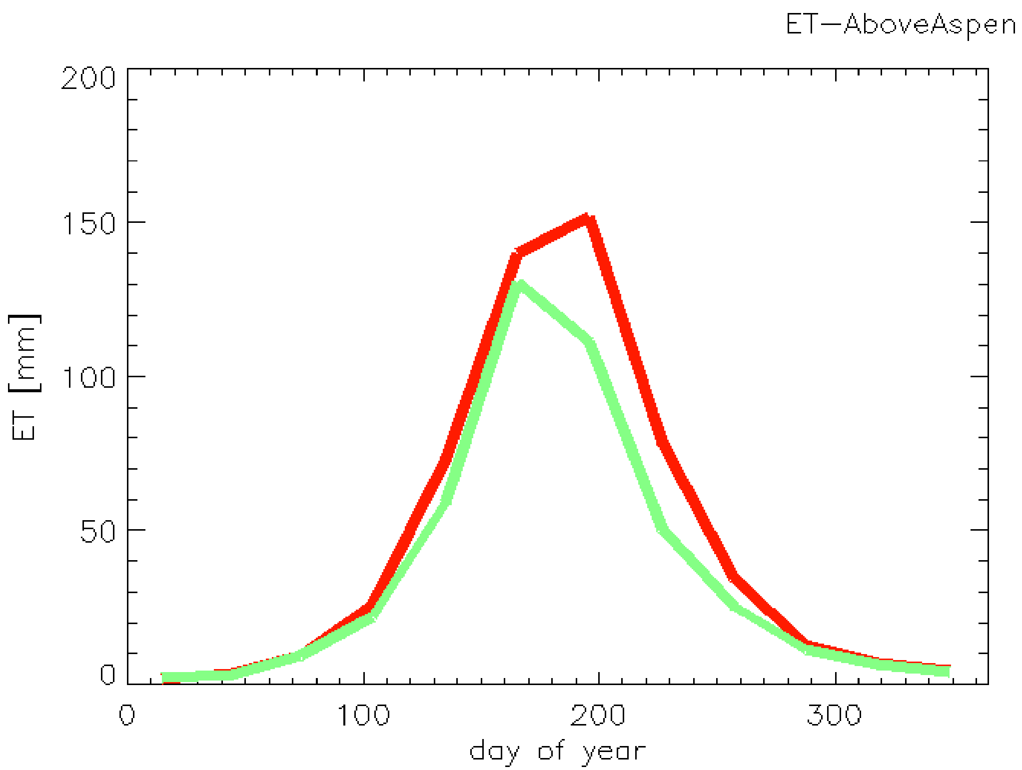
Snowpack determines spring soil moisture inputs. Compared to upland column, lowland column has longer wet period due to lateral flow inputs.

Impact of Subsurface Lateral Flow

Soil Moisture



Evapotranspiration

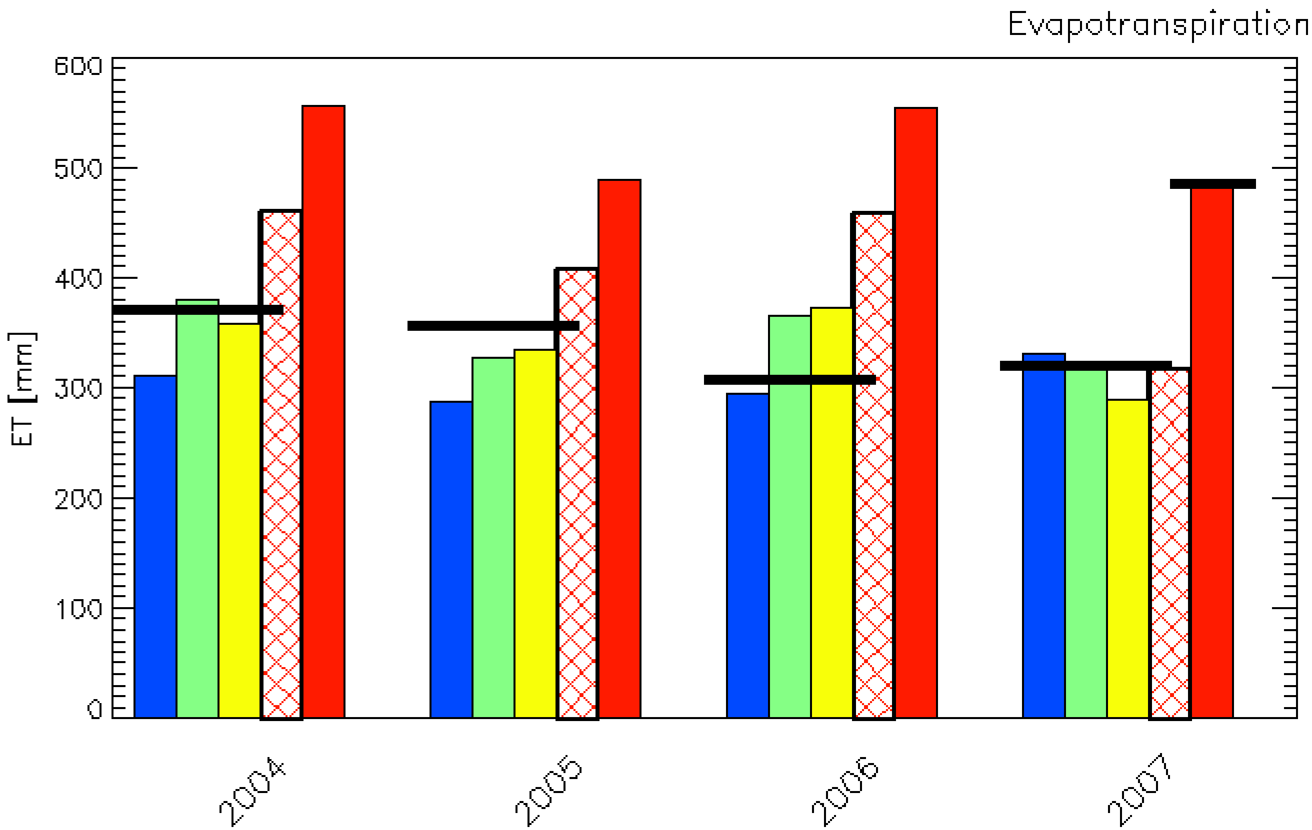


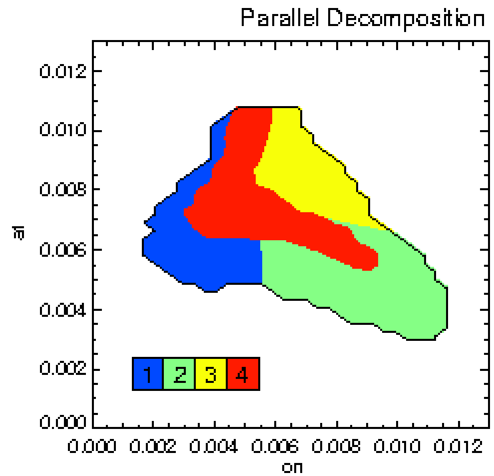
Without lateral flow (bottom), spring wet period is shorter; in some years no outflow occurs. Lateral flow extends spring wet period (top).

Increased soil moisture delays late summer dry down (red) relative to uncoupled simulation (green).

Evapotranspiration

Black line = Obs





With Lateral Flow

Without Lateral Flow

Summary

- Realistically configured model validated at Reynolds Mountain East

- 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