



Representing Land in the Earth System I: Biogeophysics

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CESM Tutorial 2026



Representing Land in ESMs:

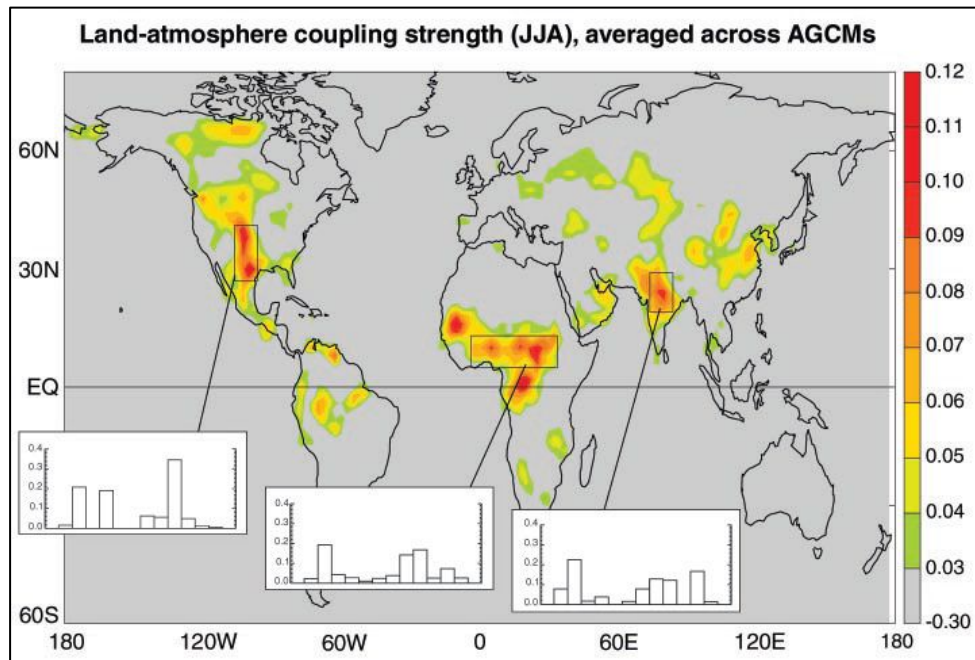
- Why?
- How?
- Future directions

Many Thanks

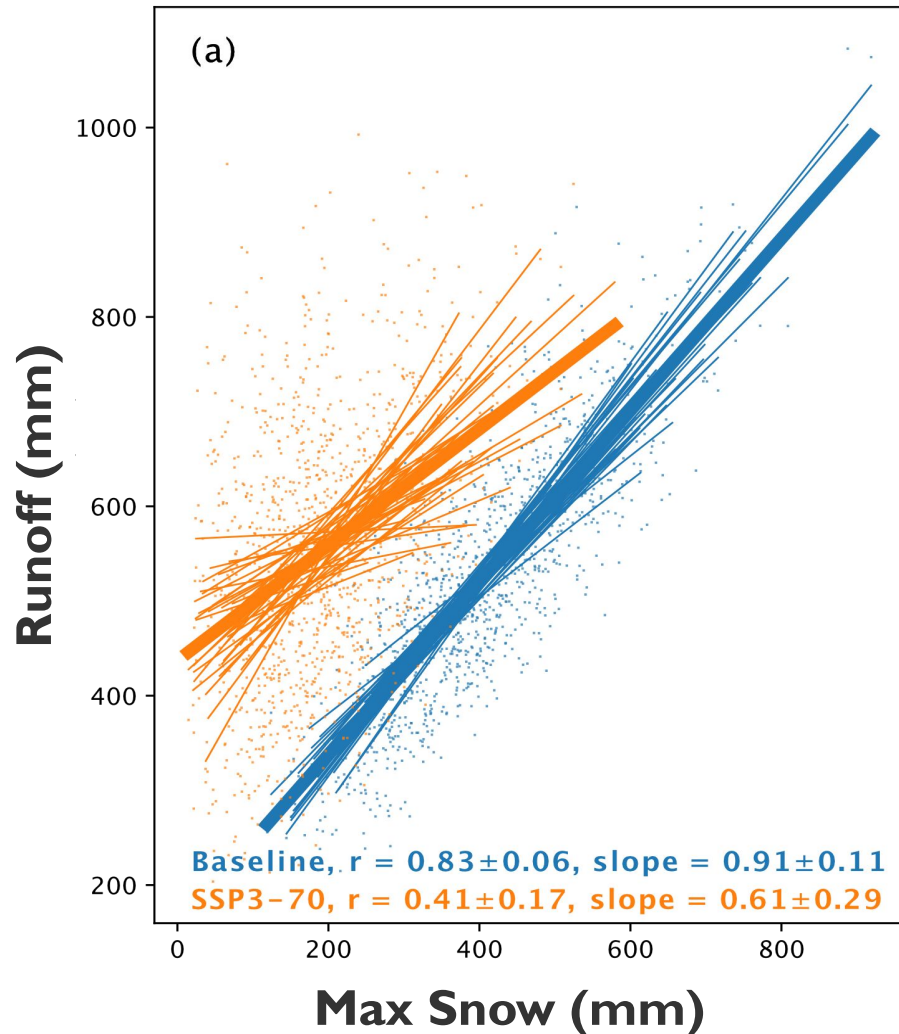
- CESM Land Model Working Group
- Dave Lawrence, Gordon Bonan
- LMWG Software Engineering Team
- LMWG Liaisons, Keith Oleson & Sam Levis

Land-Atmosphere Interactions

How much do soil moisture anomalies influence the atmosphere, the evolution of weather, and the generation of precipitation?

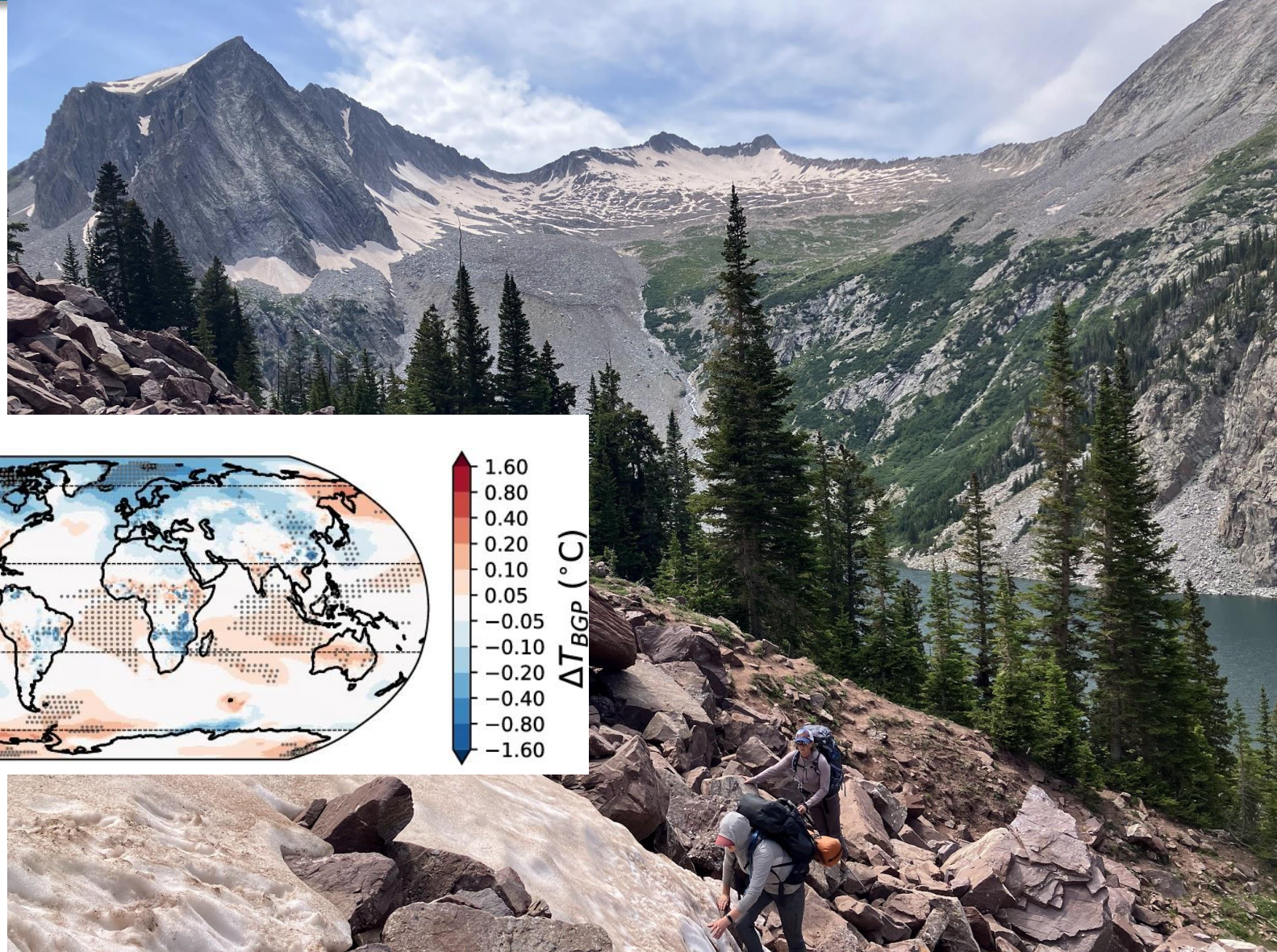


How are water (and food) resources under threat from climate change?

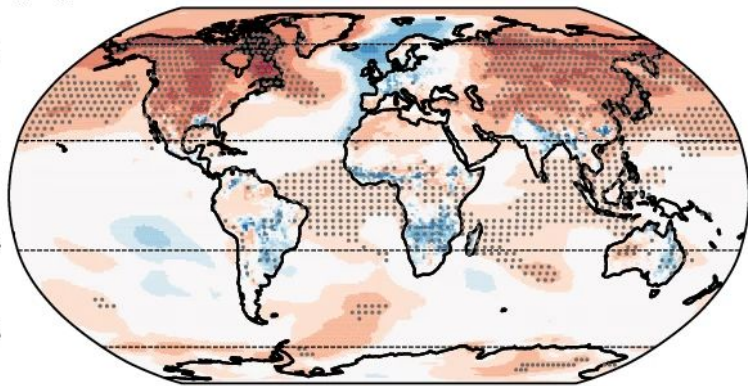


Land Use and Land Cover Change

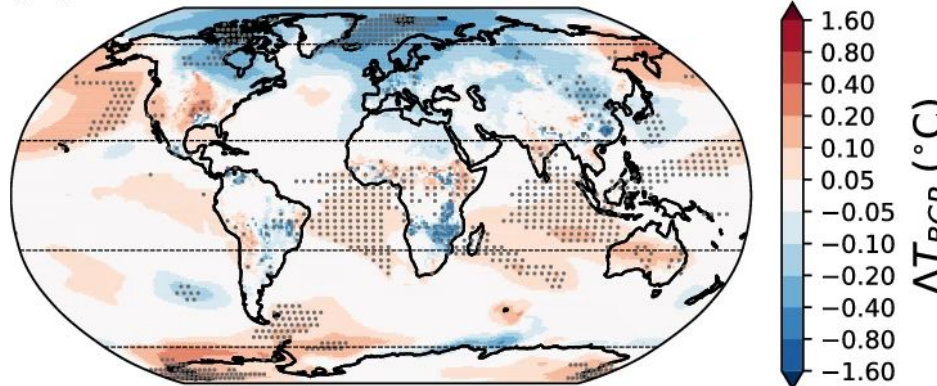
How do changes in land properties affect water, energy & biogeochemical feedbacks in the Earth system?



(a) Bastin



(c) Hurtt



How does the Earth system respond to change on Land?



Arctic Greening (courtesy NSIDC)



Permafrost Thaw (Nat. Geo.)



