Representing Land in the Earth System I: Biogeophysics

Will Wieder

CESM Tutorial 2025

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
- Dave Lawrence, Gordon Bonan
- LMWG Software Engineering Team
- LMWG Liaisons, Keith Oleson & Sam Levis

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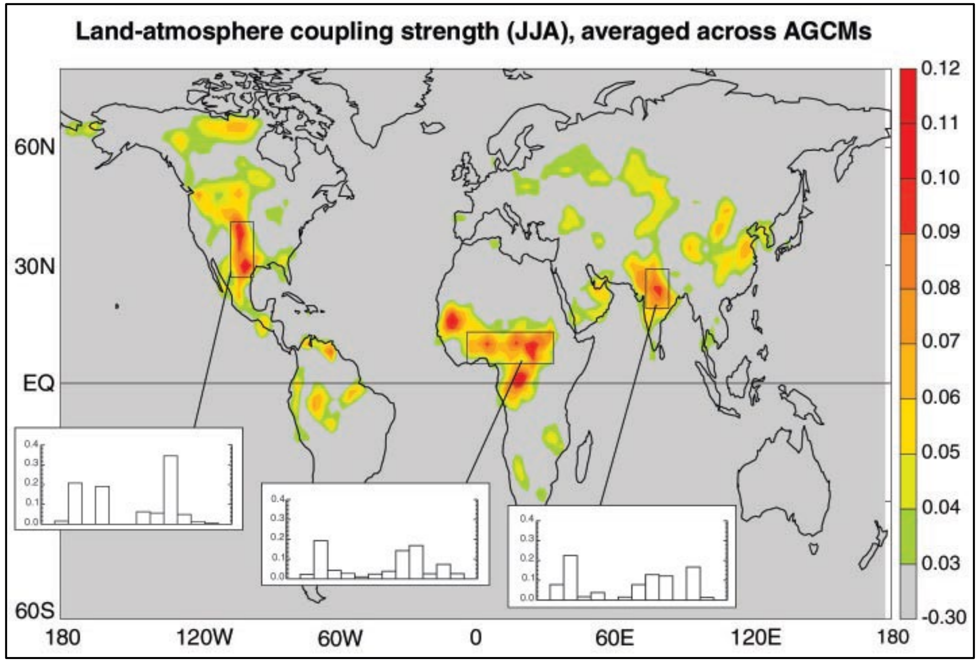
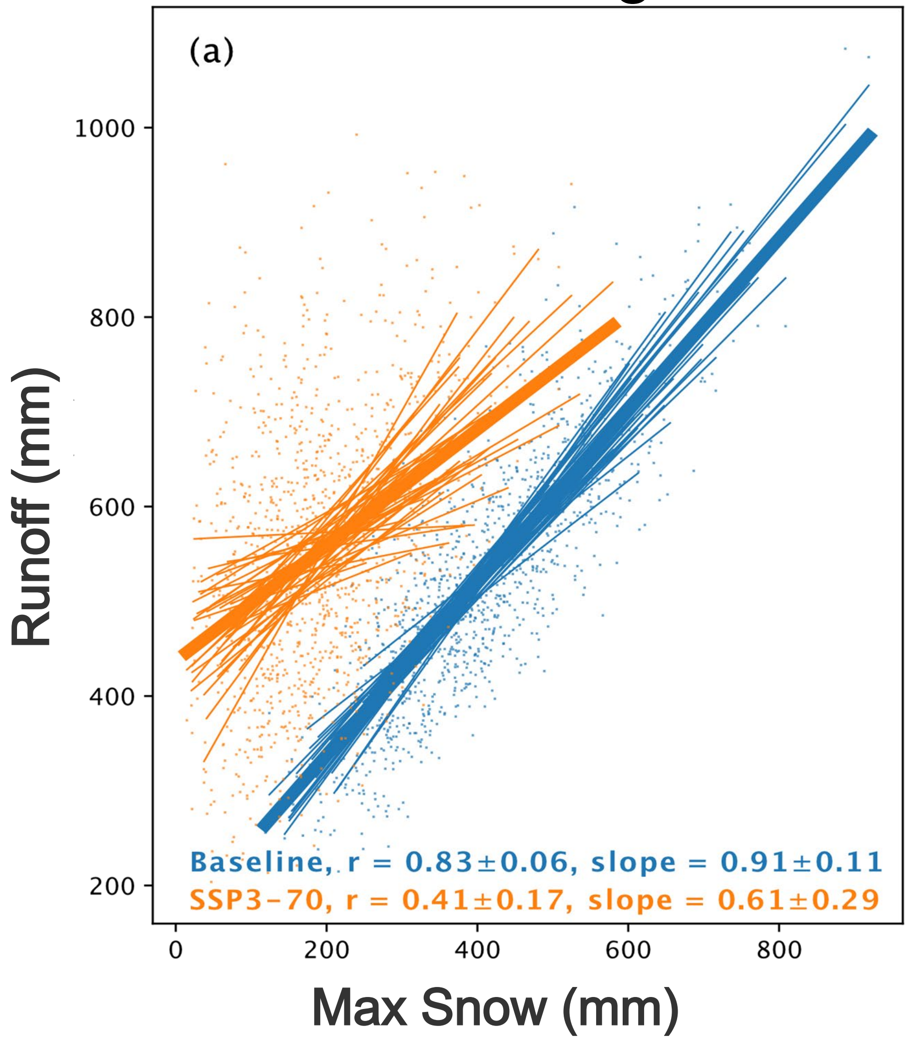
How much do soil moisture anomalies influence the atmosphere, the evolution of weather, and the generation of precipitation?



