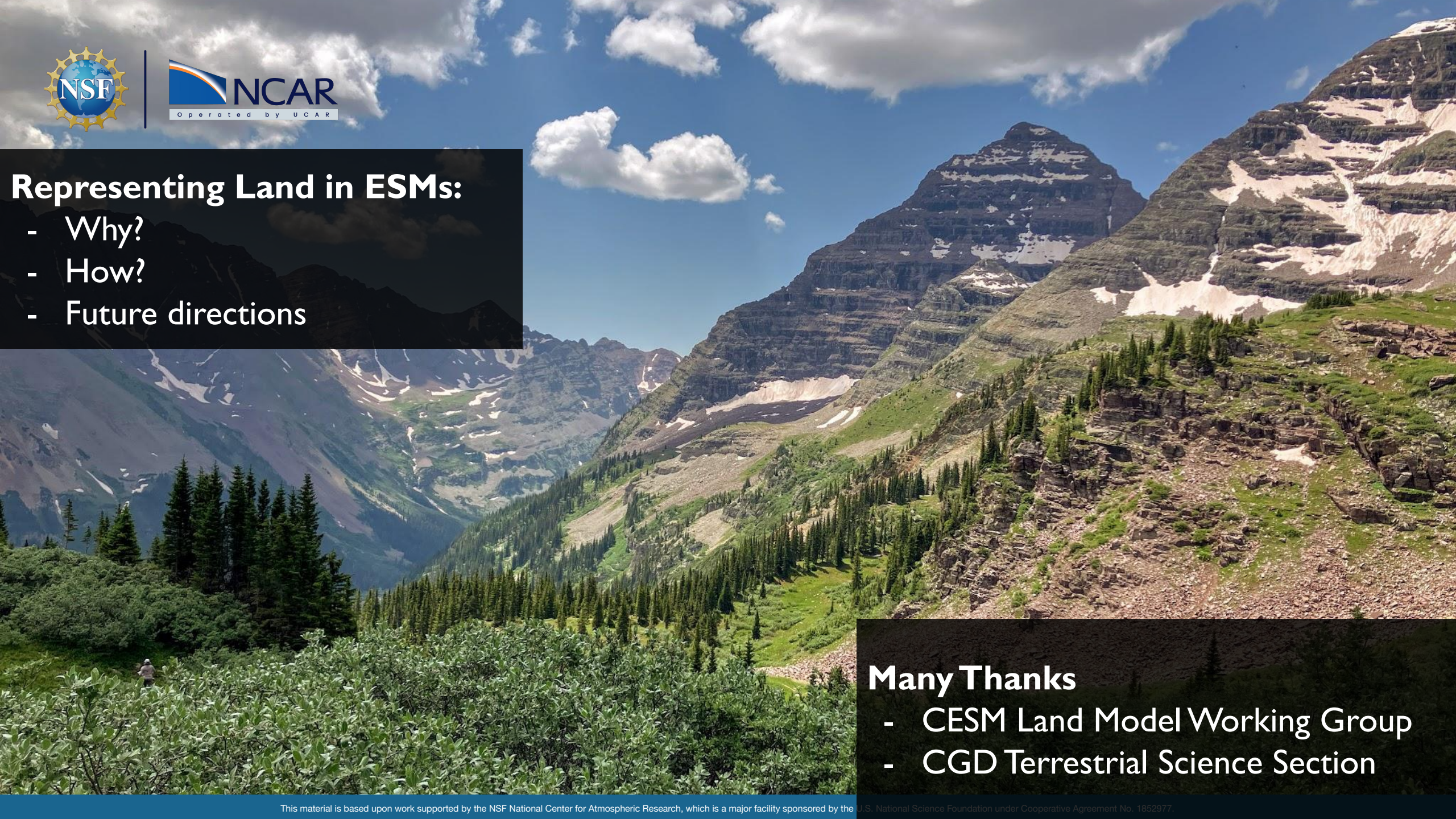


Representing Land in the Earth System I: Biogeophysics

Will Wieder

CLM Tutorial 2026

This material is based upon work supported by the NSF National Center for Atmospheric Research, which is a major facility sponsored by the U.S. National Science Foundation under Cooperative Agreement No. 1852977.



Representing Land in ESMs:

- Why?
- How?
- Future directions

Many Thanks

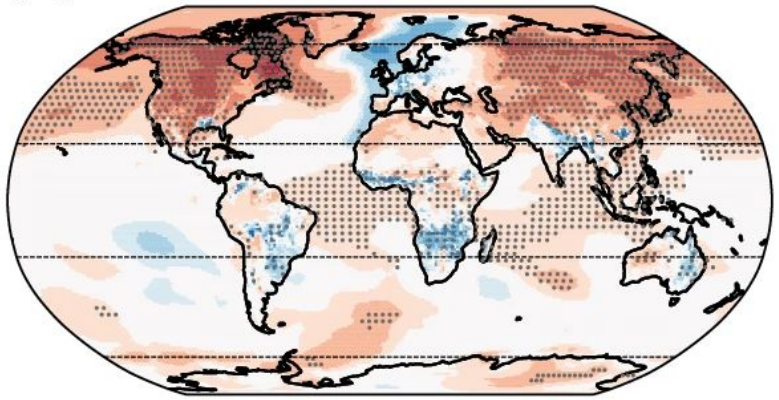
- CESM Land Model Working Group
- CGD Terrestrial Science Section

This material is based upon work supported by the NSF National Center for Atmospheric Research, which is a major facility sponsored by the U.S. National Science Foundation under Cooperative Agreement No. 1852977.

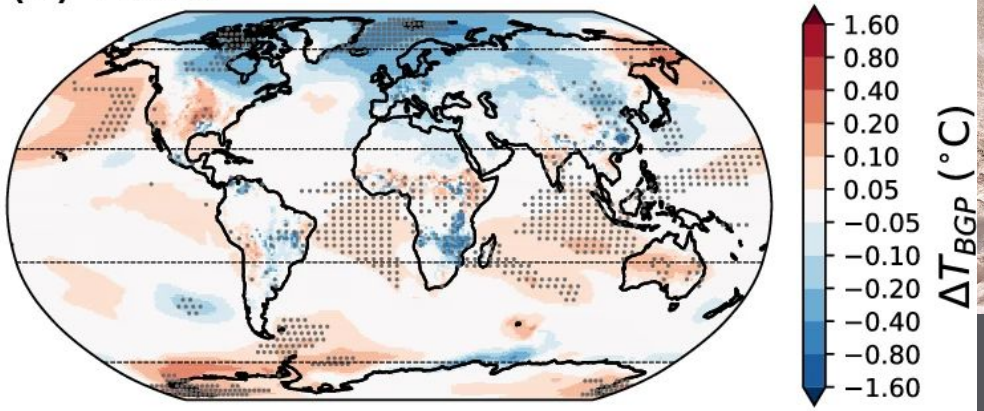
Land Use and Land Cover Change

How do changes in forest cover influence climate?

(a) Bastin



(c) Hurtt





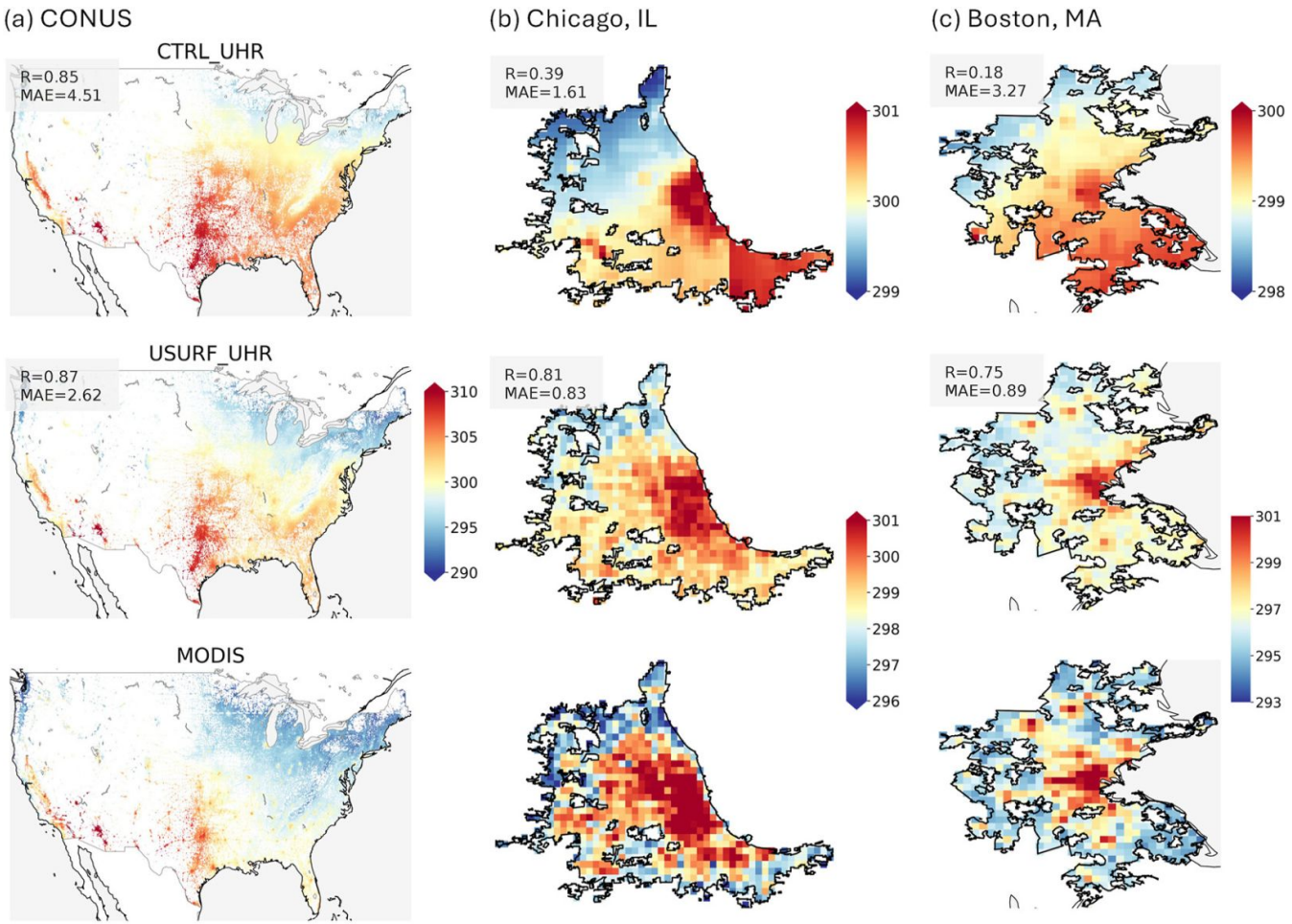
Reforestation scenarios shape global and regional temperature outcomes

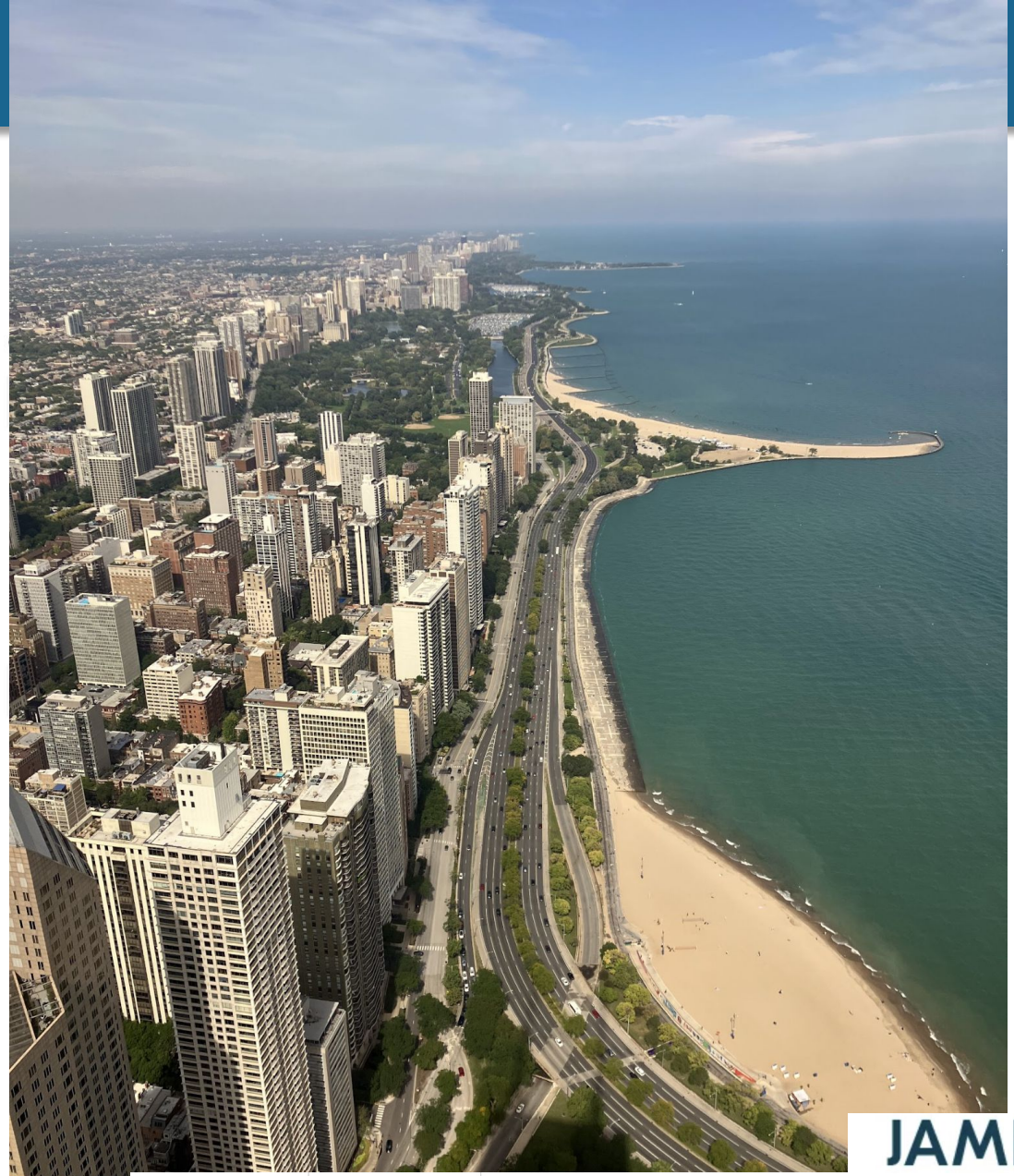
Nora L. S. Fahrenbach, Steven J. De Hertog, Felix Jäger, Peter J. Lawrence & Robert C. Jnglin Wills

Communications Earth & Environment **7**, Article number: 204 (2026) | Cite this article

Urban

How do surface properties influence the urban heat island?