Agriculture (John)

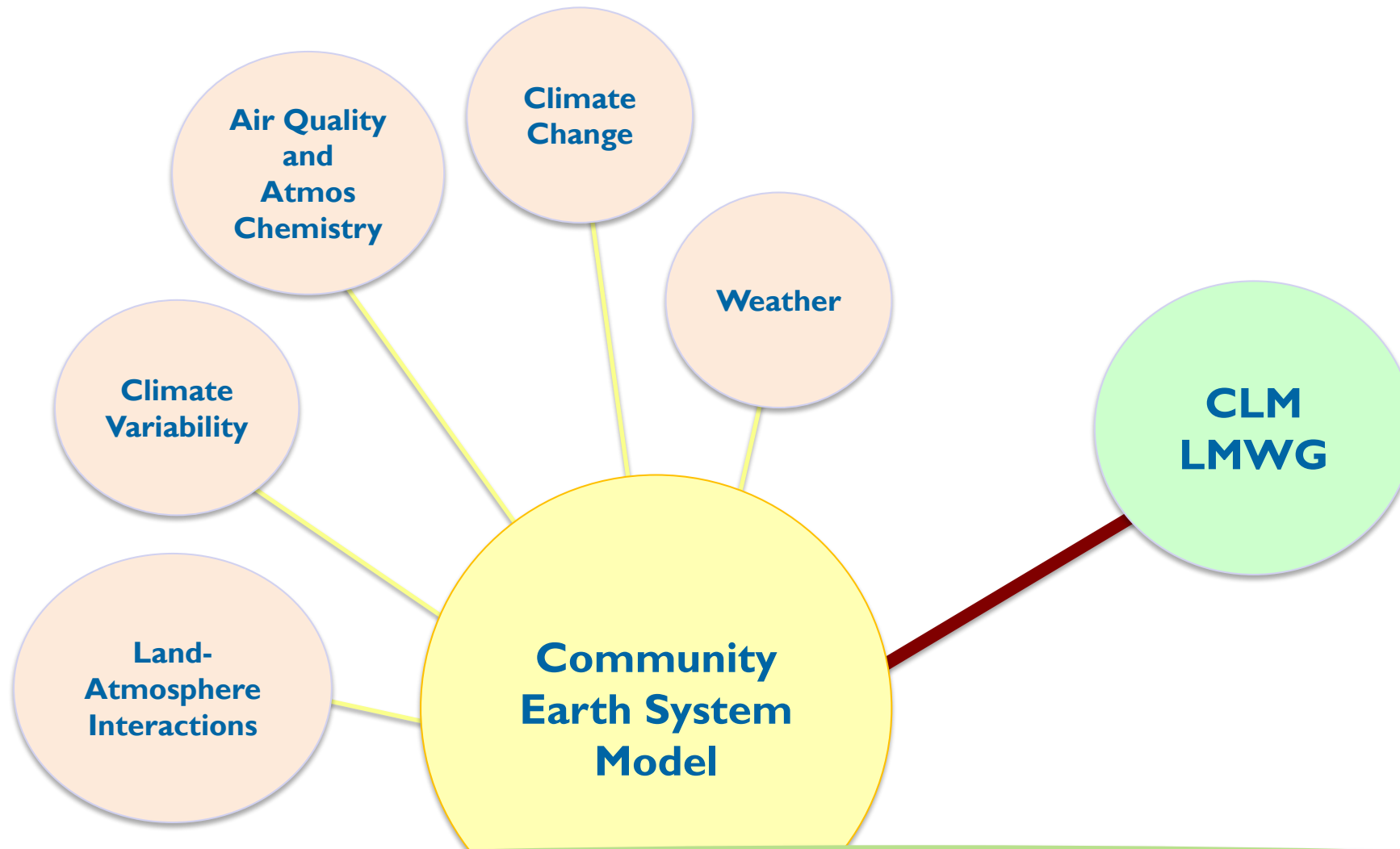


Deforestation (courtesy NPR)

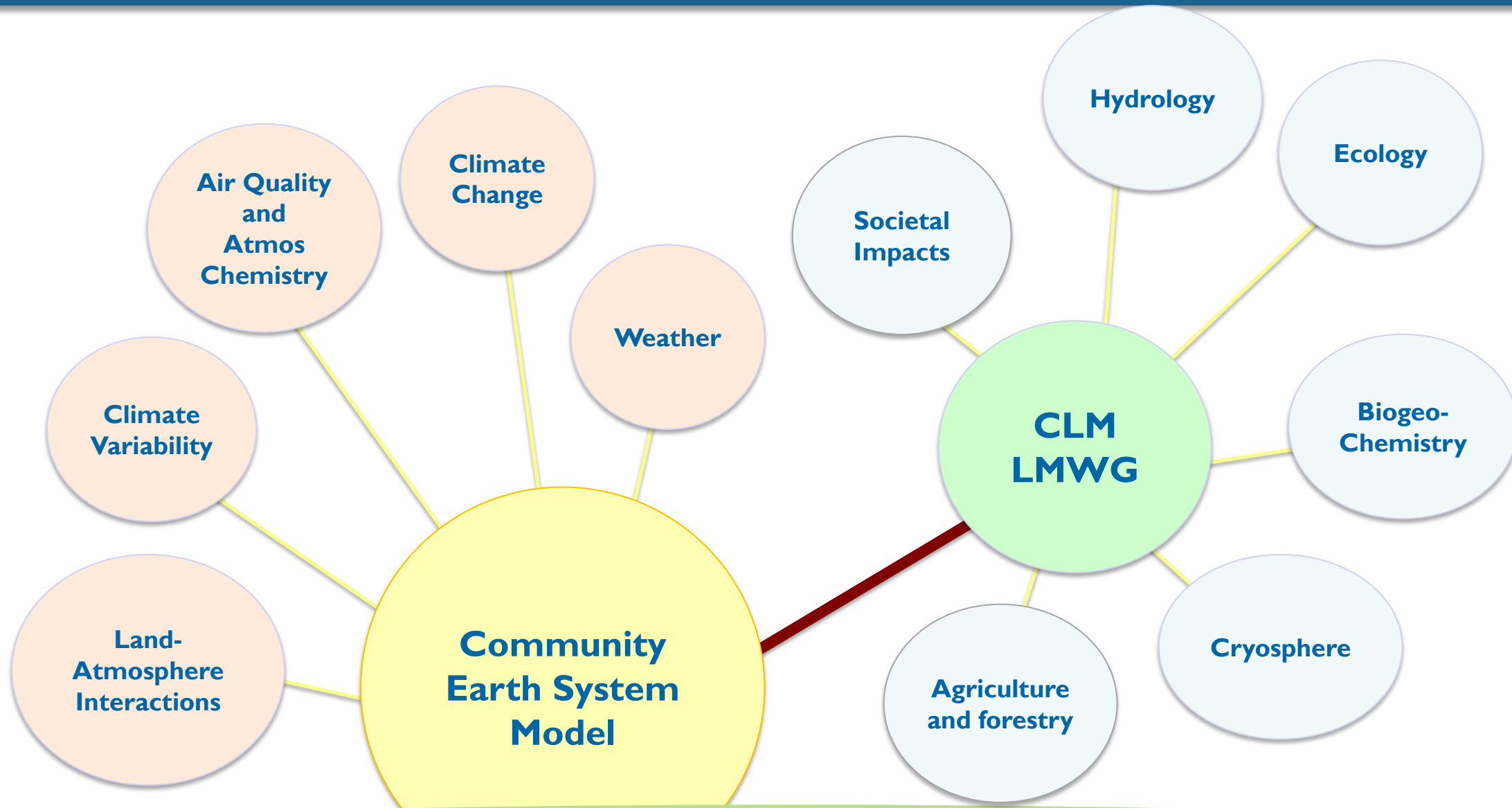


Forest Fires (Columbia)

CESM and CLM as a Community Modeling Tool



CESM and CLM as a Community Modeling Tool



Land Modeling in CESM

Motivation:

Land is the critical interface through which humanity affects and is affected by, adapts to, and mitigates global environmental change

Goal:

Comprehensive representations of land biogeophysics, hydrology, plant physiology, biogeochemistry, anthropogenic land use, agricultural management, ecosystem dynamics, and urban environments



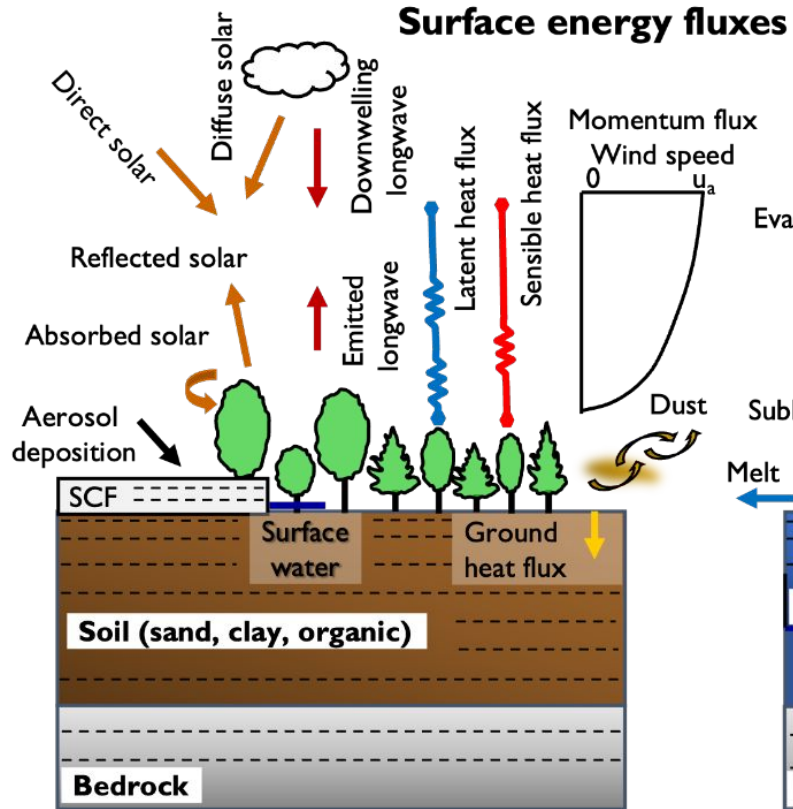
Land Modeling in ESMs: How



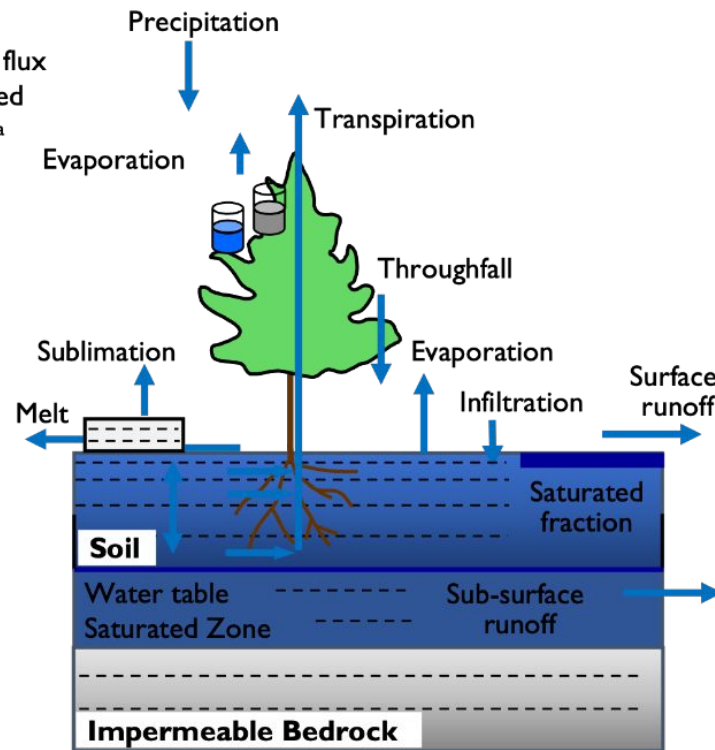
- **Exchanges** of momentum, energy, water vapor, CO₂, dust, and other trace gases/materials between land and atmosphere + routing of runoff to the ocean
- **States** of land surface (e.g., soil moisture, soil temperature, canopy temperature, snow, carbon and nitrogen stocks in vegetation and soil)
- **Characteristics** of land surface (e.g., soil texture, surface roughness, albedo, emissivity, vegetation type, and leaf area index)