Koster et al., 2004

Water

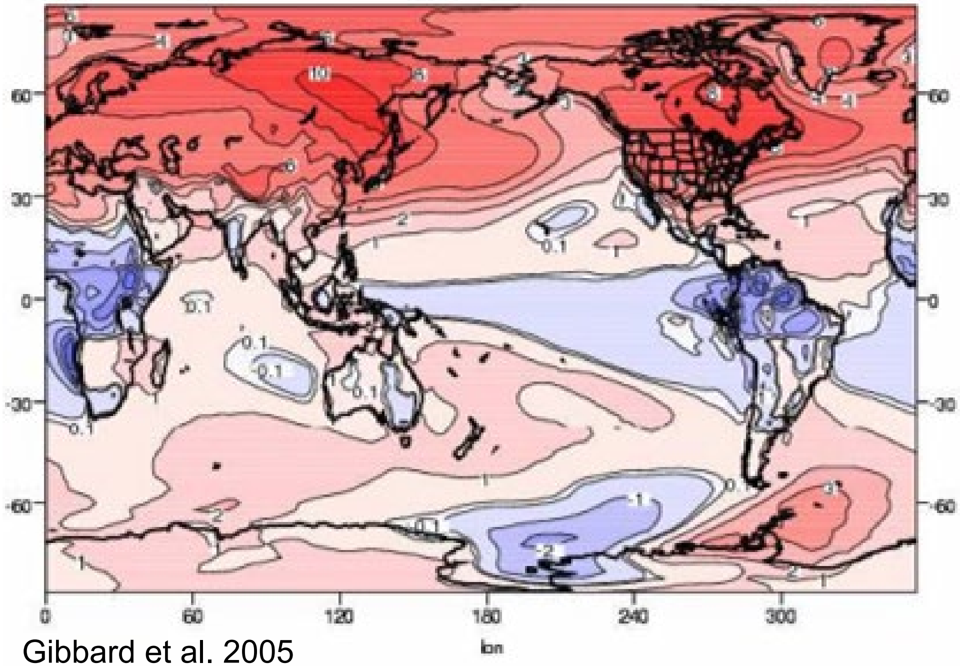
How are water (and food) resources under threat from climate change?



Wieder et al., PNAS 2022

Land Use and Land Cover Change

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



Gibbard et al. 2005

How does the Earth system respond to change on Land?

