A Hybrid-3D approach to represent hillslopes in ESMs

P. Hazenberg, J. Pelletier, P. A. Troch, and X. Zeng
University of Arizona
Tucson, AZ, USA

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Current generation LSMs

- Coarse grid size resolution (0.5-1.0°)
- Many sub-grid processes accounted for
- Historical focus on vertical exchange
Hydrology in LSMs

Key deficiencies:

- Global constant depth to bedrock (i.e. new global 1 km bedrock depth data will be implemented in new versions of various ESMs)
- Simple representation of baseflow
  \[ Q_{gw} = Q_{gw,0} \exp(-vz) \]
- No horizontal movement of water (i.e., runoff goes to oceans through river network)
- Only one-way interaction with river network
Impact of resolution increase

- Lateral flow becomes more and more important
- Elevation variations increases → The dominance of hillslopes
- Increased explicit interaction with the stream network
Representing small-scale flow in LSMs

Develop a lateral hydrological scheme which:
1. Can be linked or coupled with currently available ESMs
2. Incorporates as much of our current cross-discipline scientific knowledge while avoids over-parameterization
3. Constrain physics-based parameters (preferably estimated from large scale datasets)
4. Focusses on a scale small enough to enable comparison with in situ observations
5. Is computationally efficient
The hybrid-3D hydrological model

For each 1-5 km² pixel h3D accounts for:

1. Separately accounts for vertical and lateral flow
2. Explicit representation of hillslopes and plains
3. Extends the soil column up to bedrock
4. Lateral flow within saturated zone and overland layer

Hazenberg et al., WRR, 2015
Coupling with LSM soil column

Accounting for lateral saturated zone flow in Richards equation:

$$\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial z} \left[ K_v \left( \frac{\partial \psi}{\partial z} + 1 \right) \right] - R - G$$

Where:
- \( R \) = root extraction
- \( G \) = lateral flow through saturated zone
Hillslope scale implementation

Lateral flow through saturated zone and overland layer:

Hillslope storage Boussinesq equation (Troch et al., WRR, 2003):

\[ f \frac{\partial h}{\partial t} = \frac{1}{w} \frac{\partial}{\partial x} \left[ wK_l h \left( \sin \alpha + \frac{\partial h}{\partial x} \cos \alpha \right) \right] + R_{sat} \]

Diffusive wave equations:

\[ \frac{\partial d}{\partial t} = - \frac{1}{w} \frac{\partial}{\partial x} (vdw) + R_{of} \]

\[ 0 = \frac{\partial d}{\partial x} + S_f + S_0 \]
Recharge-Drainage experiment

For uniform hillslope:

- h3D similar runtime performance as CLM based approach
- Similar soil moisture and baseflow response as 3D Richards equation model CATHY
- About 2-3 orders of magnitude faster than CATHY

Hazenberg et al., WRR, 2015
Testing in Biosphere 2 LEO

Hazenberg et al., WRR, 2016
Upscaling to larger scales

- Hillslope flow only within grid cell
- Regional scale lateral saturated flow through plains (i.e. riparian zone) using 2D Darcy
- Two-way coupling between stream network and plain

Two-way groundwater-stream network coupling

- Variable stream network width
- Explicit surface-groundwater solution
- Allows overbank flow situations
- Possibility for seasonal wetlands

Basin scale implementation

Catchment-based testing:
• Mopex
• Amazon

Thanks for your attention!

Questions?