Key Processes within CLM / CTSM

Biogeophysics



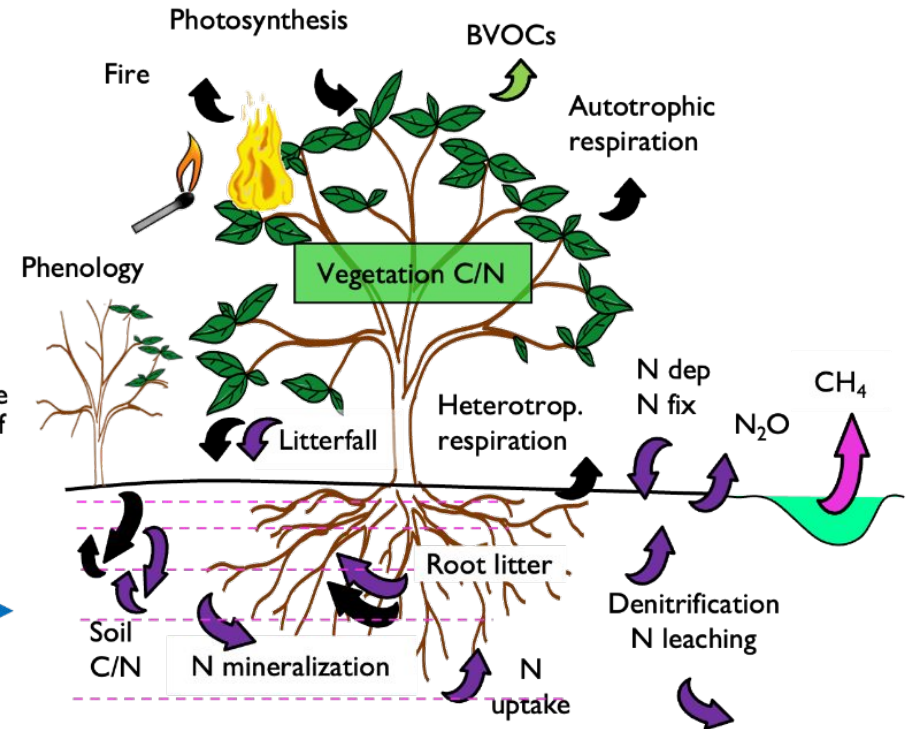
Hydrology



Biogeochemistry

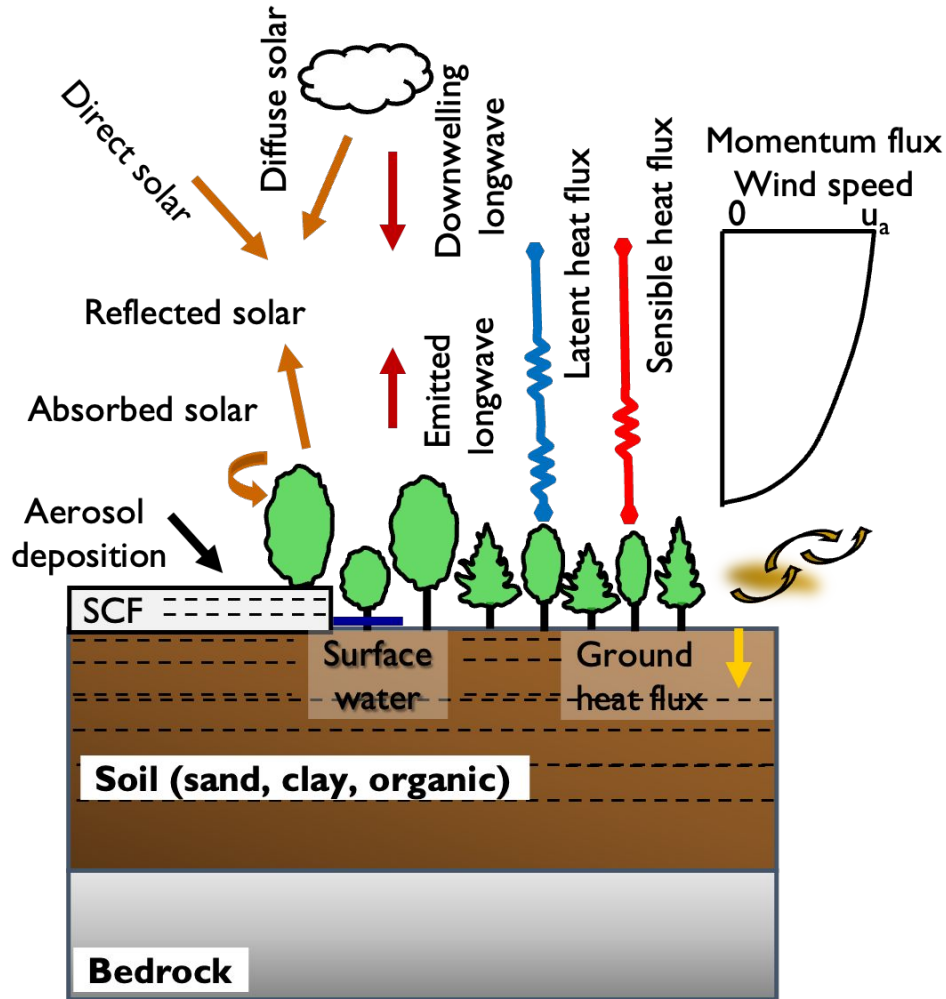
CLM5.0

Biogeochemical cycles



At each time step CLM solves the Surface Energy Balance

Surface energy fluxes

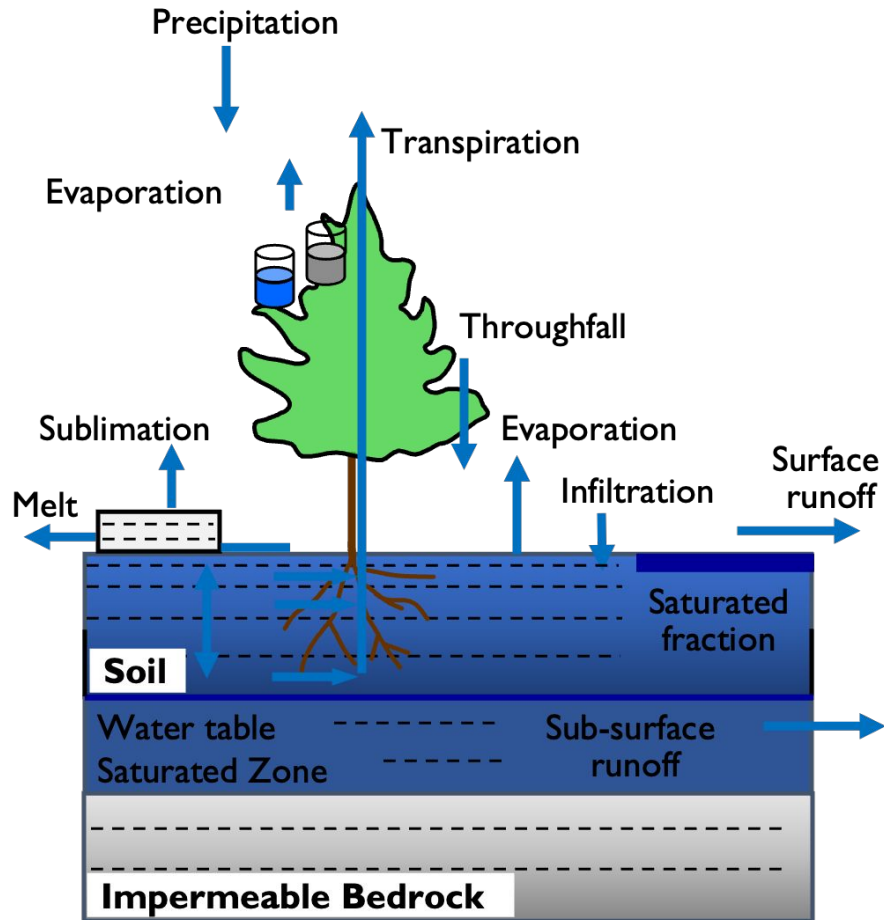


$$S_{\downarrow} - S_{\uparrow} + L_{\downarrow} - L_{\uparrow} = \lambda E + H + G$$

$S_{\downarrow}, S_{\uparrow}$ are down / upwelling solar radiation,
 $L_{\downarrow}, L_{\uparrow}$ are down / upwelling longwave radiation,
 λ is latent heat of vaporization,
 E is evaporation,
 H is sensible heat flux
 G is ground heat flux

Lawrence et al. 2019

... and the Surface Water Balance



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

P is rainfall/snowfall,

ES is soil evaporation,

ET is transpiration,

EC is canopy evaporation,

R is runoff (surf + sub-surface),

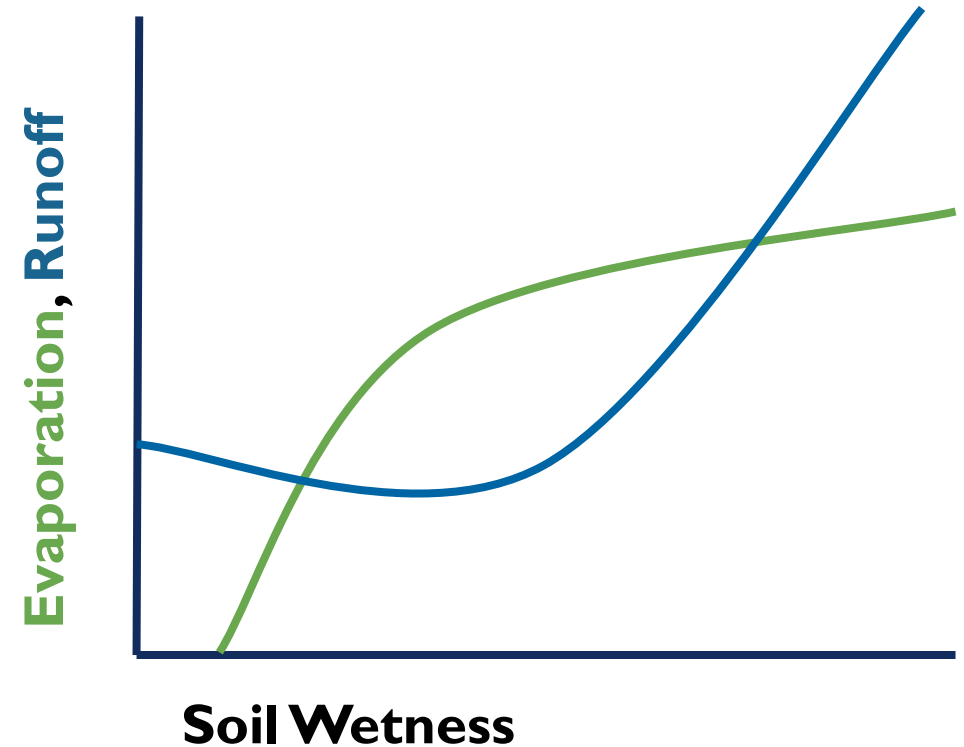
ΔW_{soil} , ΔW_{snow} , ΔW_{sfcw} , & ΔW_{can} are changes in soil moisture, snow, surface water, and canopy water over a timestep

Terrestrial energy and water cycles are intricately linked

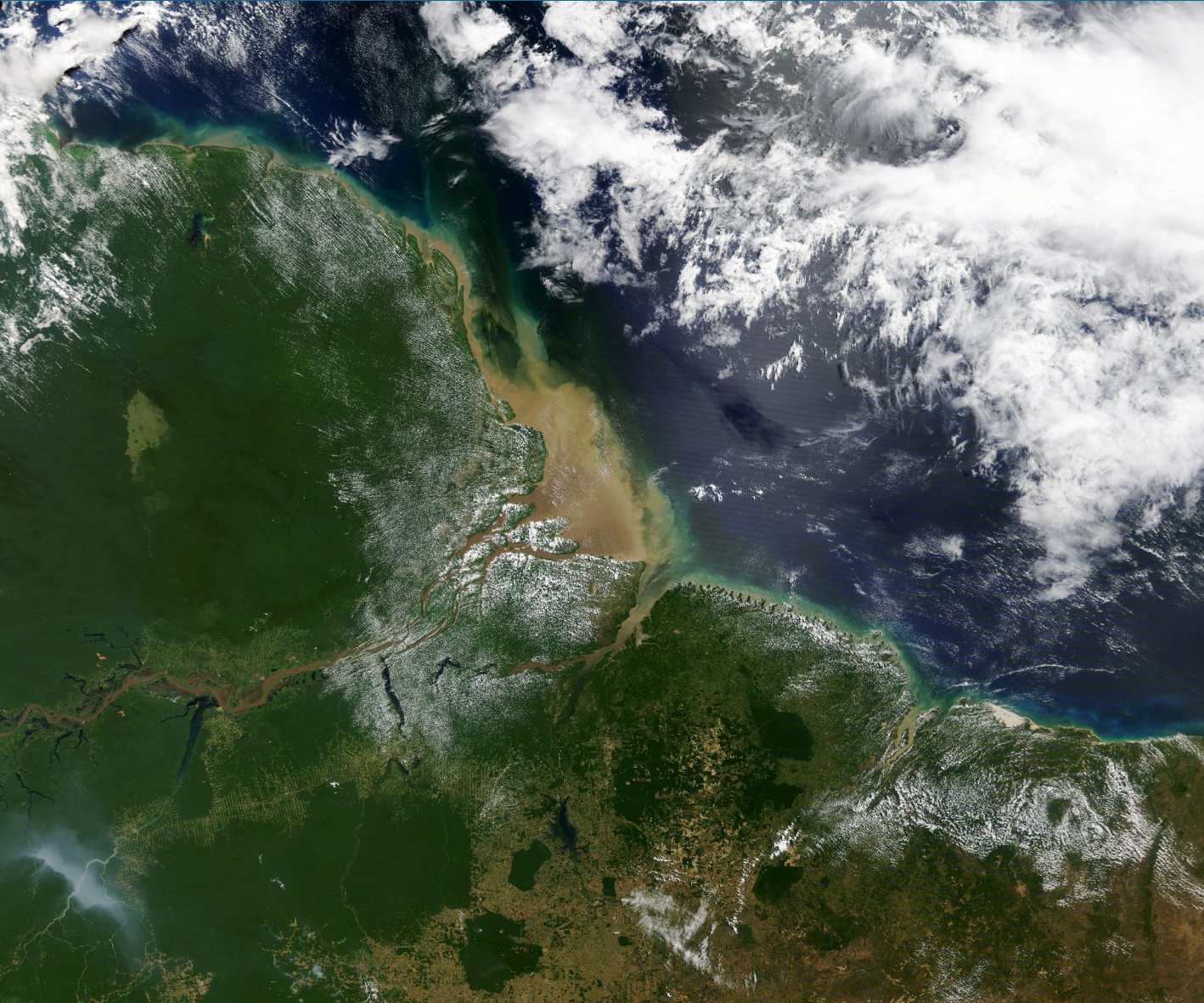
“The ability of a land-surface scheme to model evaporation correctly depends crucially on its ability to model runoff correctly. The two fluxes are intricately related through soil moisture.”

(Koster and Milly, 1997).

What is this statement missing?