Arctic Greening (courtesy NSIDC)

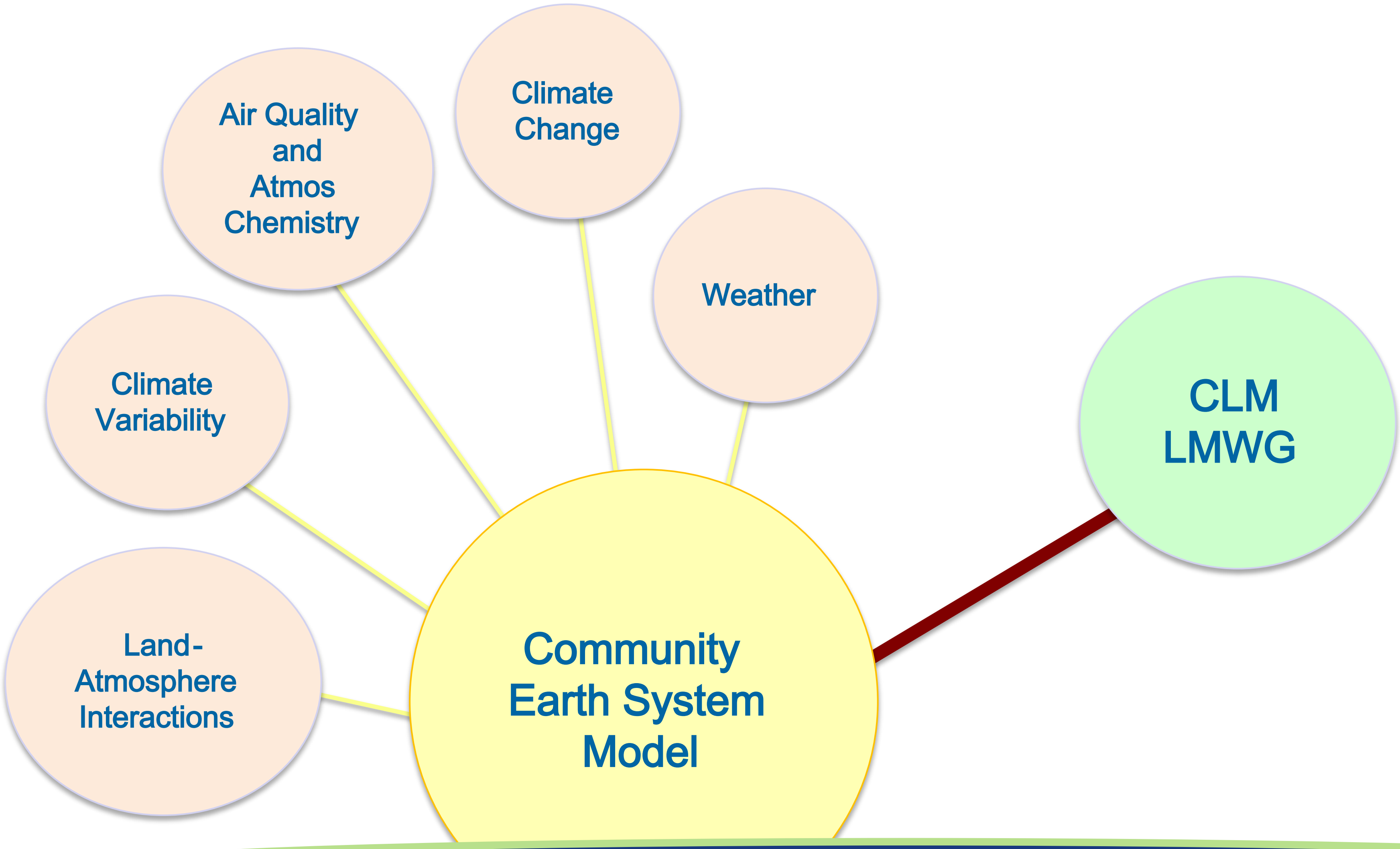
Permafrost Thaw (Nat. Geo.)

