# Permafrost, hydrology, and community modeling

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NCAR
NATIONAL CENTER FOR ATMOSPHERIC RESEARCH

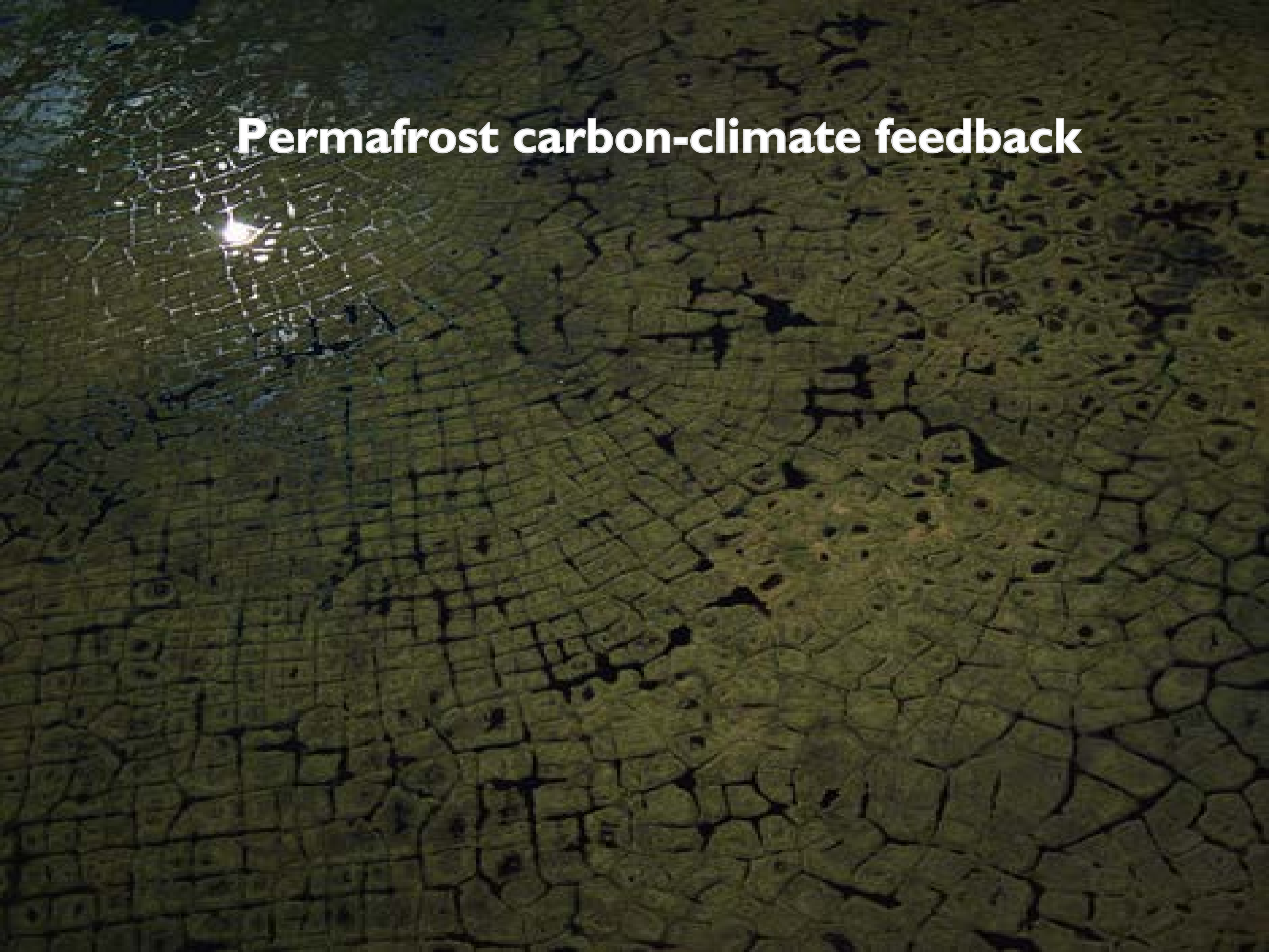
What level of complexity do we need in our land models?

- Depends on the question

How do we advance terrestrial science in the face of growing complexity?

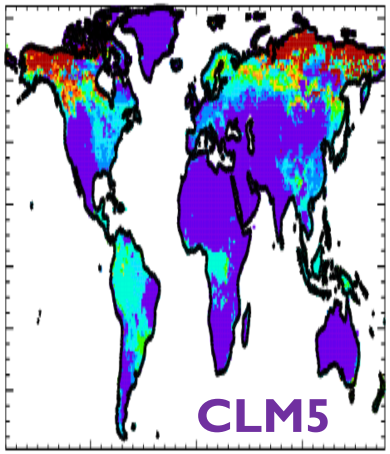
- Improvements on the status quo

# Permafrost carbon-climate feedback



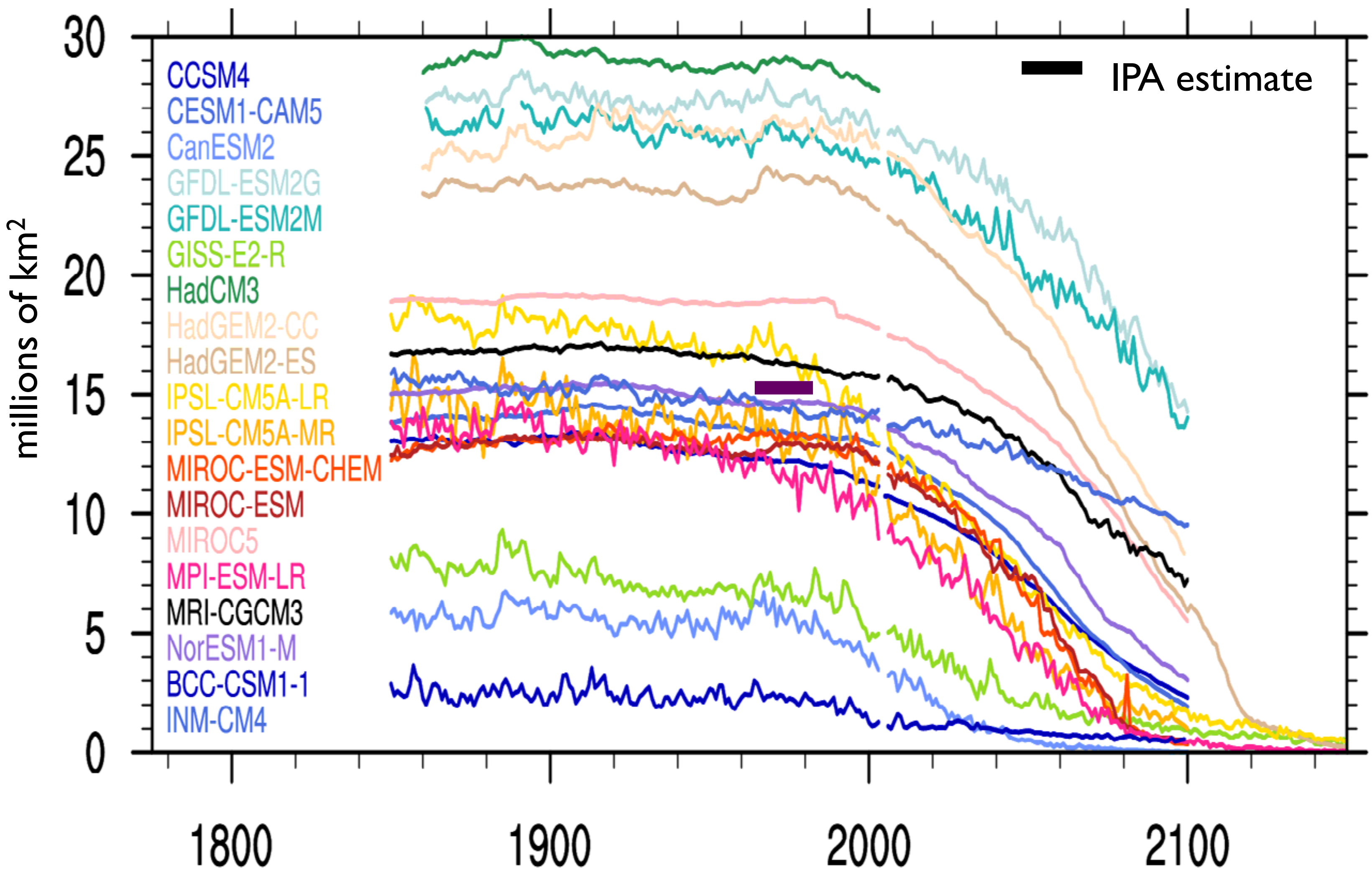
# Permafrost climate-carbon feedback

**Ecosystem Carbon**



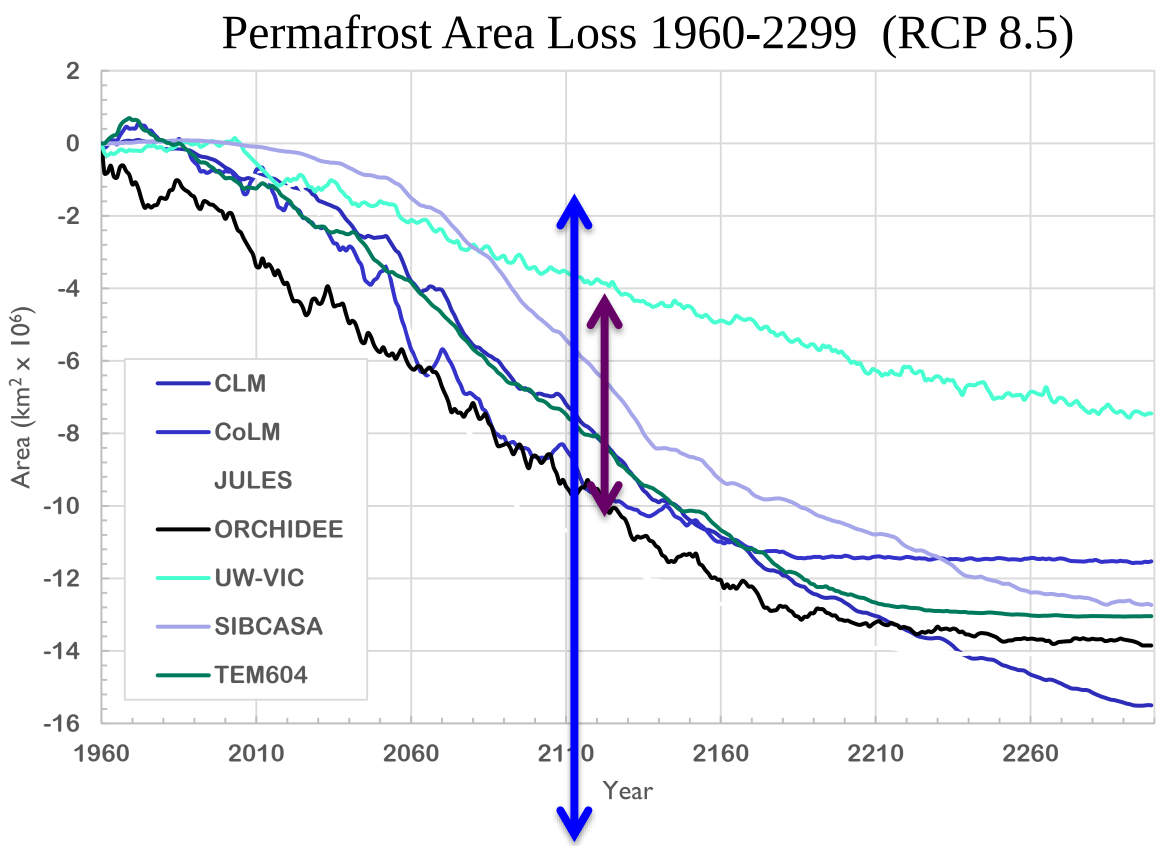

- >1700 PgC stored in permafrost soils
- Substantial permafrost thaw projected, especially at high emission scenarios
- Permafrost climate-carbon feedback not represented in CMIP5 models

# CMIP5 Models: Near-surface permafrost extent (RCP 8.5)




Koven et al., J.Clim, 2013

# PCN "Permafrost Model intercomparison"

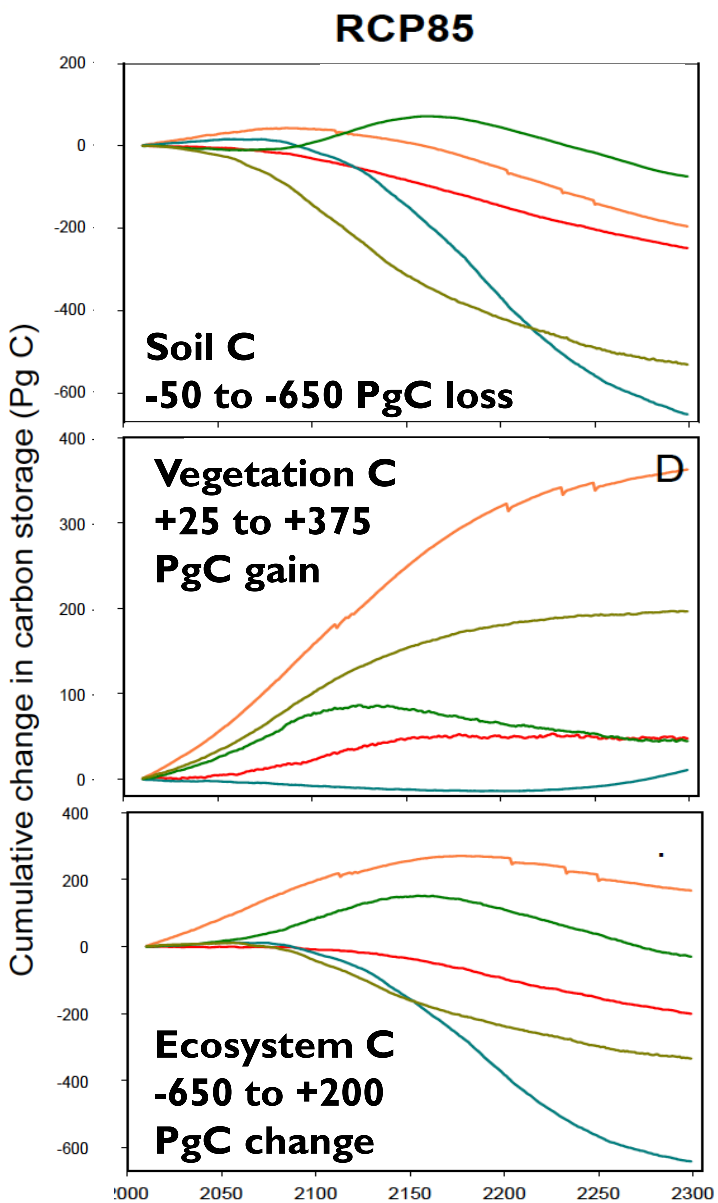



All models forced with common climate projection

**PCN 4 -10 million km²**

**CMIP5 1-18 million km²**

# PCN "Permafrost Model intercomparison"

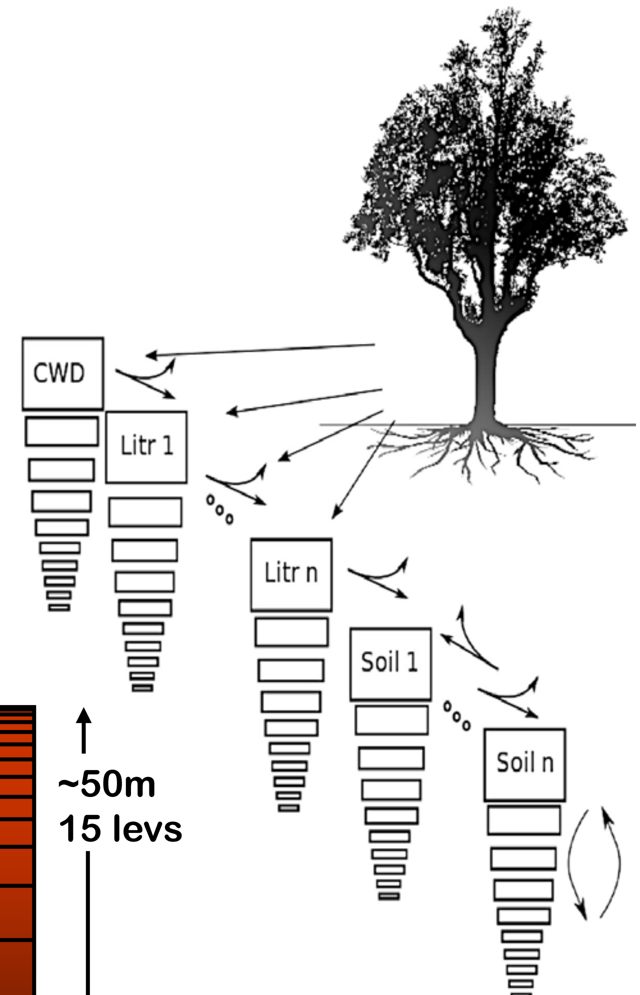


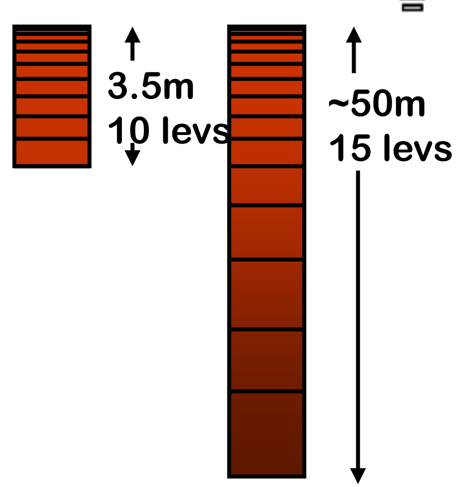

**Needs for permafrost-carbon feedback modeling**

- Standardize structural representation of permafrost and carbon

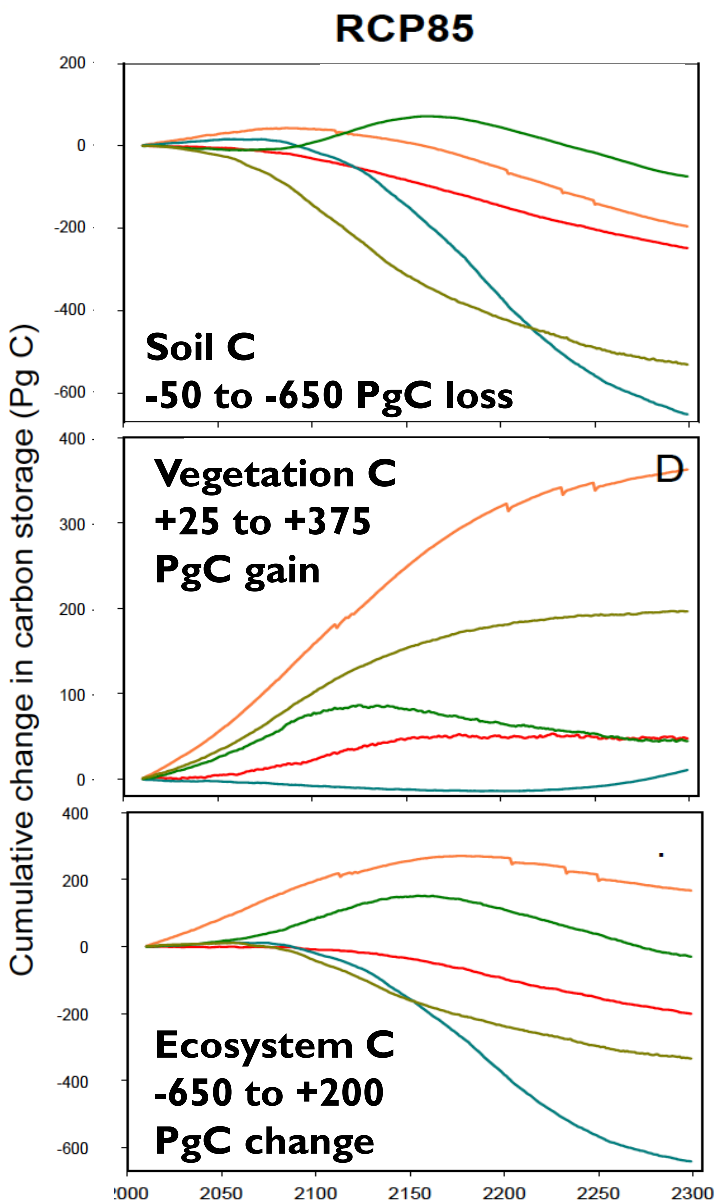
# Unique land model features for permafrost simulations

- Snow model with good snow insulation (Koven et al. 2013)
- Thermal and hydraulic properties of soil organic matter (Nicolsky et al. 2007, Lawrence and Slater, 2008)
- Deep ground column ~50m depth (Alexeev et al. 2007, Lawrence et al., 2008)
- Vertically-resolved soil BGC including nitrogen (Koven et al. 2014)
- $CH_4$ emissions (Riley et al., 2013)
- Ice impedance, perched water table (Swenson et al. 2012)
- Soil excess ice (Lee et al. 2015)
- Thermokarst processes?