Land Model Complexity: Plants

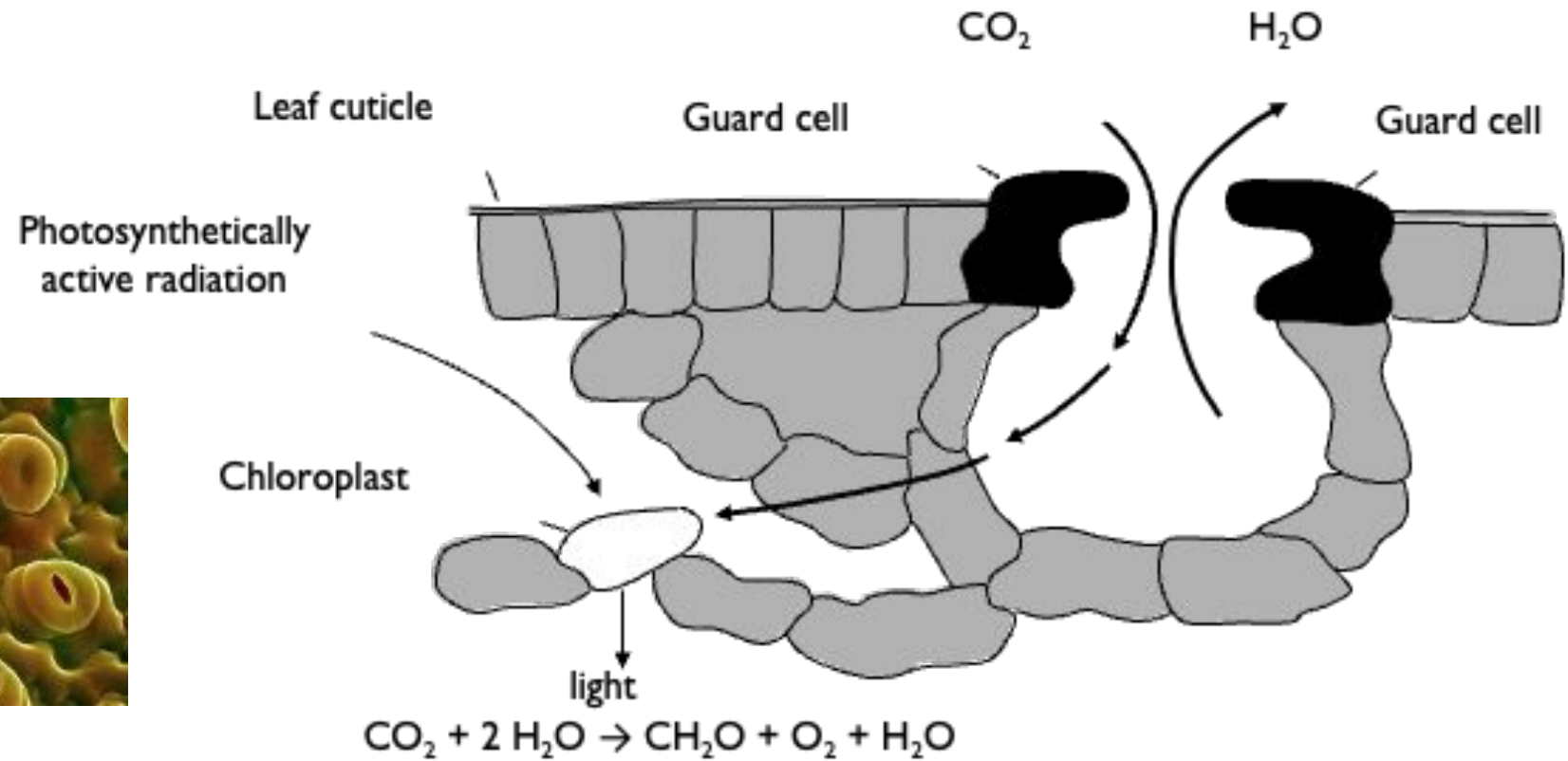
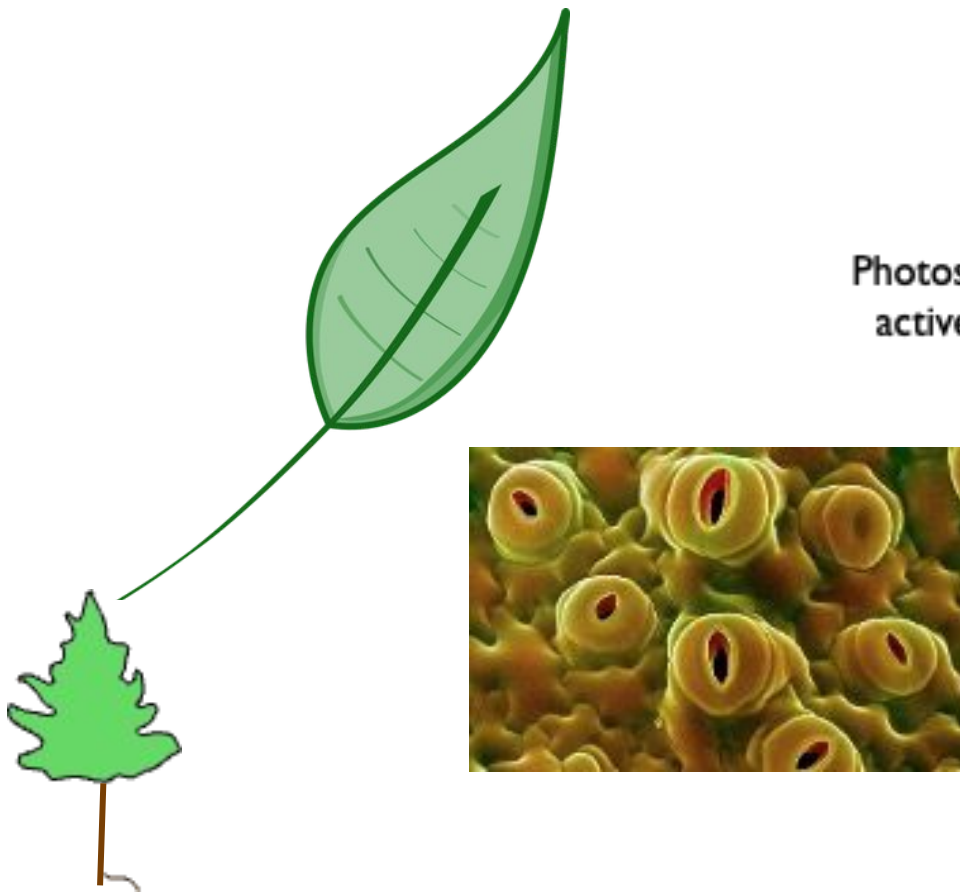


Blue marble...
...Green Earth

Photosynthesis model

Plant physiological controls on transpiration and CO₂ exchange

Function of solar radiation, humidity deficit, soil moisture, [CO₂], temperature, leaf N content



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

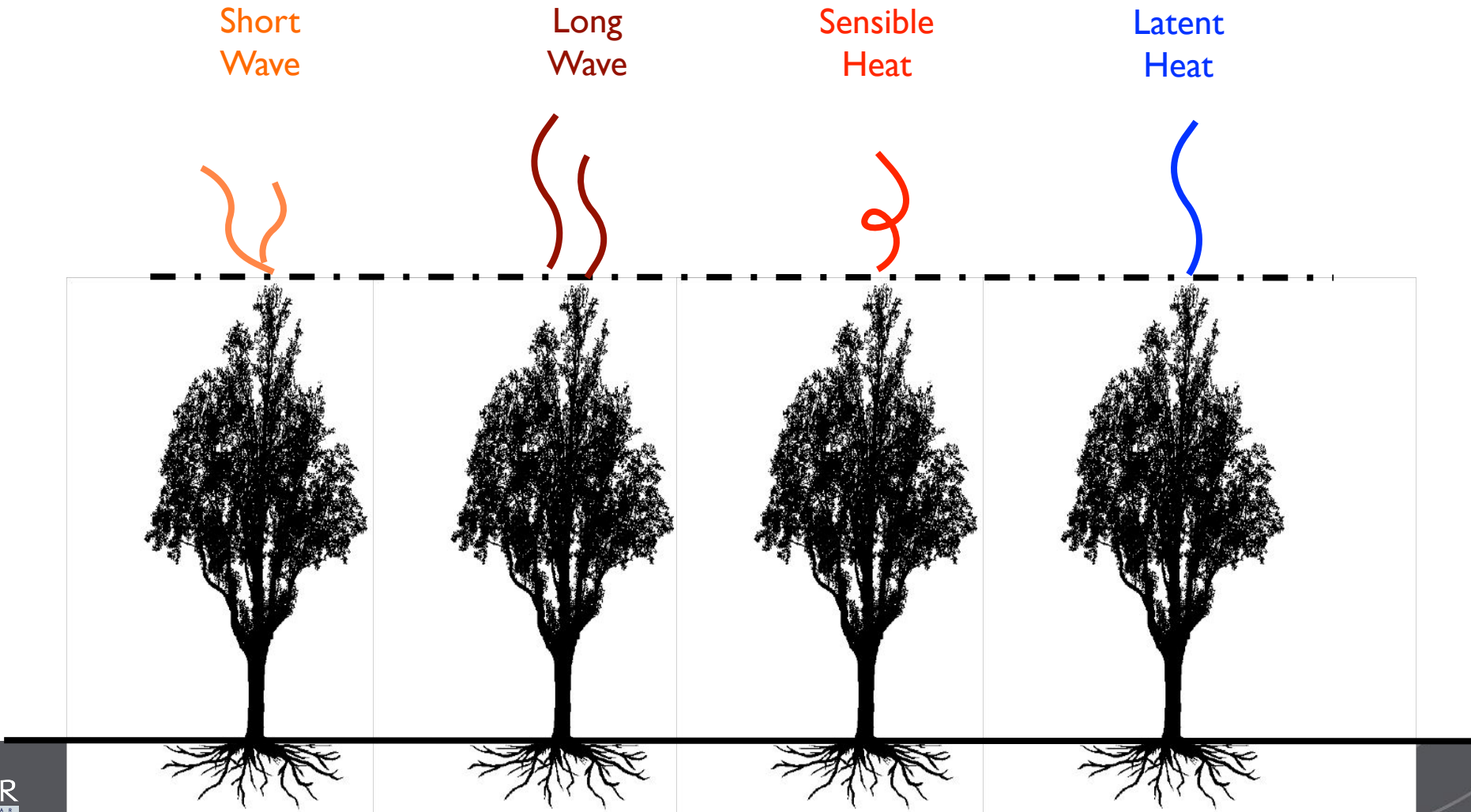
And...