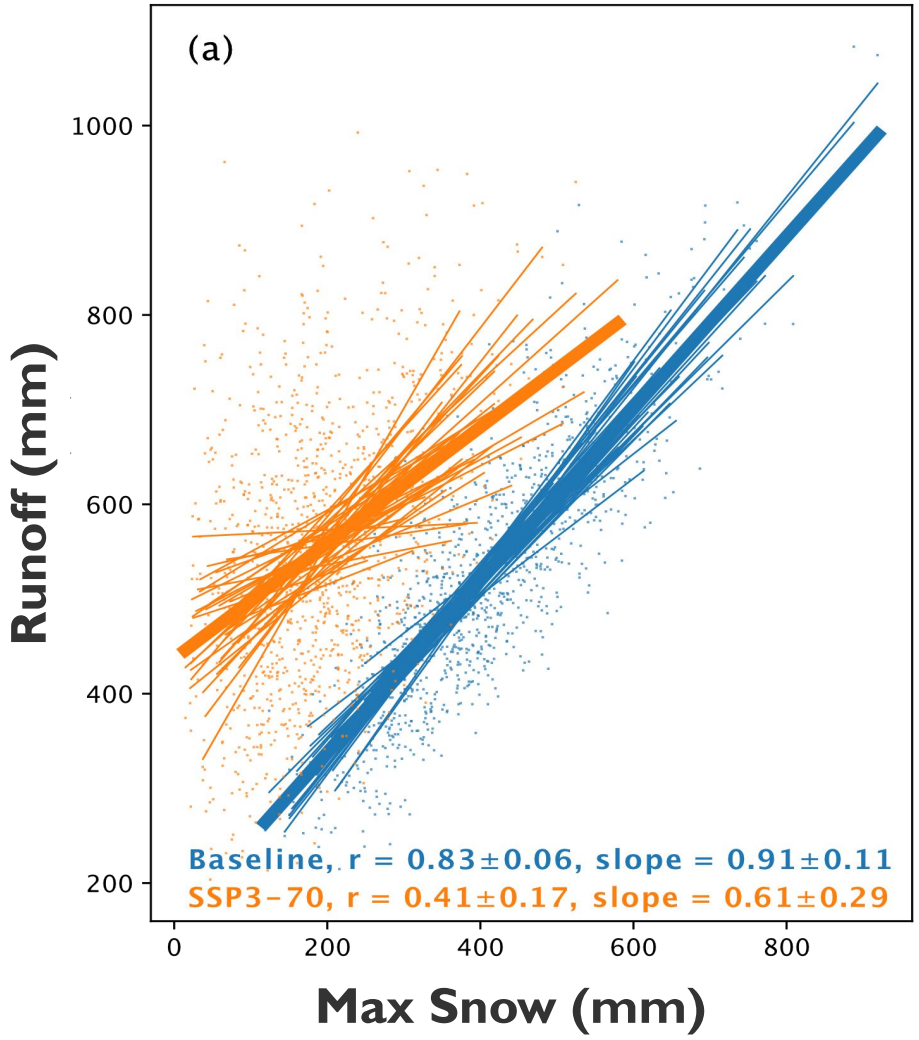
JAMES

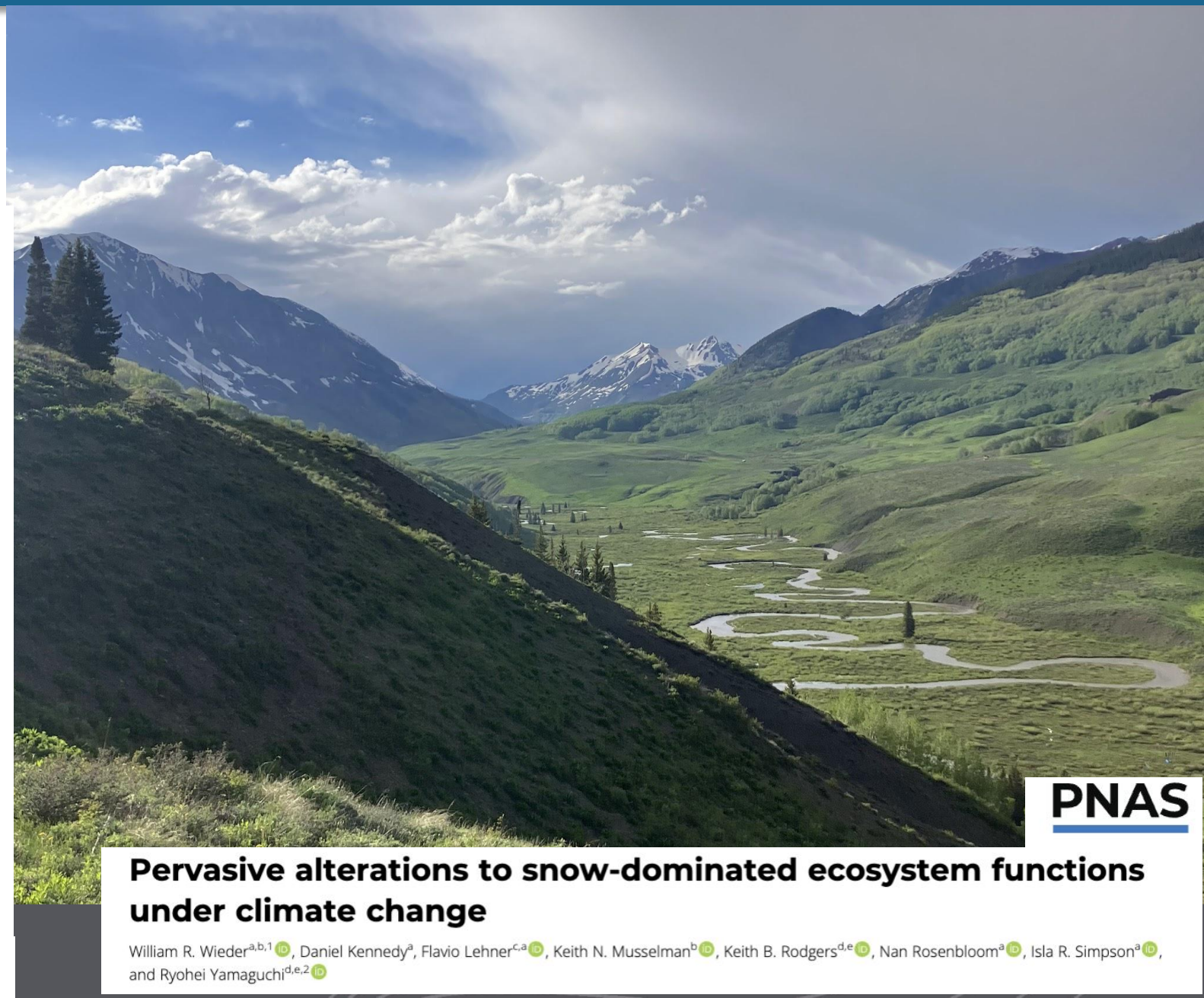
Importance of Spatially Continuous Urban Surface Properties in Urban-Resolving Earth System Modeling

Yifan Cheng, Lei Zhao, Keith Oleson, TC Chakraborty, Keer Zhang, Cenlin He, Joyce Yang

Water

How are water (and food) resources under threat from climate change?



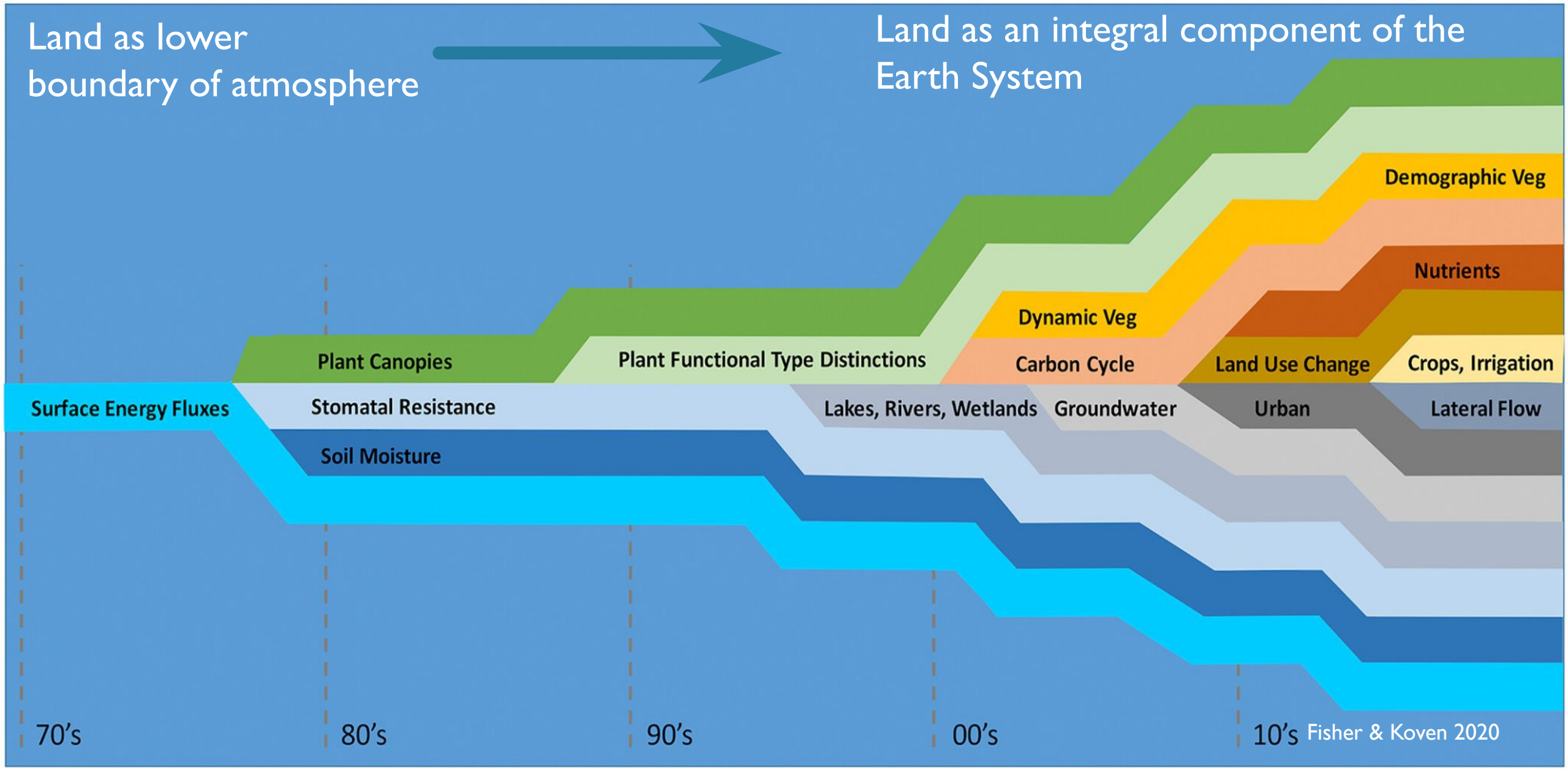


PNAS

Pervasive alterations to snow-dominated ecosystem functions under climate change

William R. Wieder[a,b,1], Daniel Kennedy[a], Flavio Lehner[c,a], Keith N. Musselman[b], Keith B. Rodgers[d,e], Nan Rosenbloom[a], Isla R. Simpson[a], and Ryohei Yamaguchi[d,e,2]