# PCN "Permafrost Model intercomparison"




**Needs for permafrost-carbon feedback modeling**

- Standardize structural representation of permafrost and carbon
- Develop data sets and methodologies to benchmark models
- Utilize models to assess sensitivities to processes
- Assess and represent C impact of permafrost thermokarst responses to warming

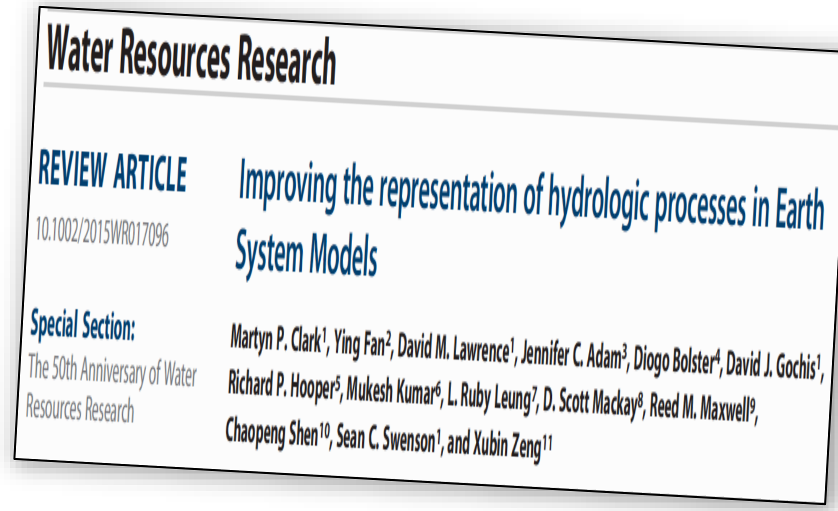
# Hydrology

Image: Kimon Maritz

# CUAHSI-NCAR collaboration

**Accelerate implementation of state-of-art hydrologic understanding into ESMs**

- Groundwater dynamics across spatial scales
  - Within grid and across grid lateral flow
- Plant hydrodynamics, soil-plant-atmosphere continuum
- Storage and transmission of water in soil
  - Mixed form of Richard's eqn.
  - Macropores
- Improve streamflow
  - Stream-aquifer interactions
  - Improved channel/floodplain routing
- Improve input datasets
  - Bedrock depth and permeability
  - River channel morphology

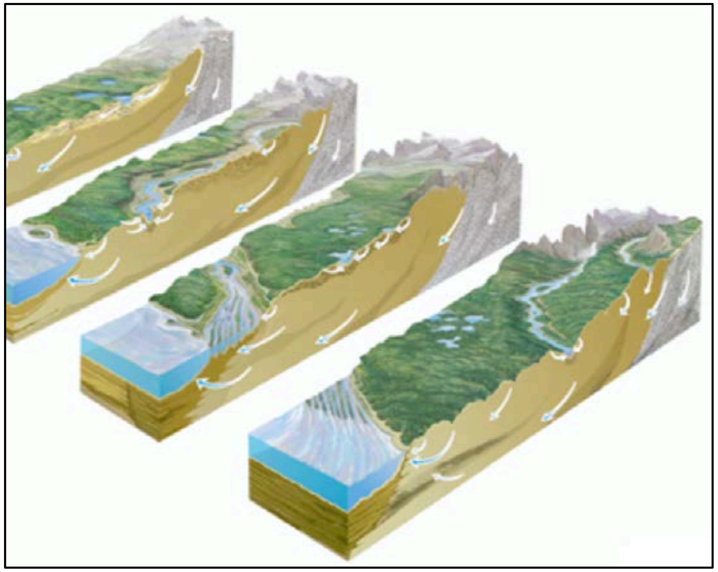

Water Resources Research

REVIEW ARTICLE
10.1002/2015WR017096

Special Section:
The 50th Anniversary of Water Resources Research

Improving the representation of hydrologic processes in Earth System Models

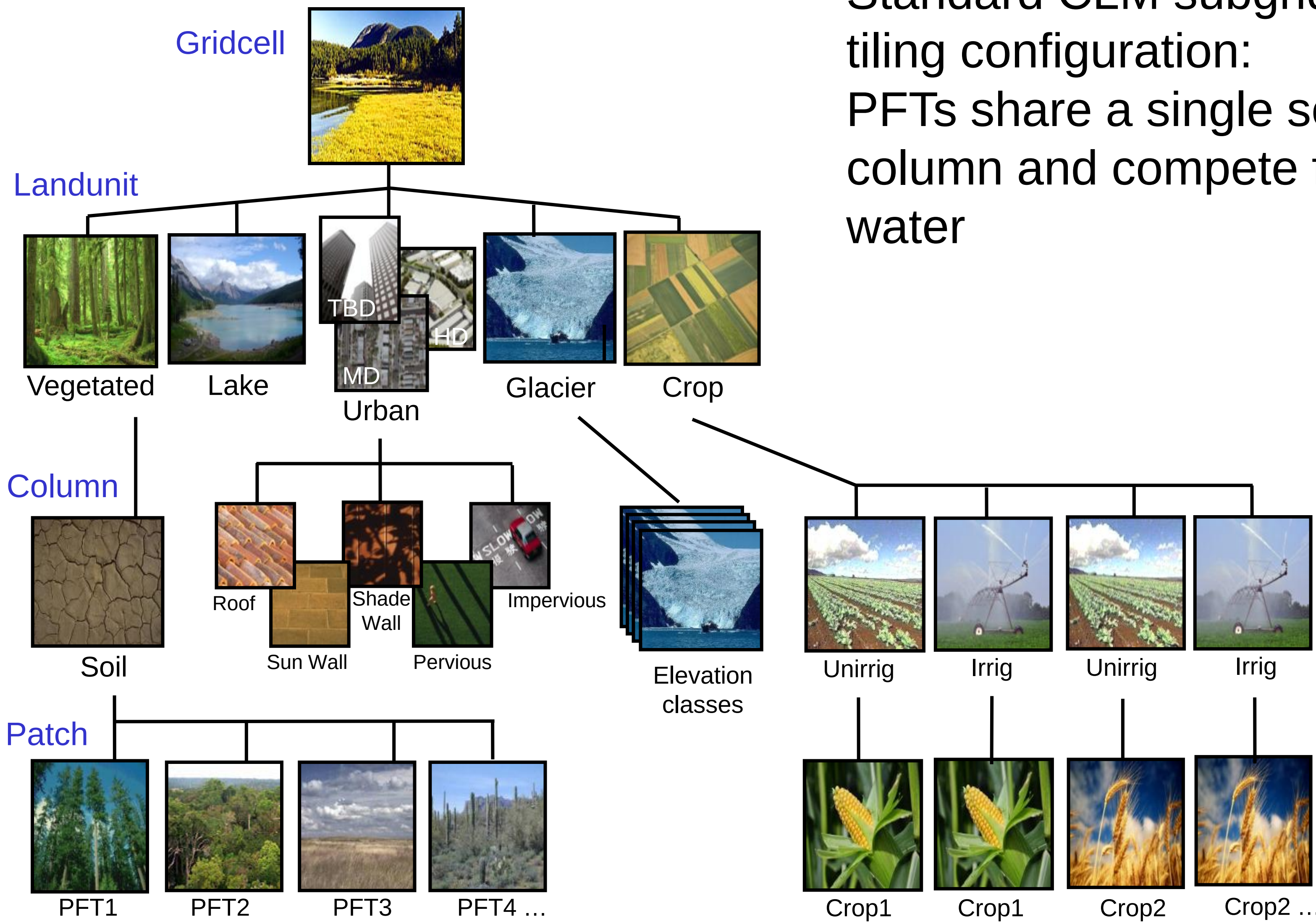
Martyn P. Clark[1], Ying Fan[2], David M. Lawrence[1], Jennifer C. Adam[3], Diogo Bolster[4], David J. Gochis[1], Richard P. Hooper[5], Mukesh Kumar[6], L. Ruby Leung[7], D. Scott Mackay[8], Reed M. Maxwell[9], Chaopeng Shen[10], Sean C. Swenson[1], and Xubin Zeng[11]



Winter et al., 1998

# Natural vegetation patterns imply controls from soil moisture convergence, slope, and aspect

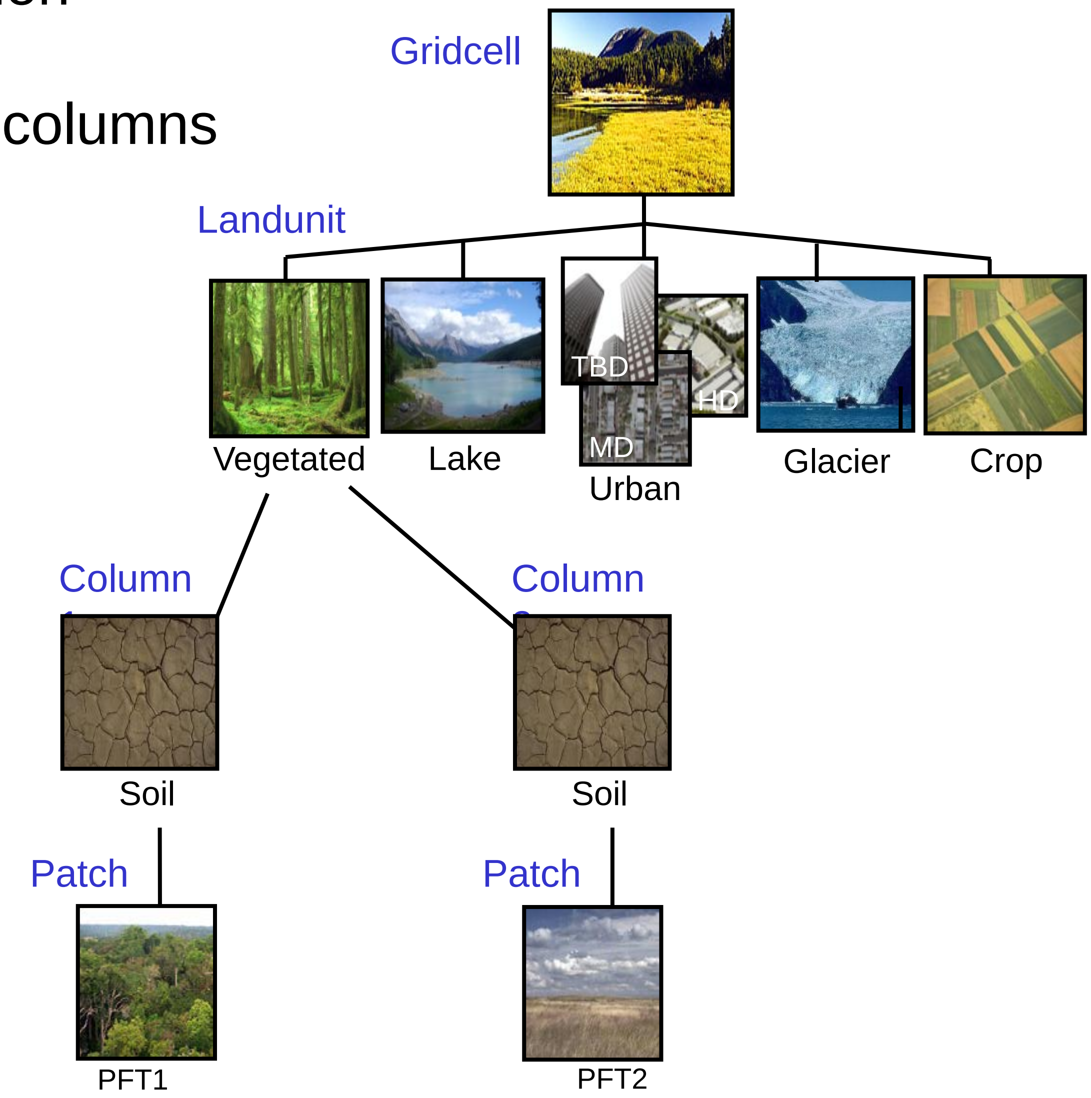
# Representing within grid lateral flow




Standard CLM subgrid tiling configuration: PFTs share a single soil column and compete for water

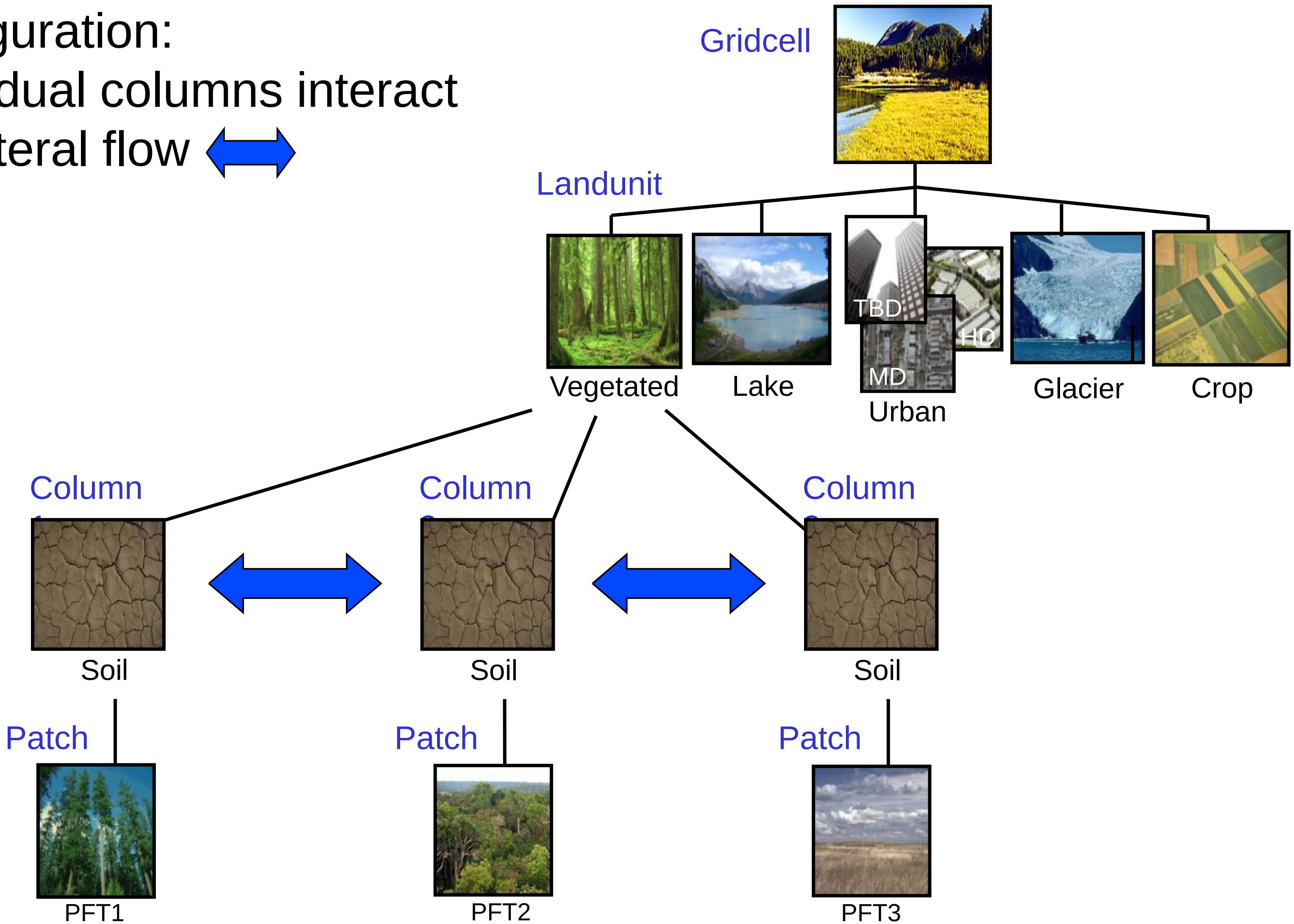
# Representing within grid lateral flow

Multicolumn  configuration
(1 pft per col):
PFTs occupy individual columns

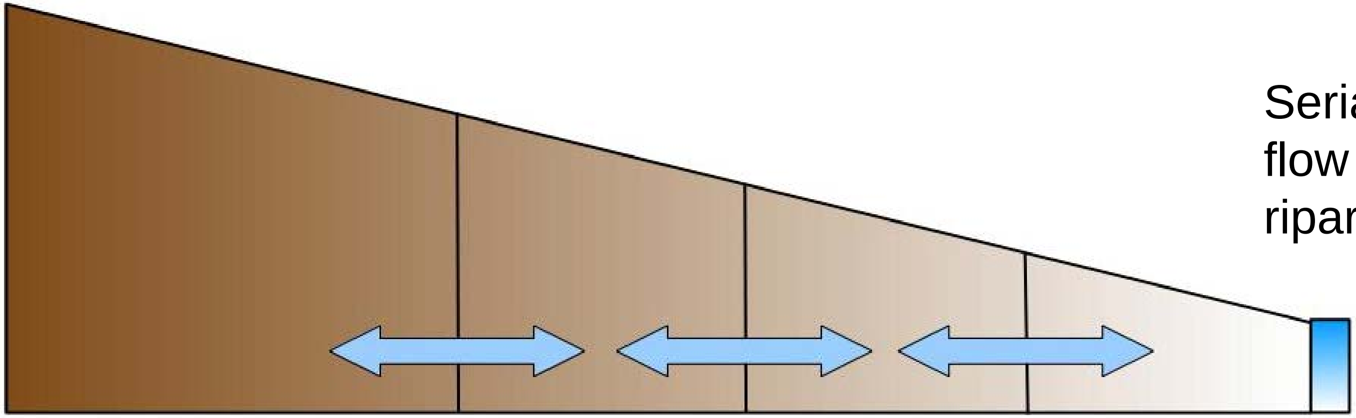


# Representing within grid lateral flow

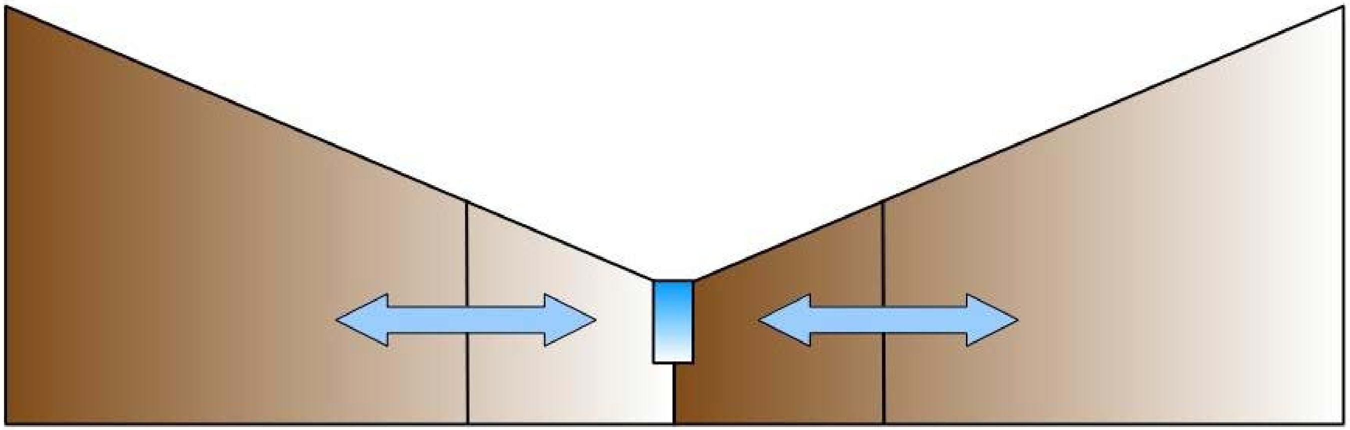
Hillslope multicolumn configuration:
Individual columns interact via lateral flow