Agriculture (John K

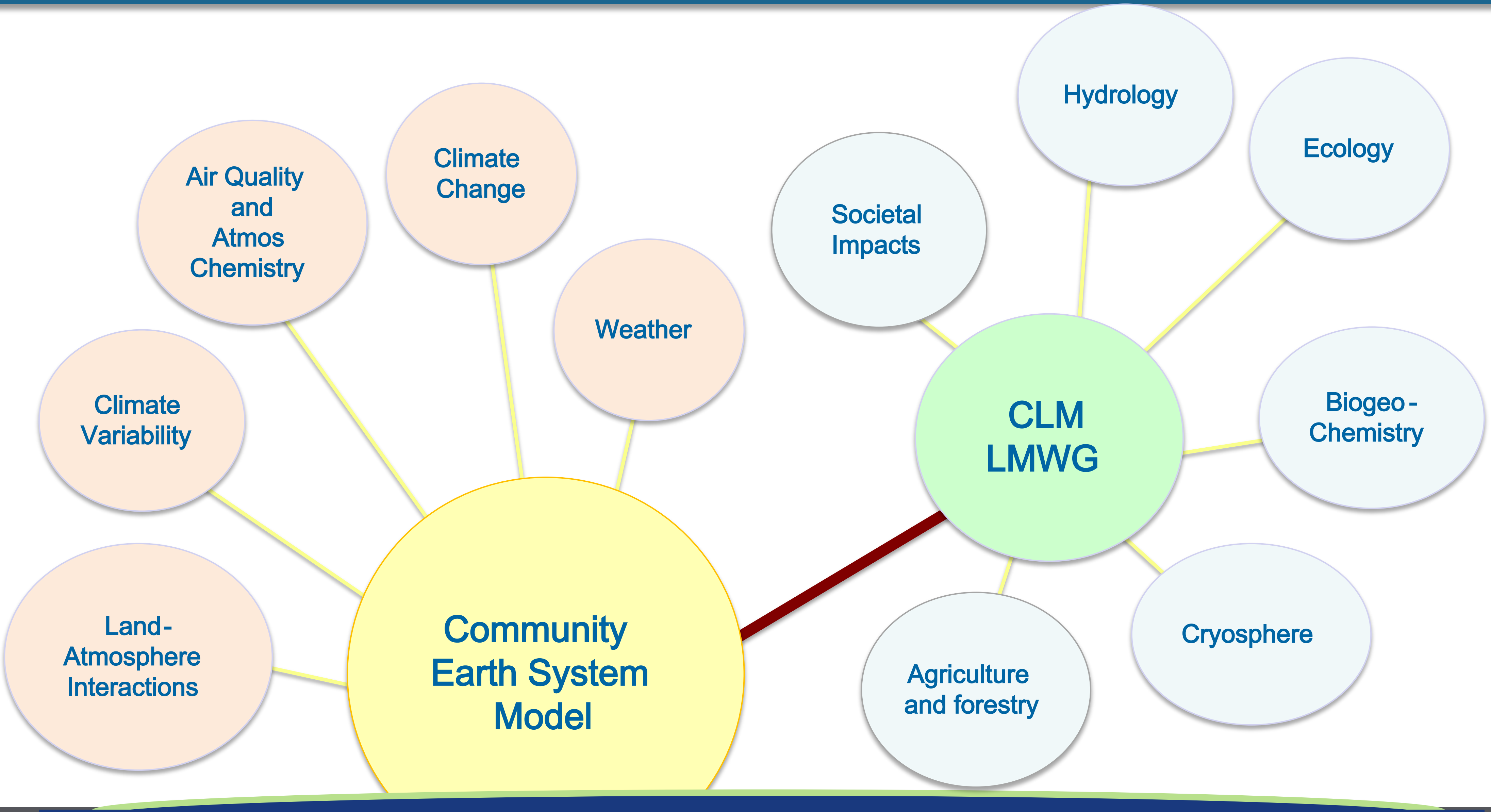
Deforestation (courtesy NPR)