- 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

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

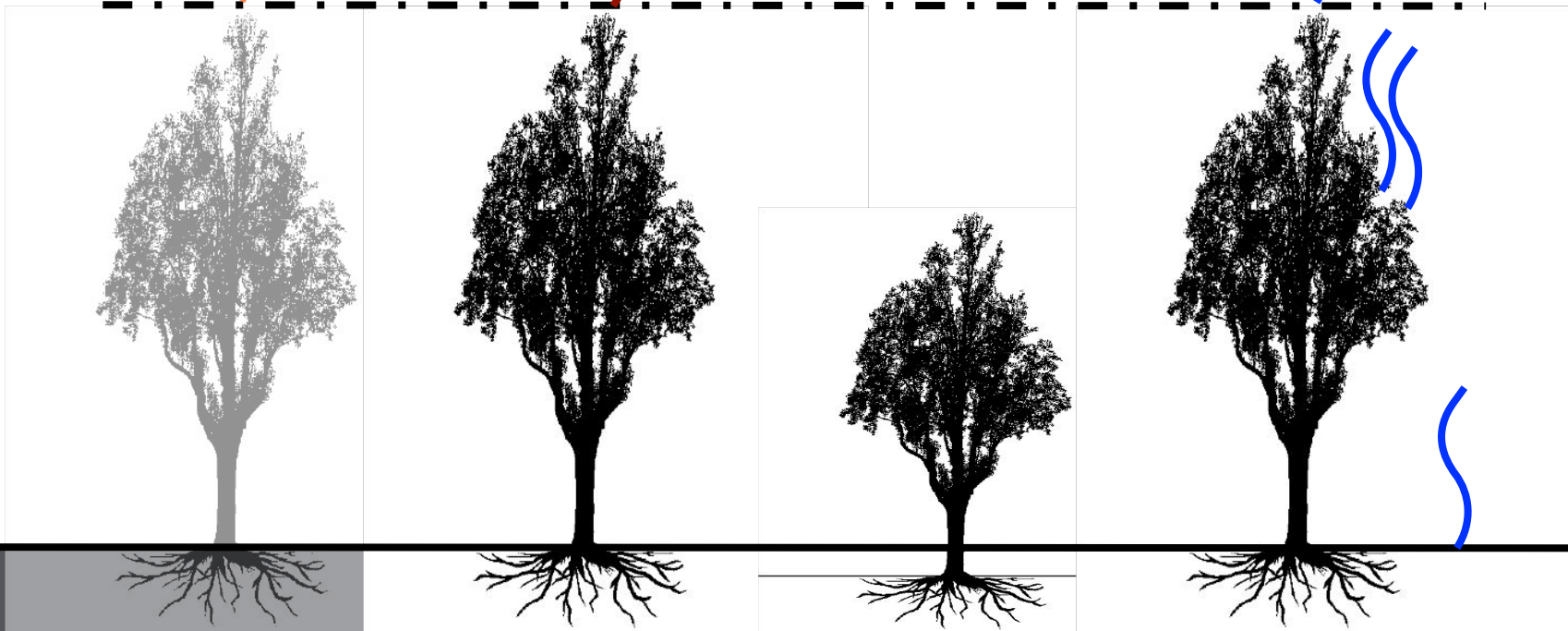
Short
Wave

Long
Wave

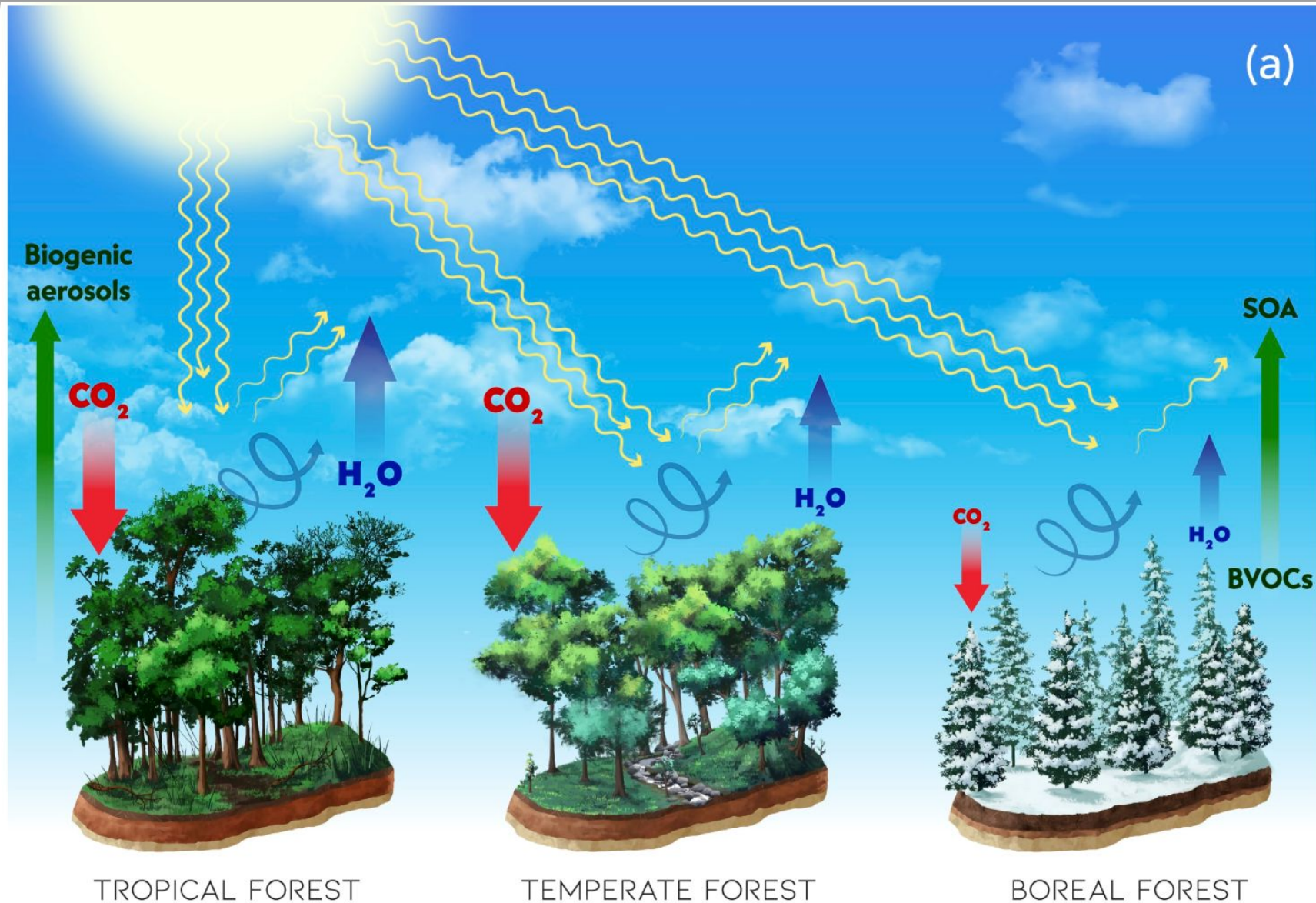
Sensible
Heat

Latent
Heat

$\Delta\text{Plants} \Rightarrow \Delta\text{Surface Energy Budget}$

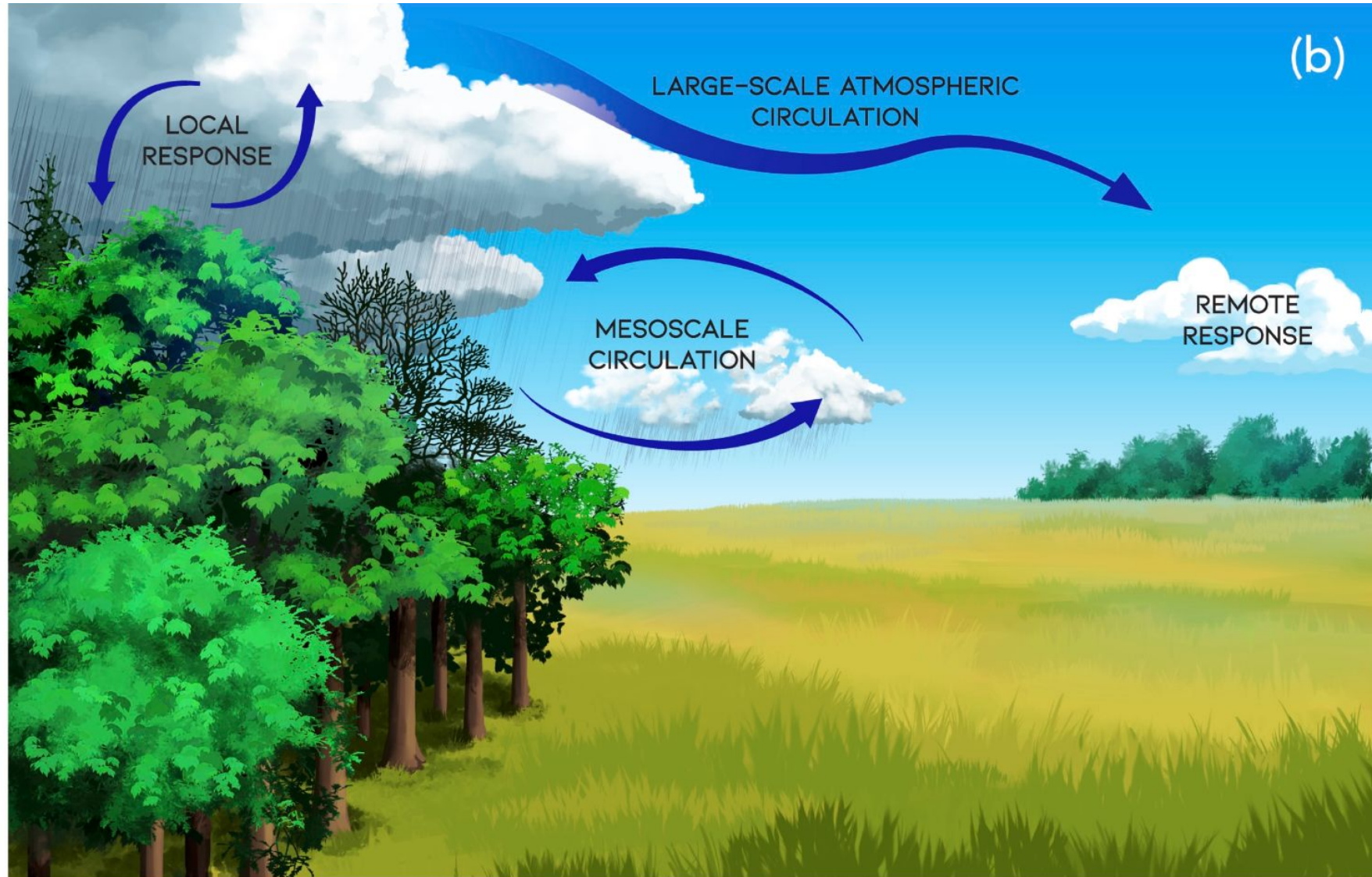


Not all forests have the same climate impact



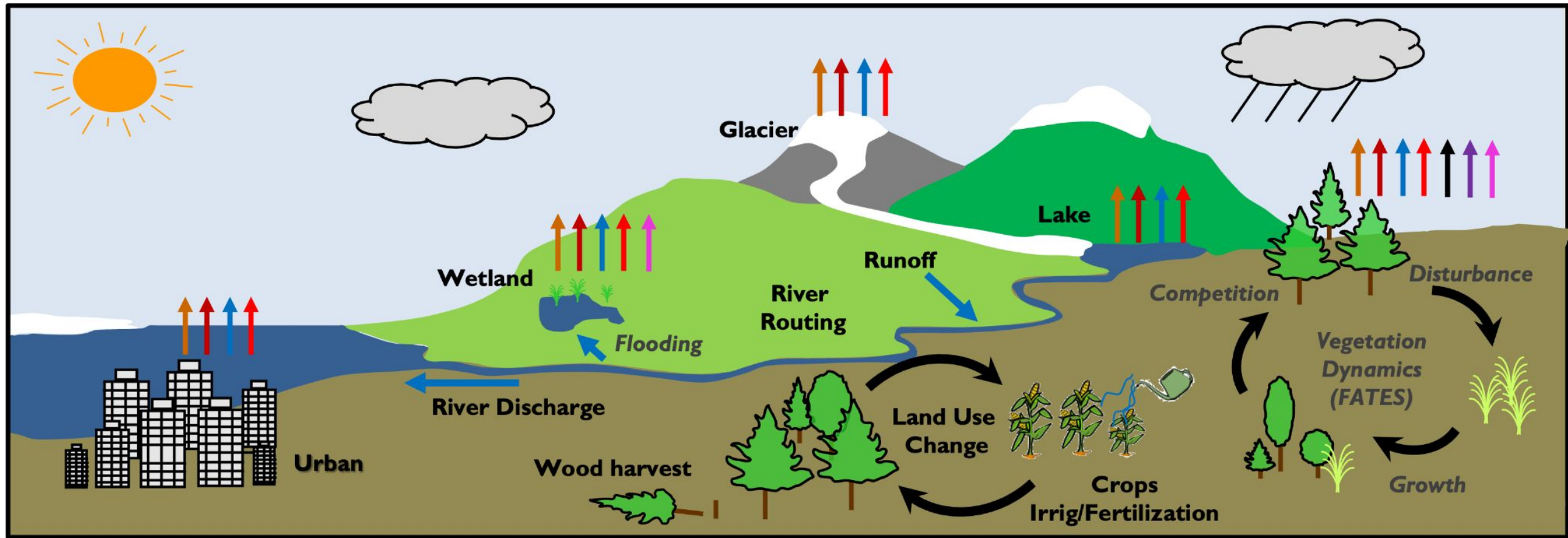
Bonan 2008
Bonan et al. 2024

Not all forests have the same climate impact



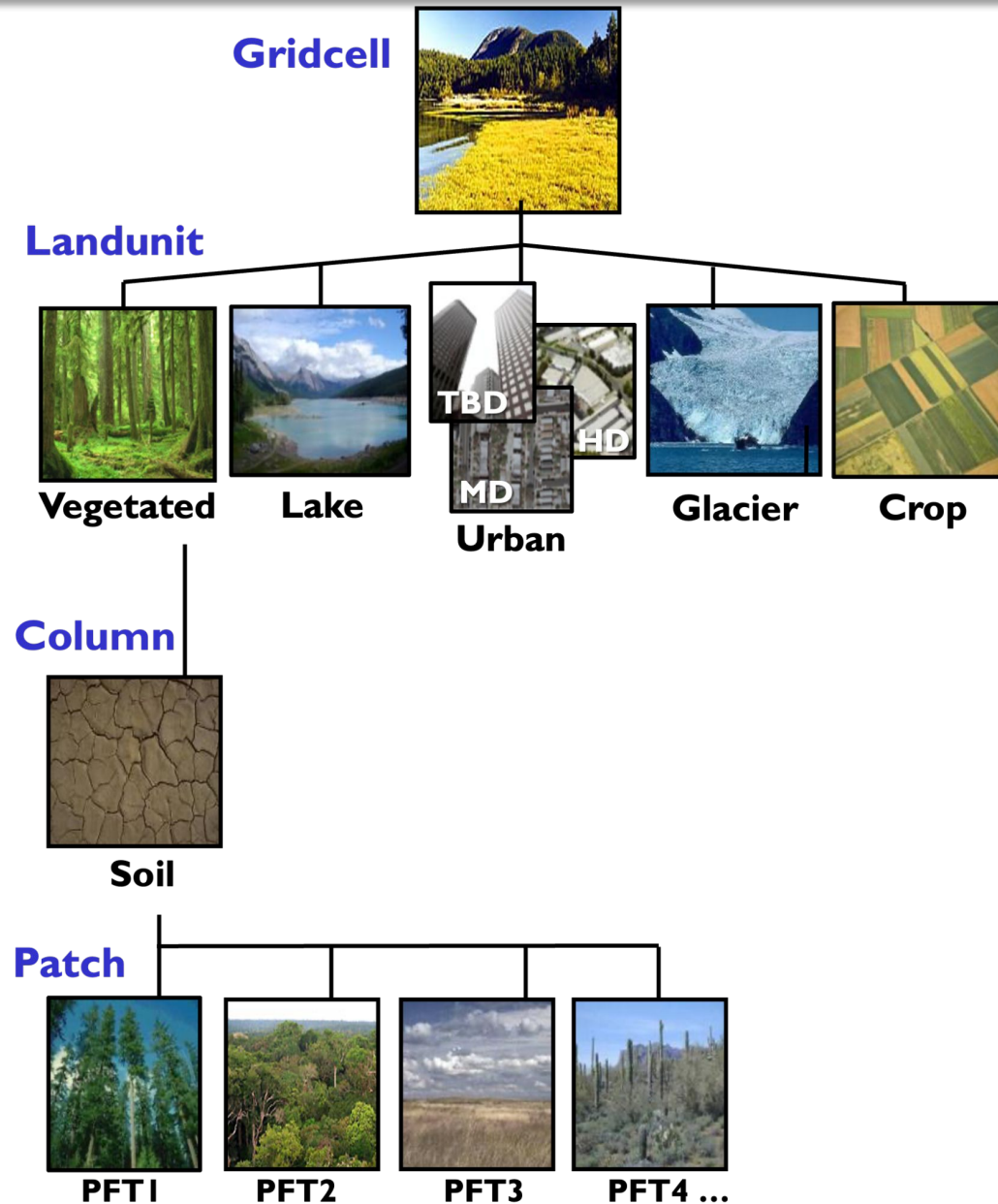
Bonan 2008