# Representative hillslopes

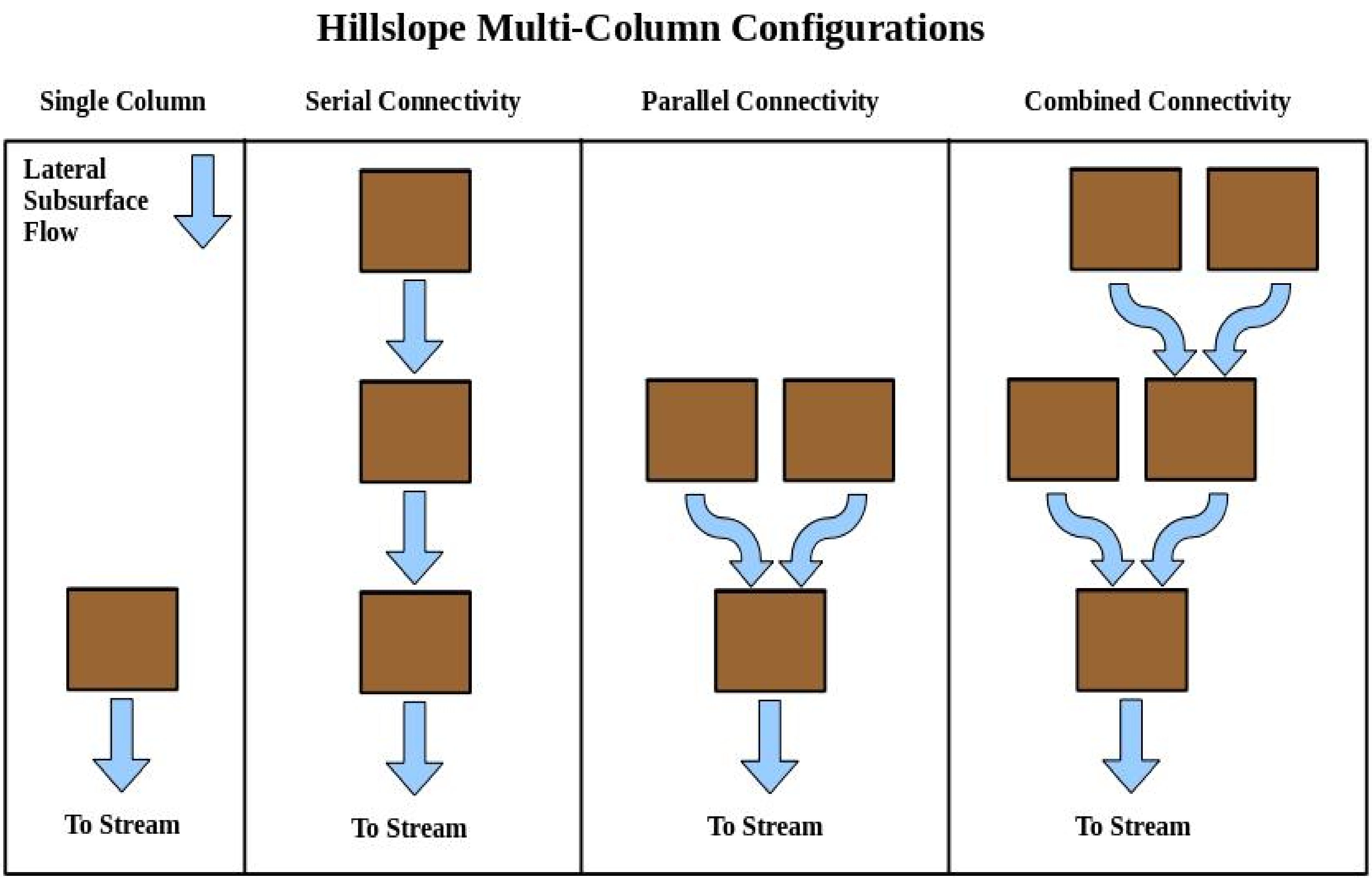


Serial subsurface flow inputs to riparian zone

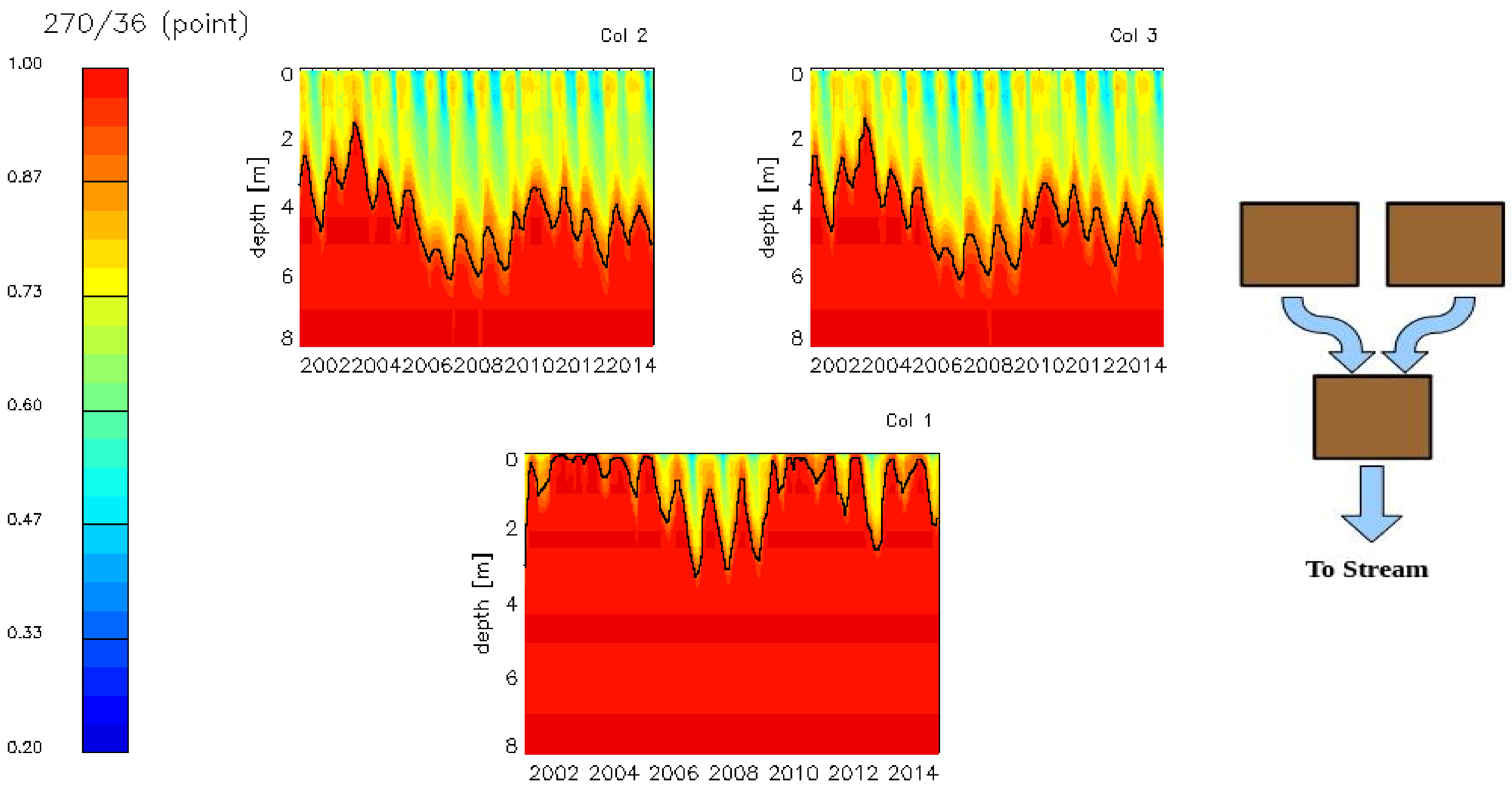


Independent (parallel) subsurface flow inputs to riparian zone

# Hillslope Connectivity

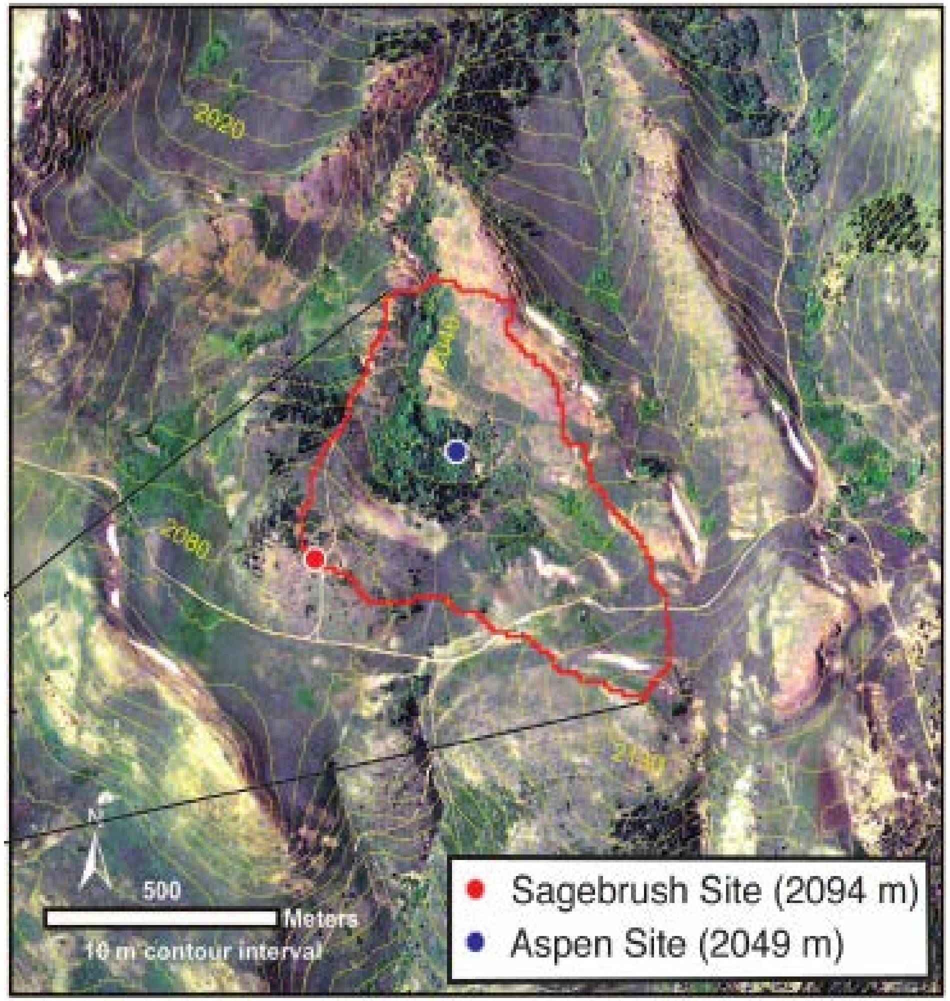


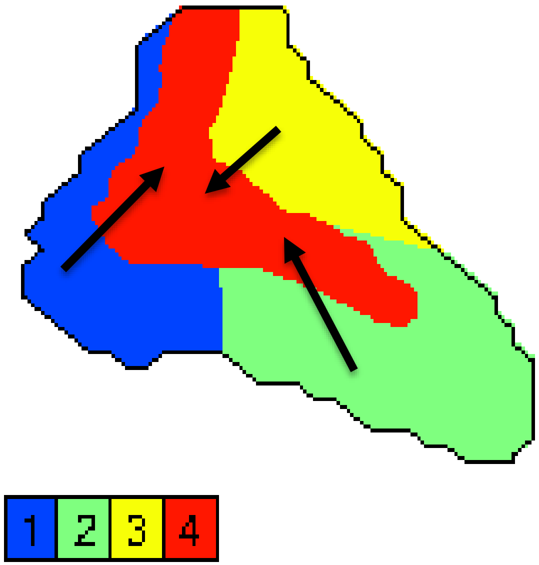
# Soil moisture convergence




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

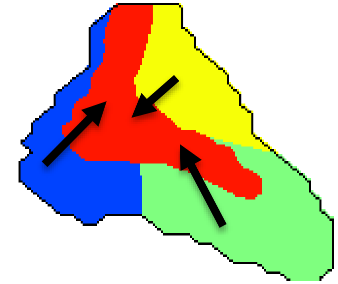
# Test Case: Reynolds Mountain East Catchment
# NSF Critical Zone Observatory



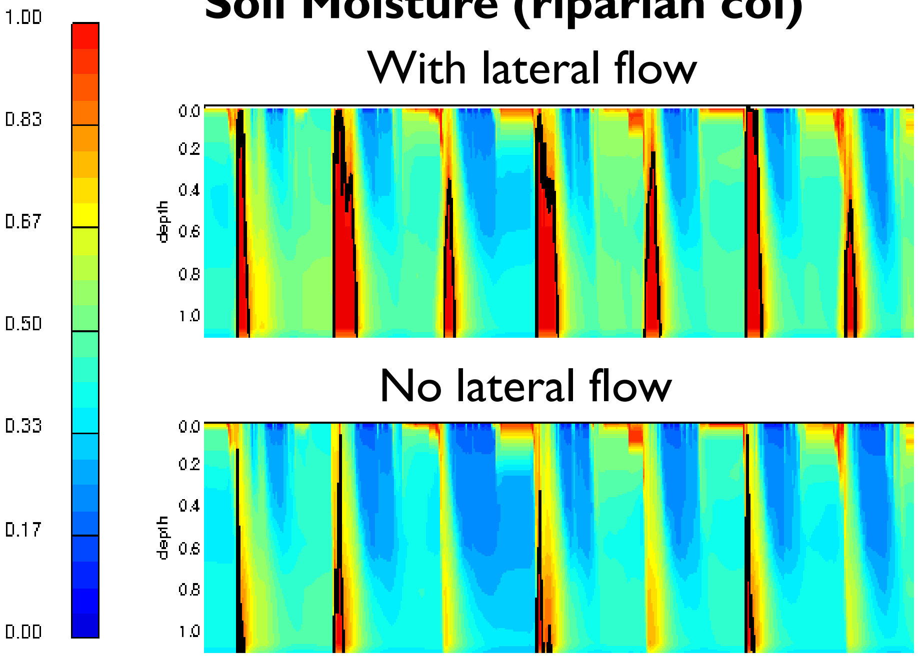

Flerchinger, G., et al.., 2010

# Impact of subsurface lateral flow

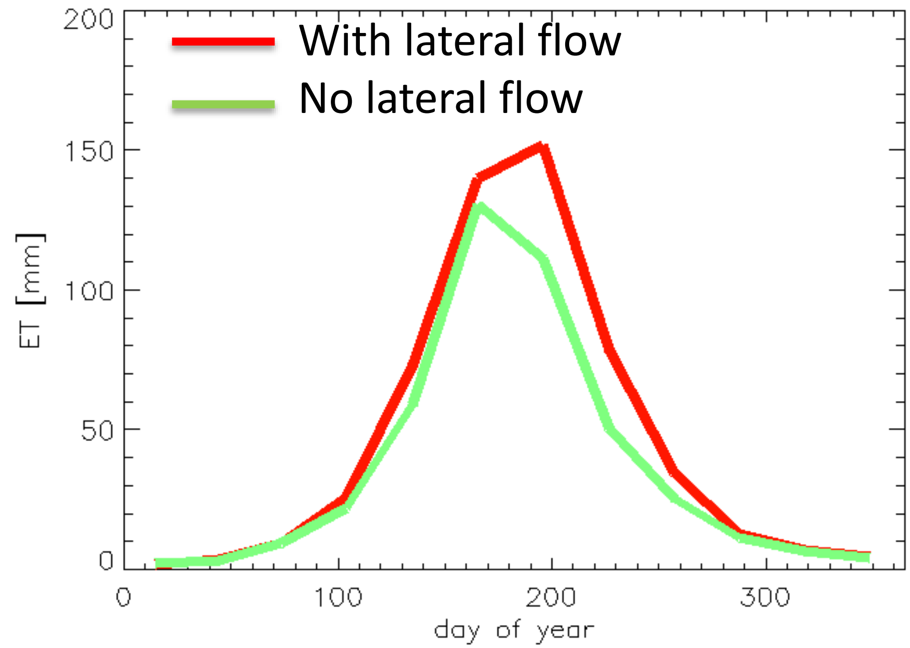


**Snow water equiv**

**Soil Moisture (riparian col)**



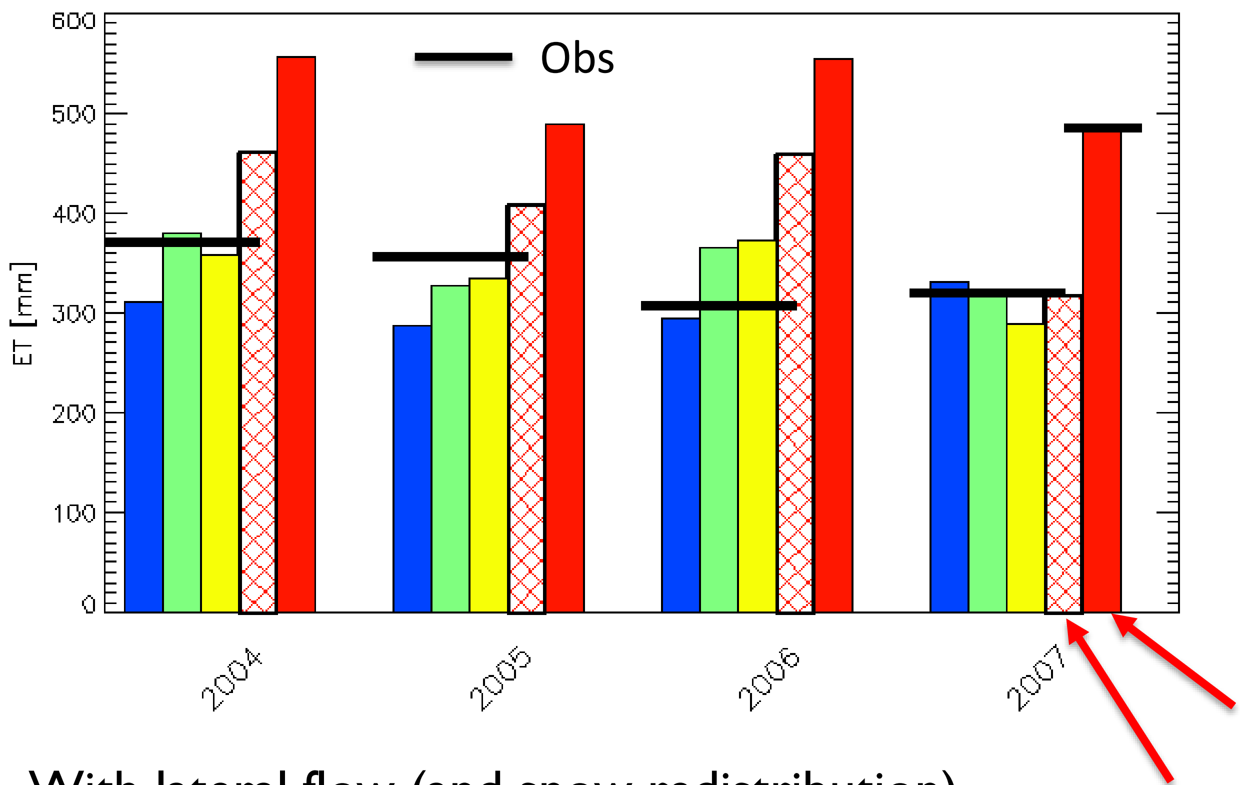

**ET (riparian col)**

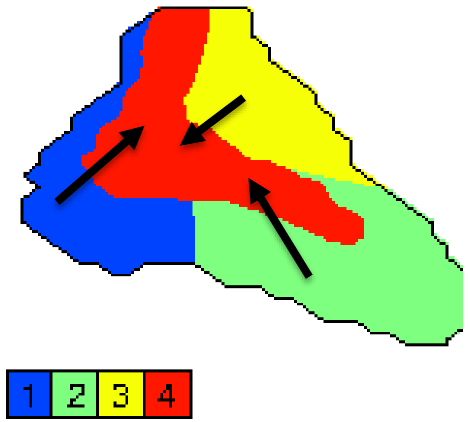



Without lateral flow, spring wet period is shorter; in some years no outflow occurs. Lateral flow extends spring wet period

Increased soil moisture delays late summer dry down (red) relative to no lateral flow simulation (green).