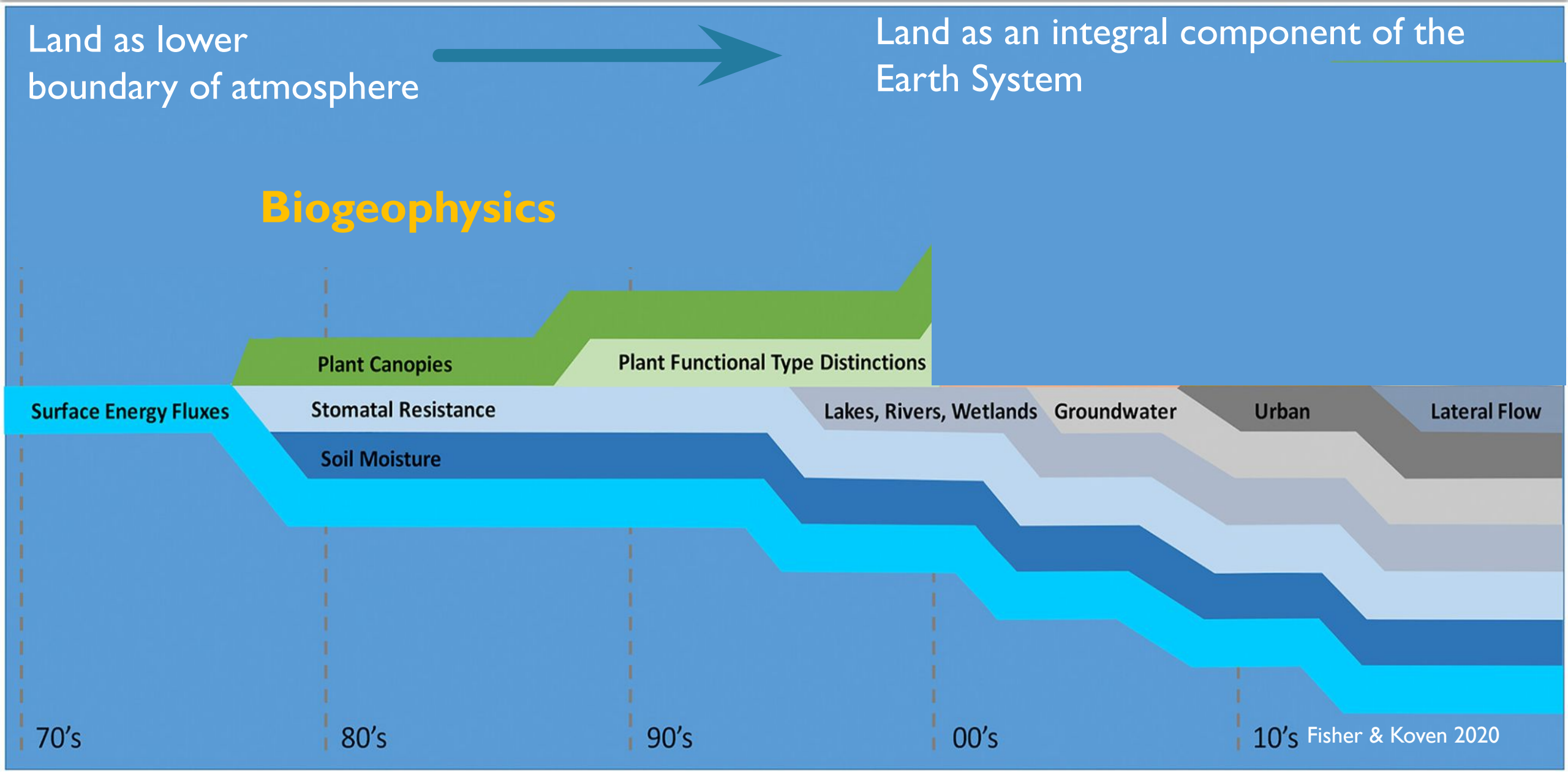
the Evolution of land modeling



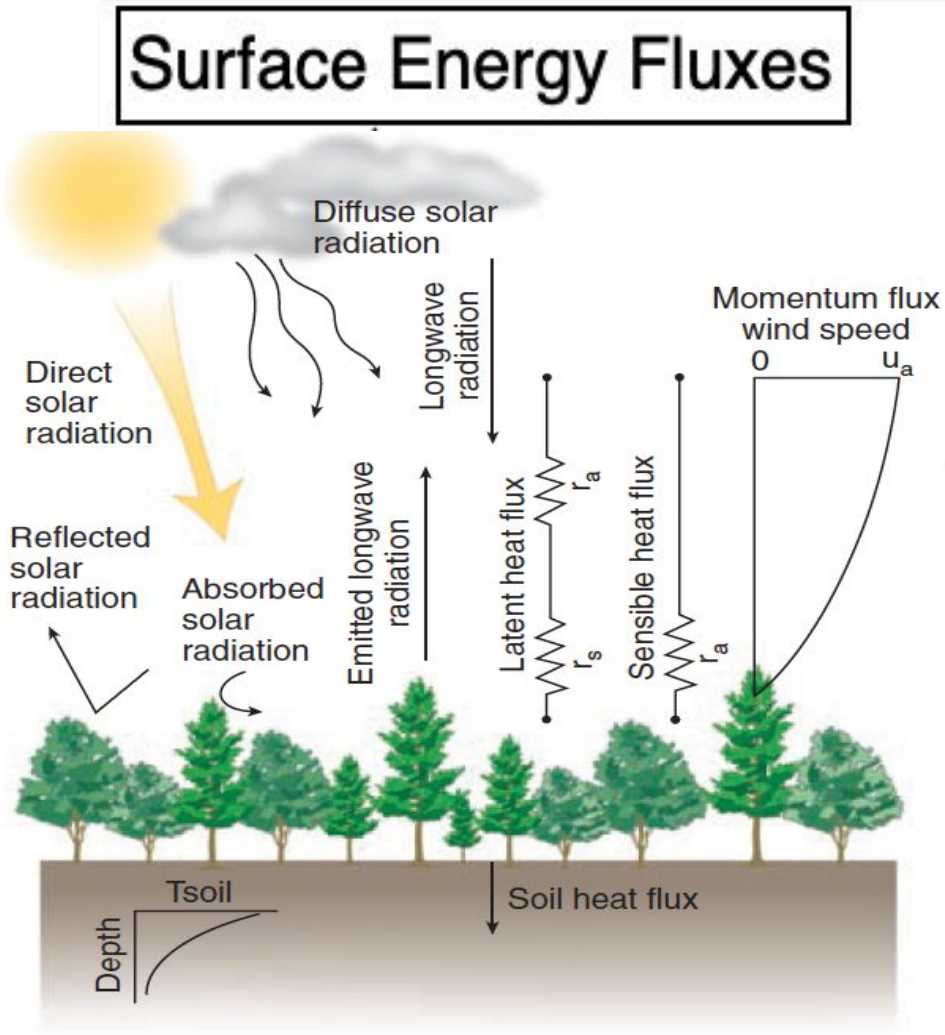
the Evolution of land modeling

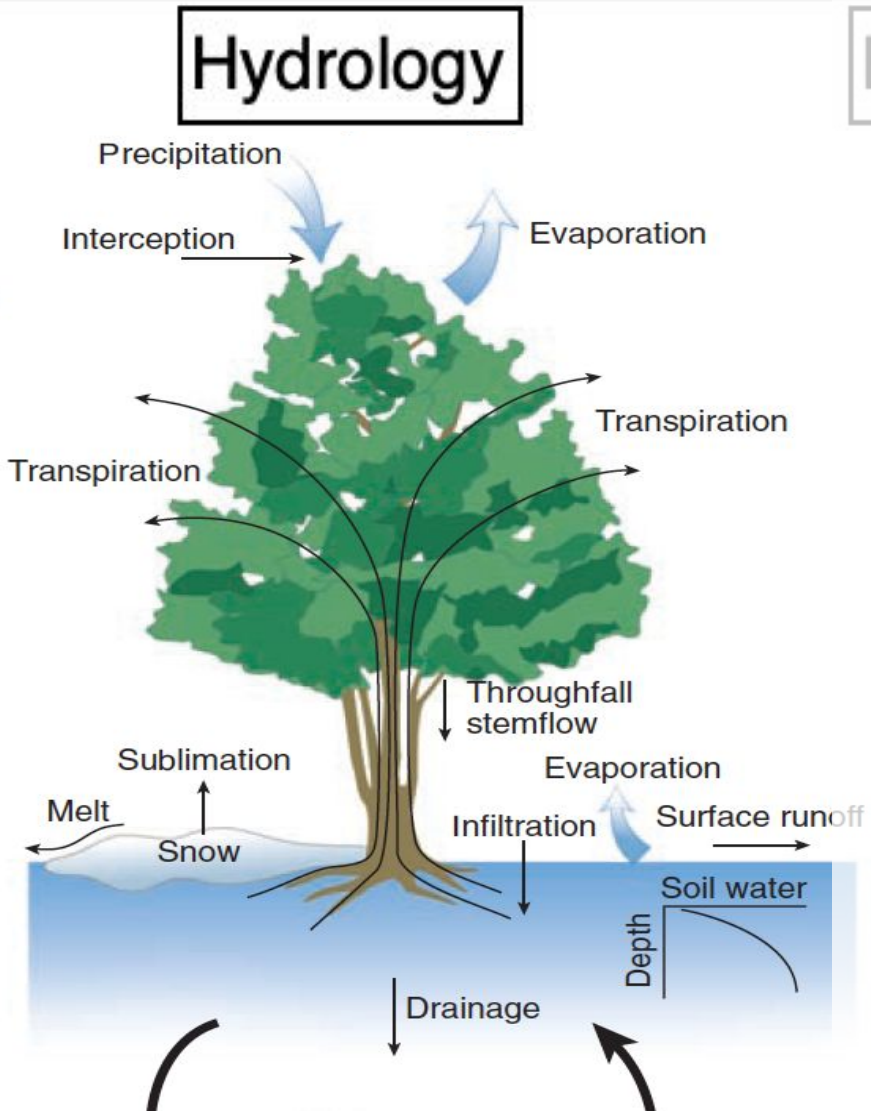
Land as lower boundary of atmosphere

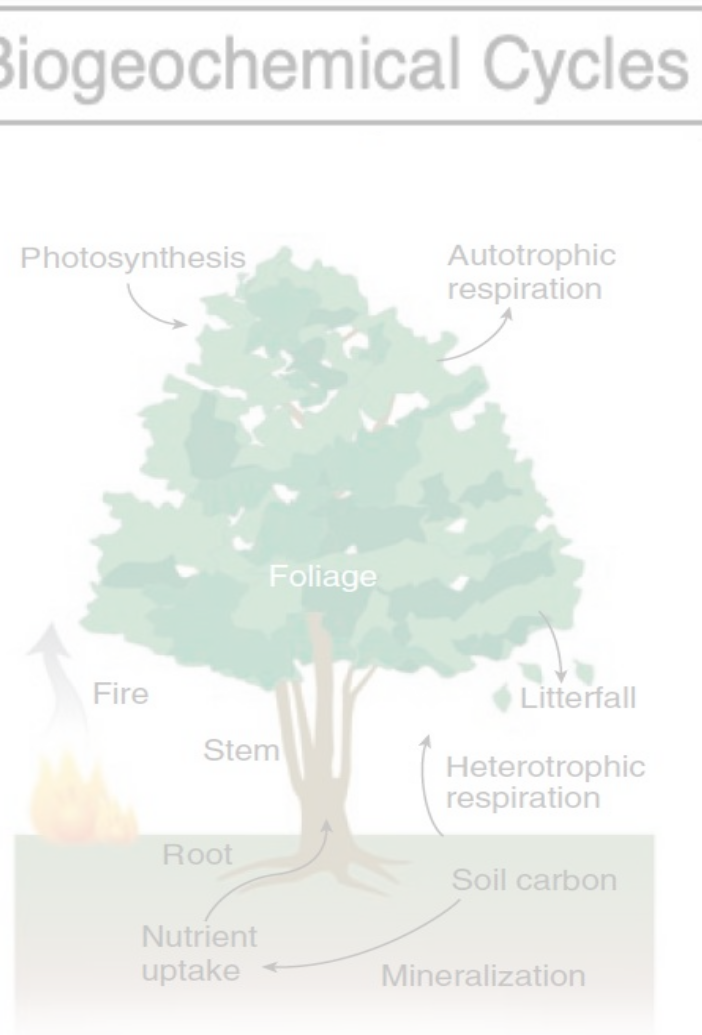
Land as an integral component of the Earth System



Biogeophysics: Satelity Phenology (SP mode)





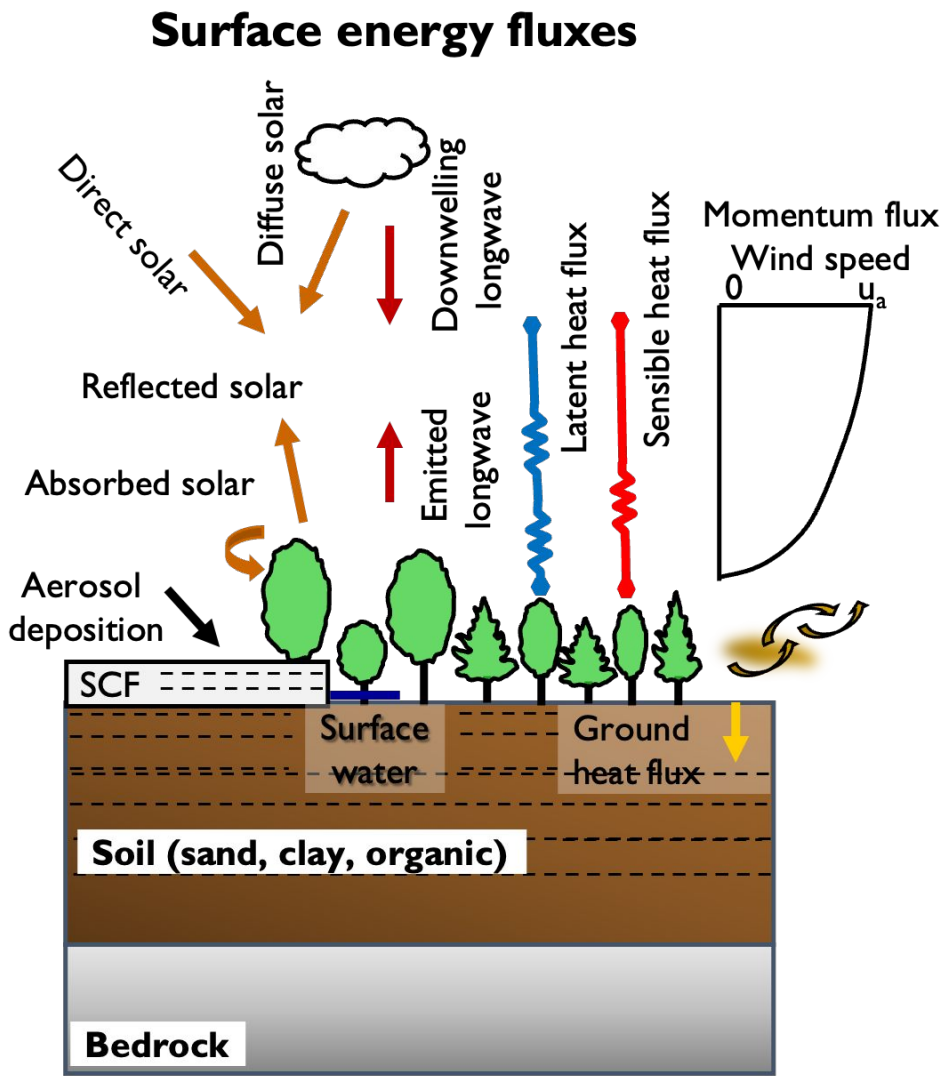


Land Modeling in ESMs: How



- **Exchanges** of momentum, energy, water vapor, CO_2, dust, and other trace gases/materials between land and atmosphere + routing of runoff to the ocean
- **States** of land surface (e.g., soil moisture, soil temperature, canopy temperature, snow, ~~carbon and nitrogen stocks in vegetation and soil~~)
- **Characteristics** of land surface (e.g., soil texture, surface roughness, albedo, emissivity, vegetation type, and leaf area index)

At each time step CLM solves the Surface Energy Balance



Lawrence et al. 2019

$$S^{\downarrow}-S^{\uparrow} + L^{\downarrow}-L^{\uparrow} = \lambda E + H + G$$

$S^{\downarrow}$, $S^{\uparrow}$: down / upwelling solar radiation,

$L^{\downarrow}$, $L^{\uparrow}$: down / upwelling longwave radiation,

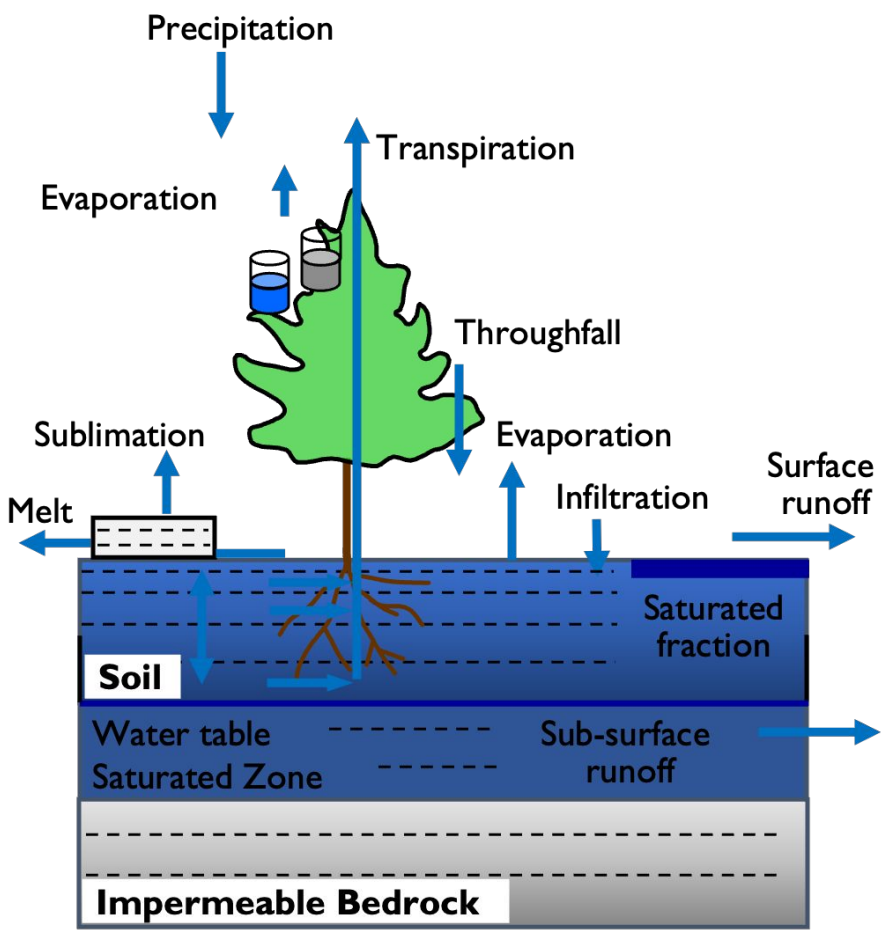
λ: latent heat of vaporization,

E: evaporation,

H: sensible heat flux

G: ground heat flux

… and the Surface Water Balance



$$P = ES + ET + EC + R + (\Delta W_{soil} + \Delta W_{snow} + \Delta W_{sfcw} + \Delta W_{can}) / \Delta t$$

P: rainfall/snowfall,

ES: soil evaporation,

ET: transpiration,

EC: canopy evaporation,

R: Runoff (surf + sub-surface),

ΔW_{soil}, ΔW_{snow}, ΔW_{sfcw}, & ΔW_{can}: changes in soil moisture, snow, surface water, and canopy water over a timestep

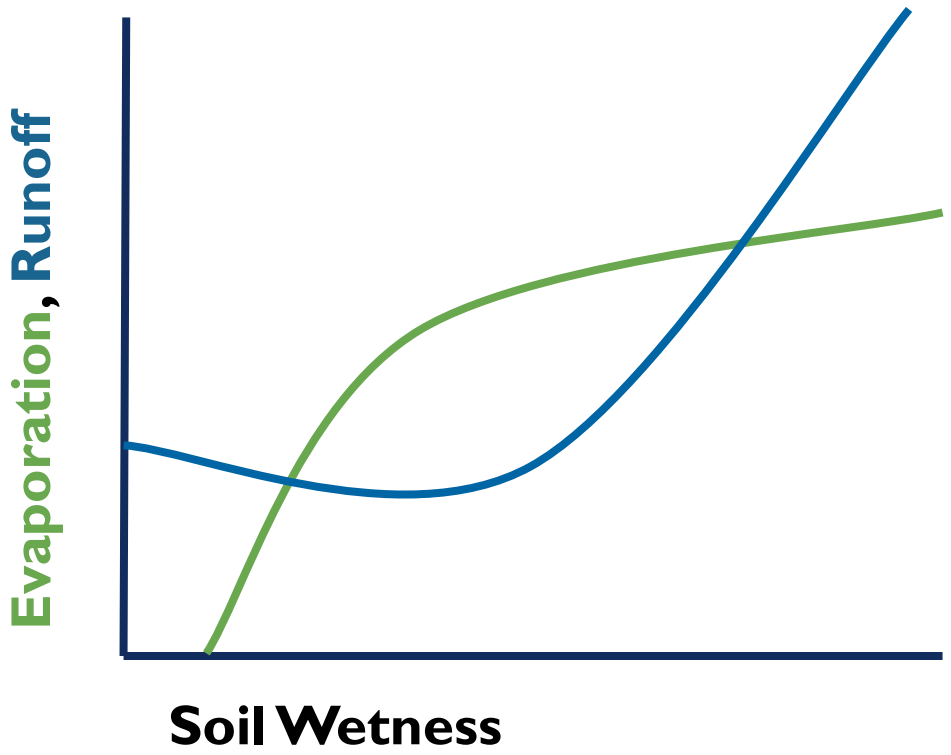
Lawrence et al. 2019

Terrestrial energy and water cycles are intricately linked

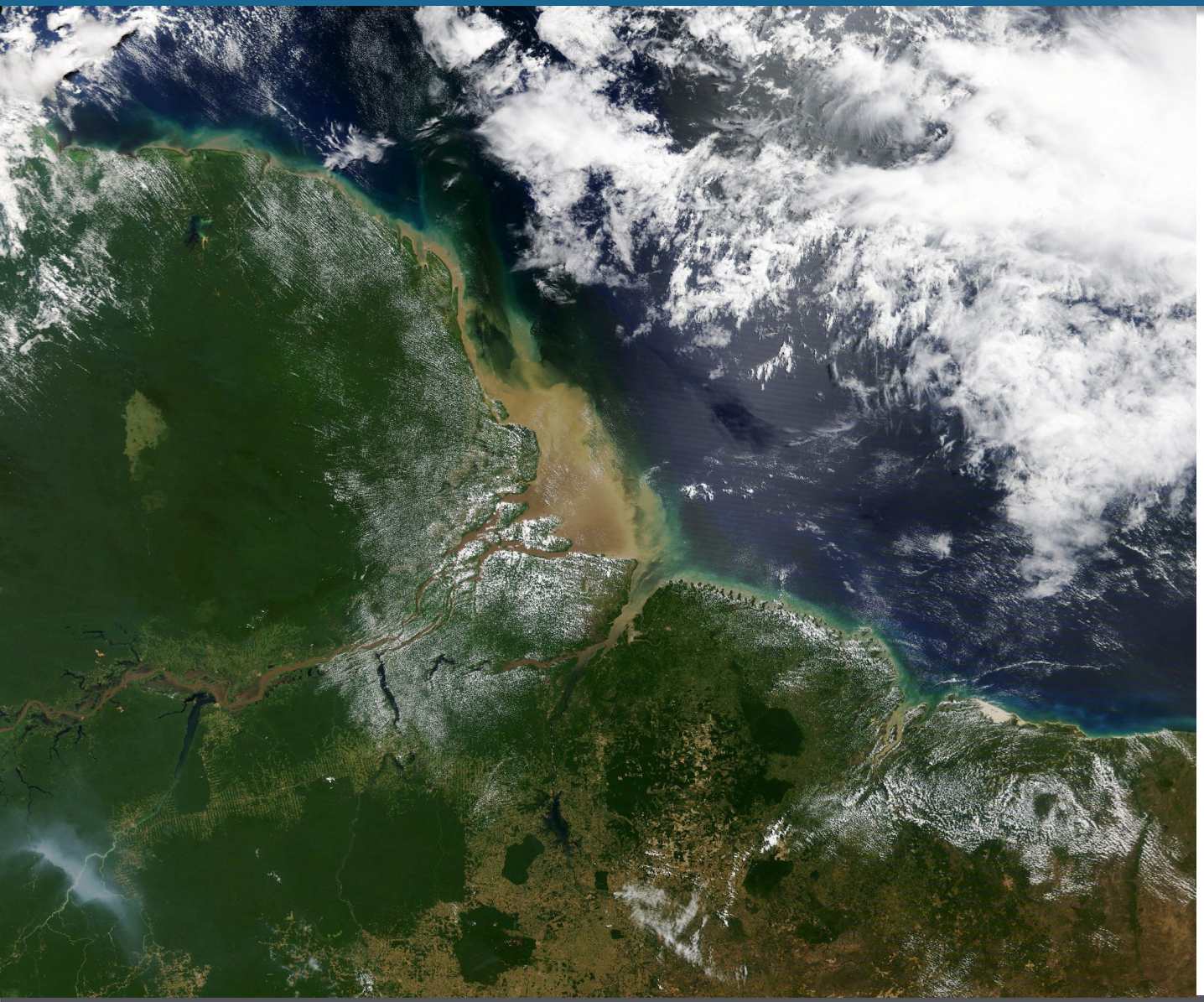
"The ability of a land-surface scheme to model evaporation correctly depends crucially on its ability to model runoff correctly. The two fluxes are intricately related through soil moisture."