Bonan et al. 2024

Land Surface Heterogeneity

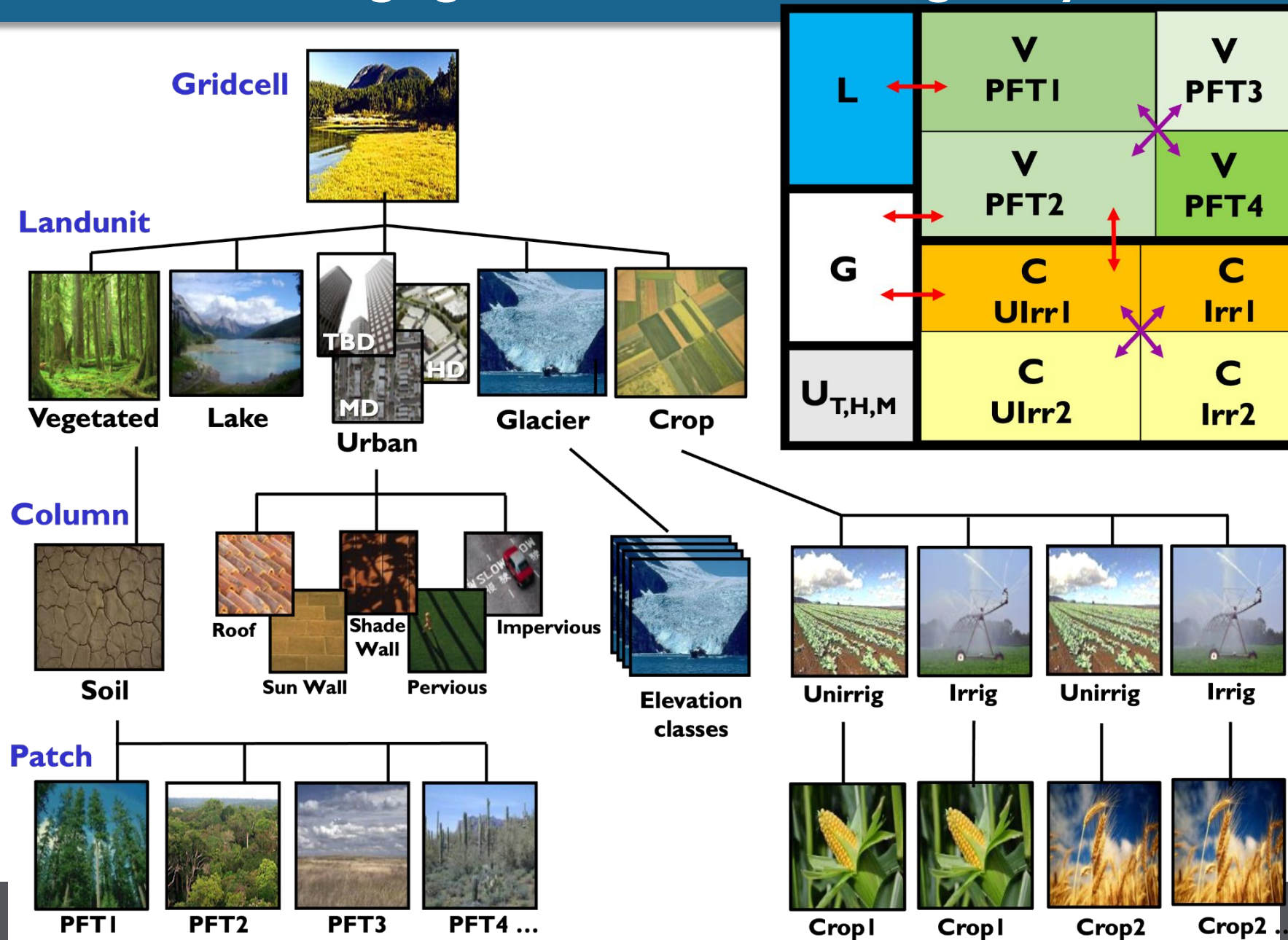


Lawrence et al. 2019

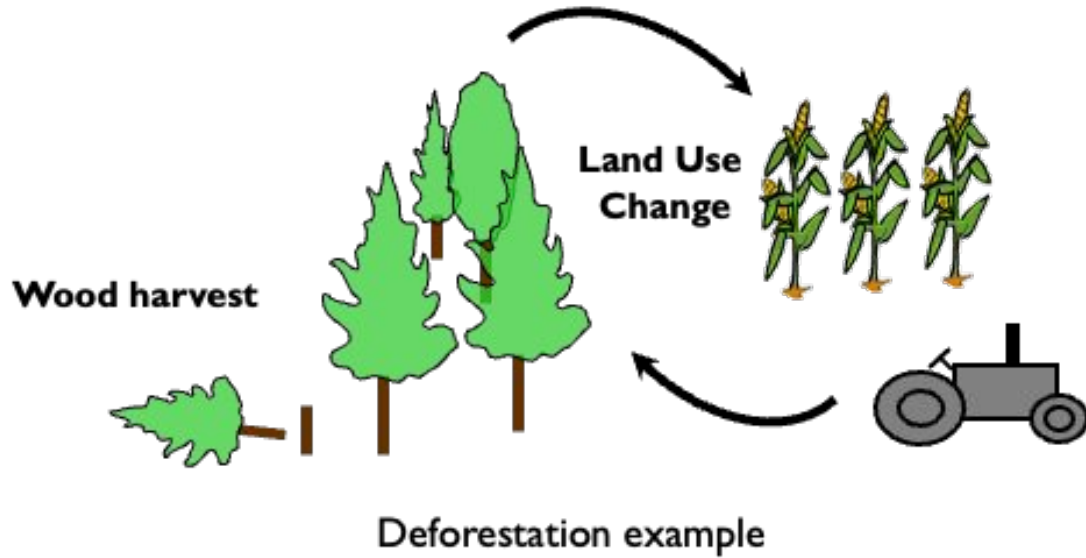
Changing Land Surface Heterogeneity



Changing Land Surface Heterogeneity

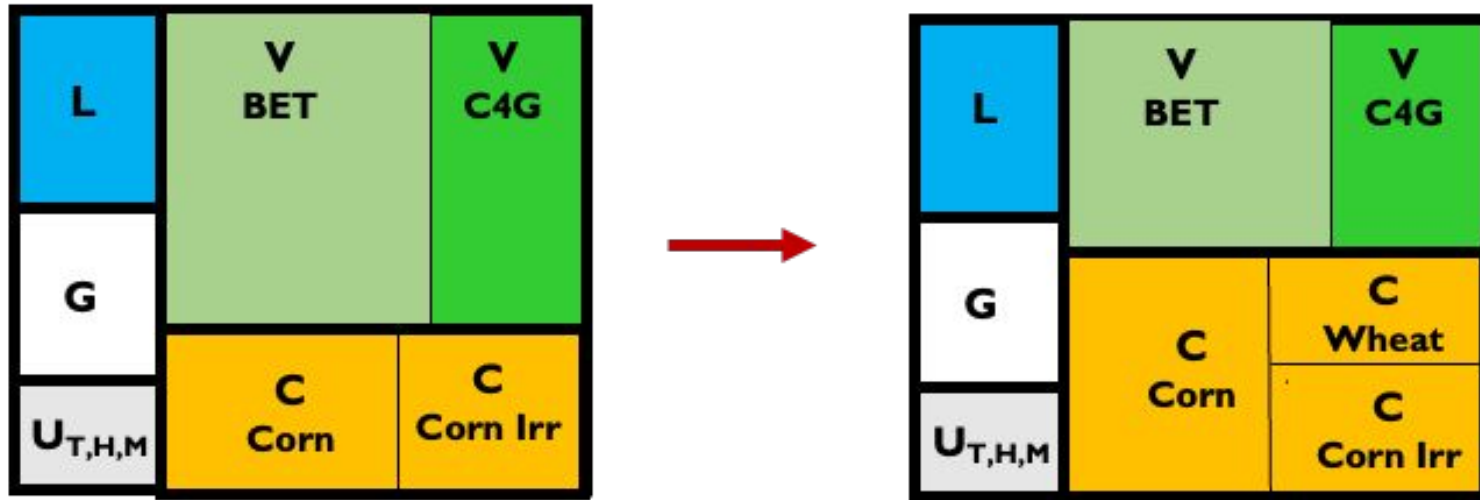


Land Use / Land Cover Change



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

Create datasets
Conserve mass



Land Modeling in ESM: Priorities

Ecosystems:
FATES



Food:
Crop Model*



Water:
Hillslope
Hydrology



Urban: CLM-U*



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