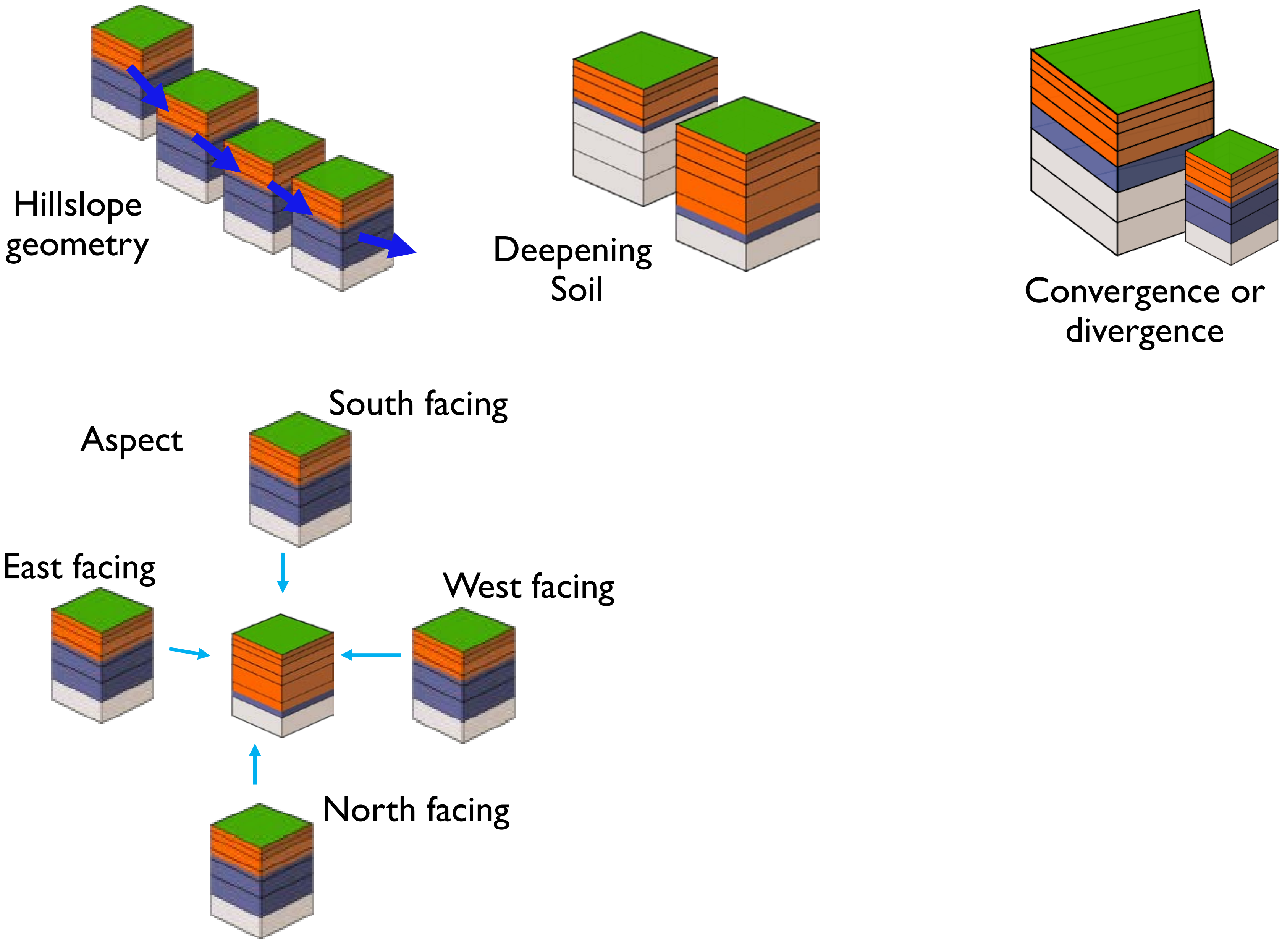
# Evapotranspiration




With lateral flow (and snow redistribution) are able to represent observed difference in upland versus riparian ET *and* basin streamflow amplitude and hydrograph

# Representative hillslope characterization



# Characterizing representative hillslopes DEM Analysis

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

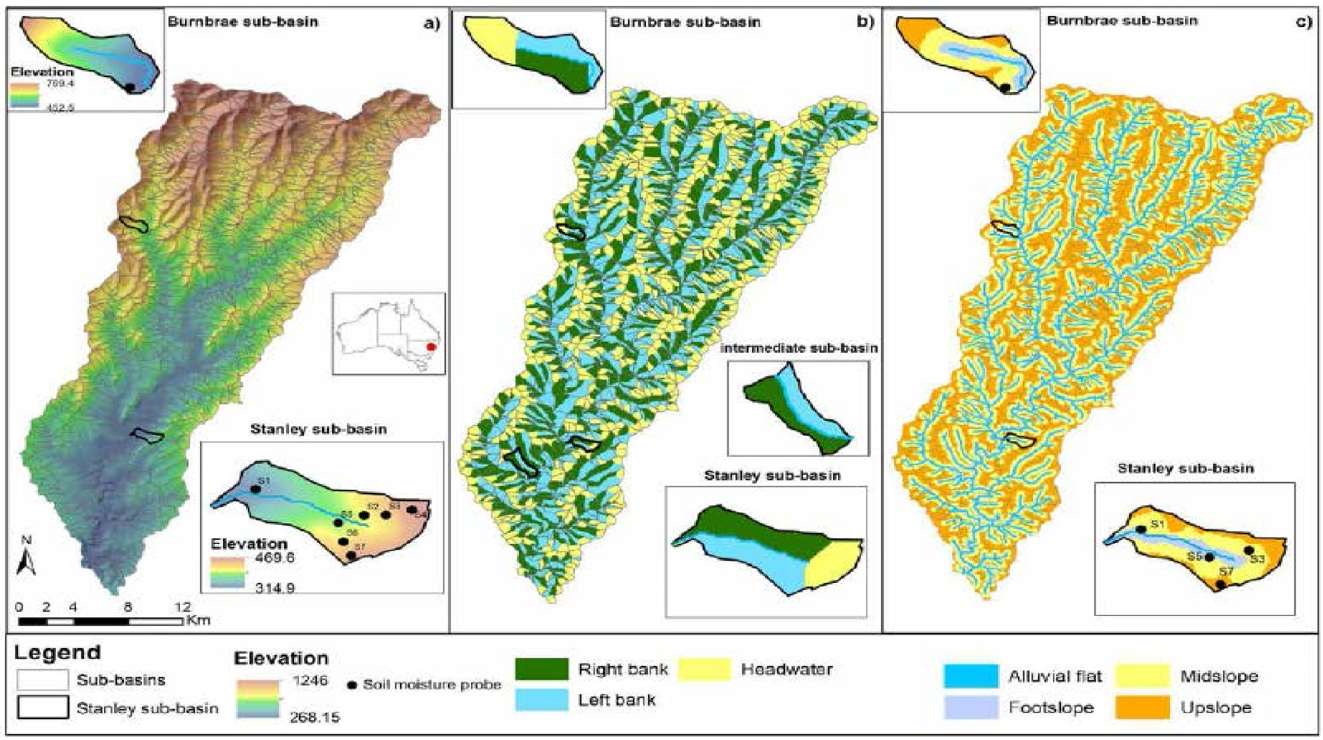
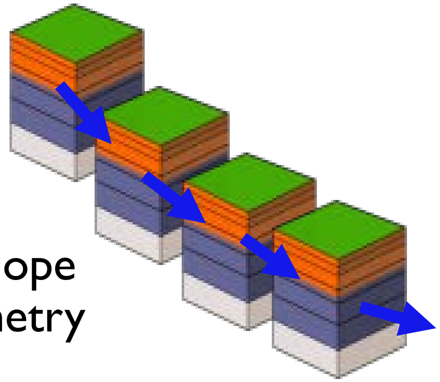


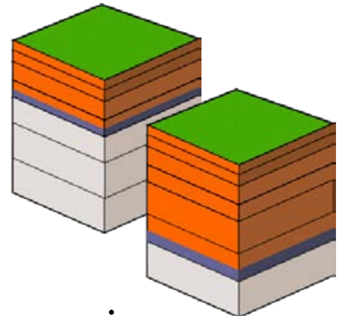

**Fig. 4.** Krui River catchment and the Stanley and Burnbrae sub-basins in Australia. SMART delineates (a) first order sub-basins (b) hillslopes and (c) landforms of the catchment. Soil moisture probes in (c) are used for model comparison.

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

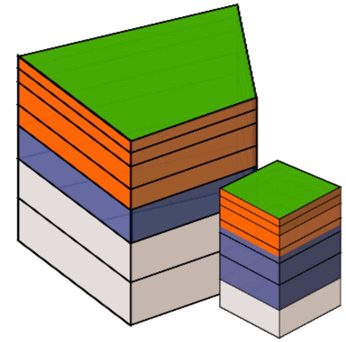
# Representative hillslope characterization



Hillslope geometry

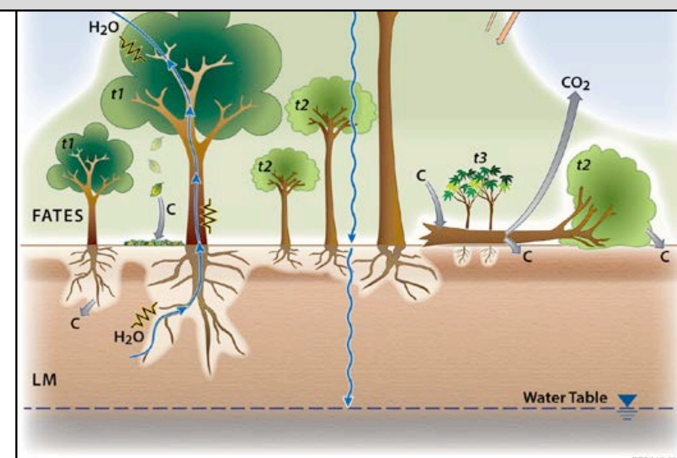


Deepening Soil



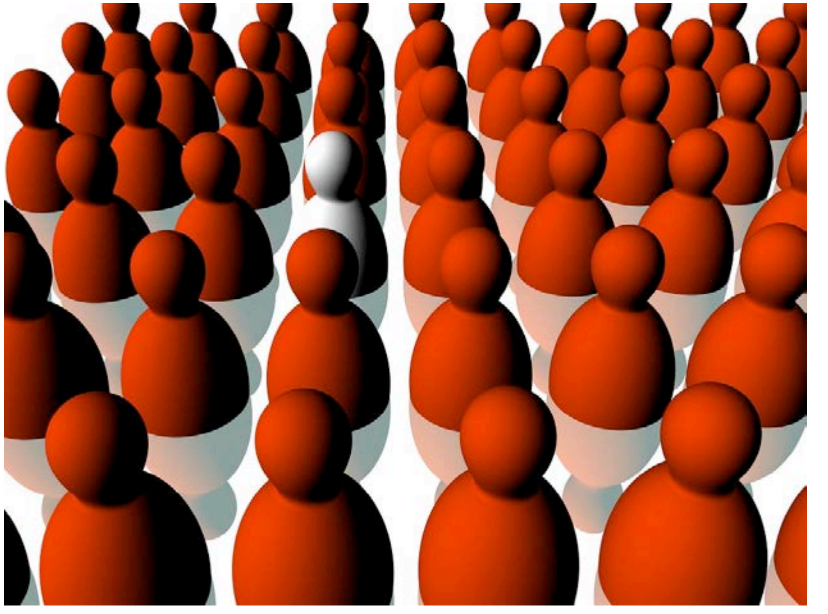
Convergence

How much complexity do we need to engage catchment hydrologists?

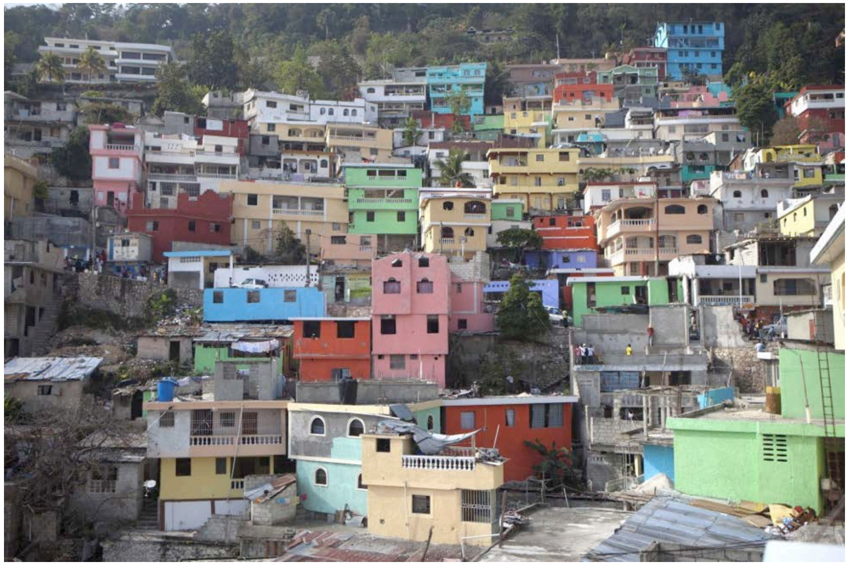


# Two issues with land model development

NCAR UCAR



- **Model proliferation**:
  - Many land models, with each group making different decisions at different points in development process
  - Limited development resources spread across many models
  - duplicated effort
- **The shantytown syndrome**:
  - Ad-hoc approach to model development
  - Accumulation of technical debt

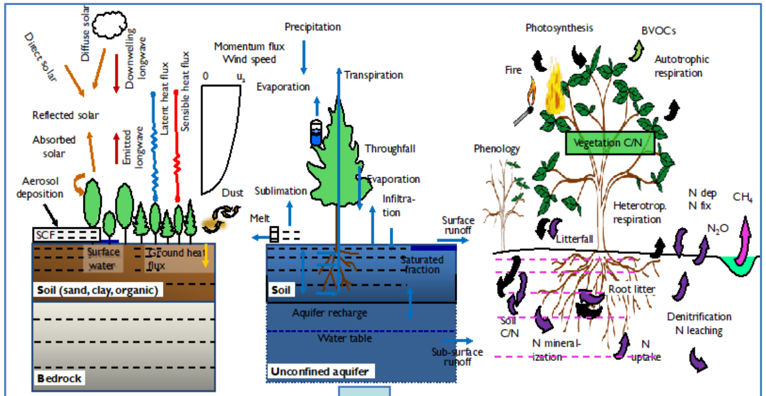


- Model proliferation and shantytown syndrome make it difficult to test underlying hypotheses and identify clear paths to model improvement

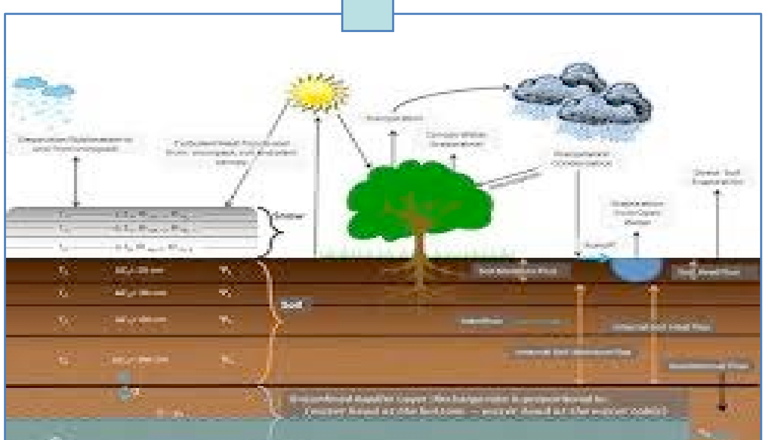
# The Community Terrestrial Systems Model

## a model for research and prediction in climate, weather, water, and ecosystems

CLM (CGD)




CTSM



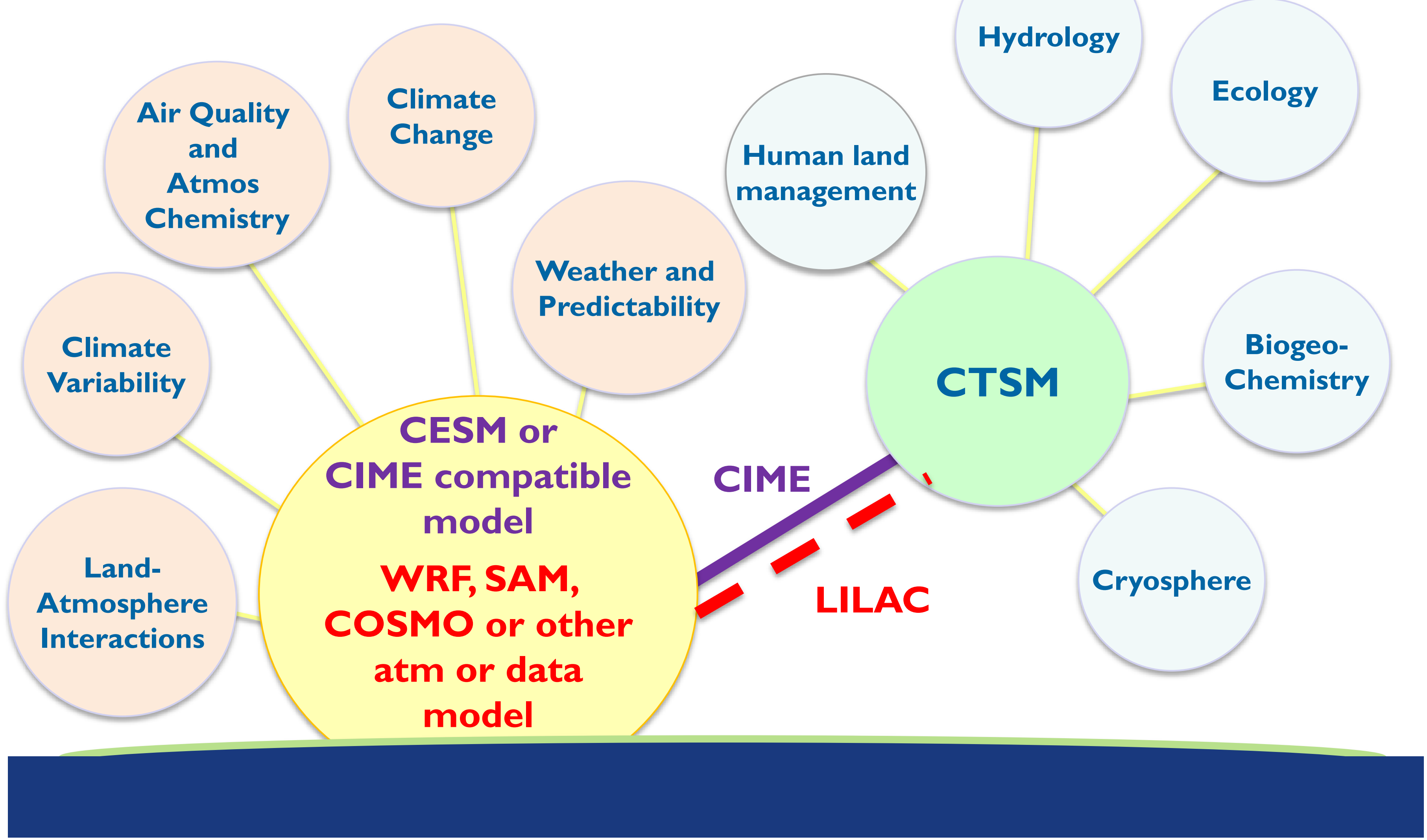
Noah-MP, WRF-Hydro (RAL)