(Koster and Milly, 1997).

What is this statement missing?



Land Model Complexity: Plants



Blue marble…

…Green Earth

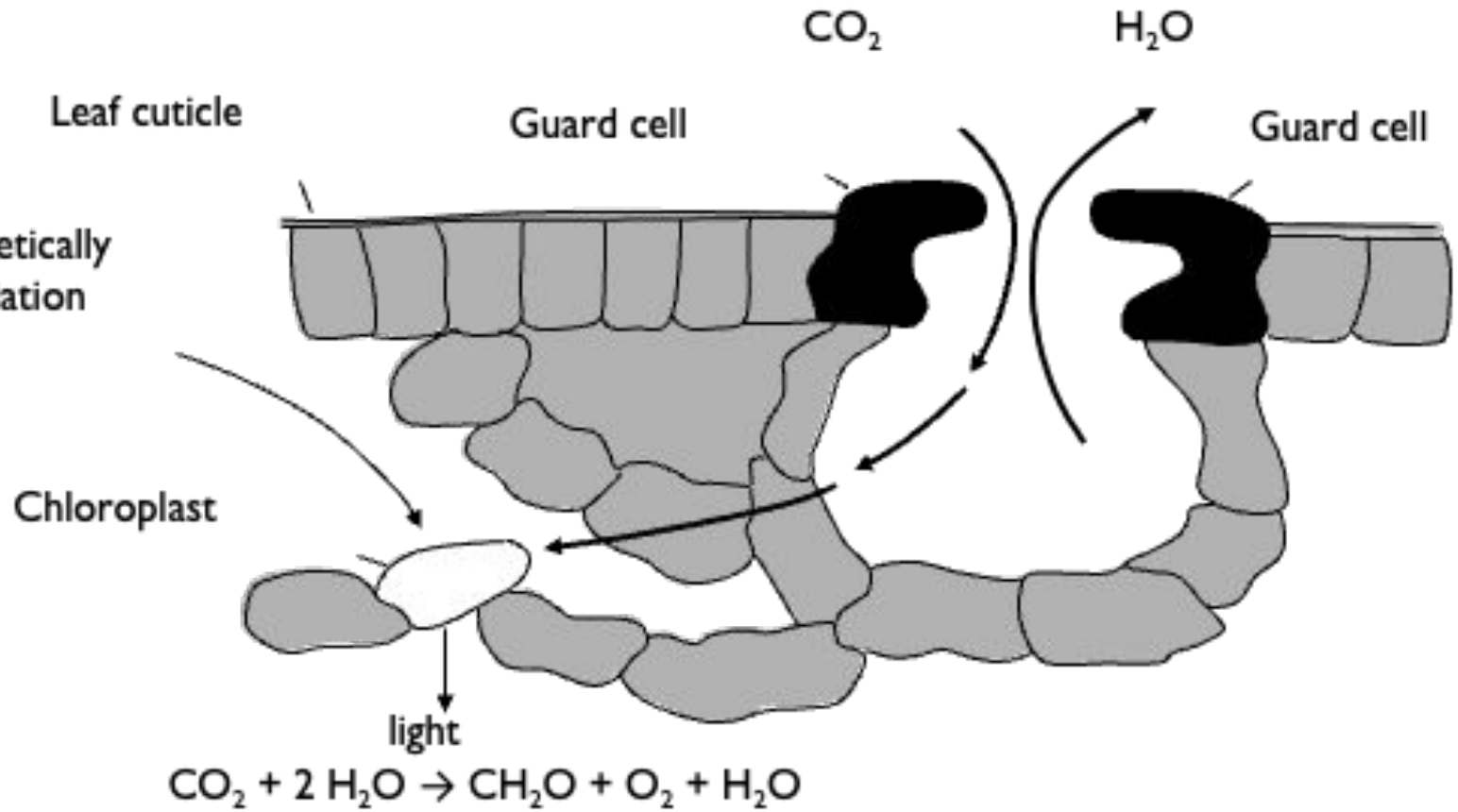
Photosynthesis model

Plant physiological controls on transpiration and CO_2 exchange

Function of solar radiation, humidity deficit, soil moisture, [CO_2], temperature, leaf N content



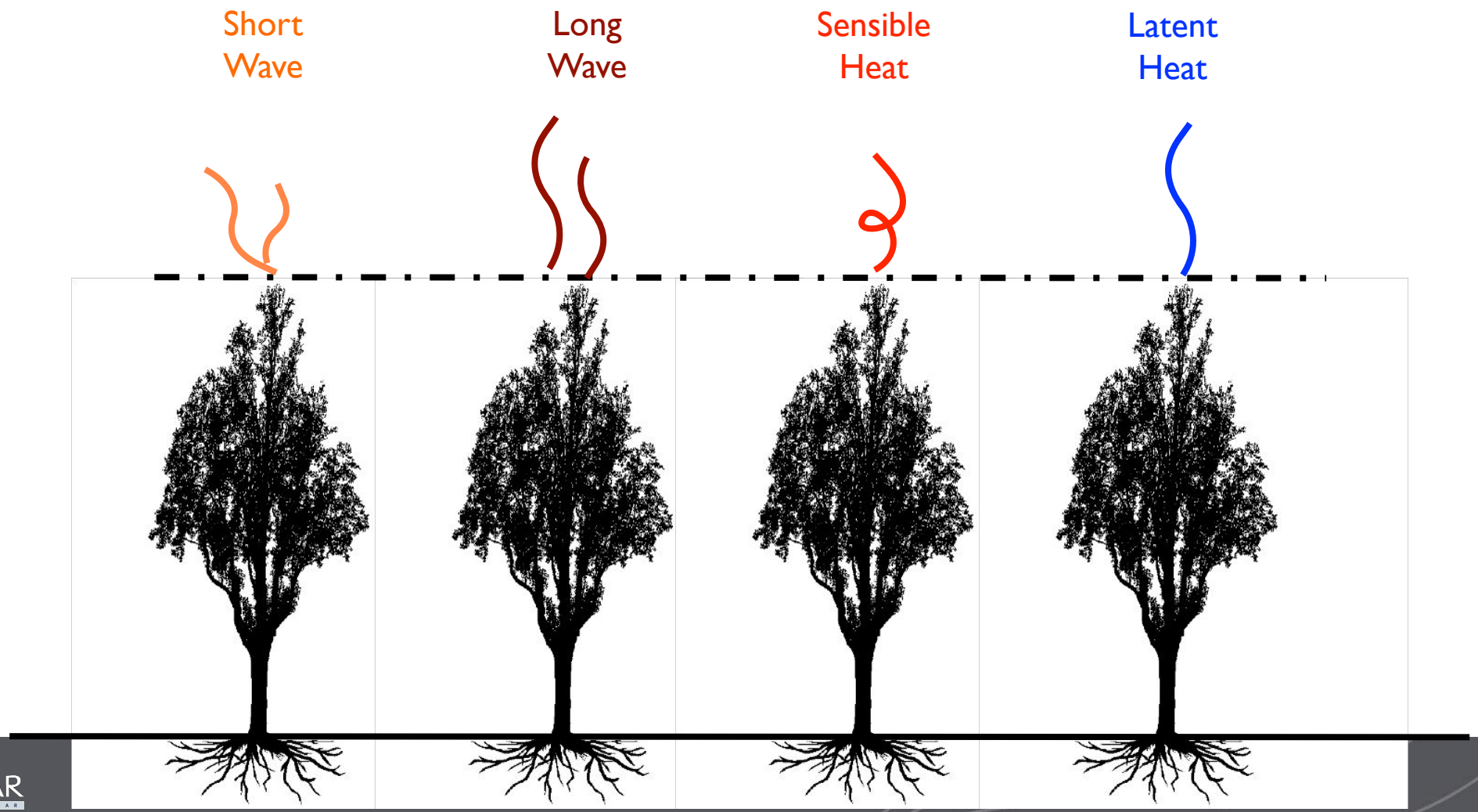




$$CO_2 + 2\,H_2O \rightarrow CH_2O + O_2 + H_2O$$

How do plants and climate interact?

Terrestrial surface energy budget



How do plants and climate interact?

