Watershed Concepts in CLM

Justin Perket\textsuperscript{1,2}, Ying Fan\textsuperscript{1}, Dave Lawrence\textsuperscript{2}, Martyn Clark\textsuperscript{2}, Sean Swenson\textsuperscript{2}, and NSF-INSPIRE Hydrology Process Team

1. Rutgers University, New Brunswick, NJ
2. National Center for Atmospheric Research, Boulder, CO

LMWG
March 2017
Boulder, CO
Hydrology Concepts: What we know

1) Down-slope convergence creates valleys which can support vegetation and ET in rain-less periods

2) Terrain factors change systematically along a topographic gradient, e.g. from ridge to valley, in general:
   a) Soil and regolith become thicker
   b) Slope becomes gentler

3) Uplands and lowlands are primarily linked through lateral flow below the water table
Project Motivation

- Land water strongly influence surface energy & BGC fluxes, and exchanges with atmosphere/ocean
- Climate influences freshwater availability/quality
- Lateral subsurface flow critical to represent terrestrial water, but missing from most Land Surface / Earth System Models
- Need efficient representation of hillslope hydrology dynamics within gridcells for global water cycle interactions with climate
Implementing Hillslope Flow

Current Default CLM Hierarchy:

[Diagram showing the hierarchy of land units, land uses, and components within a grid cell.]
Implementing Hillslope Flow

• ~1x1° Gridcell level assumes role of drainage basin

• Few representative multi-column hillslopes per basin (if not singular)

• Lateral connections between neighboring columns in hillslope

Hillslopes in “HydroCLM” Hierarchy:

- Gridcell
- Land units: Vegetated, Lake, Urban, Glacier, Crop
- Plant Functional Types: PFT1, PFT2, PFT3, PFT4...
Implementing Hillslope Flow

- Columns have distinct:
  - Elevations
  - Slopes
  - Surface areas
  - Bedrock depths
  - Vegetation

- Lateral saturated flow between columns based on water table gradient
What we know in general:

1. Down-slope convergence creates wetter valleys which can support vegetation and ET in rain-less

2. Terrain factors change systematically along a topographic gradient, e.g. from ridge to valley, in general:
   • Soil and regolith become thicker
   • Slope becomes gentler
After individual evaluation of each parameter’s sensitivity:

<table>
<thead>
<tr>
<th>Trial</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Single Column</td>
</tr>
<tr>
<td>B</td>
<td>4 Columns, Connected, Deepening Soil</td>
</tr>
<tr>
<td>C</td>
<td>B + Converging Basin</td>
</tr>
<tr>
<td>D</td>
<td>Full suite, C + Slowing Slope</td>
</tr>
</tbody>
</table>
"Default" single column can’t retain moisture from spring melt events
Effects of Applying Basin Topography

- Basin representation with a combination of terrain factors can significantly reduce dry periods in lowland ...

A) Single Column Hillslope

D) Last Column of Full Suite

Total Water Content (m³/m³)

Depth (m)

Effects of Applying Basin Topography

• ... While keeping dry periods in upland
Hillslope Runoff Compared with Obs.

- Water Year 2004-2008, comparing with weir outflow
- Little change in soil storage
- More spring melt infiltration = more later ET
Effects of Applying Basin Topography

- Unstressed lowlands while retaining moisture stress upland
- Influence of vegetation heterogeneity, LAI
- Two-way street: how will hydrology affect carbon cycle? – long-term climate feedbacks
Hillslope topographic function

- Systematic approach: Confine hillslope to few parameters
- Column Widths and areas from topographic function

\[ z(x, y) = H(1 - \frac{x}{L})^n + \omega y^2 \]

\[ W(x) = W_0 e^{c_1([1-\frac{x}{L}]^{2-n} - 1)} \]

\[ c_1 = \frac{-2\omega L^2}{H(2-n)n} \]
Hillslope topographic function

\[ z(x, y) = H \left( 1 - \frac{x}{L} \right)^n + \omega y^2 \]

\[ W(x) = W_0 e^{c_1 \left( \left[ 1 - \frac{x}{L} \right]^2 - n \right)} - 1 \]

\[ c_1 = \frac{-2\omega L^2}{H(2-n)n} \]
Column output – Height Variation

\[ z(x, y) = H \left(1 - \frac{x}{L}\right)^n + \omega y^2 \]
Column output – Height Variation