- More efficient use of NCAR and community development resources
- Integrate and expand land modeling research community
- Code improvements
    - Modularity; alternative hypotheses
    - Hierarchy of complexity (weather, water, climate, ecosystem applications)
    - Increase flexibility of spatial disaggregation
    - Expose state variables for DA
    - Eliminate hard coded parameters
- Accelerate advances
- Enable more hypothesis-driven science

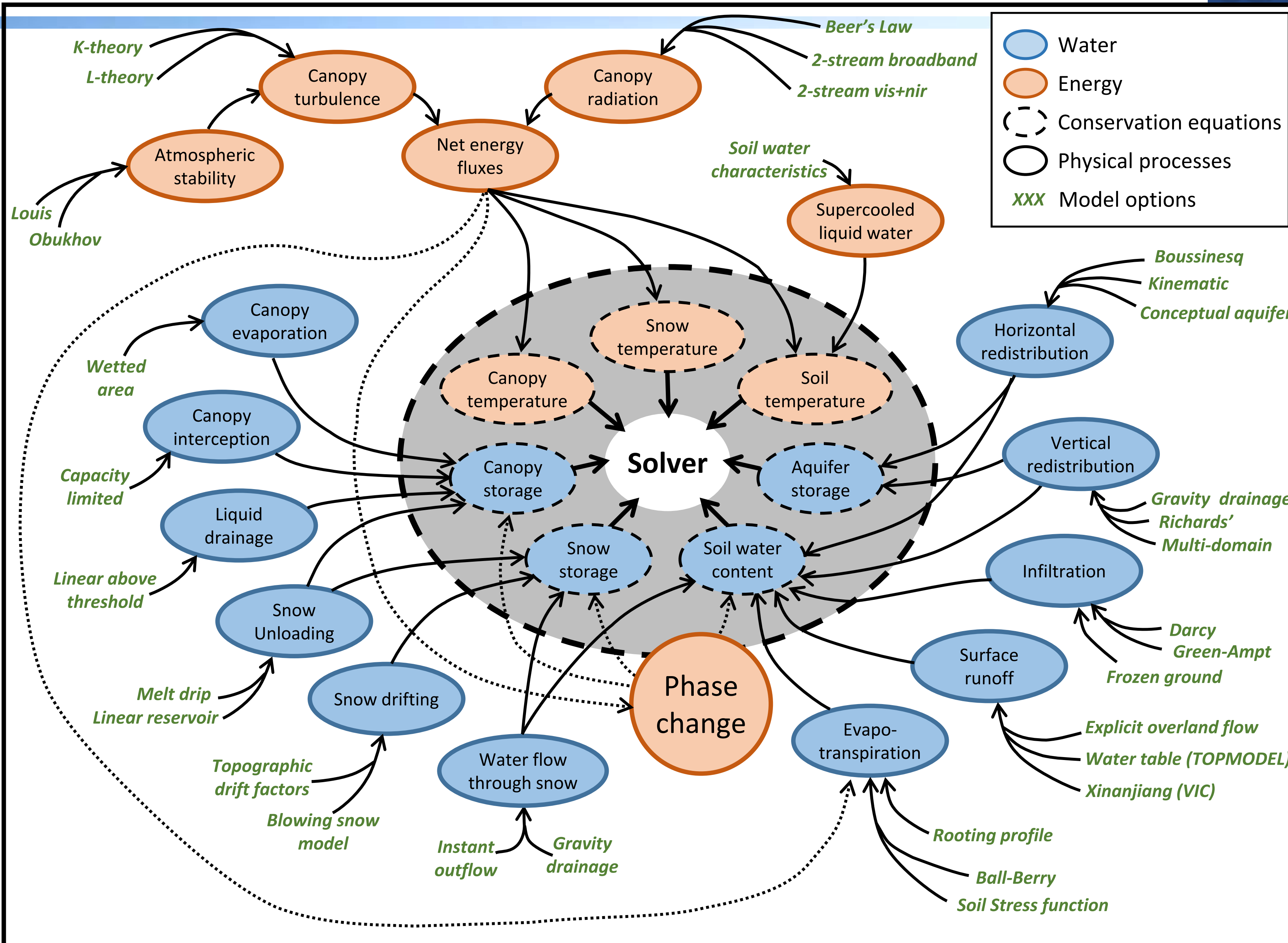
# Community Terrestrial Systems Model (CTSM) as a community modeling tool

**CIME – Common Infrastructure for modeling the Earth**

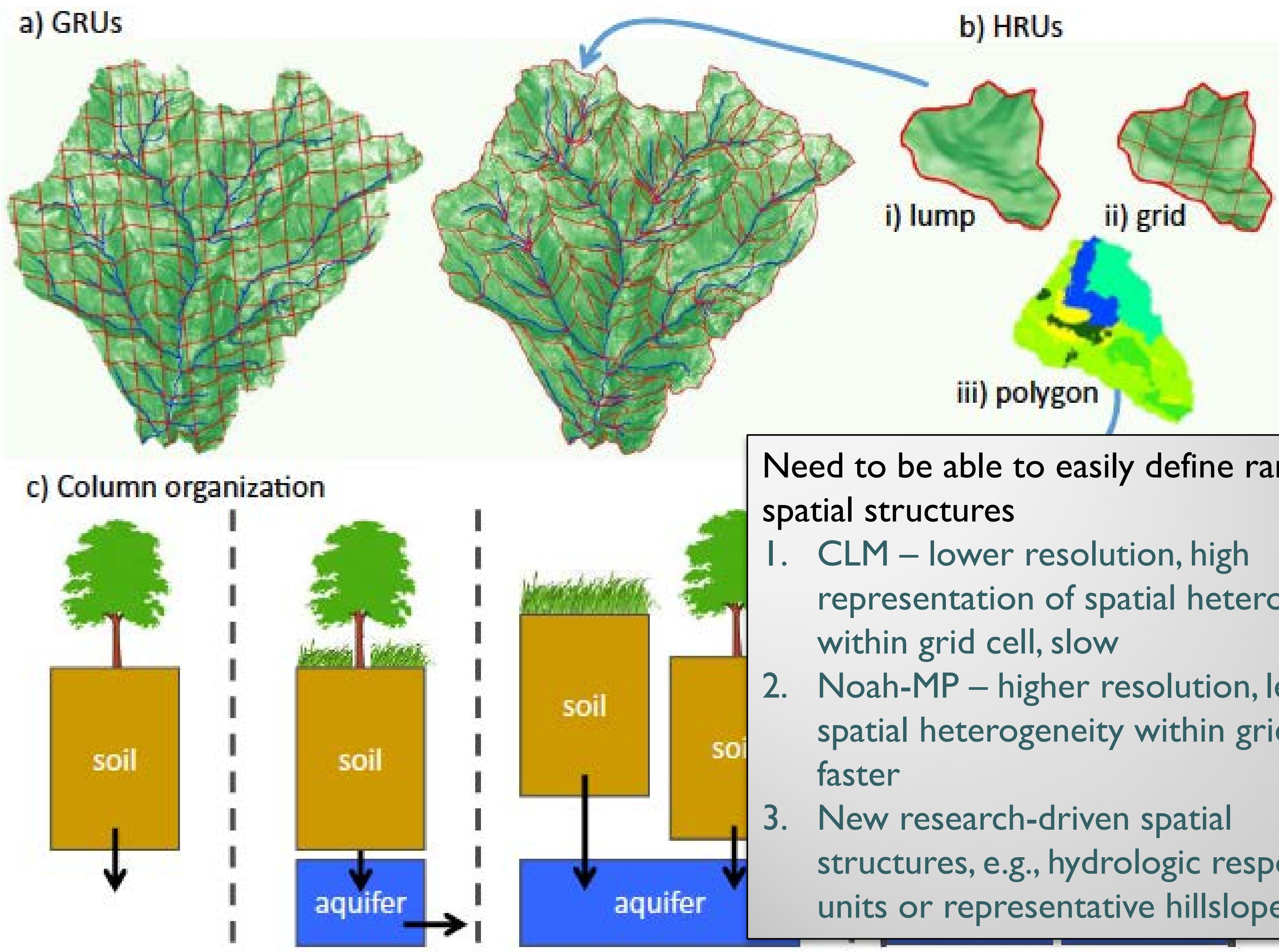
**LILAC – Light-weight Infrastructure for Land-Atmosphere Coupling**



# Modularization and Process flexibility



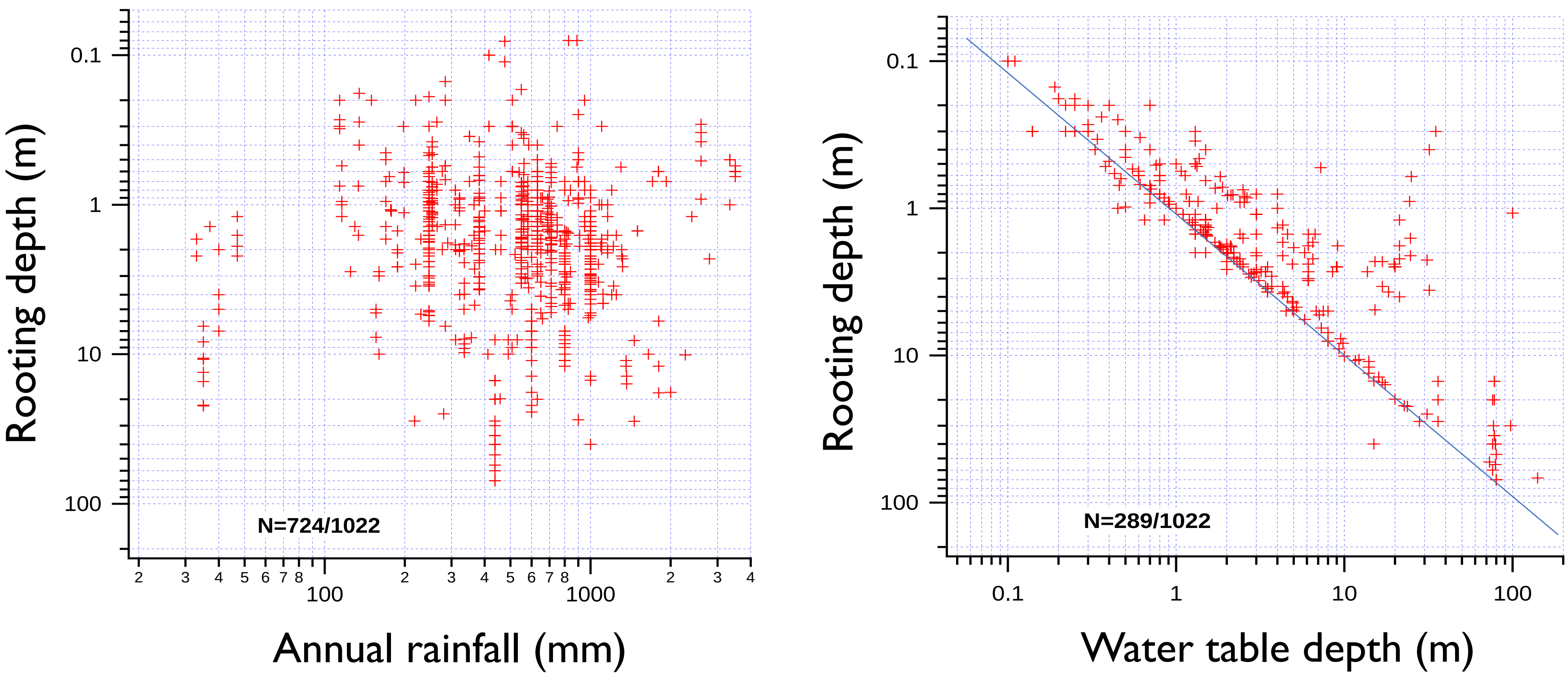
# Spatial flexibility




Need to be able to easily define range of spatial structures

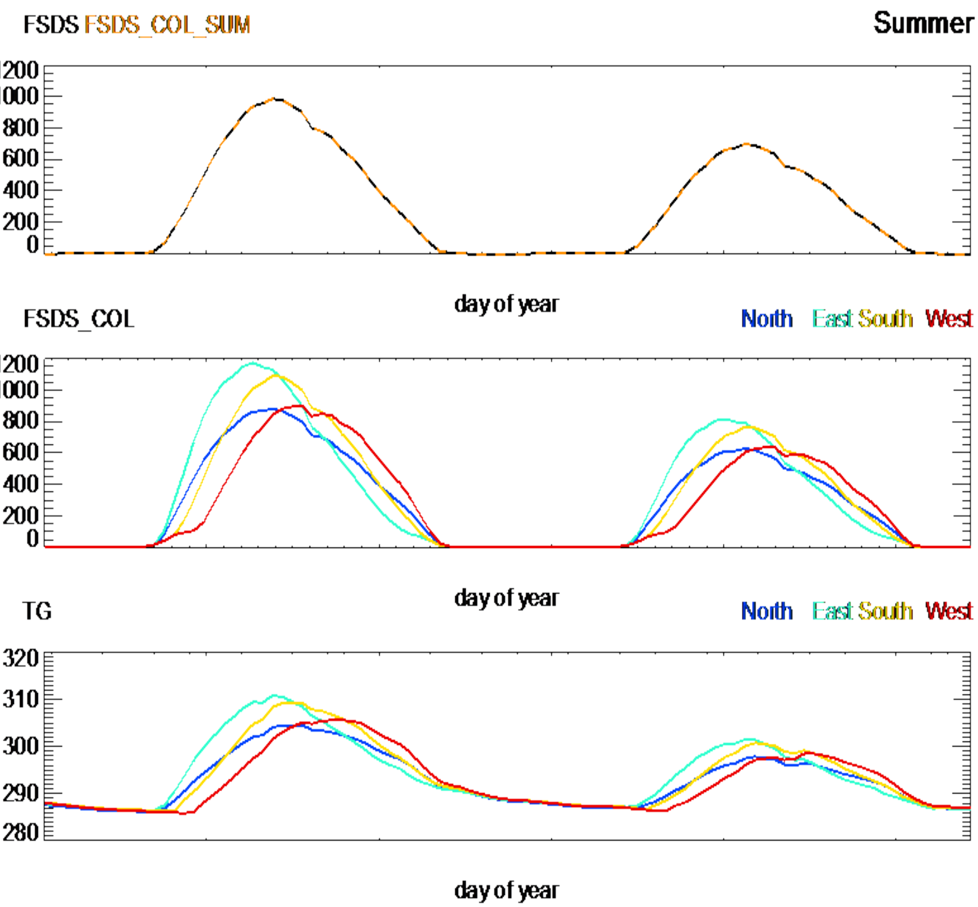
1. CLM – lower resolution, high representation of spatial heterogeneity within grid cell, slow
2. Noah-MP – higher resolution, less spatial heterogeneity within grid cell, faster
3. New research-driven spatial structures, e.g., hydrologic response units or representative hillslopes

# Rooting depth relationship with water




Subsurface characteristics such as bedrock depth and soil properties critical

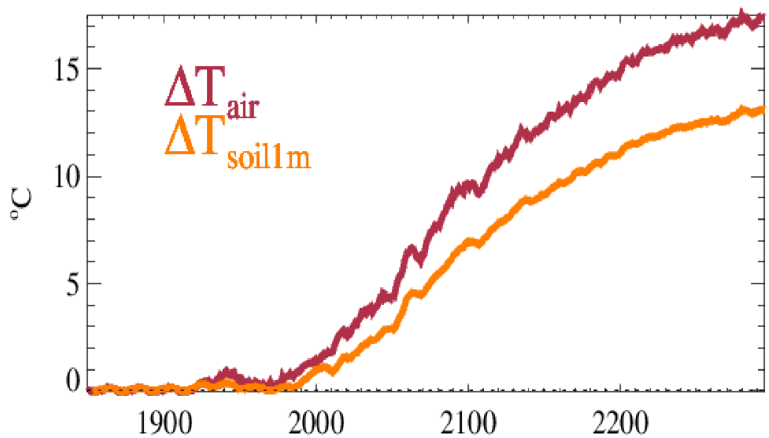
Fan, unpublished

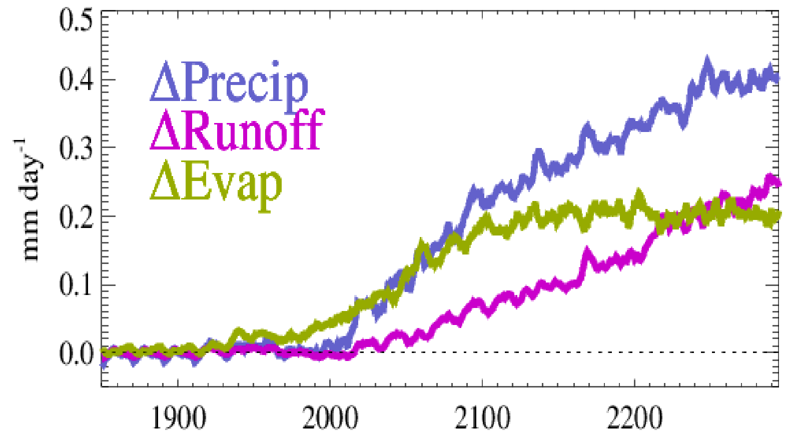


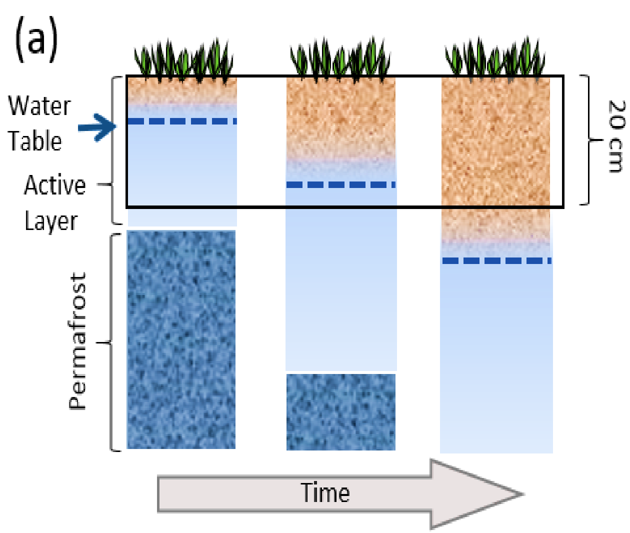
FSDS FSDS_COL_SUM
Summer
1200
1000
800
600
400
200
0
day of year
FSDS_COL
North
East South
West
1200
1000
800
600
400
200
0
day of year
TG
North
East South
West
320
310
300
290
280
day of year

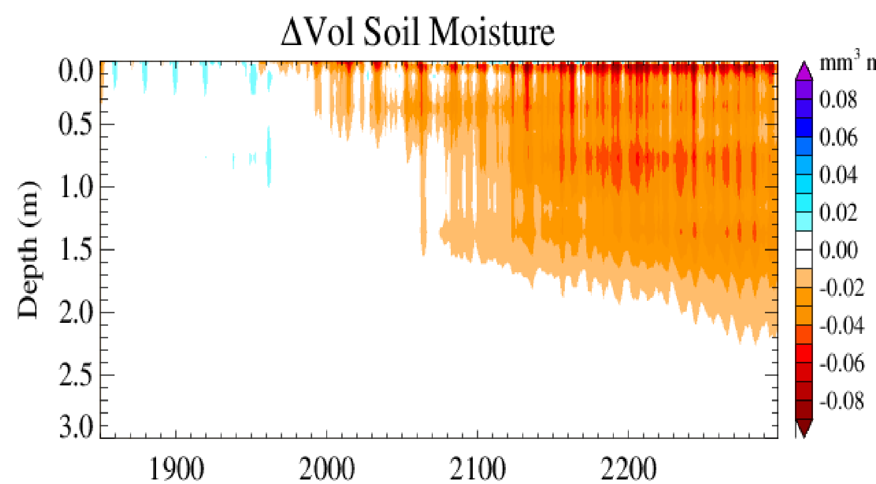
# Example: Uncertainty related to soil moisture projections

CESM Projections of temperature and water balance for permafrost domain (RCP8.5)