Albedo

CO_2, H_2O, T

Roughness

Evaporation, Transpiration

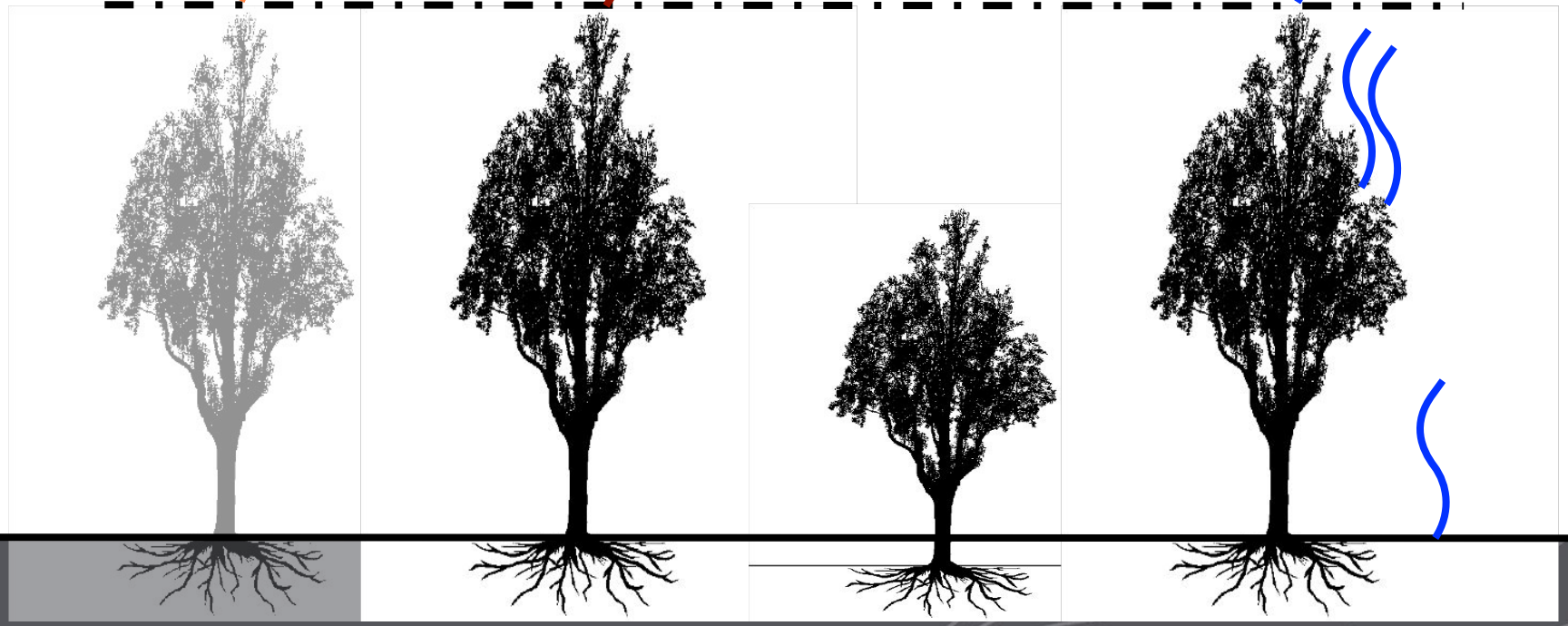
Short Wave

Long Wave

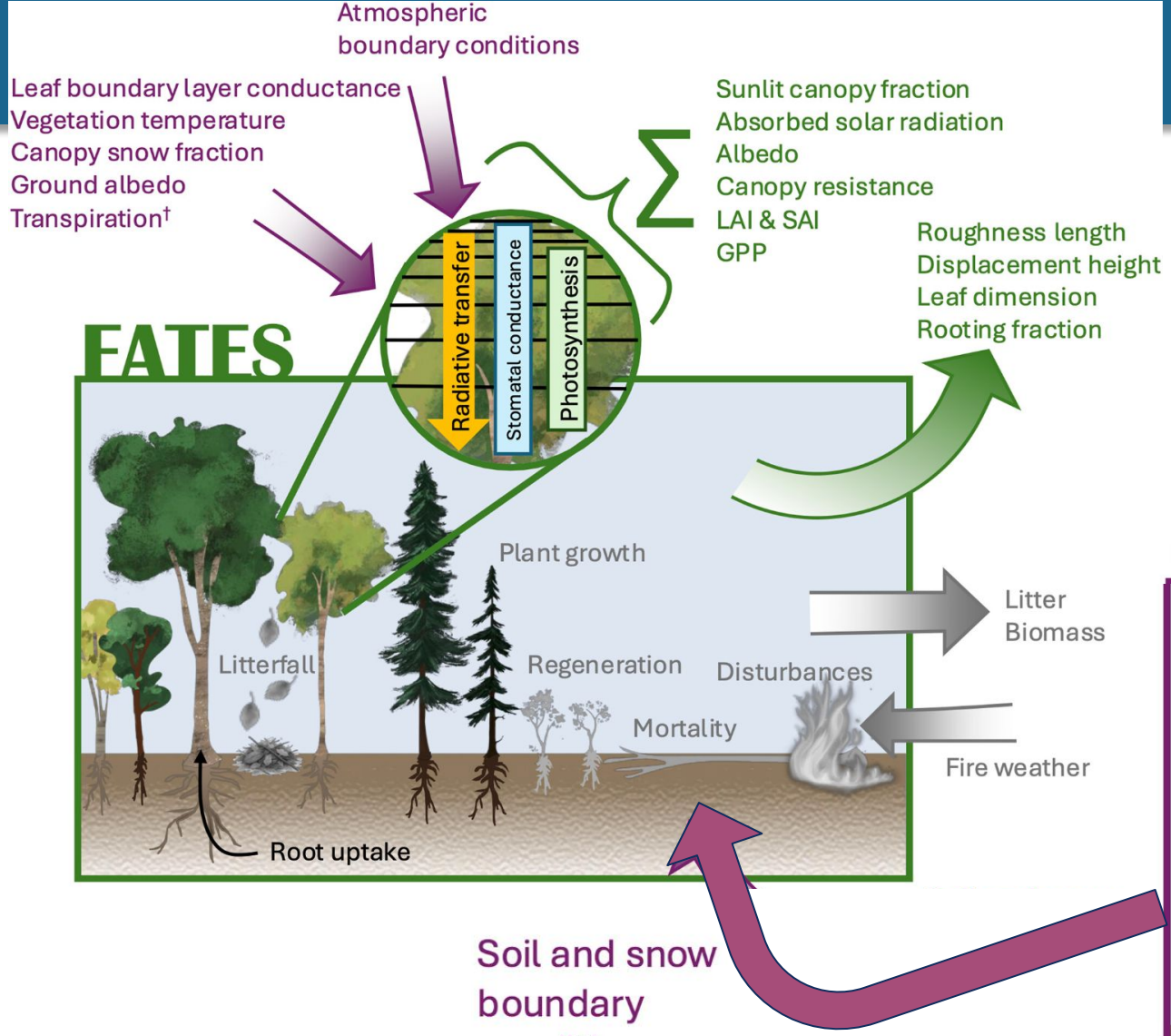
Sensible Heat

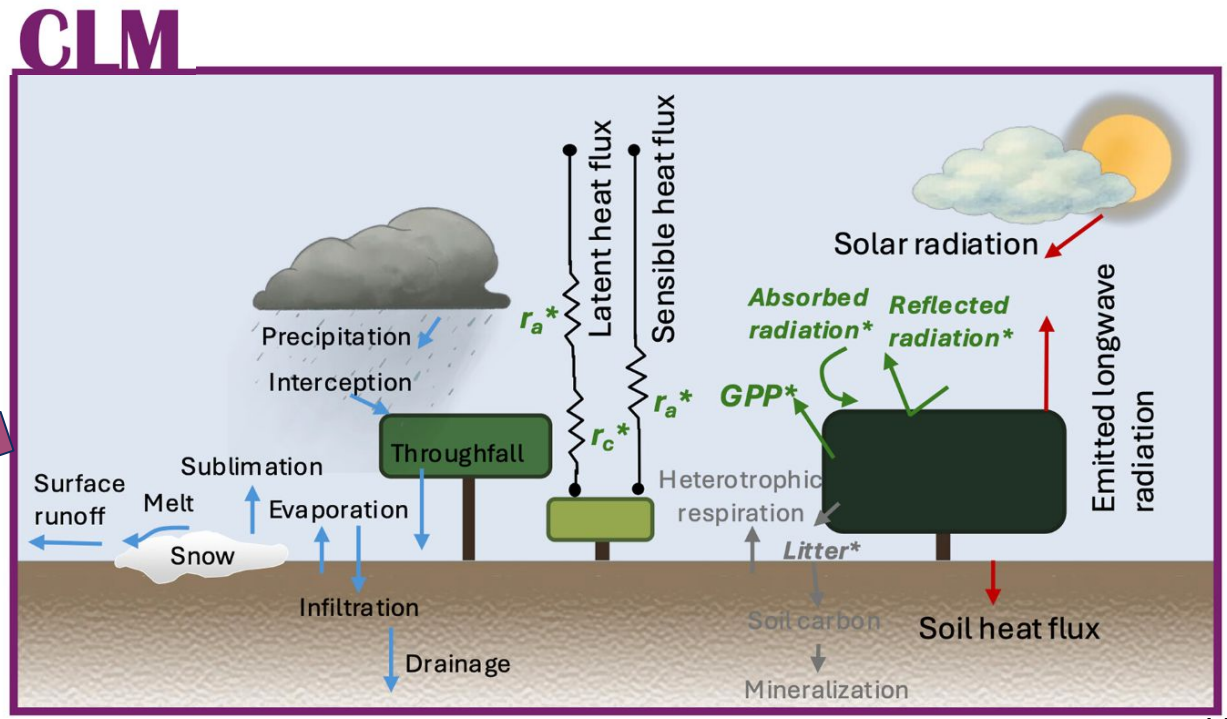
Latent Heat

ΔPlants => ΔSurface Energy Budget



CLM-FATES-SP





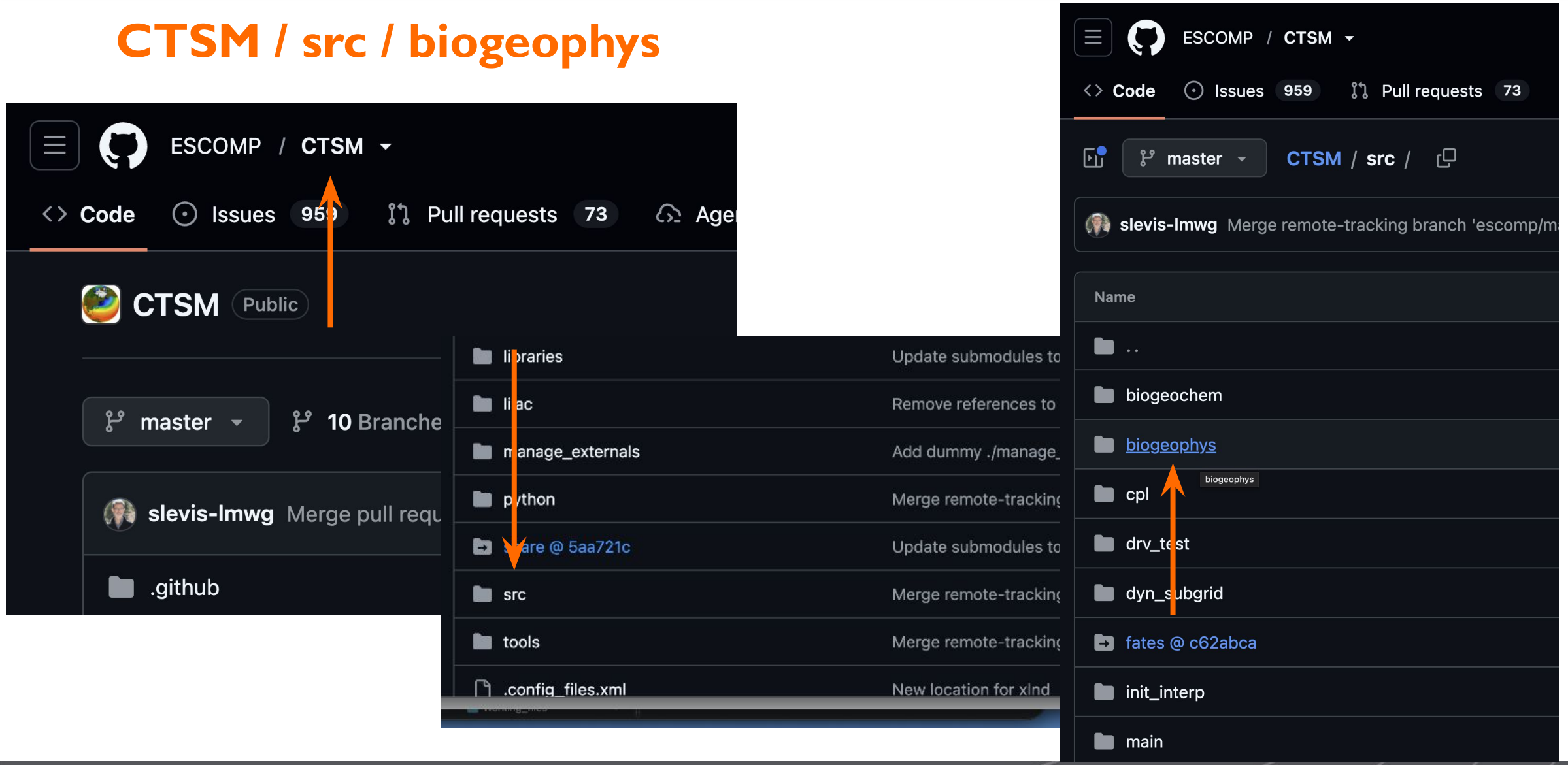
JAMES

Contrasting Parametric Sensitivities in Two Global Vegetation Models Using Parameter Perturbation Ensembles

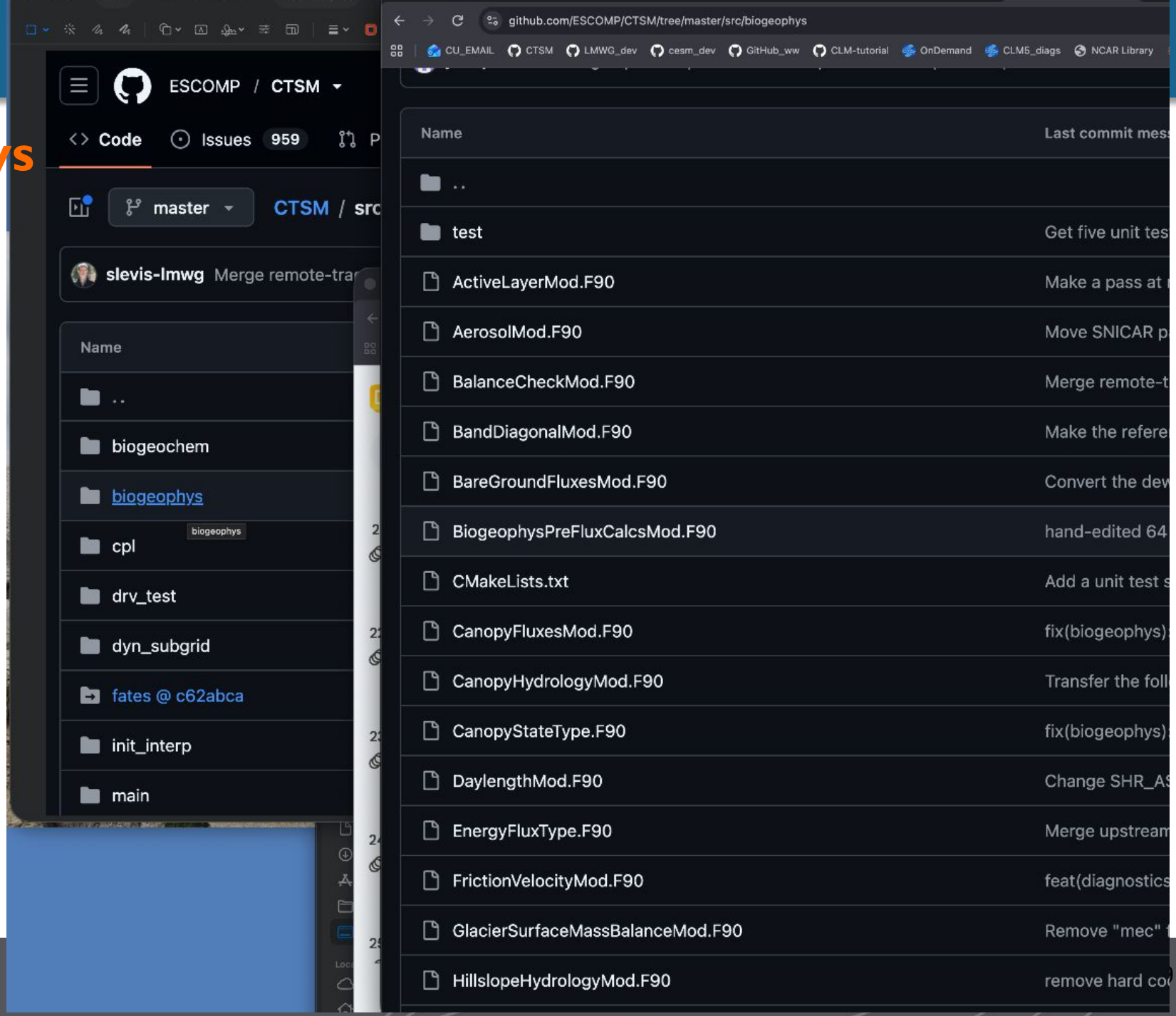
A. C. Foster, L. R. Hawkins, D. Kennedy, G. B. Bonan, R. A. Fisher, J. F. Needham, R. G. Knox, C. D. Koven, W. R. Wieder, K. Dagon, D. M. Lawrence