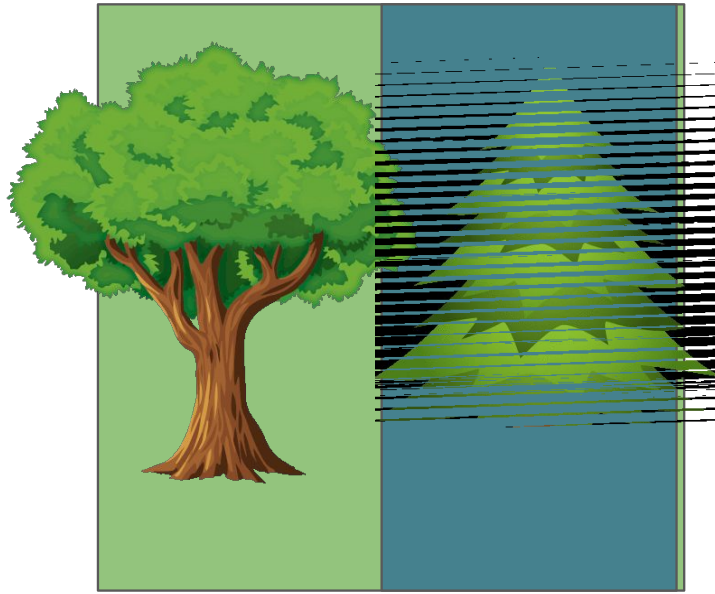
Interactive Fires



Questions & Discussion

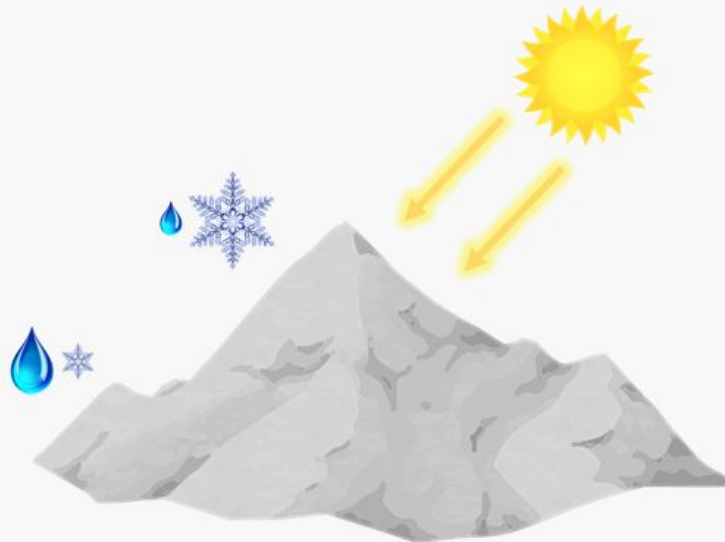


Hillslope Hydrology: subgrid heterogeneity in soil moisture



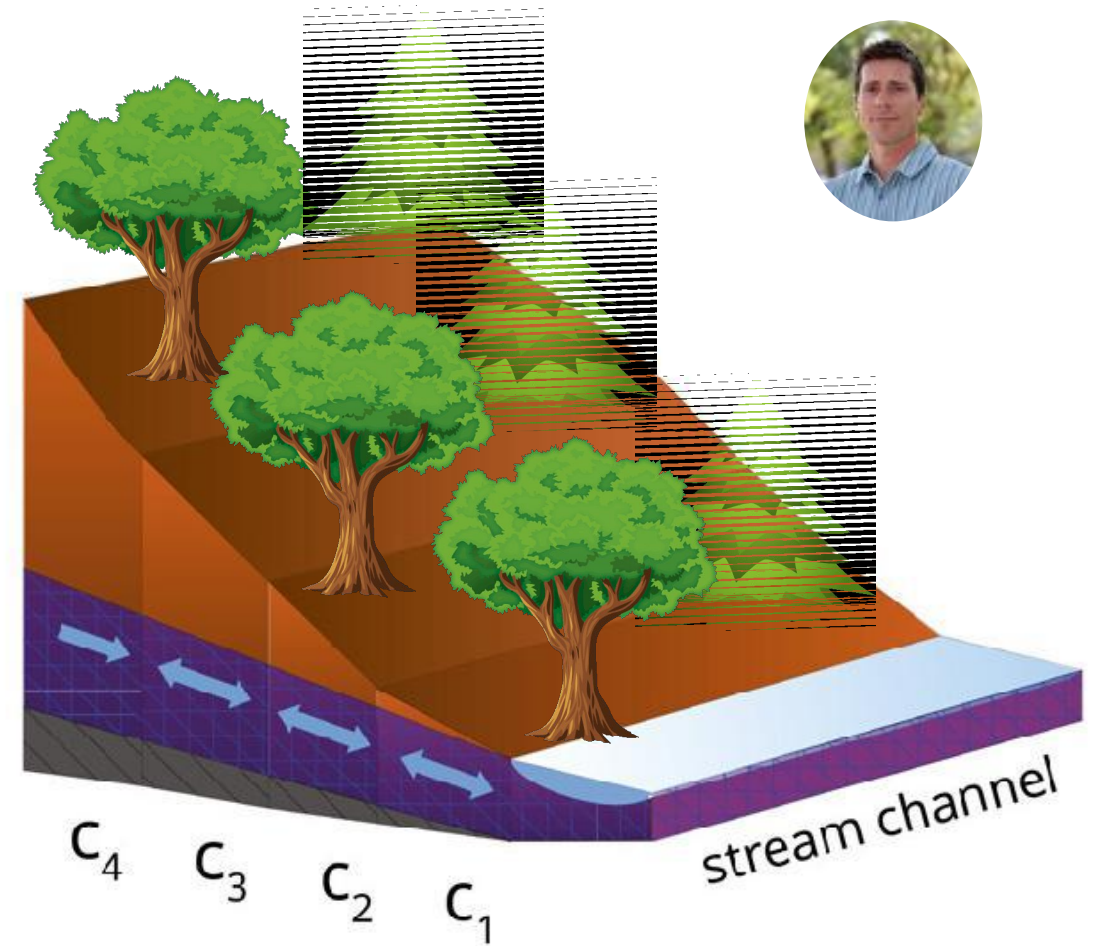
Aspect:

N-S-E-W facing



Relief:

Low vs high



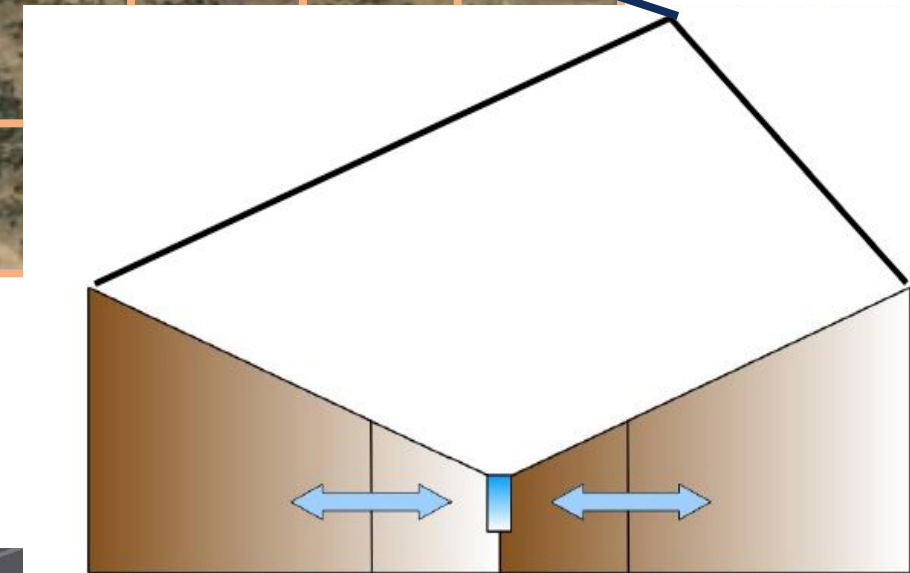
Lateral Subsurface Flow

From Swenson & Lawrence 2025

Subgrid Hillslope Processes

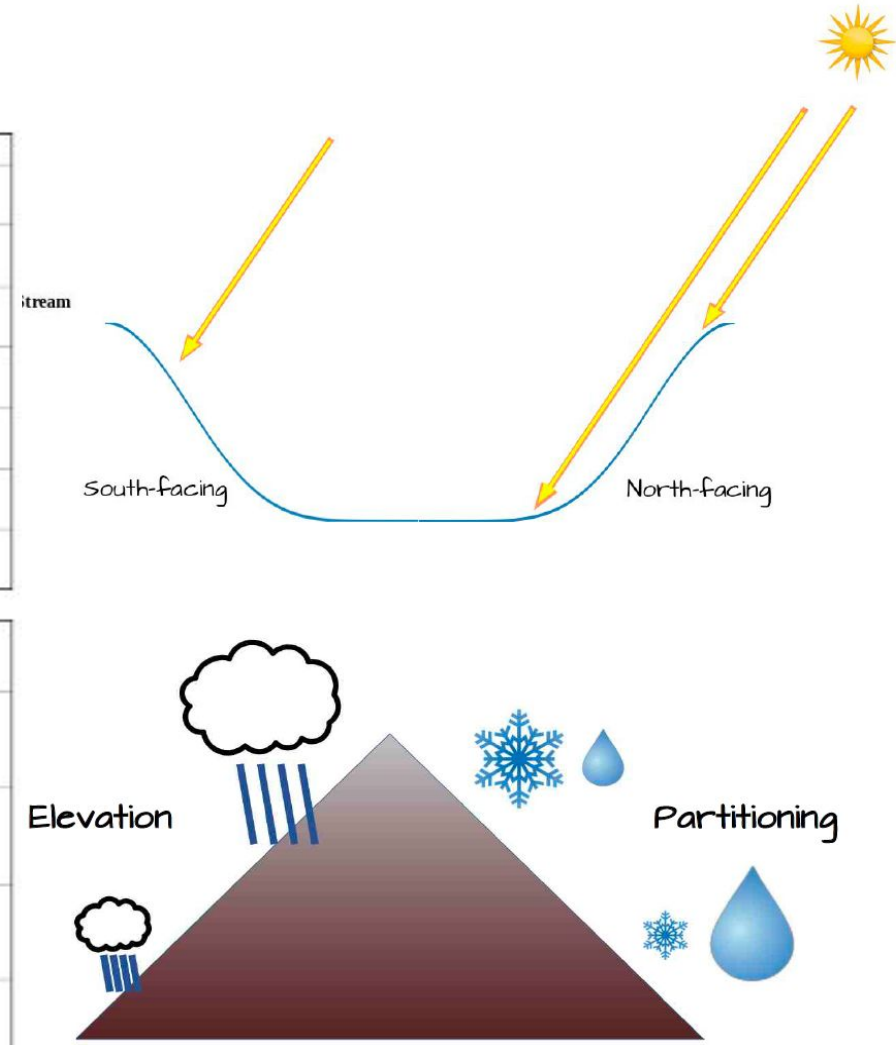
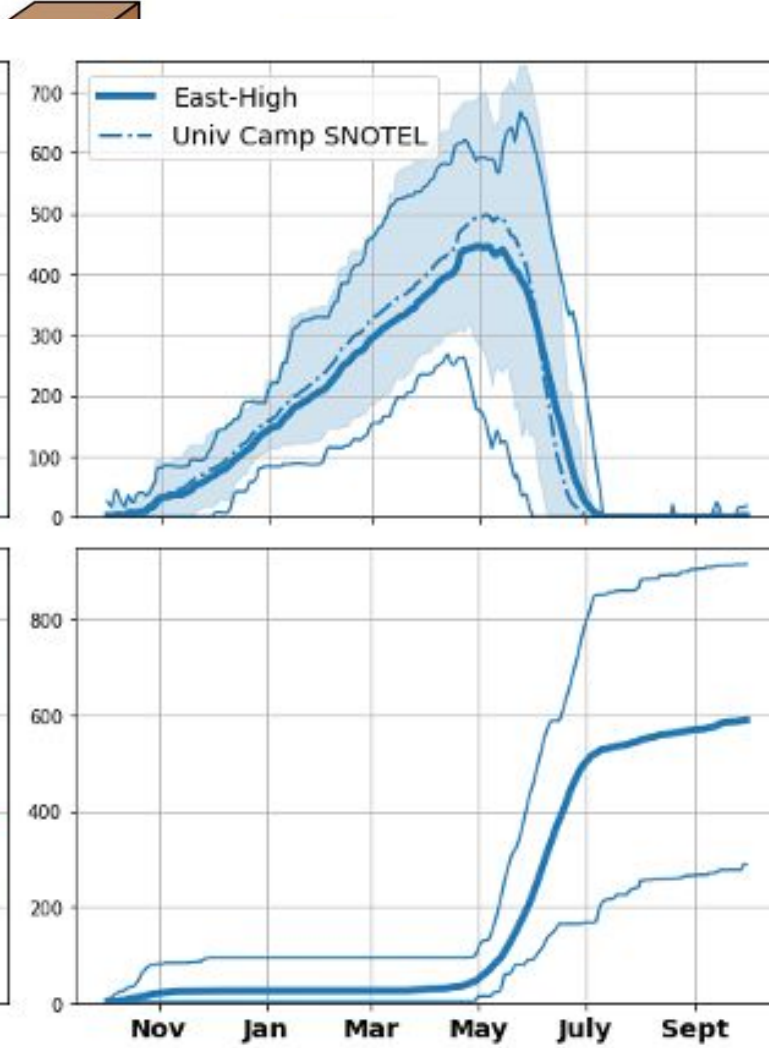
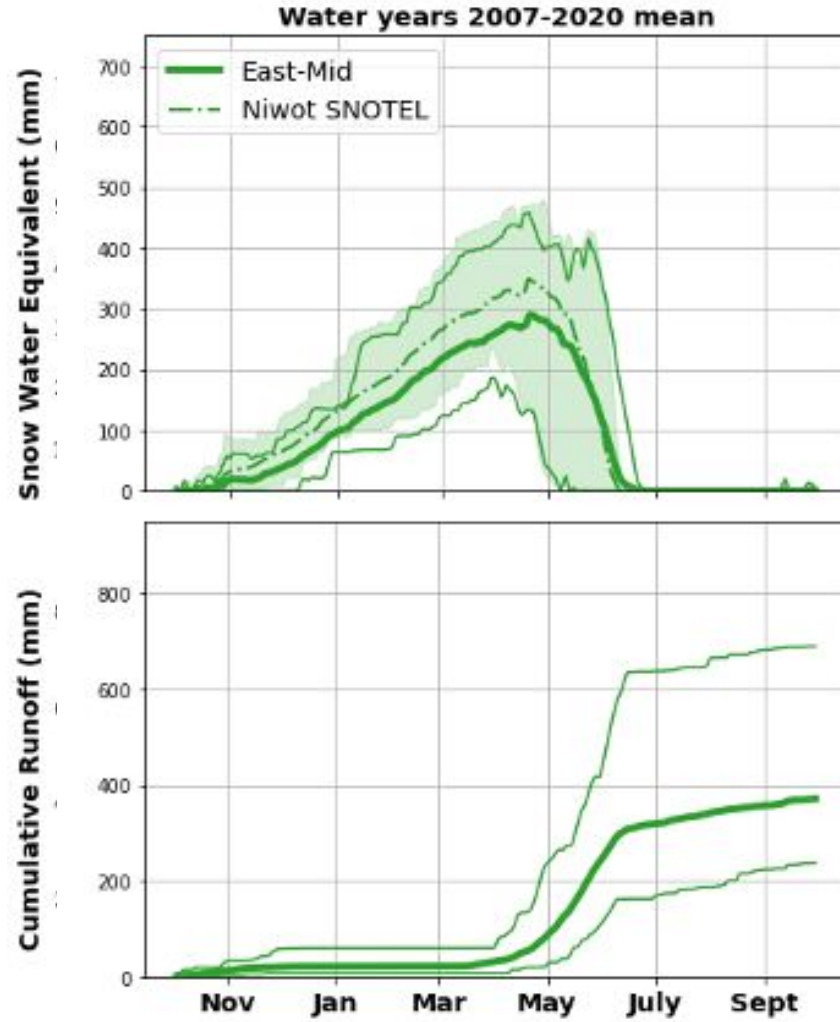
CESM grid cell ($\sim 1^\circ \times 1^\circ$)