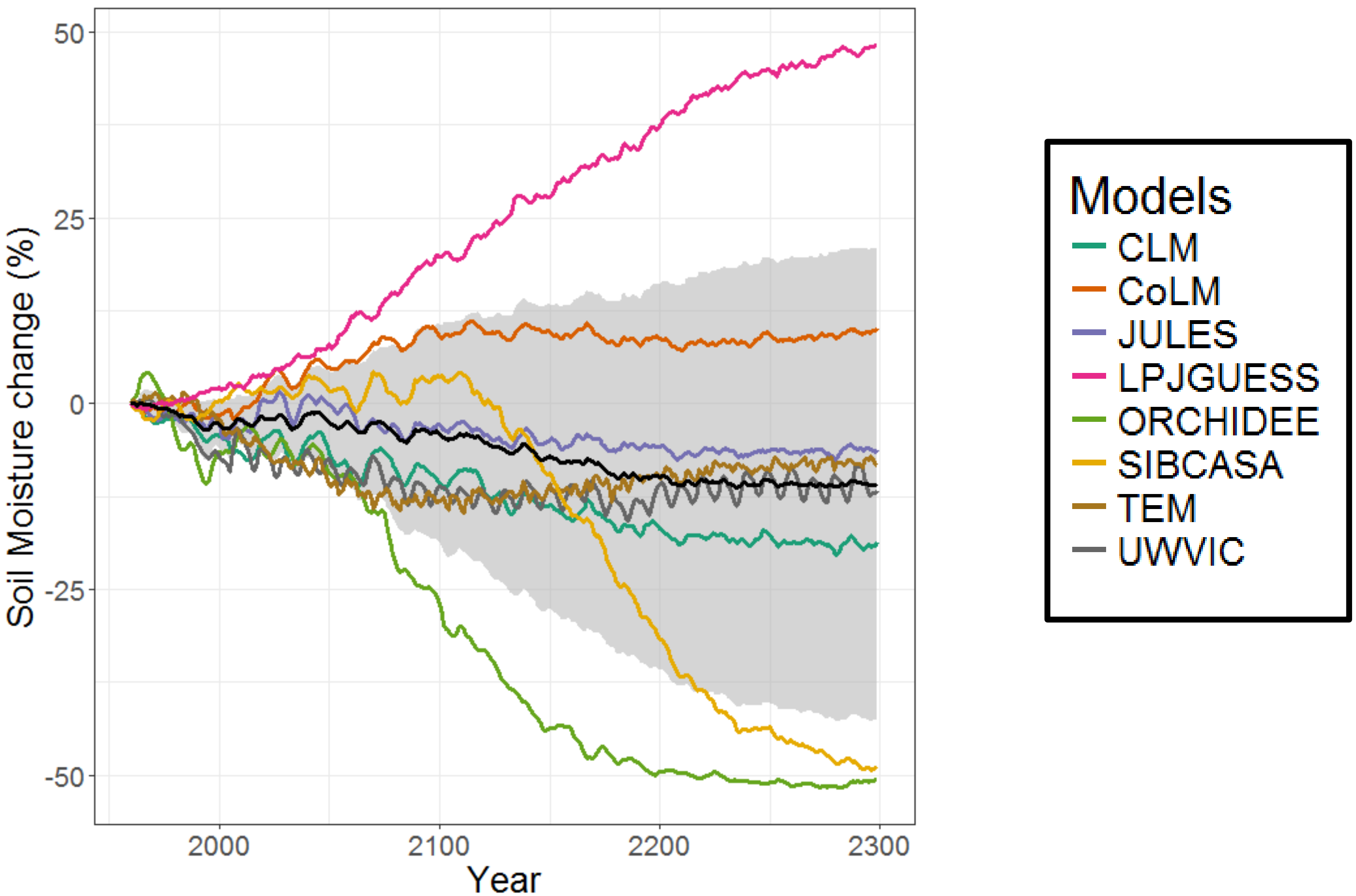


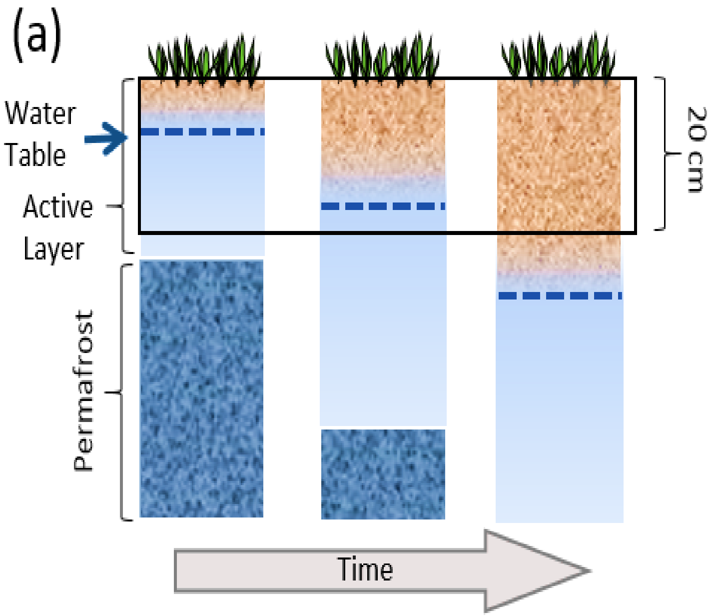



# High uncertainty in permafrost-domain soil moisture projections in PCN models

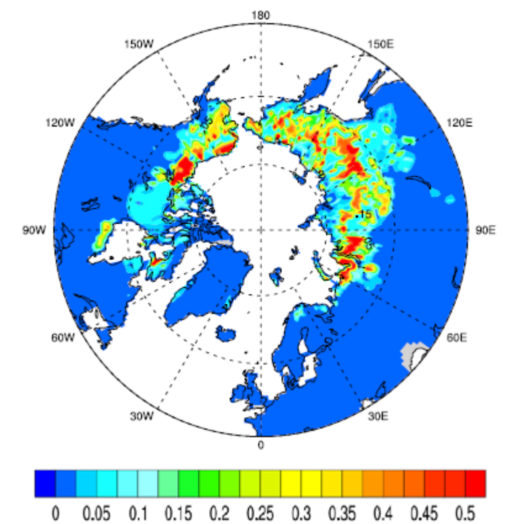



Andresen et al., in prep

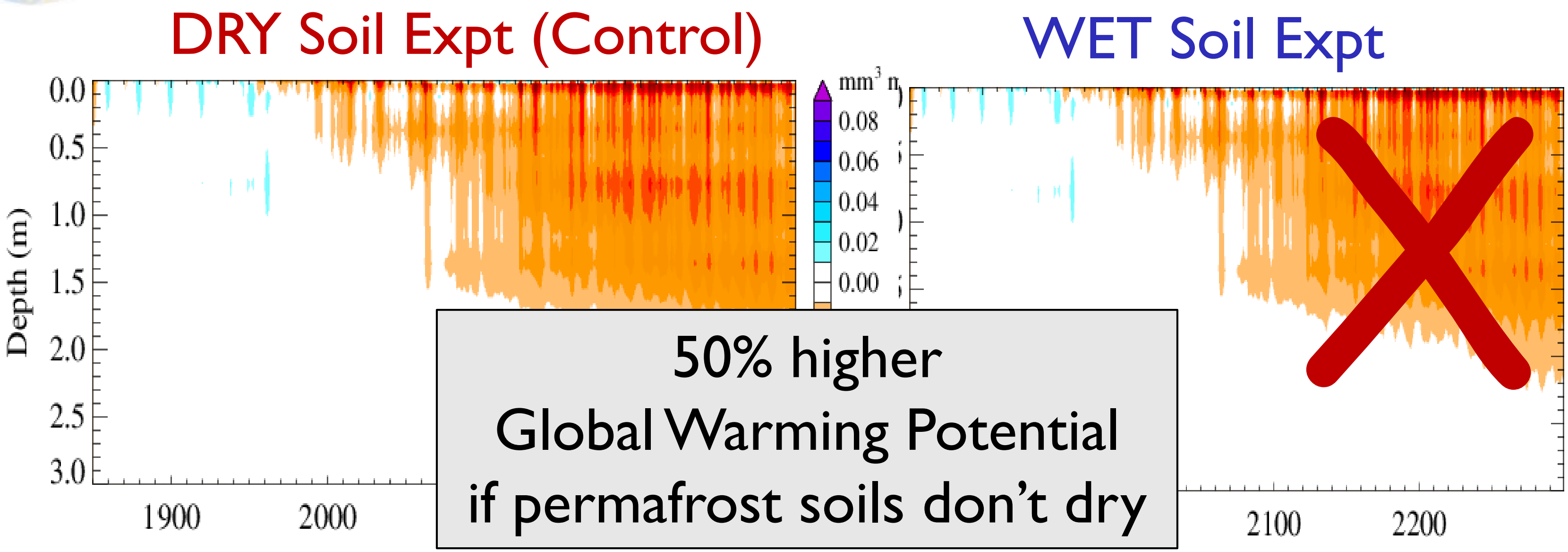
# Active layer deepening and soil subsidence

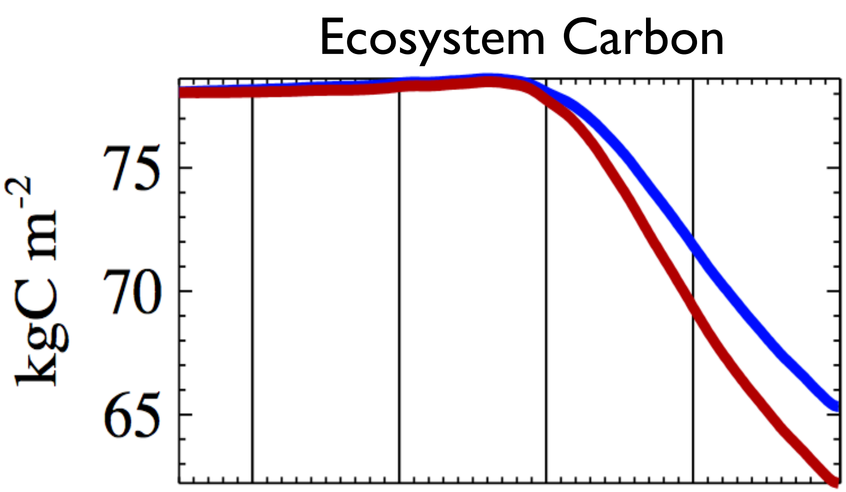


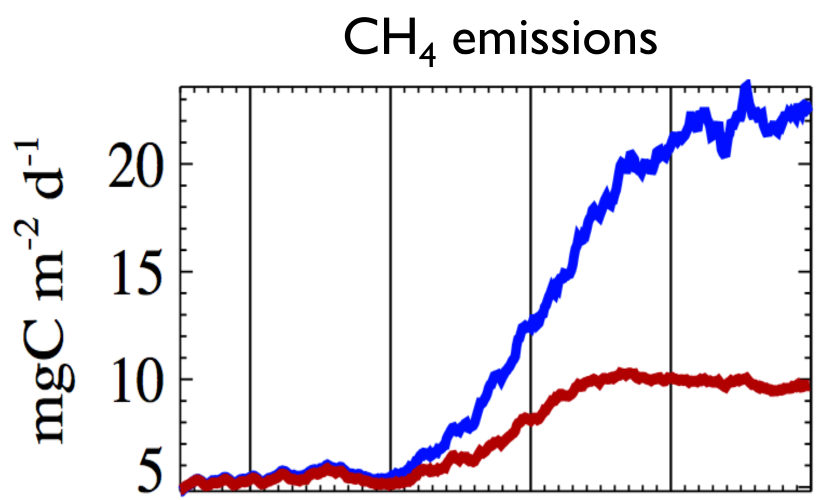

CLM projection of subsidence by 2100



# Permafrost carbon-climate feedback with and without soil drying




Lawrence et al., ERL, 2015

# What's New for CLM5

Hydrology: dry surf. layer, var. soil depth w/ deeper (8.5m) max soil, revised GW and canopy interc

Snow: canopy snow updates, wind effects, firn model (12 layers), glacier MEC, fresh snow dens.

Rivers: MOSART(hillslope → tributary → main channel)

Nitrogen: flexible leaf C:N ratio, leaf N optimization, C cost for N (FUN)

Carbon: revisions to carbon allocation and decomposition

Fire: updates, trace gas and aerosol emissions

Vegetation: plant hydraulics and hydraulic redistribution, deep rooted tropical trees, Ecosystem Demography (FATES), prognostic roots, ozone damage

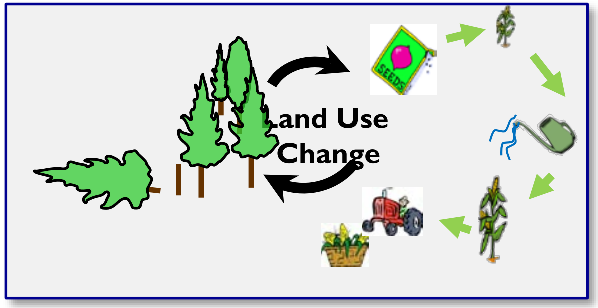
Crops: global crop model with transient irrig. and fertilization (8 crop types), grain prod. pool

Land cover/use: dynamic landunits, revised PFT-distribution, wood harvest by mass, shifting cultivation

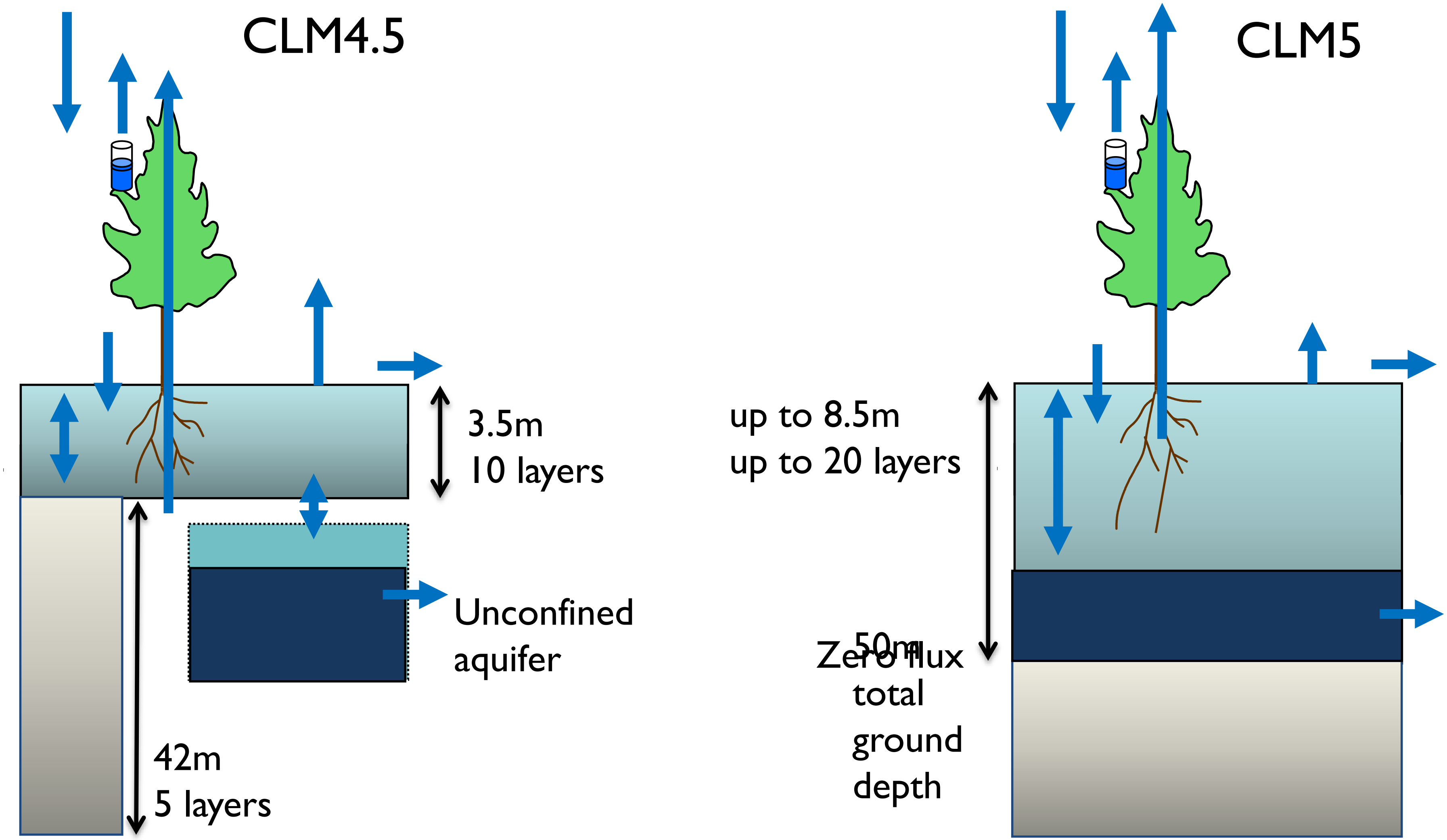
Isotopes: carbon and water isotope enabled