Biogeophysics

CTSM / src / biogeophys

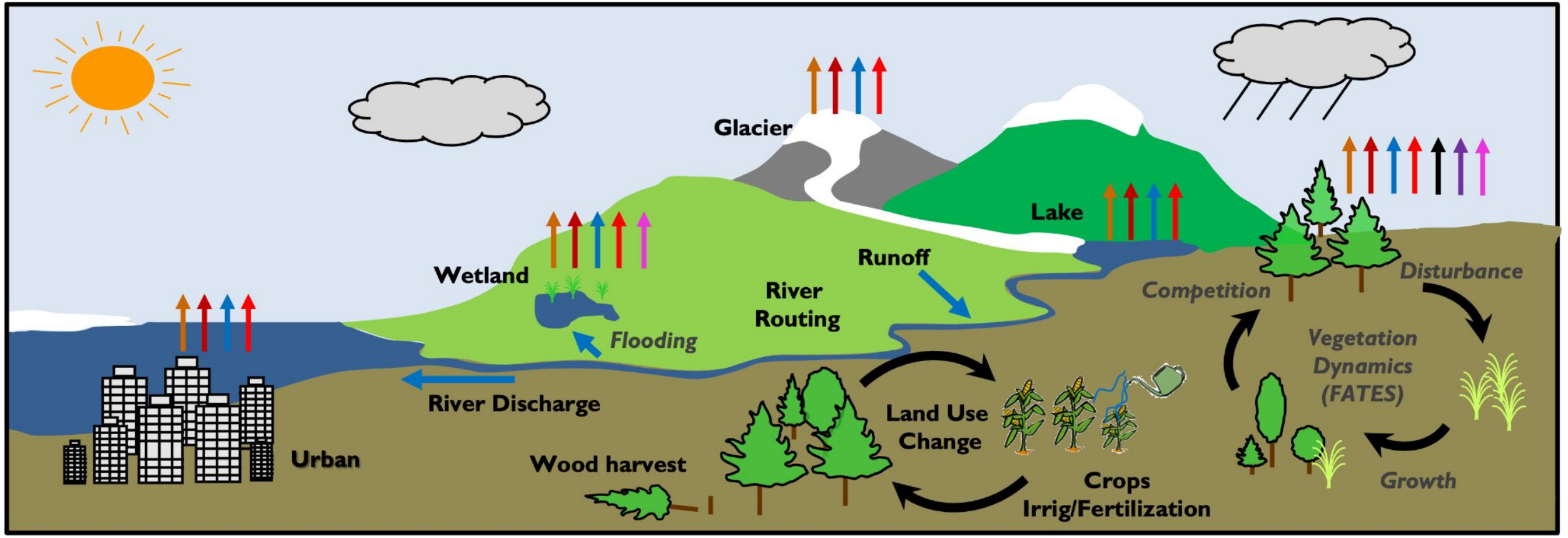


CTSM / src / biogeophys



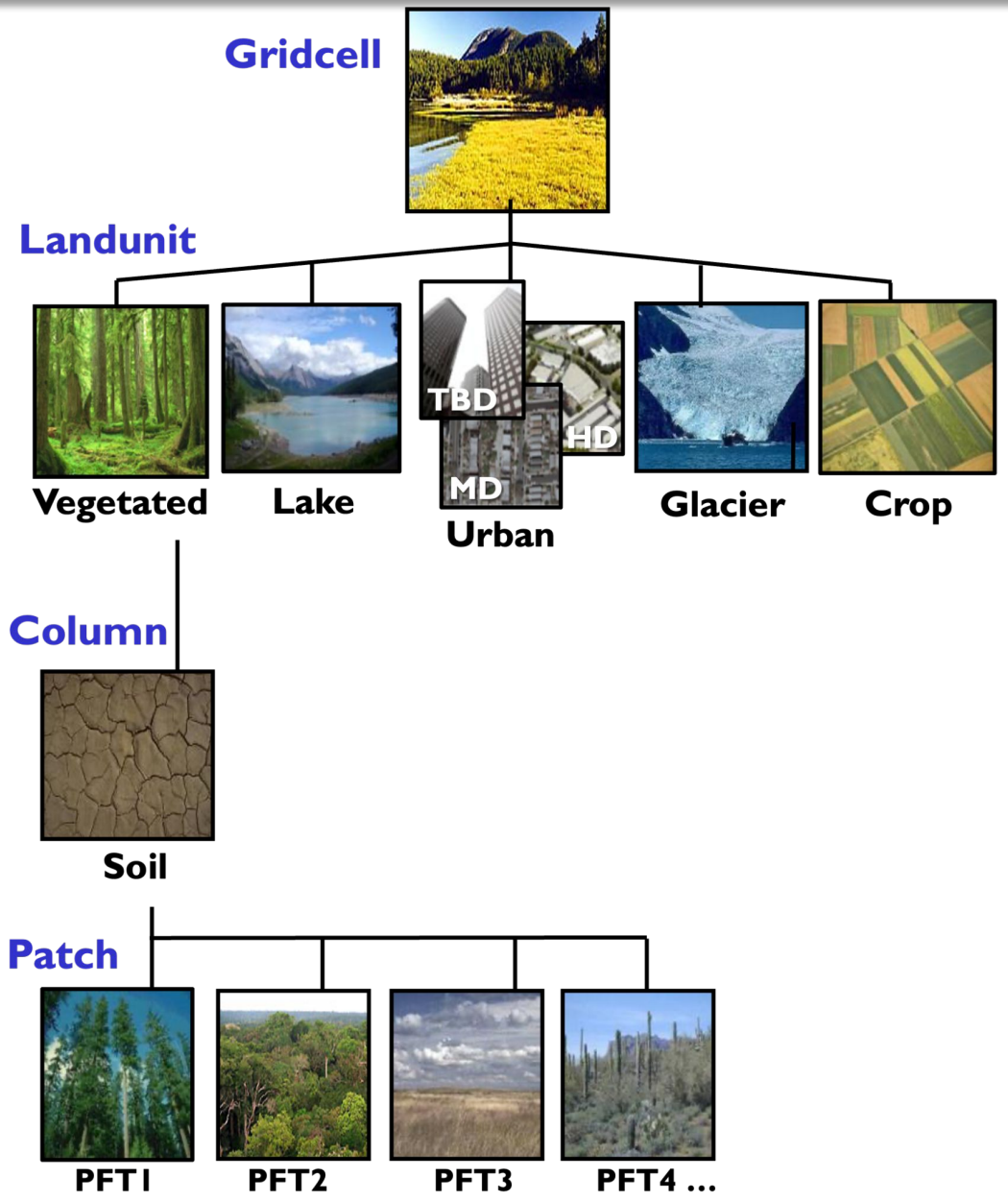


Land Surface Heterogeneity



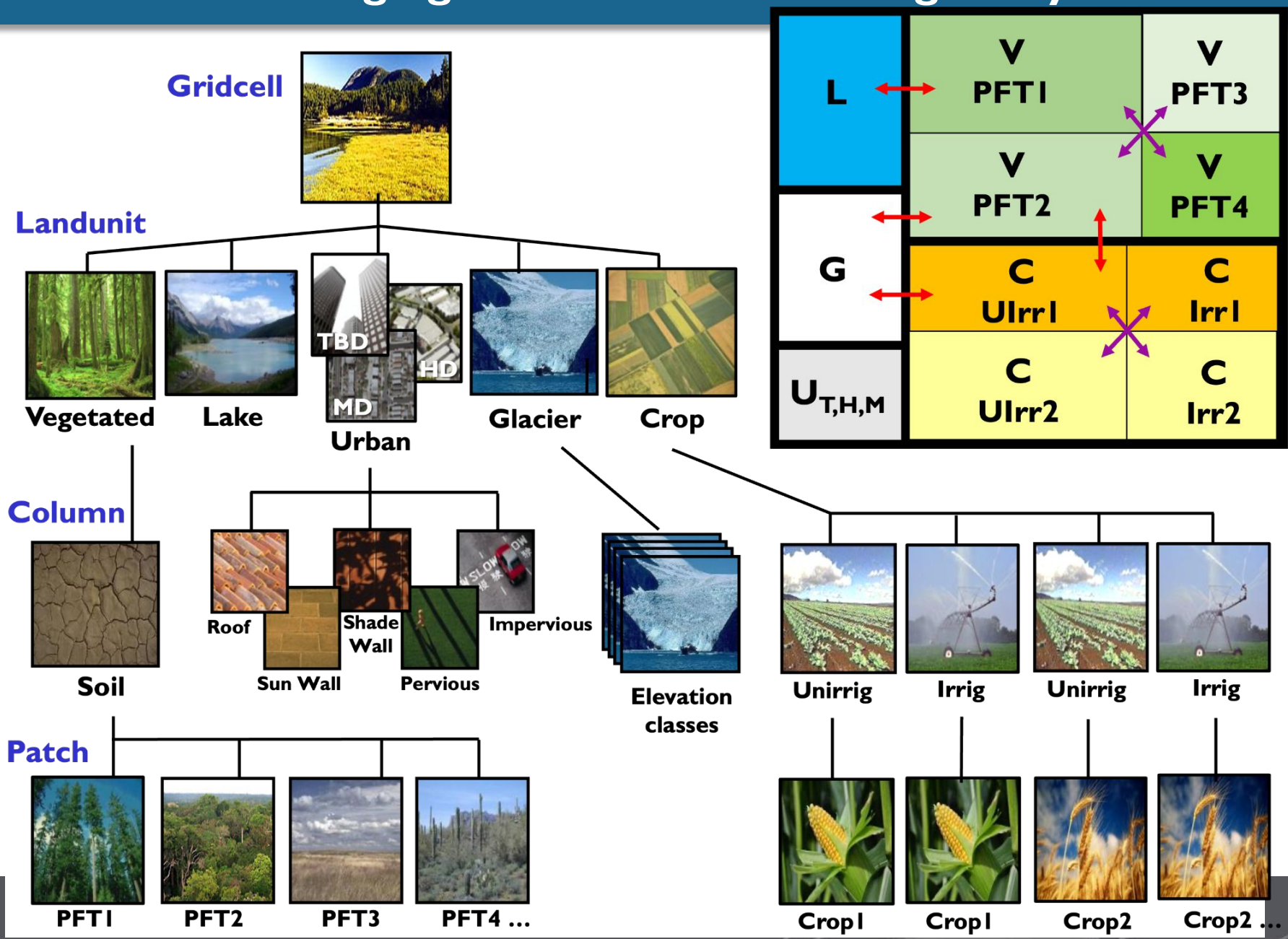
Lawrence et al. 2019

Changing Land Surface Heterogeneity



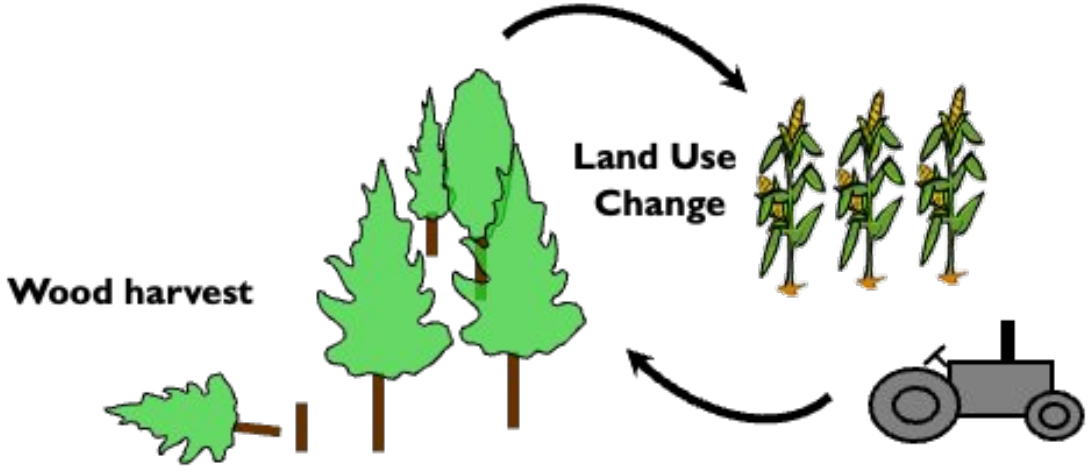
Lawrence et al. 2019

Changing Land Surface Heterogeneity

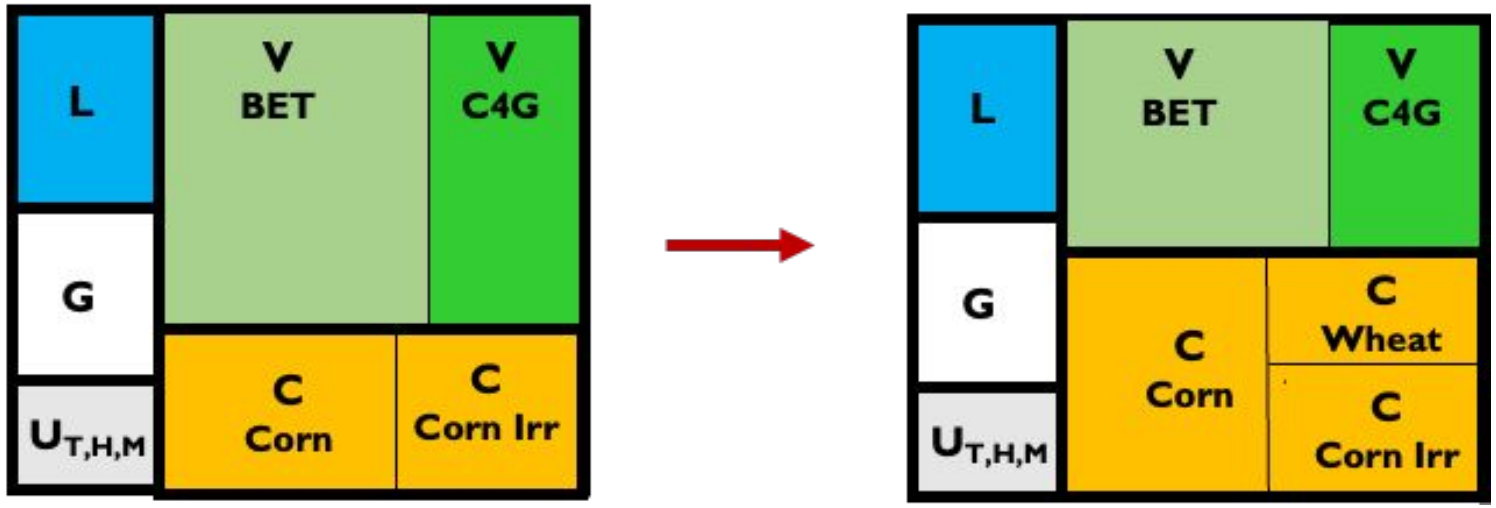


Lawrence et al. 2019

Land Use / Land Cover Change



Deforestation example



Landscape-scale dynamics

Long-term dynamical processes that affect fluxes in a changing environment (disturbance, land use, succession)

Create datasets

Conserve mass

Abbreviated list of land biophysical features in CESM3+

Emission Driven Focus

Updated surface datasets, dust scheme, roughness length, snow optical properties, excess ice, crop calendars, more…

Calibration Capabilities & Parameter Uncertainty

Transient Urban Extent

Transient Hillslope Capabilities

Transient FATES with LULCC

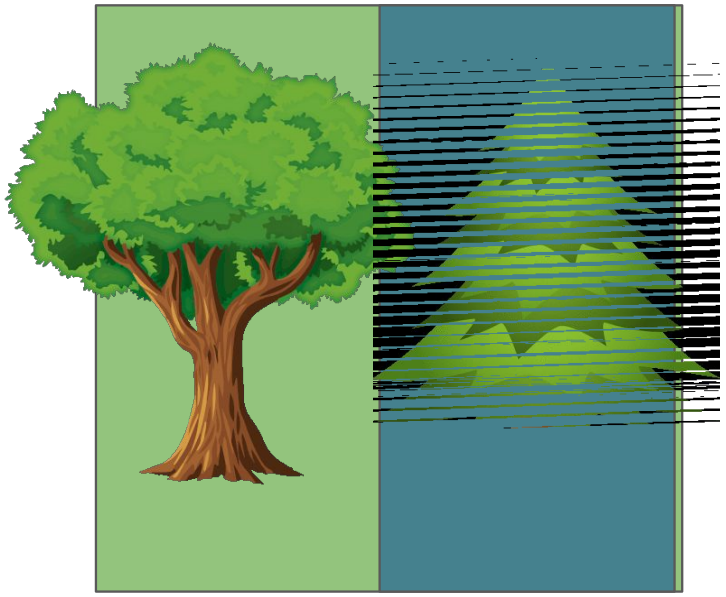
Interactive Fires



Questions & Discussion



Hillslope Hydrology: subgrid heterogeneity in soil moisture

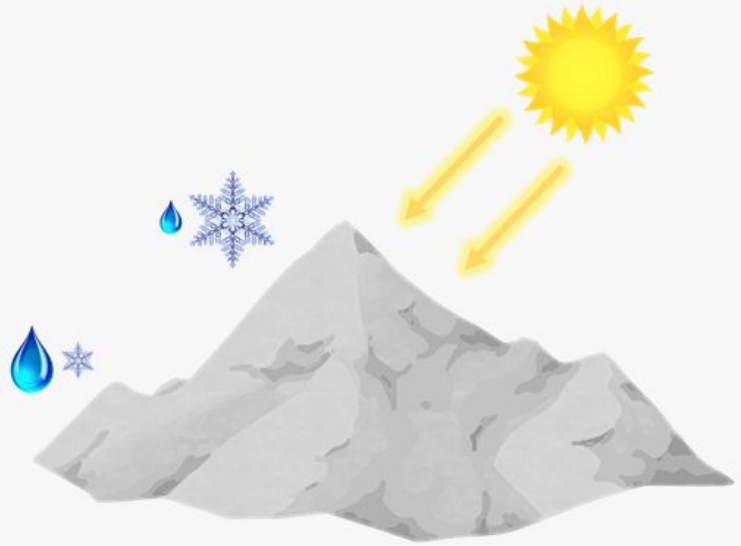


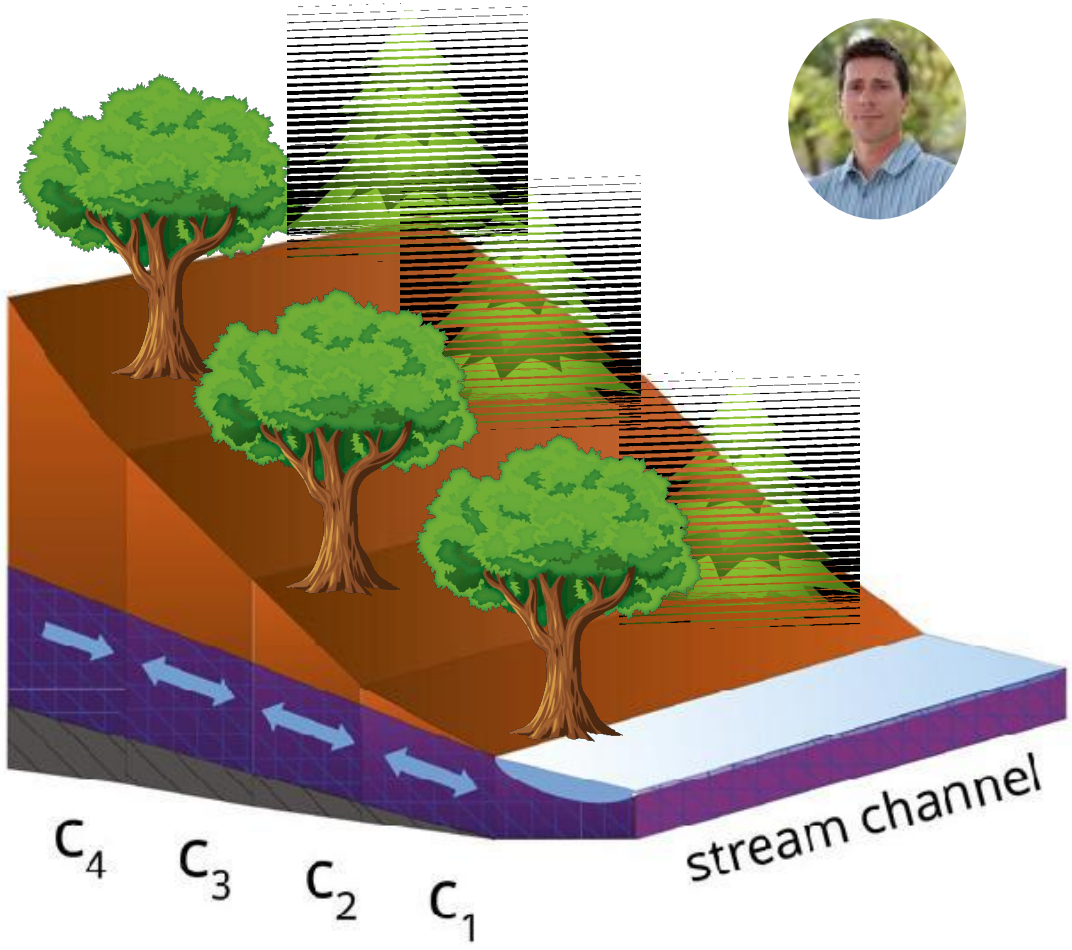
Aspect:

N-S-E-W facing

Relief:

Low vs high





Lateral Subsurface Flow

From Swenson & Lawrence 2025

Subgrid Hillslope Processes

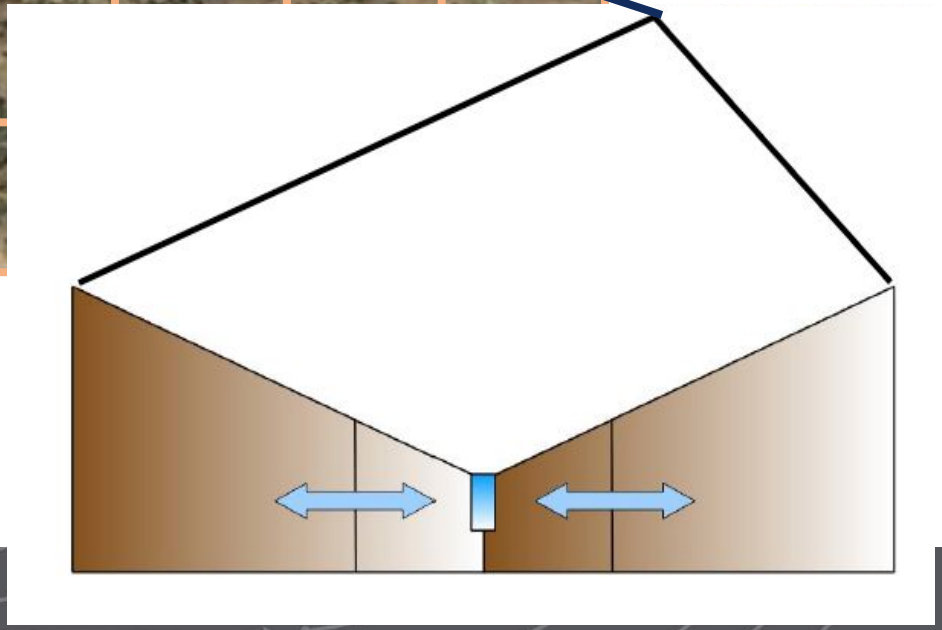
CESM grid cell (~1°x1°)