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

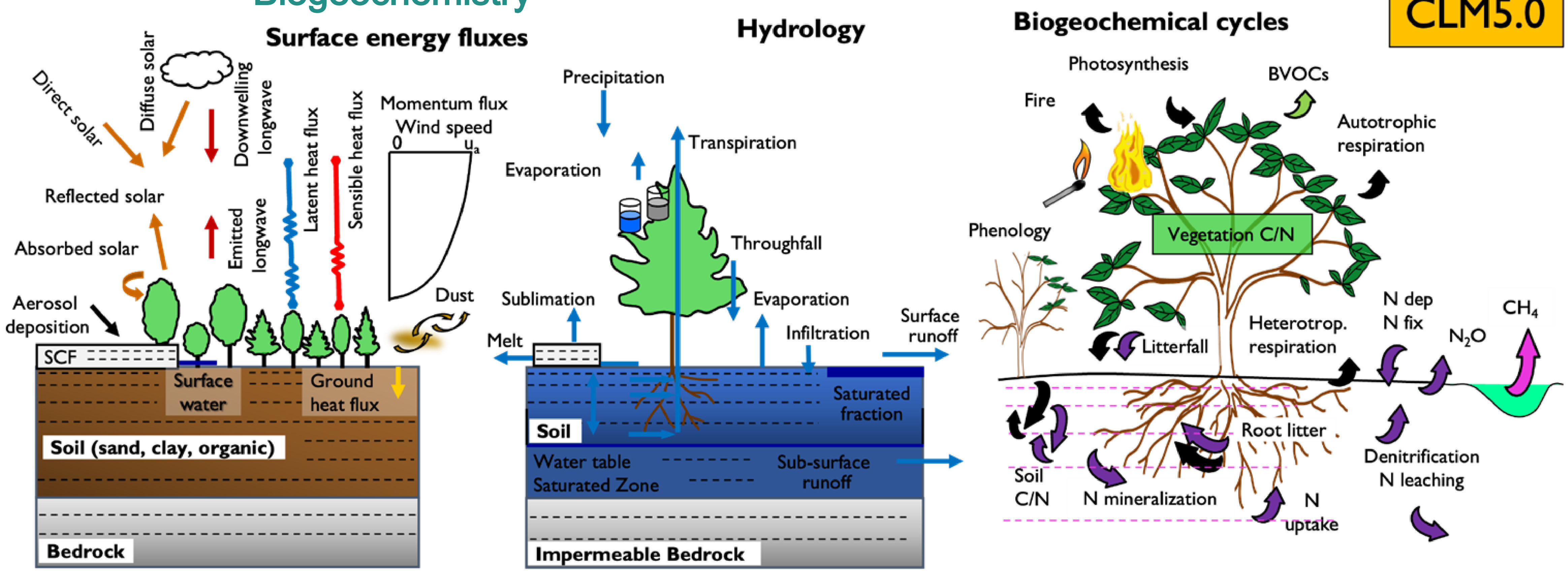
Land Modeling in ESMs: How

- **Exchanges** of momentum, energy, water vapor, CO_2, dust, and other trace gases/materials between land and atmosphere + routir of runoff to the ocean
- **States** of land surface (e.g., soil moisture, soil temperature, canop 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 inde