**CLM5 default configuration**

**CLM5 optional feature**

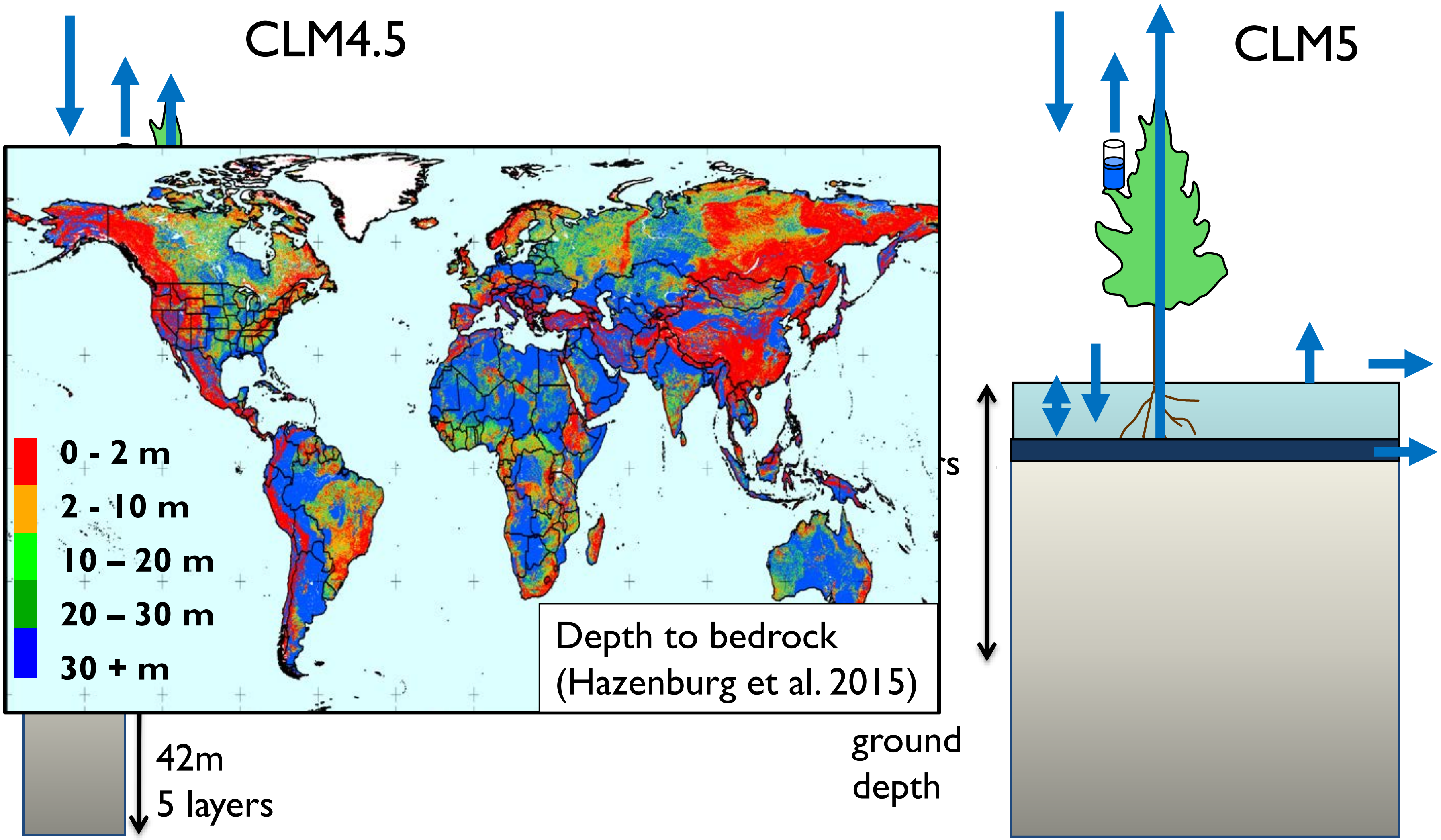


# CLM5: Soil hydrology updates



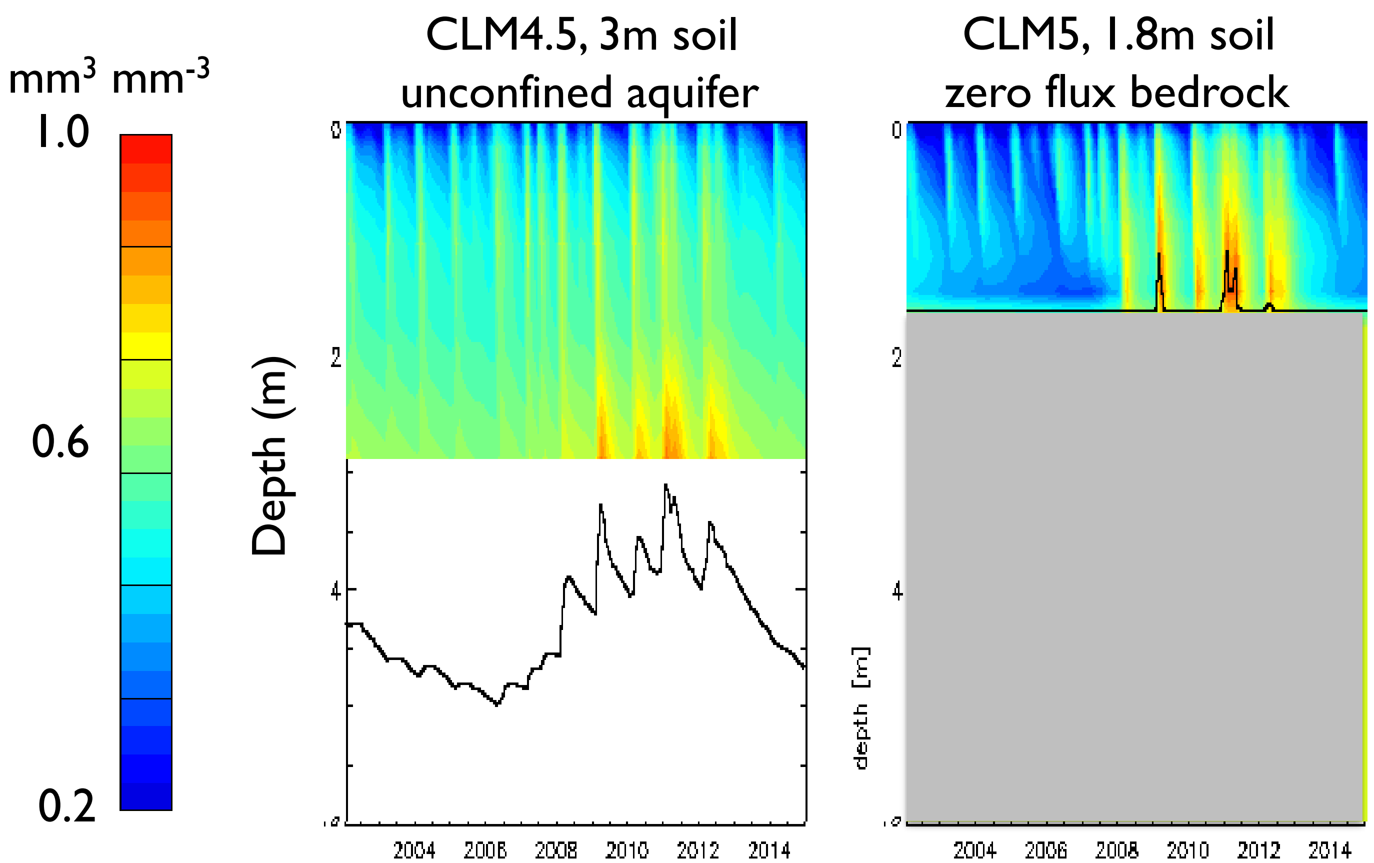

Brunke et al., 2015; Swenson and Lawrence, 2015

# CLM5: Soil hydrology updates



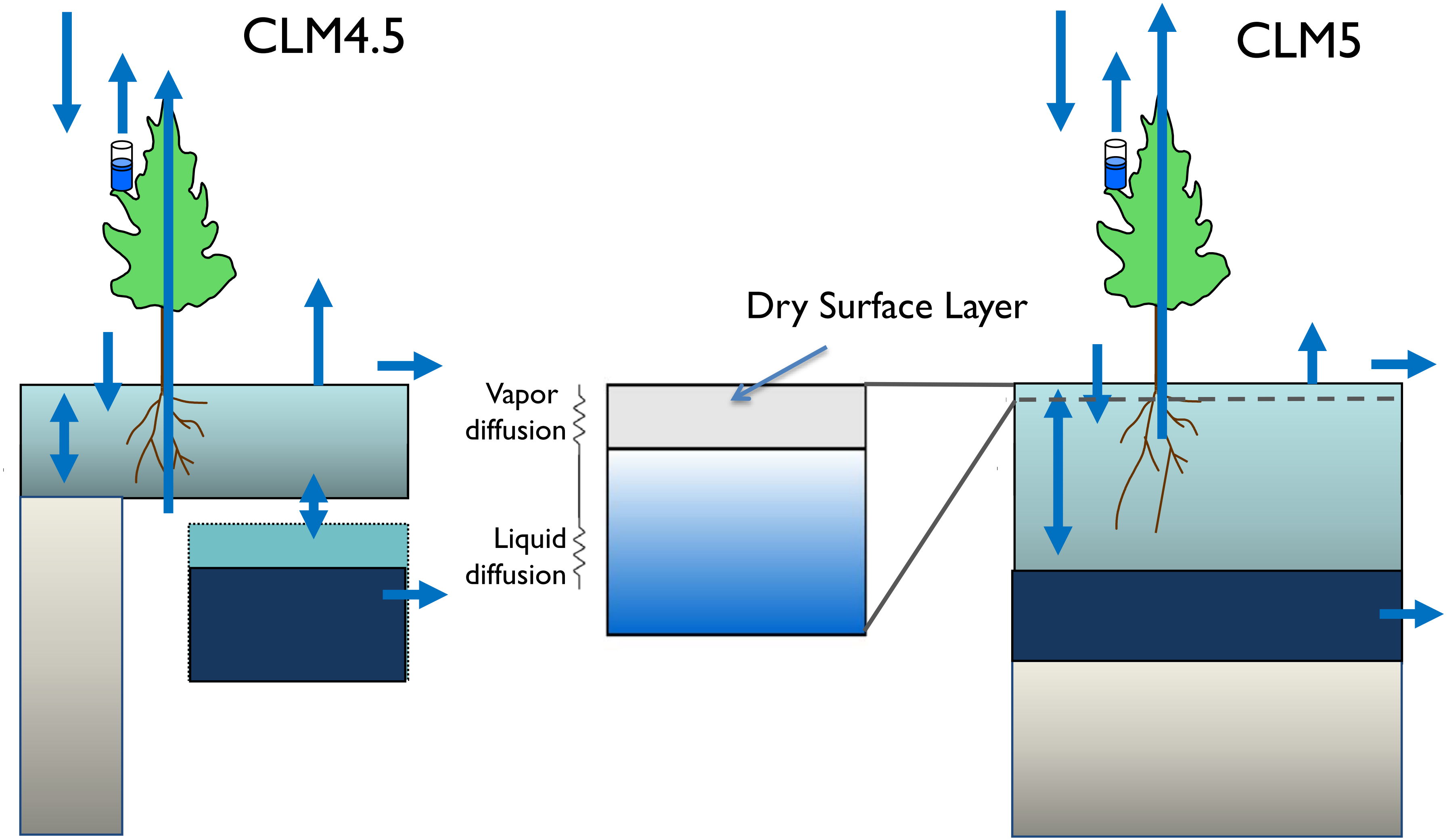
# Variable soil depth

## Soil Moisture




Swenson and Lawrence, 2015

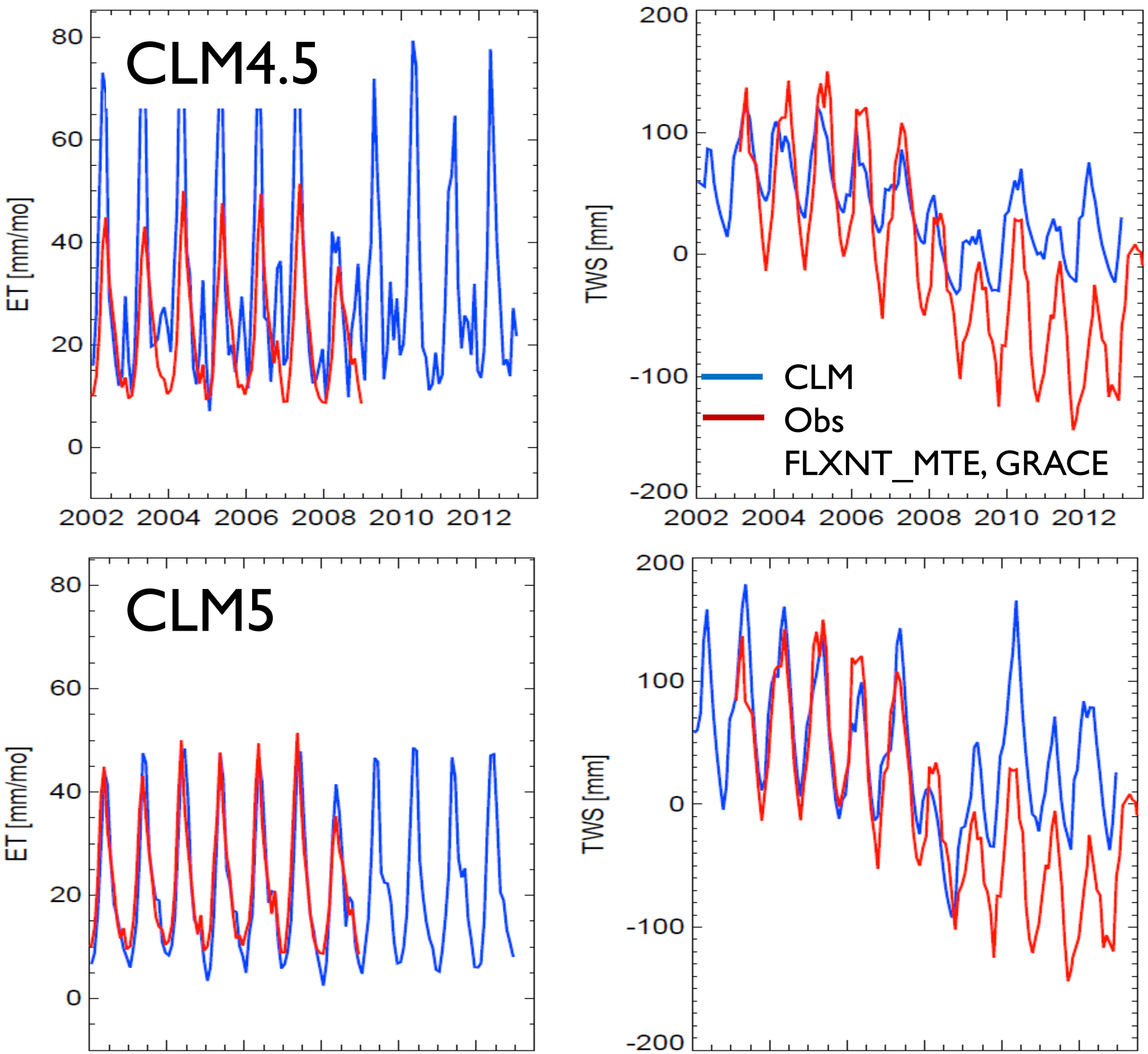
# CLM5: Soil hydrology updates

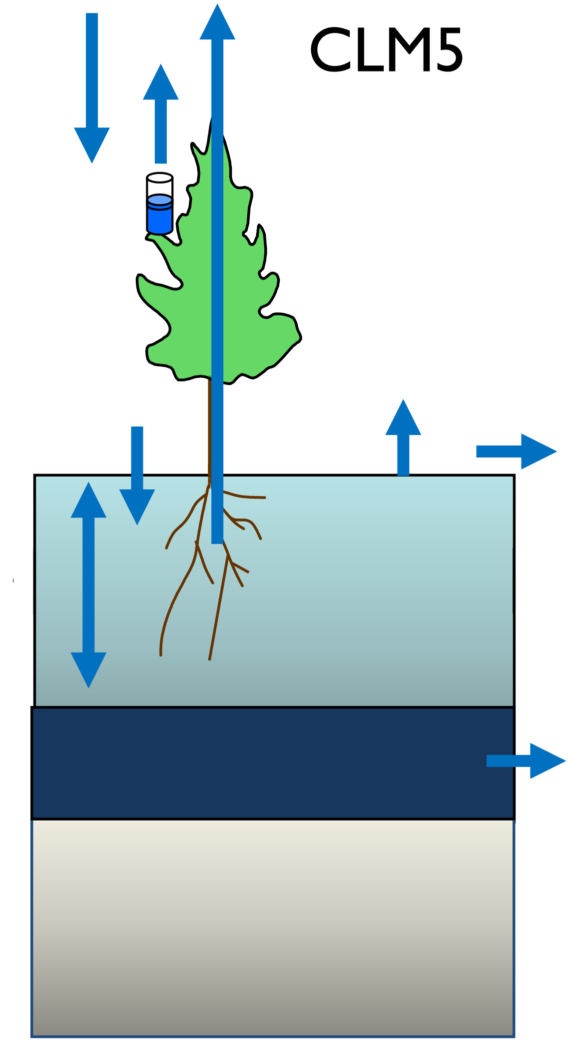



Swenson and Lawrence, 2014

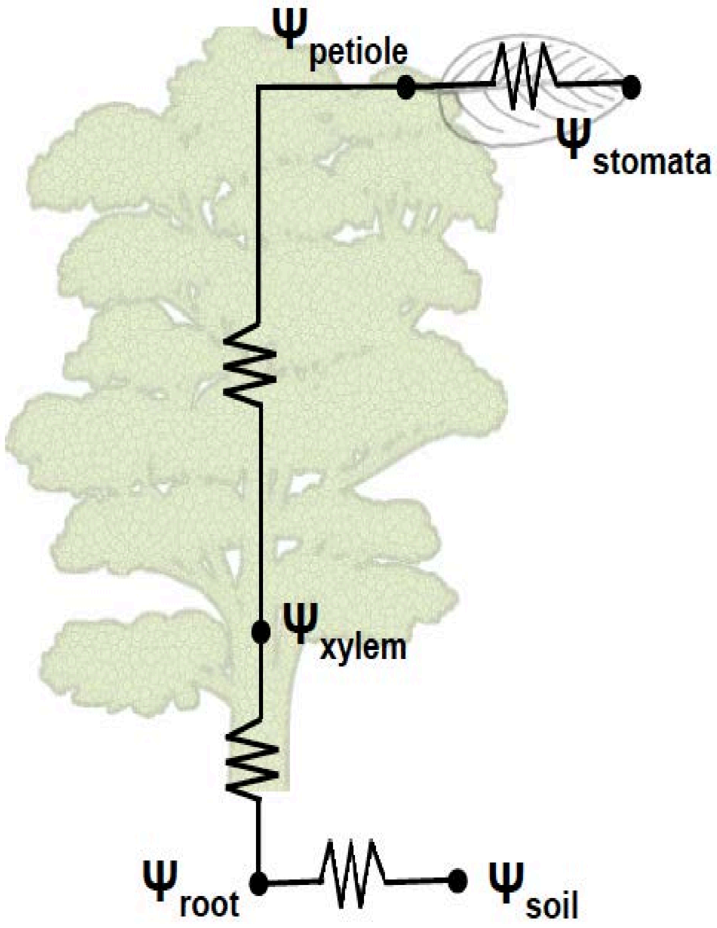
# CLM5: Soil hydrology updates

## Semi-arid region: Iran



# CLM5: Plant Hydrodynamics

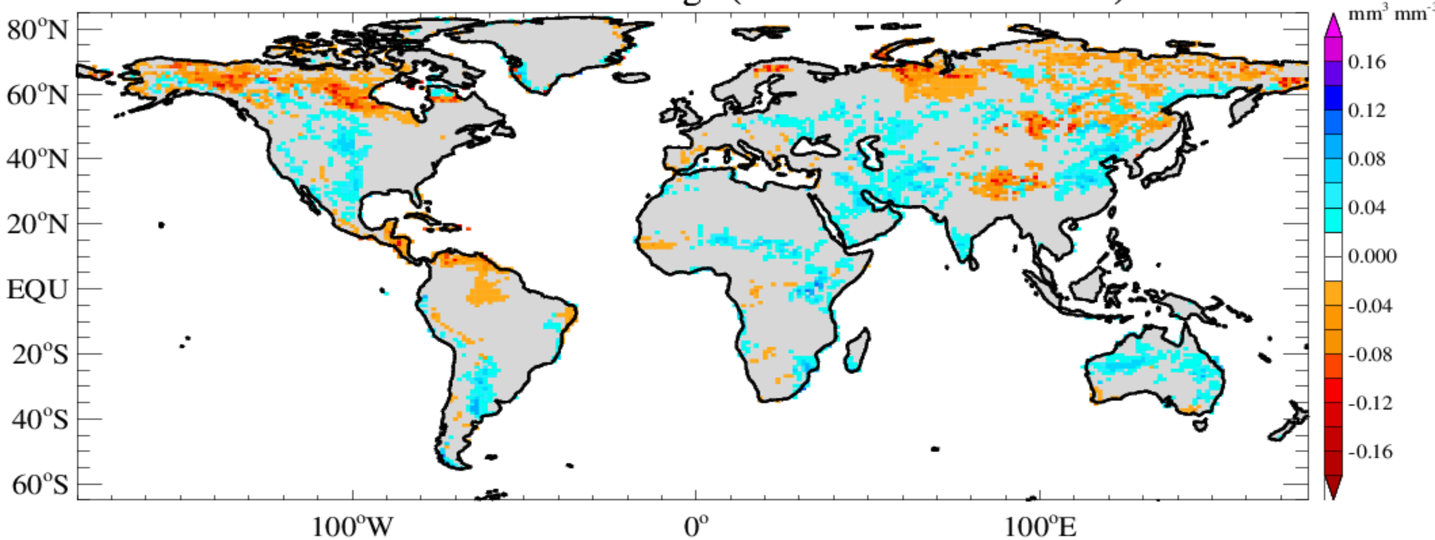



Why plant hydrodynamics

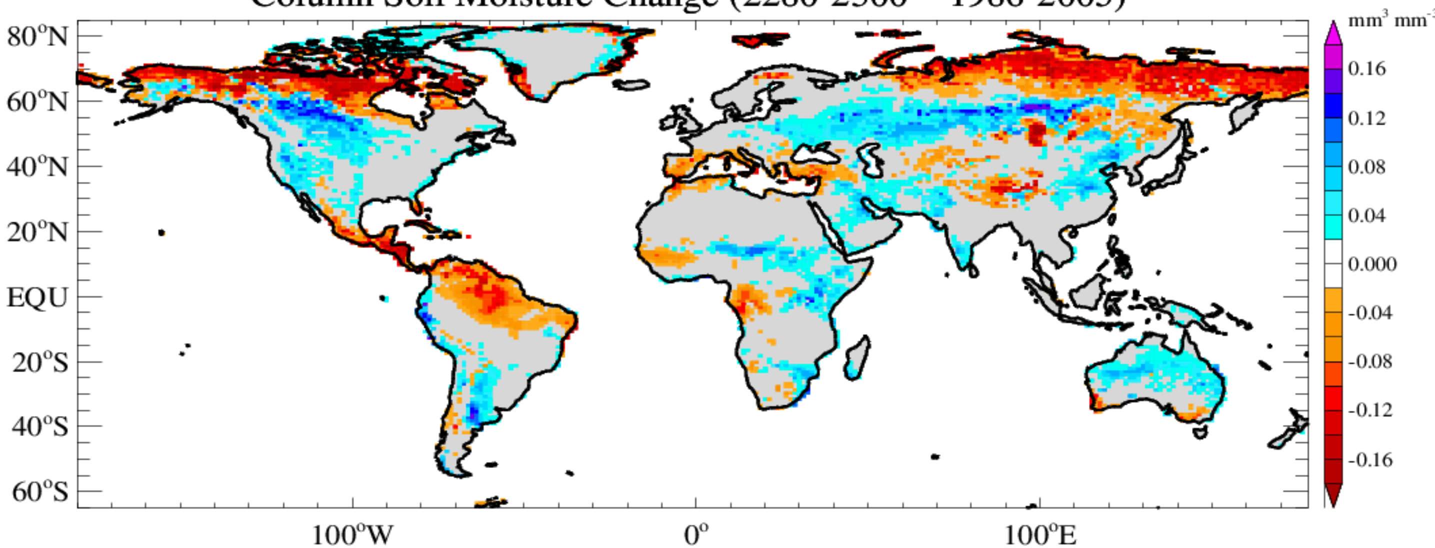
- BTRAN (soil moisture stress), and it's parameters, $\theta_{crit}$ and $\theta_{wilt}$, have no physical meaning and cannot be measured.
- Flux tower ET convolutes transpiration with canopy and soil evap making it difficult to use for process-level assessment. With plant hydrodynamics, sap flow measurements could be utilized.
- Satellites increasingly observe properties related to canopy or leaf water content.