Observed vegetation patterns imply lateral movement of water and strong influence of **slope and aspect**







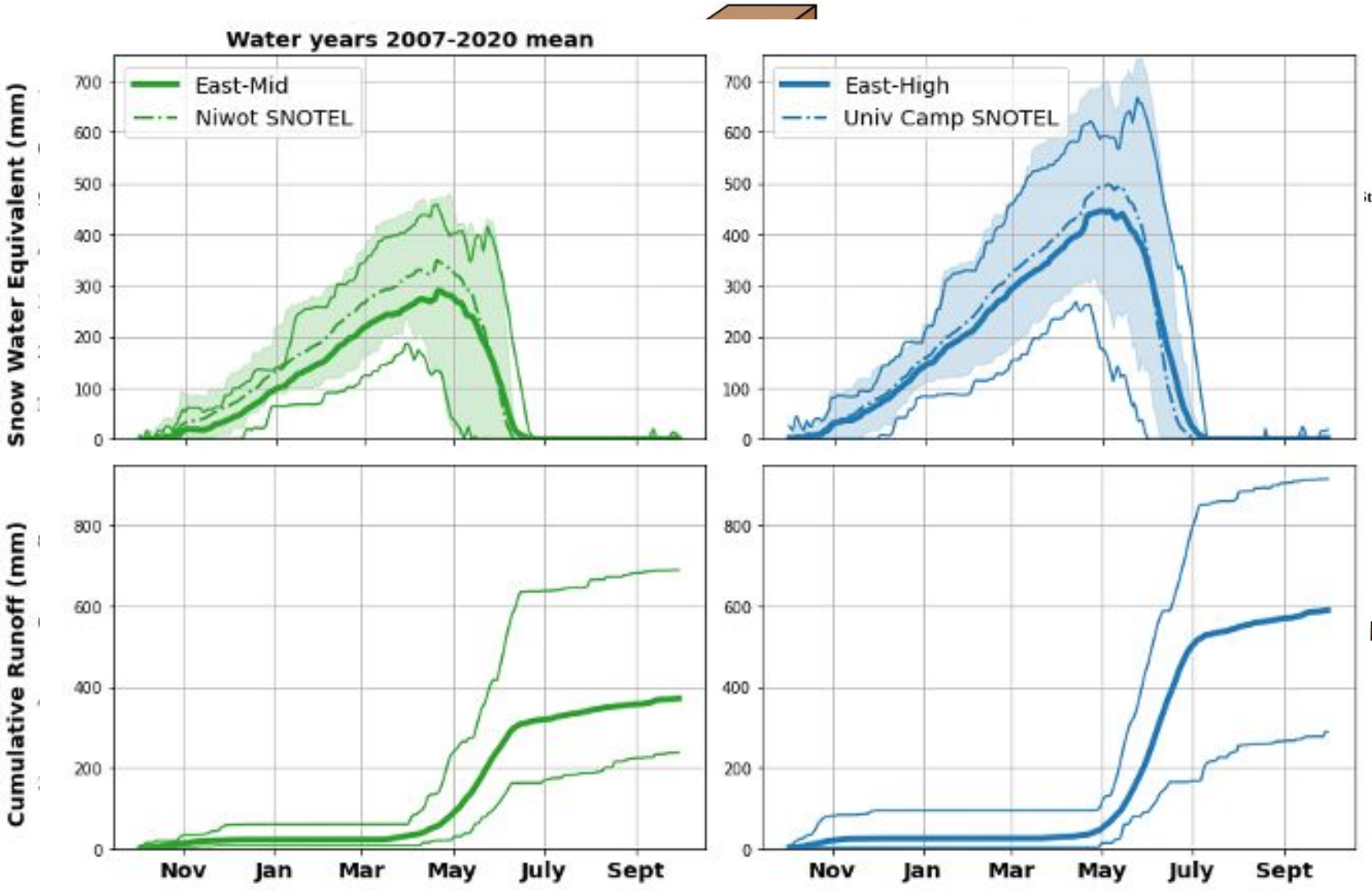


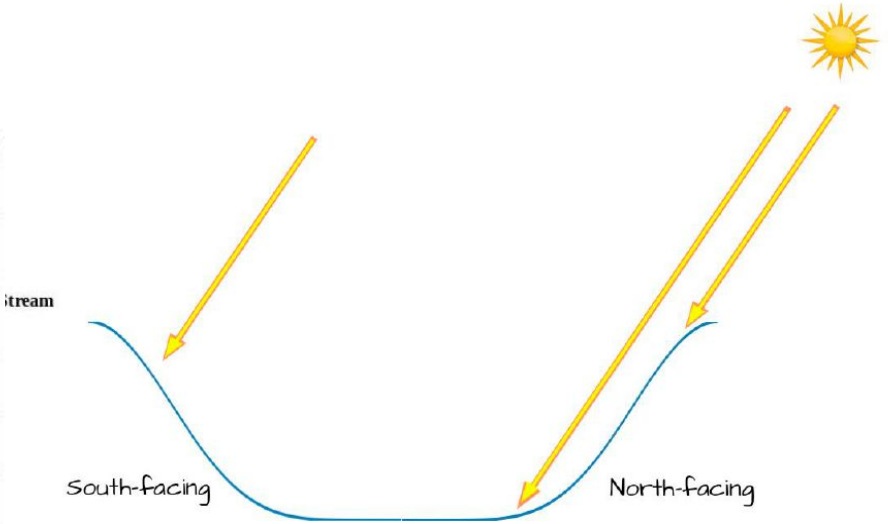
Fan et al. WRR, 2019
Swenson et al. JAMES 2019
Swenson & Lawrence 2025

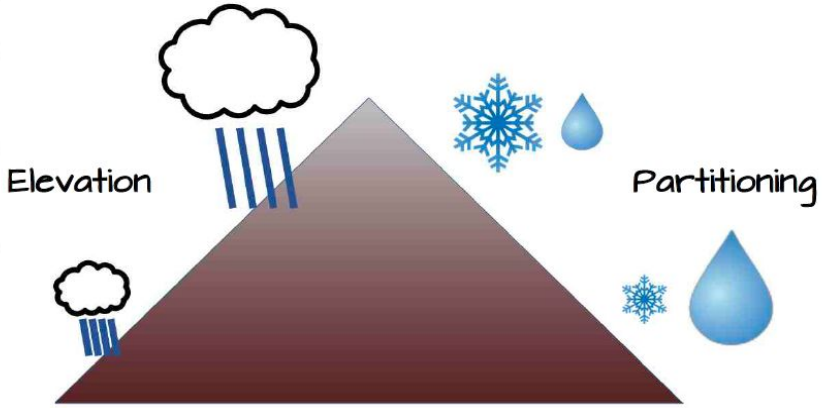
Hillslope Hydrology

Explicit Lateral Flow Within Gridcell

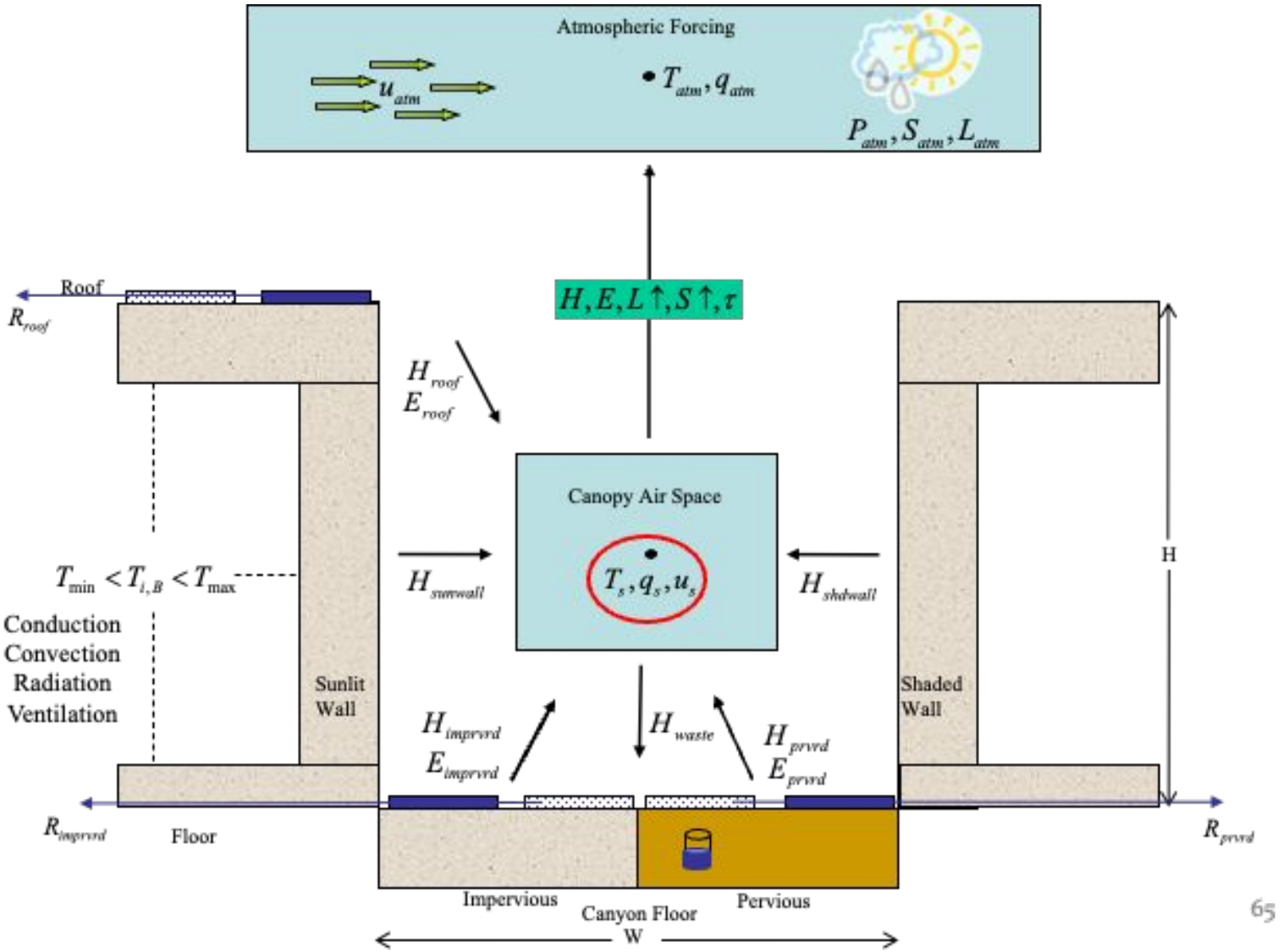
Downscaled Meteorology







CLM-Urban Model (CLM-U)





Land Modeling in ESM: Priorities

Ecosystems:
FATES



Food:
Crop Model*



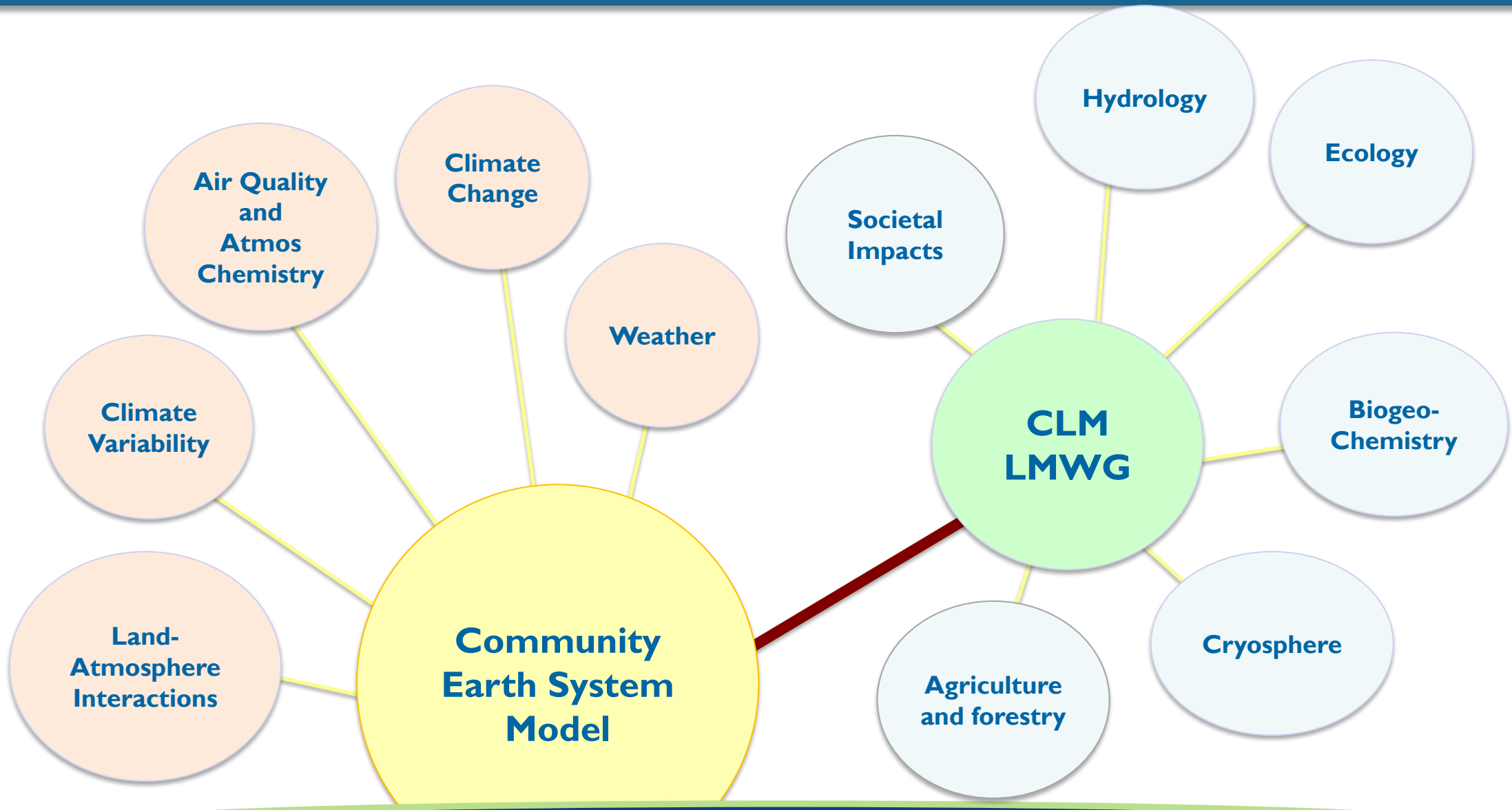
Water:
Hillslope
Hydrology



Urban: CLM-U*



CESM and CLM as a Community Modeling Tool



Land Complexity: Submodules of CLM

Biogeophysics (SP mode)

- Photosynthesis and stomatal resistance
- Hydrology
- Snow
- Soil thermodynamics
- Surface albedo and radiative fluxes

Biogeochemistry (BGC mode, above +)