Key Processes within CLM / CTSM

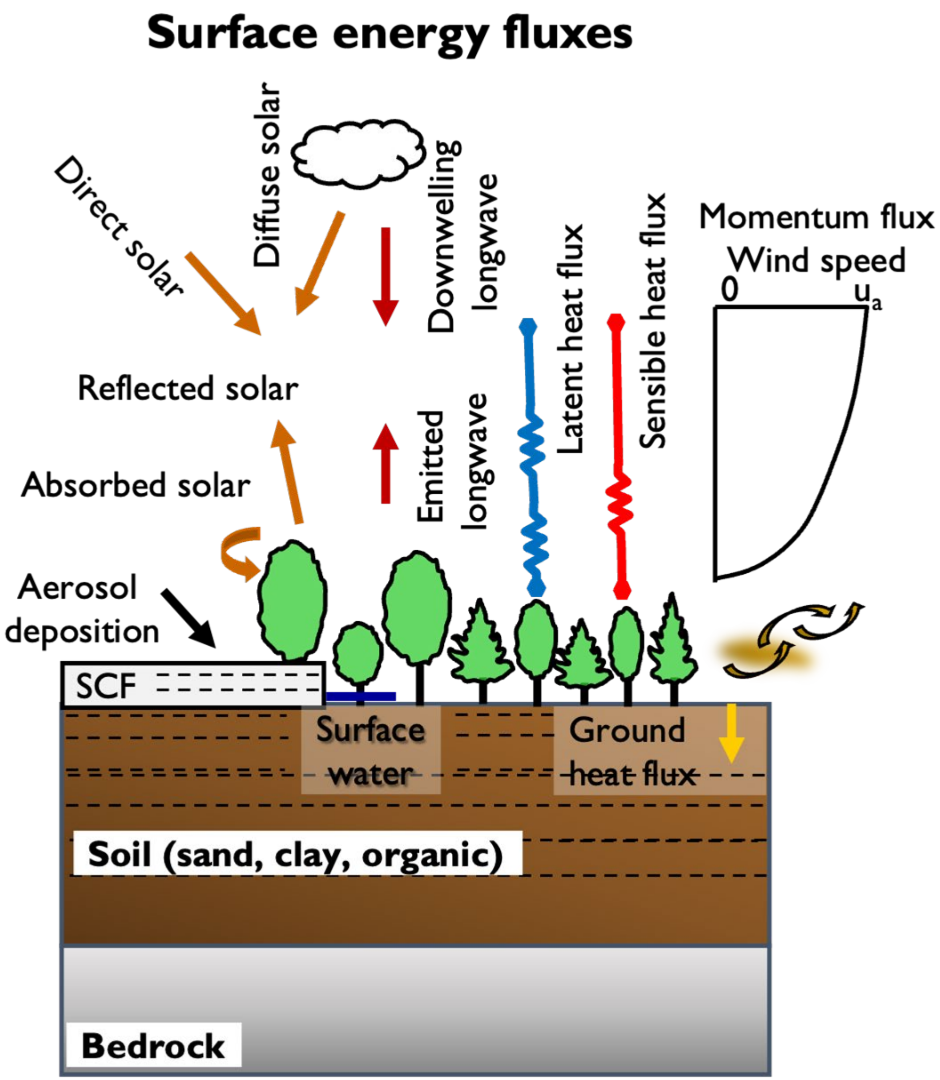
Biogeophysics

Biogeochemistry



Lawrence et al. 2019

At each time step CLM solves the Surface Energy Balance



Lawrence et al. 2019

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

$S\downarrow$, $S\uparrow$ are down / upwelling solar radiation,

$L\downarrow$, $L\uparrow$ are down / upwelling longwave radiation,

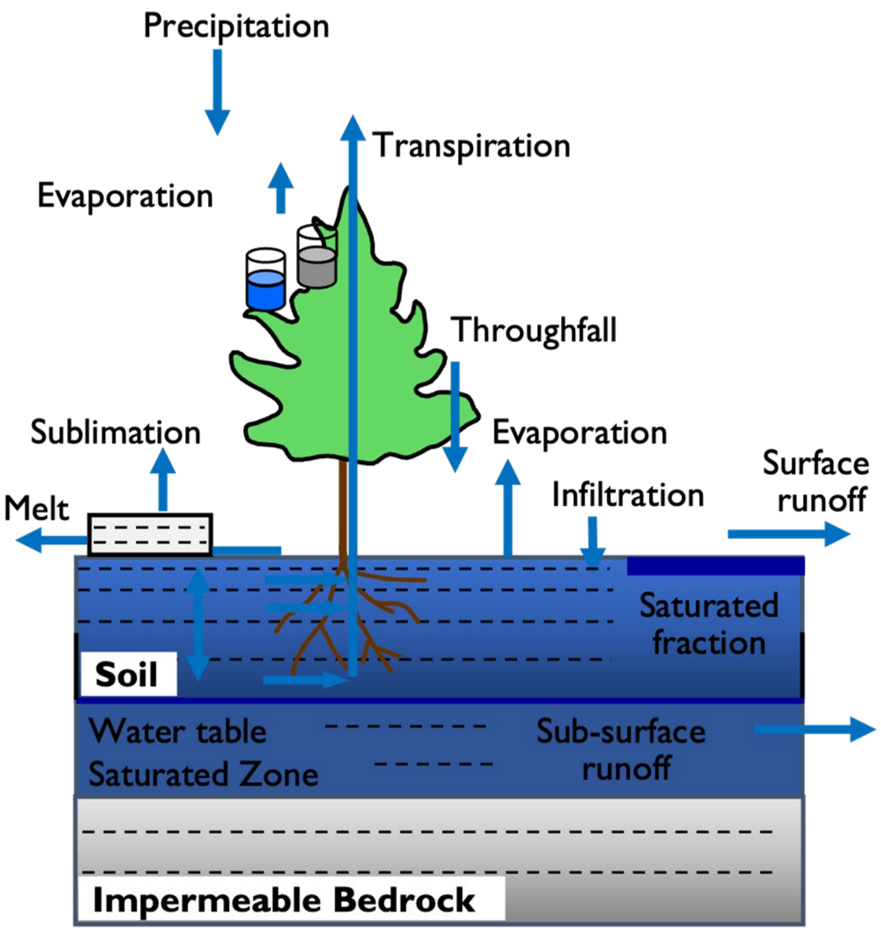
λ is latent heat of vaporization,