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

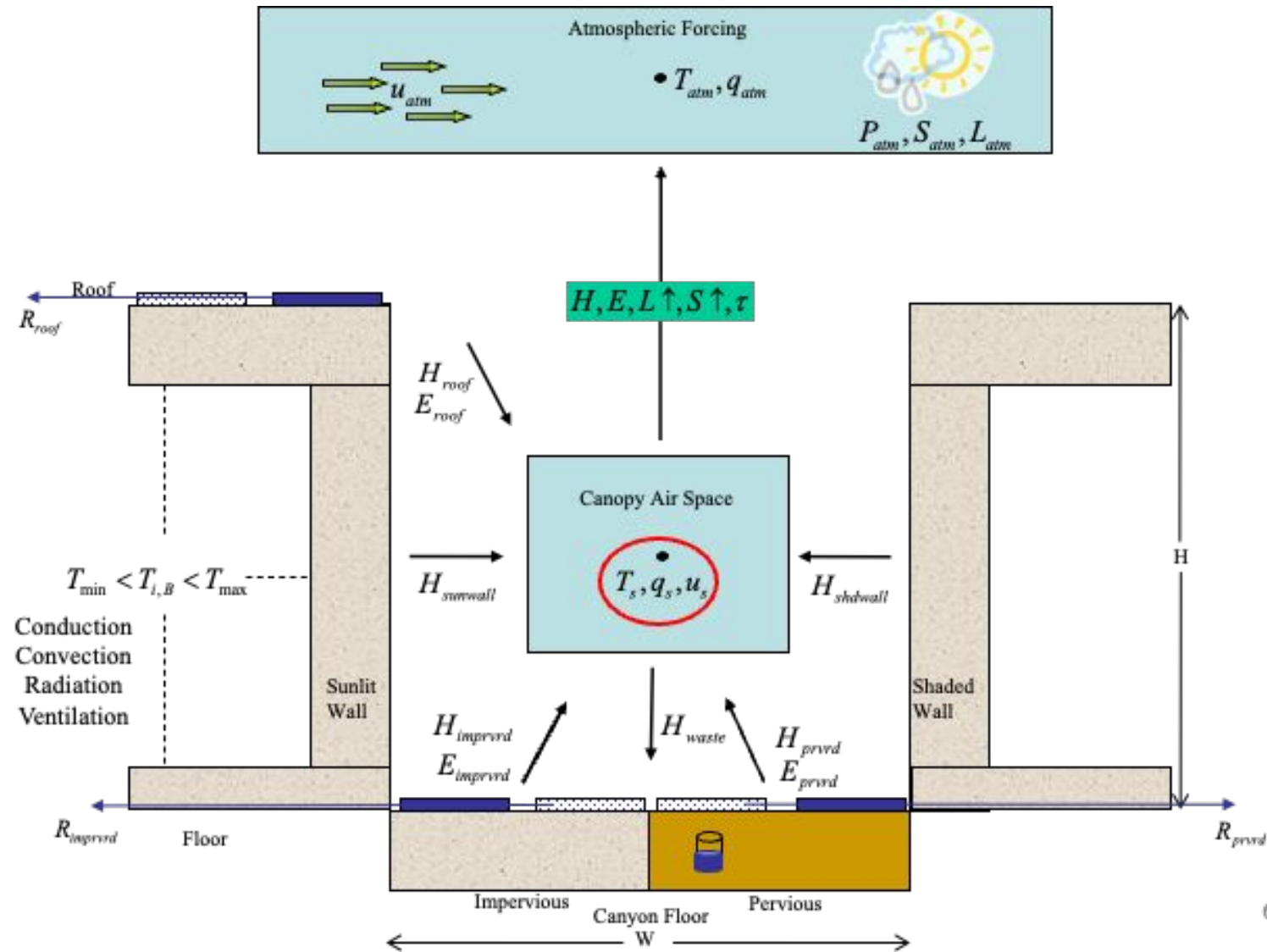


Fan et al. WRR, 2019
Swenson et al. JAMES 2019
Swenson & Lawrence 2025





CLM-Urban Model (CLM-U)

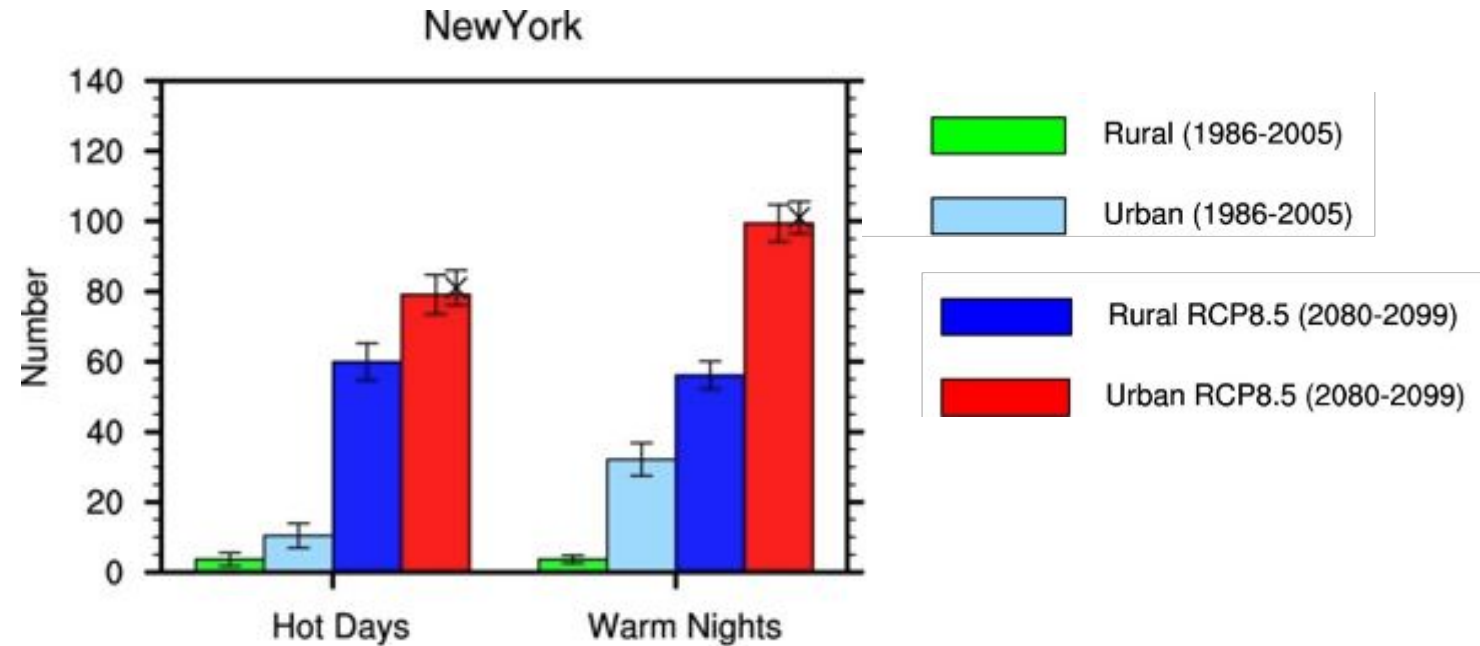


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CLM-Urban Model (CLM-U)

- **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

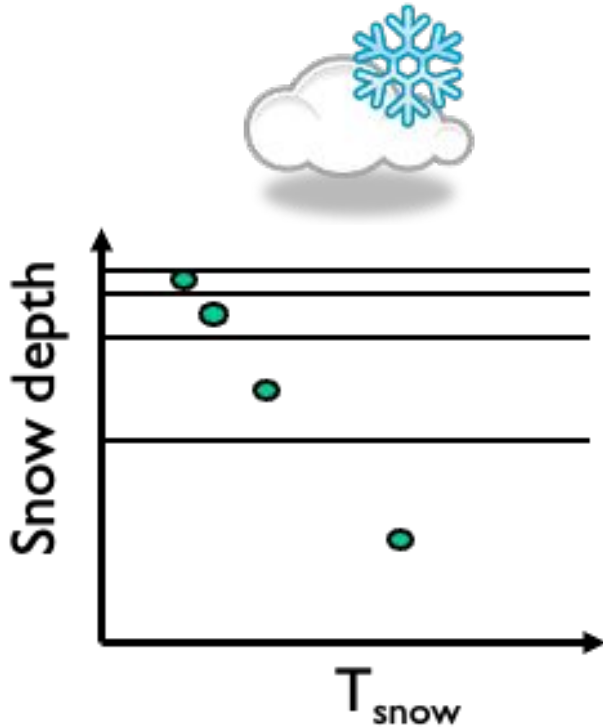
21st century climate change

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

Land Model Complexity: Snow

State Variables

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

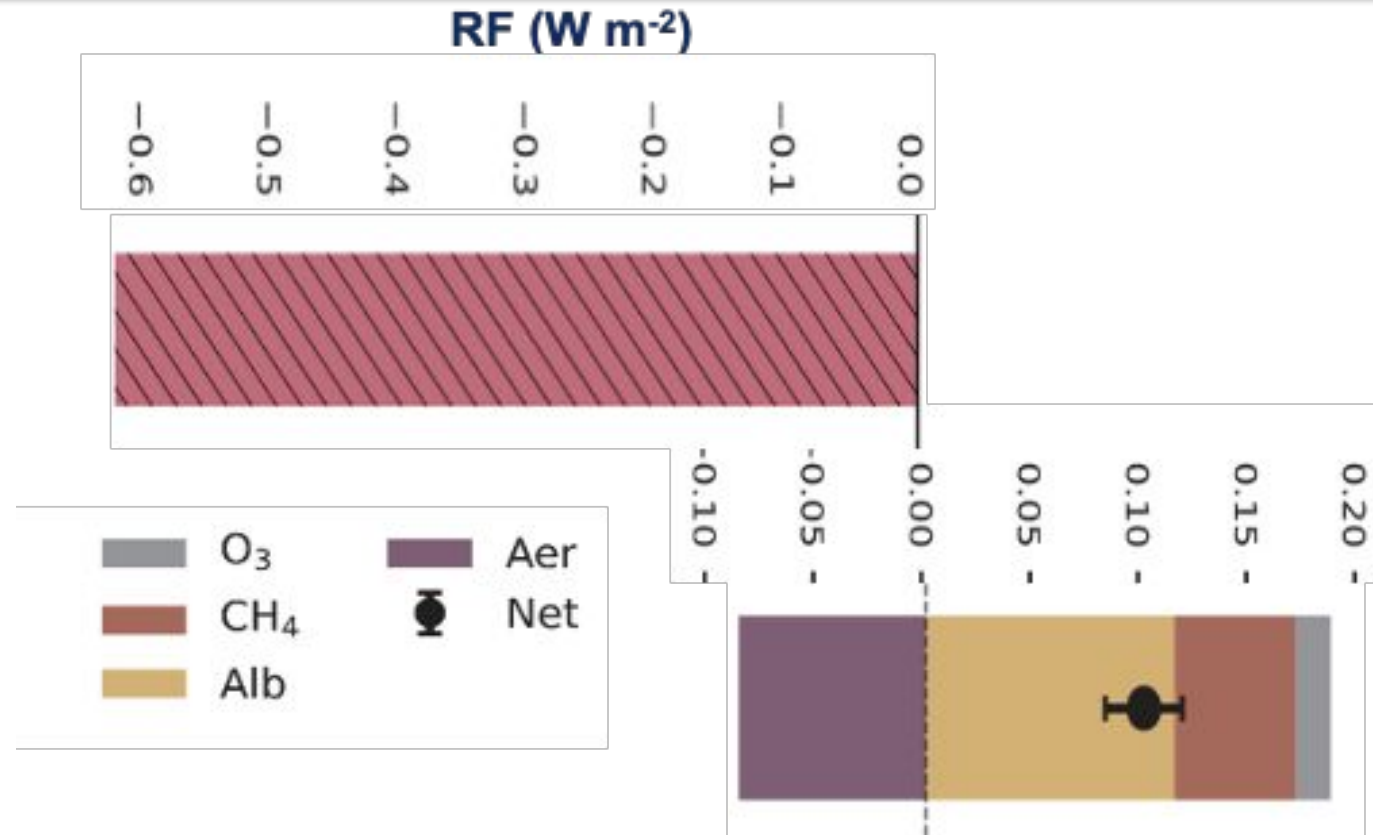


- Up to 10-layers of varying thickness
- **Represented processes**
 - Accumulation and fresh snow density: $f(T, \text{wind})$
 - Melt, refreezing, aging
 - Compaction
 - destructive metamorphism: $f(T, \text{wind})$
 - overburden
 - melt-freeze cycles
 - Sublimation
 - Water and energy transfer across 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 CO₂ removal

RF from other sources



Full understanding of climate impacts from reforestation requires ESMs
Changes in albedo and BVOC emissions from reforestation offset 1/3 of radiative forcing
(RF) from CO₂ removal in CESM2

Weber et al. Science 2024