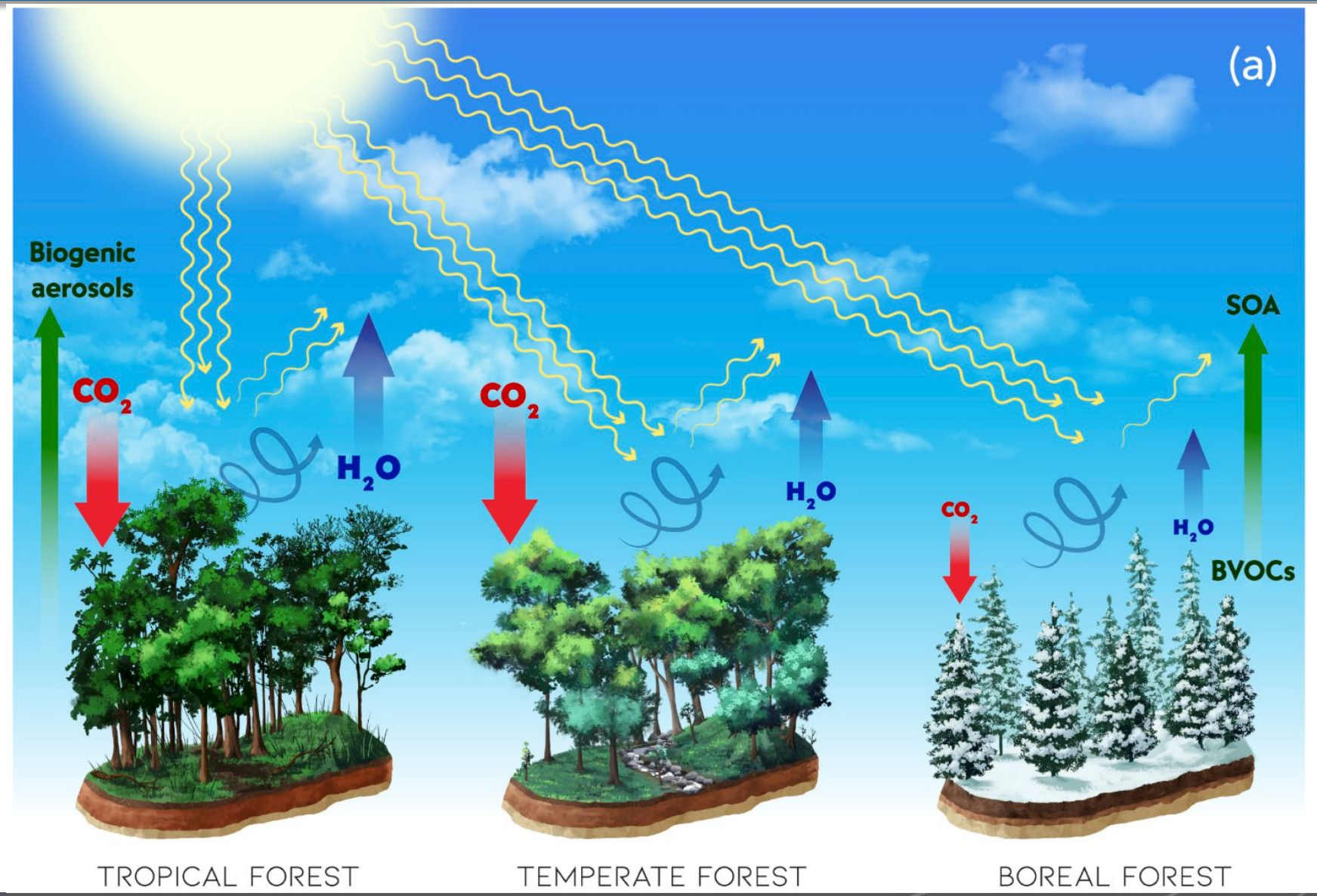
- Carbon / nitrogen pools, allocation, respiration
- Vegetation phenology
- Plant Mortality
- Decomposition
- External nitrogen cycle
- Methane production and emission

And…

- Urban
- Crop and irrigation
- Lakes
- Fire and fire emissions
- Dust emissions
- Biogenic Volatile Organic Compound emissions
- Glaciers and ice sheets
- River flow
- Vegetation demography

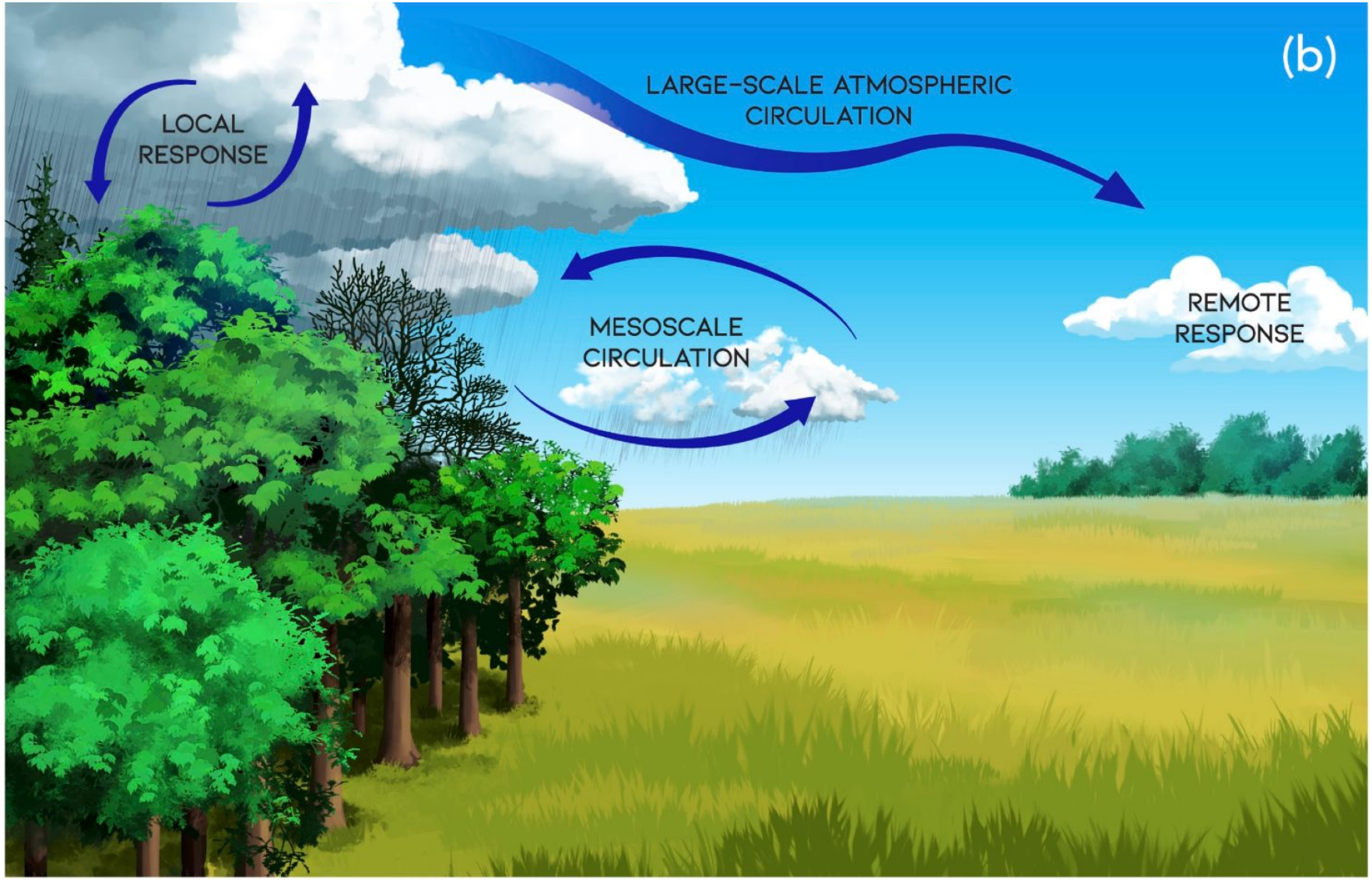
Lawrence et al. 2019

Not all forests have the same climate impact



Bonan 2008
Bonan et al. 2024

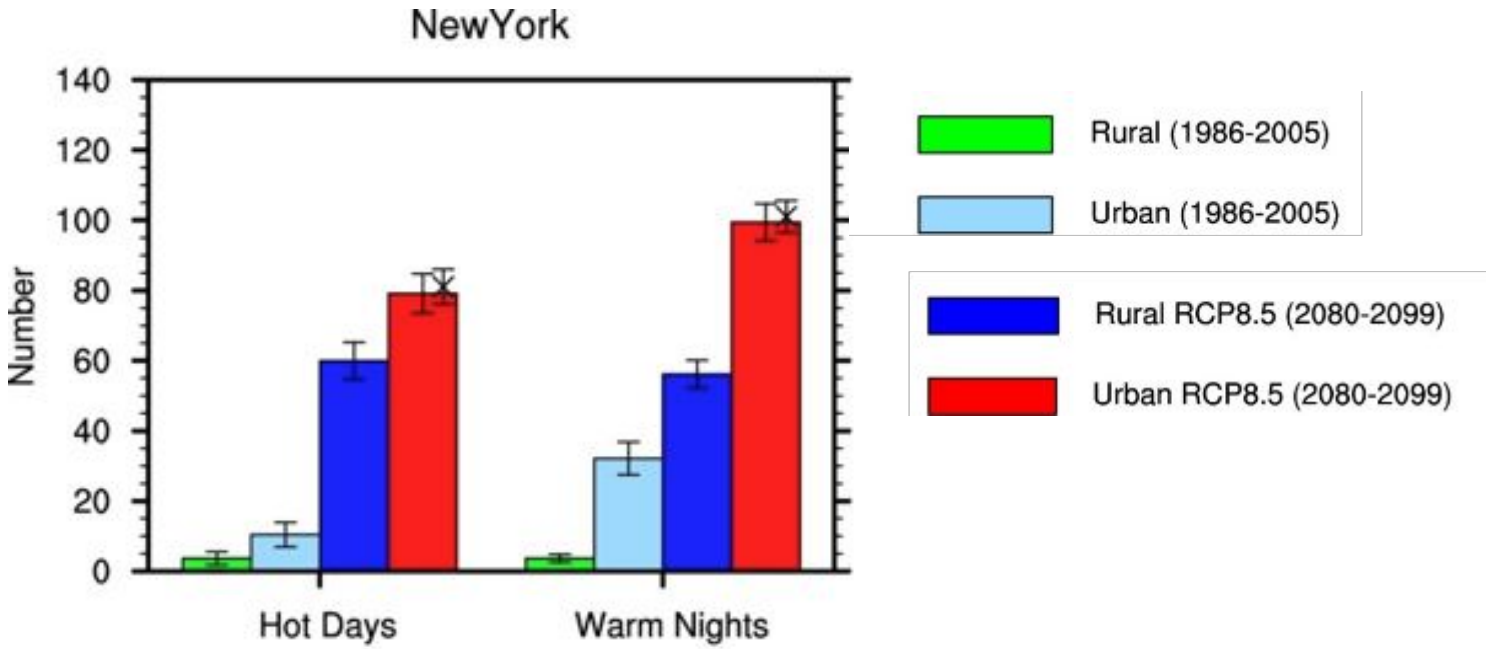
Not all forests have the same climate impact



Bonan 2008
Bonan et al. 2024

CLM-Urban Model (CLM-U)

- **New Urban Extent (2000-2100)**: Gao and O'Neill (2020), Gao and Pesaresi (2021), replaces static circa-2000 Jackson et al. (2010)
- **Dynamic Urban Capability** - changes in urban extent over time (Fang et al. 2024)
- **Improved Urban Properties:** Oleson and Feddema (2019), modifies Jackson et al. (2010)
- **Explicit Air Conditioning Adoption**: Li et al. (2023)



Present-day climate

Cities have more hot days and warm nights than rural land

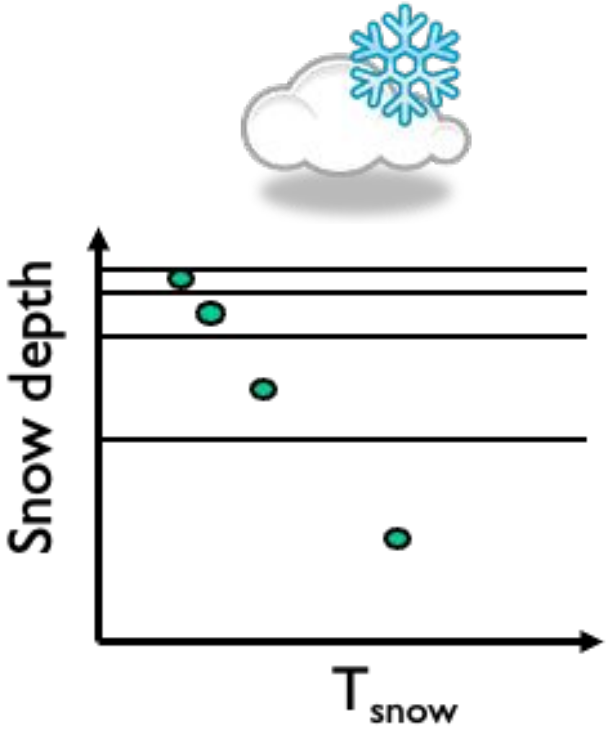
21st century climate change

Cities increase more in hot days and warm nights than does rural land

Land Model Complexity: Snow

State Variables

$$N, w_{liq,i}, w_{ice,i}, \Delta z_i, T_i$$

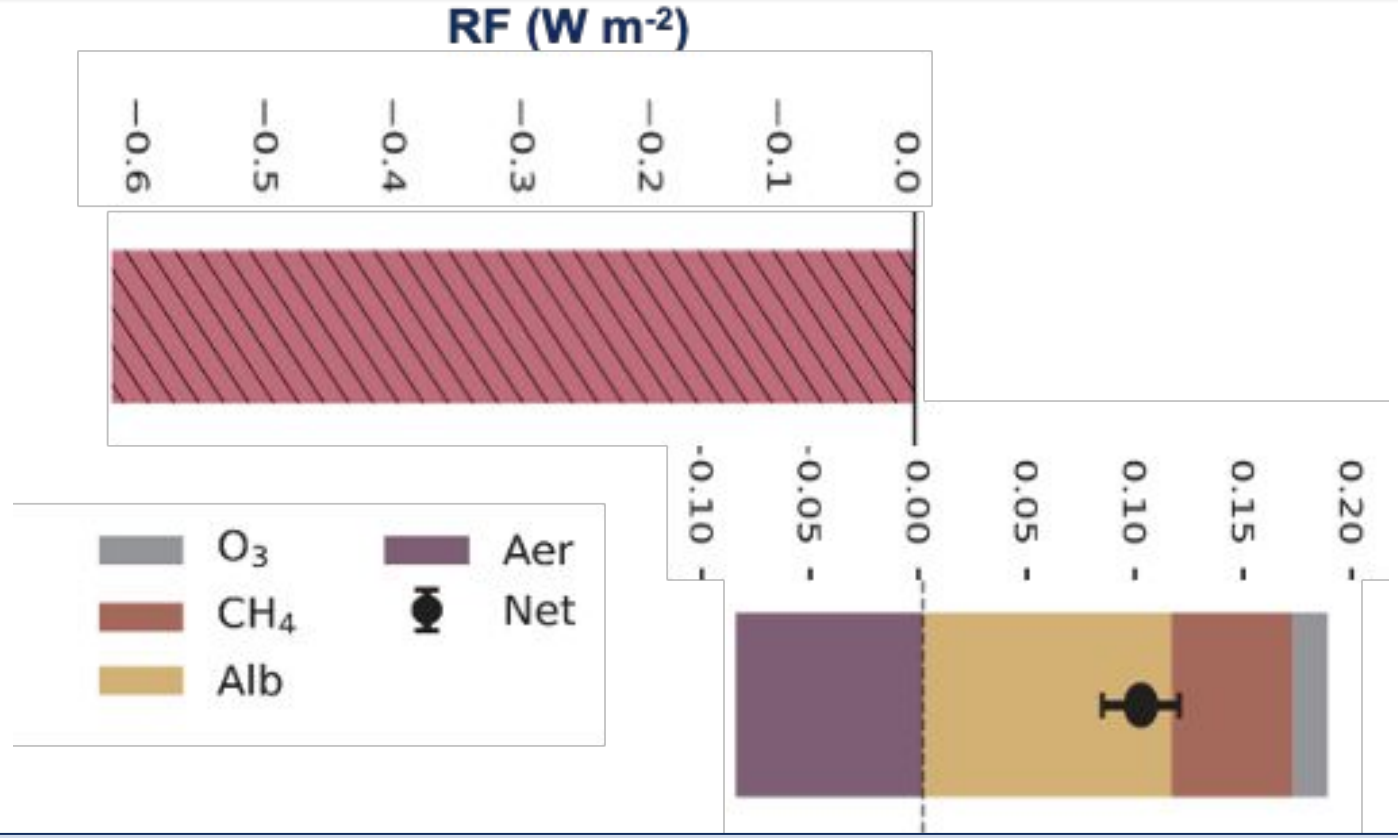


- Up to 10-layers of varying thickness
- **Represented processes**
  - Accumulation and fresh snow density: *f* (T, wind)
  - Melt, refreezing, aging
  - Compaction
    - destructive metamorphism: *f*(T, wind)
    - overburden
    - melt-freeze cycles
  - Sublimation
  - Water and energy transfer across snow layers
  - Aerosol (black carbon, dust) deposition
  - Canopy snow storage and unloading
  - Canopy snow radiation
  - Snow burial of vegetation
  - Snow cover fraction
- **Missing processes**
  - Blowing snow
  - Subgrid variations in snow depth
  - Depth hoar

Earth system to reforestation

RF from CO_2 removal

RF from other sources



Full understanding of climate impacts from reforestation requires ESMs

Changes in albedo and BVOC emissions from reforestation offset ⅓ of radiative forcing (RF) from CO_2 removal in CESM2

Weber et al. Science 2024