E is evaporation,

H is sensible heat flux

G is ground heat flux

… and the Surface Water Balance



Lawrence et al. 2019

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

P is rainfall/snowfall,

ES is soil evaporation,

ET is transpiration,

EC is canopy evaporation,

R is runoff (surf + sub-surface),

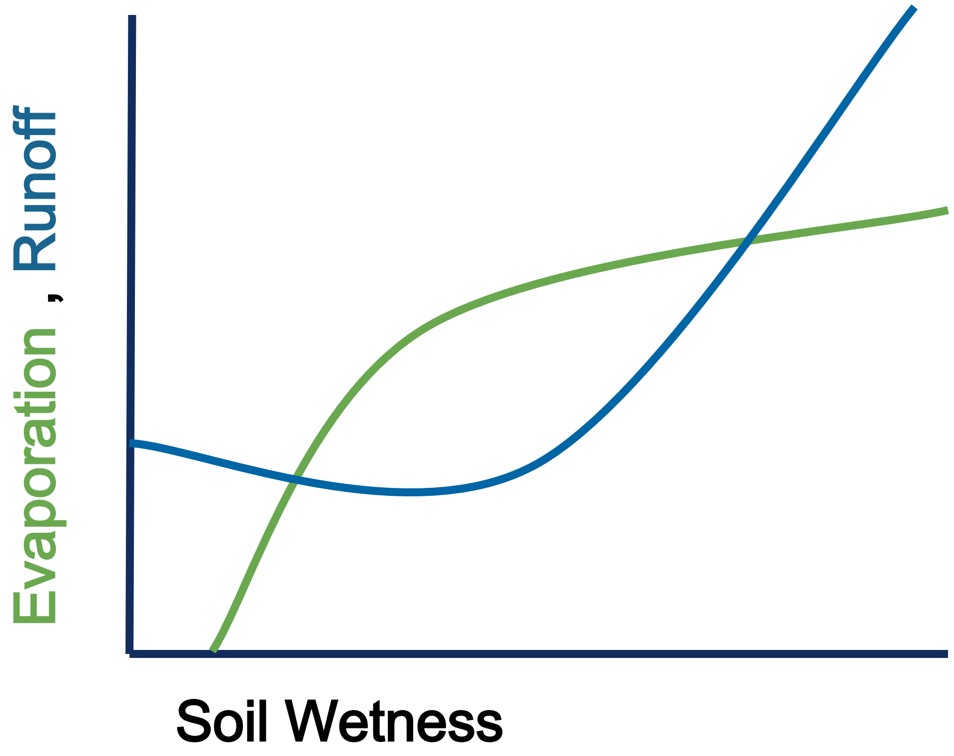
ΔW_{soil}, ΔW_{snow}, ΔW_{sfcw}, & ΔW_{can} are changes in soil moisture, snow, surface water, and canopy water over a timestep