# Water-Carbon interactions: Hydrology and the permafrost-carbon feedback

Column Soil Moisture Change (2080-2100 – 1986-2005)

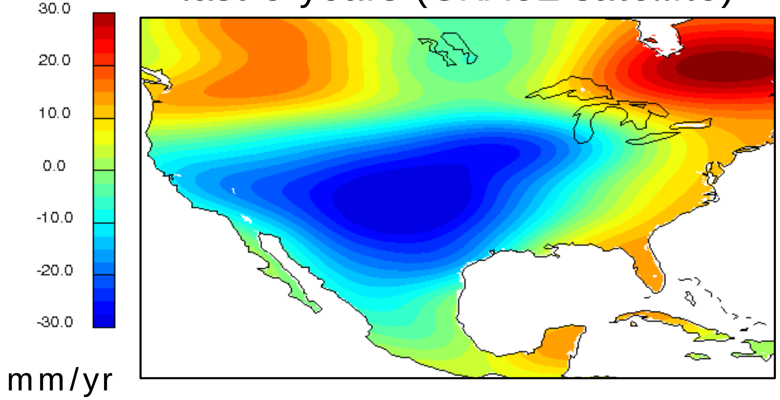



Column Soil Moisture Change (2280-2300 – 1986-2005)



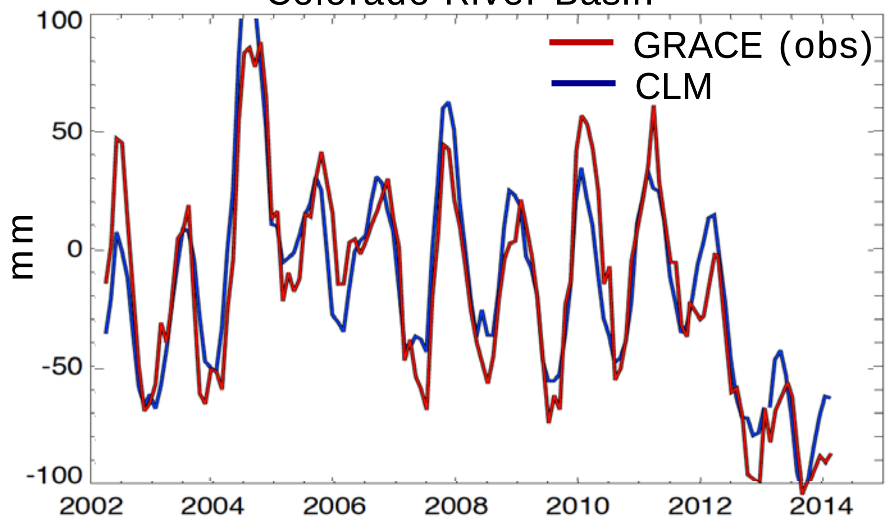
# Using CLM to assess human groundwater withdrawal

Land water storage trend over last 5 years (GRACE satellite)

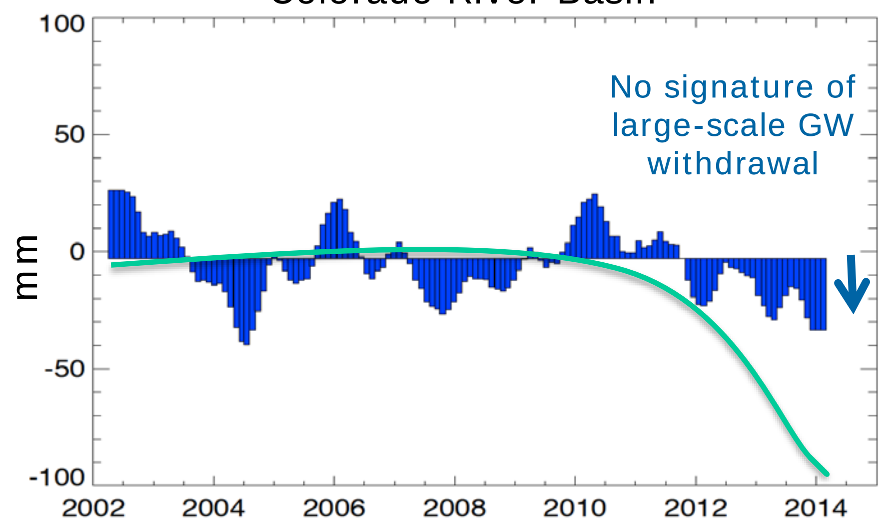


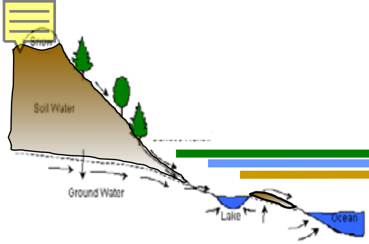

Recent studies suggest that anthropogenic groundwater depletion in **Colorado River basin** during recent drought threatens future water supply

Land Water Storage Anomaly Colorado River Basin



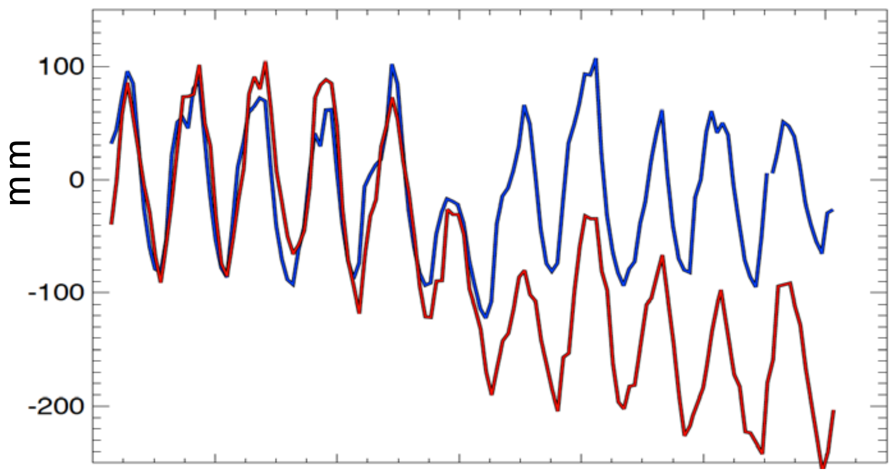

Obs Water Storage – CLM Water Storage Colorado River Basin



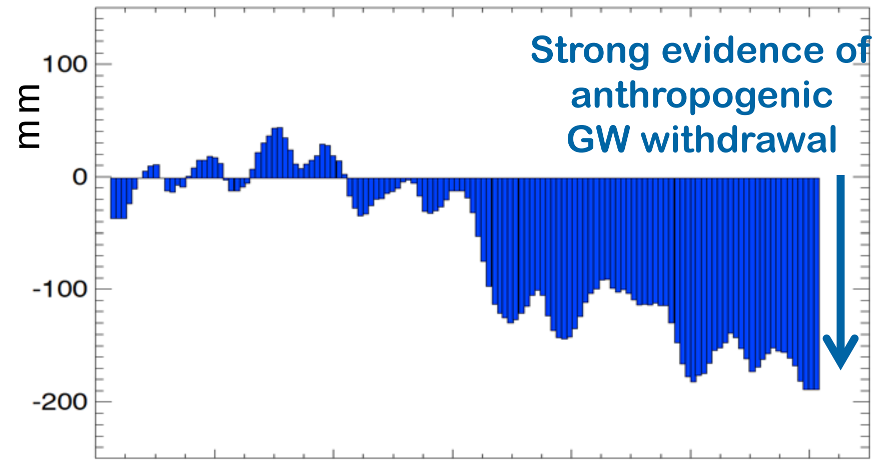



# Using CLM to assess human groundwater withdrawal

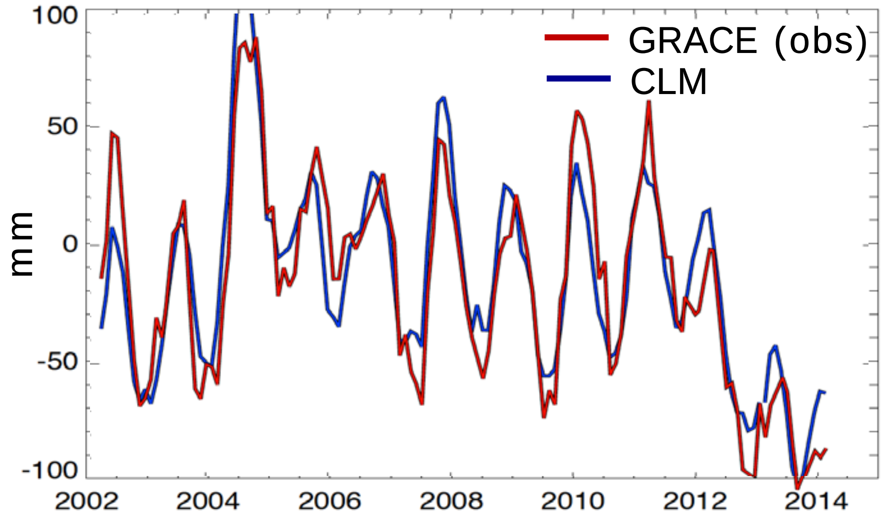
Land Water Storage Anomaly
NW Iran



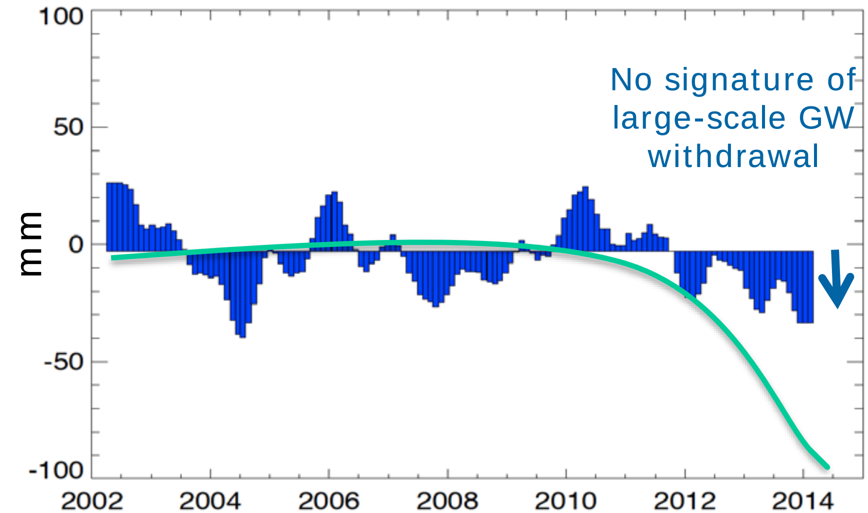

Obs Water Storage – CLM Water Storage
NW Iran




Colorado River Basin




Colorado River Basin



# mizuRoute tool

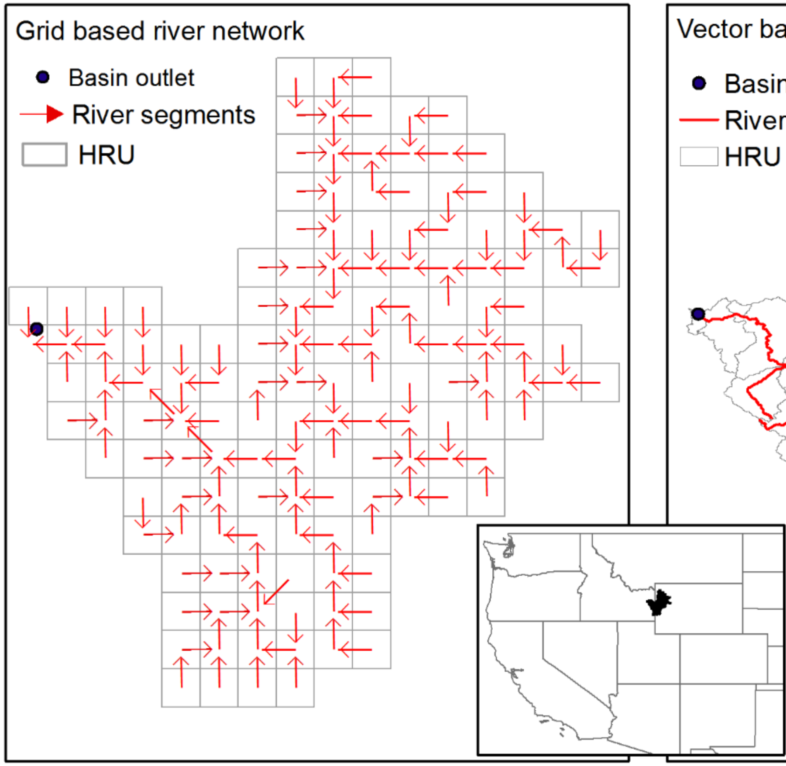
Stand-alone routing tool for *large-domain* and *multi-decadal* streamflow estimates based on runoff outputs from *multi-hydrologic models*

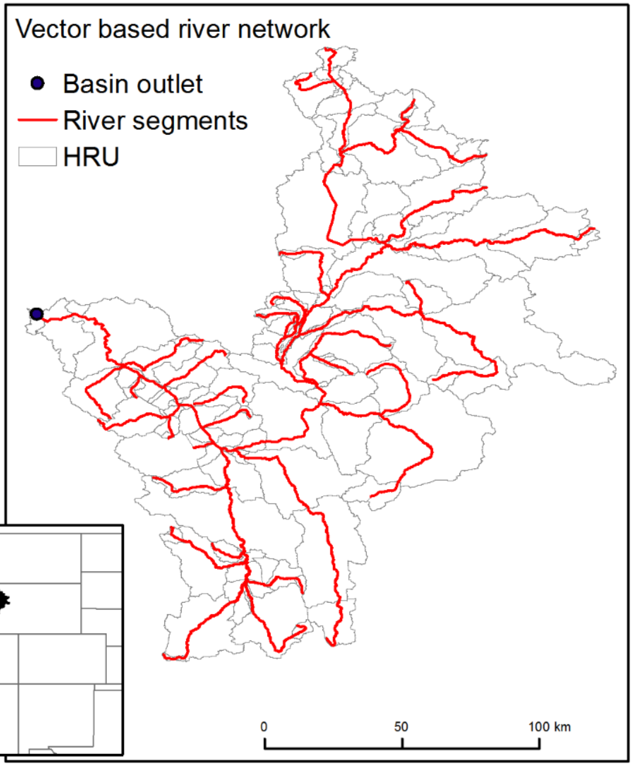
## Lohmann (1996)

- Gridded river network
- Unit-hydrograph

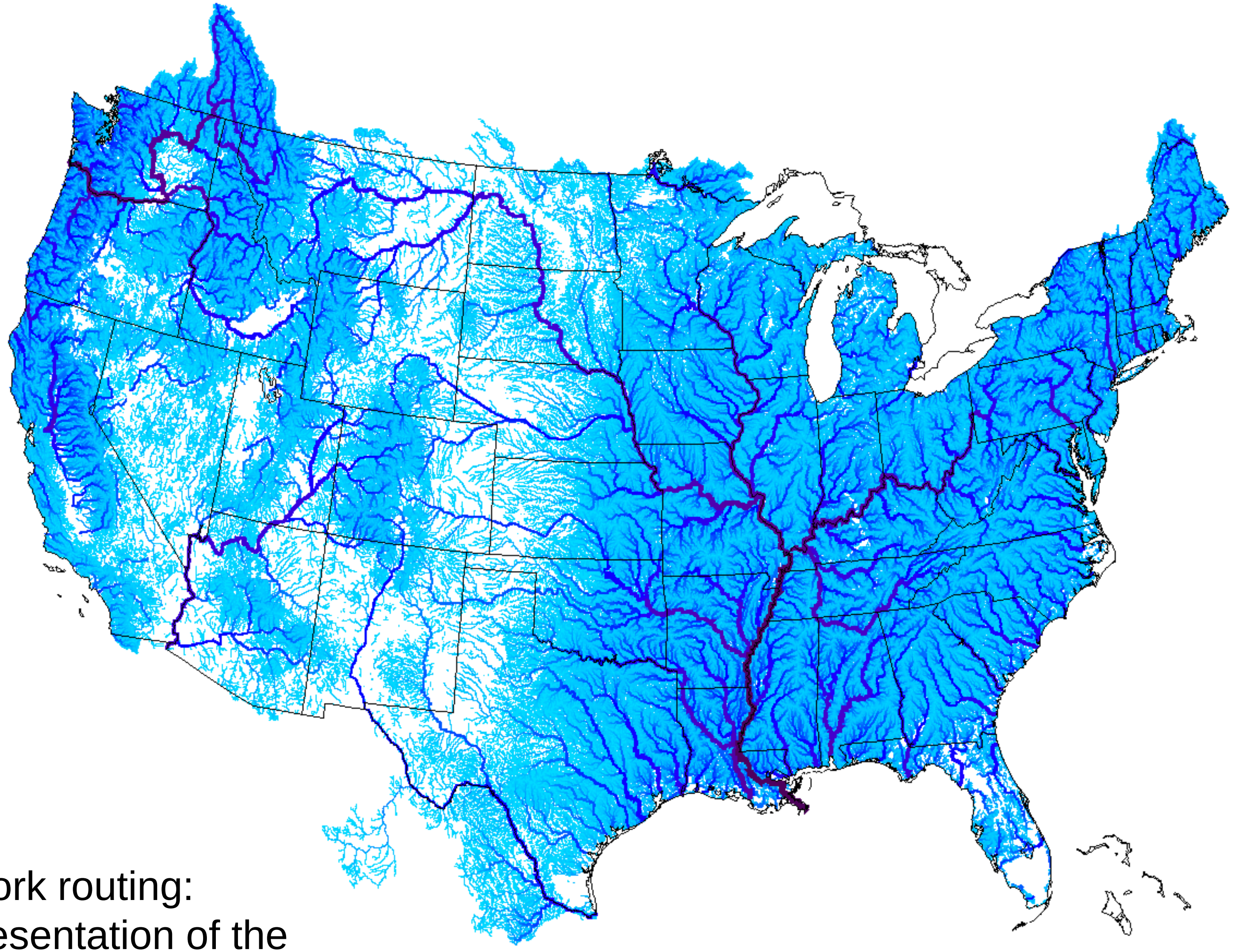
## mizuRoute (2016)

- Vector or gridded river network
- Unit-hydrograph or Kinematic Wave



# Application to higher-resolution NHD+ network



Benefits of network routing:

- Physical representation of the river network simplifies adding physical objects such as lakes and reservoirs.