Hill top

Hill bottom

Top Height (H/L) 60%
Column output – Profile Curve Variation

\[ z(x, y) = H(1 - \frac{x}{L})^n + \omega y^2 \]

\[ W(x) = W_0 e^{c_1 \left[1 - \frac{x}{L}\right]^{2-n} - 1} \]

\[ c_1 = \frac{-2\omega L^2}{H(2-n)n} \]
Hill top

Hill bottom

n=0.5

n=1.0

n=1.5

“Hand-tuned Hill”

Veg. Trans.

Soil Evap.

Veg. Evap

Surface Flow

Subsurface Flow

Column output – Profile Curve Variation
Column output – Profile Curve Variation

Hill top

Hill bottom

**n=0.5**

**n=1.0**

**n=1.5**

“Hand-tuned Hill”

**DOY of 1/2 Volume:**

- Subsurface
- Surface
\[ z(x, y) = H\left(1 - \frac{x}{L}\right)^n + \omega y^2 \]

\[ W(x) = W_0 e^{c_1(1 - \frac{x}{L})^{2-n} - 1} \]

\[ c_1 = \frac{-2\omega L^2}{H(2-n)n} \]
Column output – Plane Curvature Variation

![Graph showing plane curvature variation on hilltop and hill bottom with different curvature values, ω = -8 \times 10^{-5}, ω = 0, and ω = +5 \times 10^{-5}.]
Column output – Plane Curvature Variation

Hill top

Hill bottom

Hand-tuned Hill

\[ \omega = -8 \times 10^{-5} \]

\[ \omega = 0 \]

\[ \omega = +5 \times 10^{-5} \]
What have we learned?

• Simple hydrology concepts applied to ESM makes a difference!
  • Need terrain influences on Darcy’s law (depth, slope, convergence) together to capture basin behavior
  • Hillslope columns (redistributing water, buffering stress) generate subgrid mosaic of dry and wet

• Topographic heterogeneity
  → groundwater heterogeneity
  → vegetation water/energy

Photo credit: www.wcc.nrcs.usda.gov
Questions to Answer with Global Implementations

1. How, and where, is water stress affected?
2. How is redistribution of groundwater affected by natural and anthropogenic climate forcings?
3. What is the role of water availability in ecosystem carbon uptake?
4. Are hillslope regions and their BGC processes different in their sensitivity to climate changes?
Acknowledgements

CUAHSI-NCAR First Synthesis Workshop

Jennifer Adam
Ed Beighley
Jonathan Buzan
Martyn Clark
Cedric David
Aubrey Dugger

Ying Fan-Reinfelder
Alejandro Flores
Elizabeth Garcia
David Gochis
Gordon Grant
Raha Hakimdavar

Rick Hooper
Maoyi Huang
Jen Jefferson
Jim Kirchner
David Lawrence
Ben Livneh

Scott Mackay
Reed Maxwell
Chris Milly
Grey S. Nearing
Bart Nijssen
Jessica L. Osuna

Justin Perket
Audrey Sawyer
Chaopeng Shen
Kyongho Son
Sean Swenson
David Tarboton

John Volk
Nic Wayand
Zhenghui Xie
Xubin Zeng
Qinghuan Zhang

Photo credit: Jim Kirchner

Improving the representation of hydrologic processes in Earth System Models

Martyn P. Clark¹, Ying Fan¹, David M. Lawrence¹, Jennifer C. Adam², Diogo Bolster³, David J. Gochis¹, Richard P. Hooper⁴, Mukesh Kumar⁵, L. Ruby Leung⁶, D. Scott Mackay⁶, Reed M. Maxwell⁶, Chaopeng Shen⁷, Sean C. Swenson⁸, and Xubin Zeng⁹

CUAHSI - NCAR First Synthesis Workshop

Photo credit: Jim Kirchner