Terrestrial water and energy cycles are intricately linked

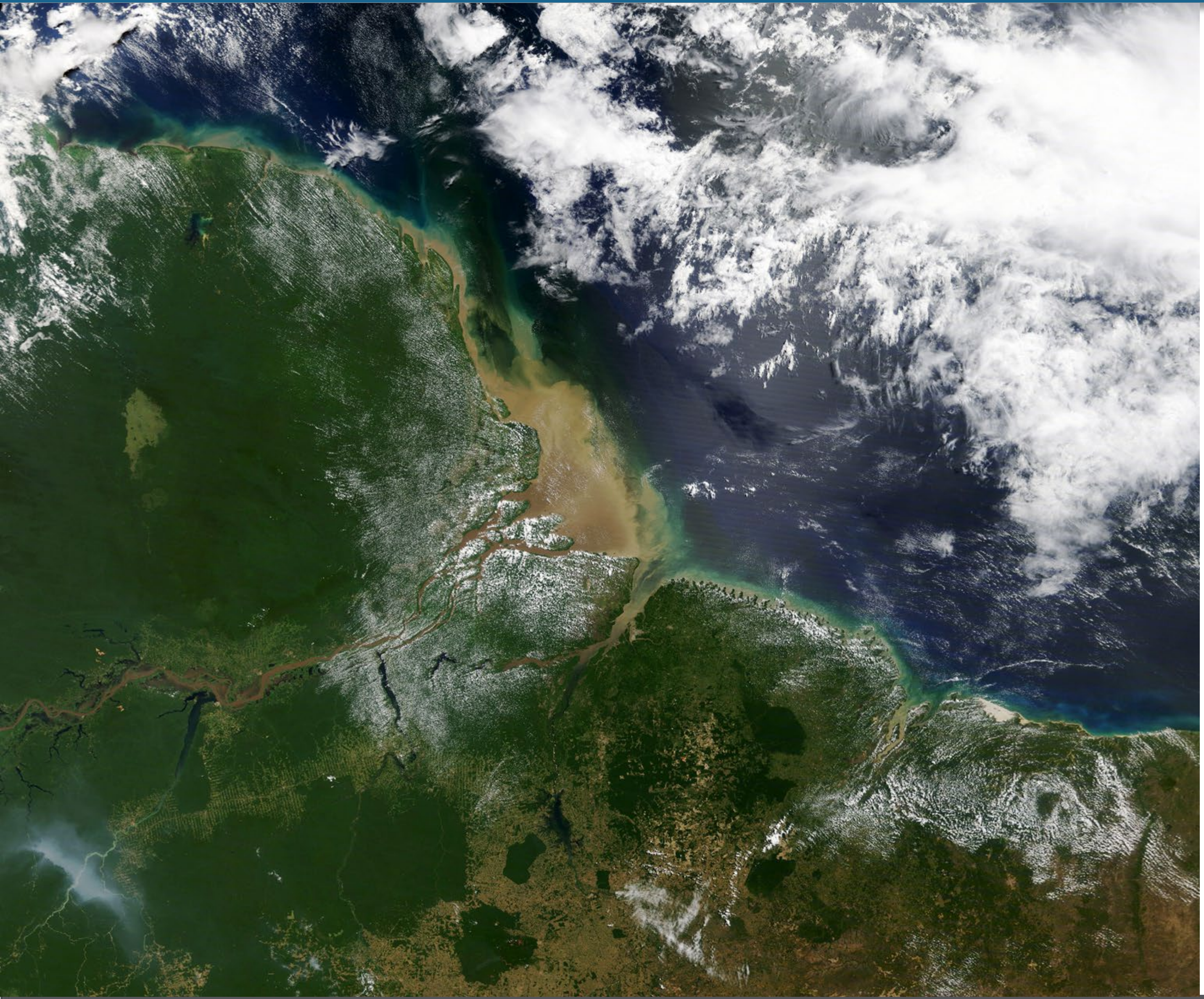
"The ability of a land-surface scheme to model evaporation correctly depends crucially on its ability to model runoff correctly. The two fluxes are intricately related through soil moisture."

(Koster and Milly, 1997).

What is this statement missing?



Land Model Complexity: Plants



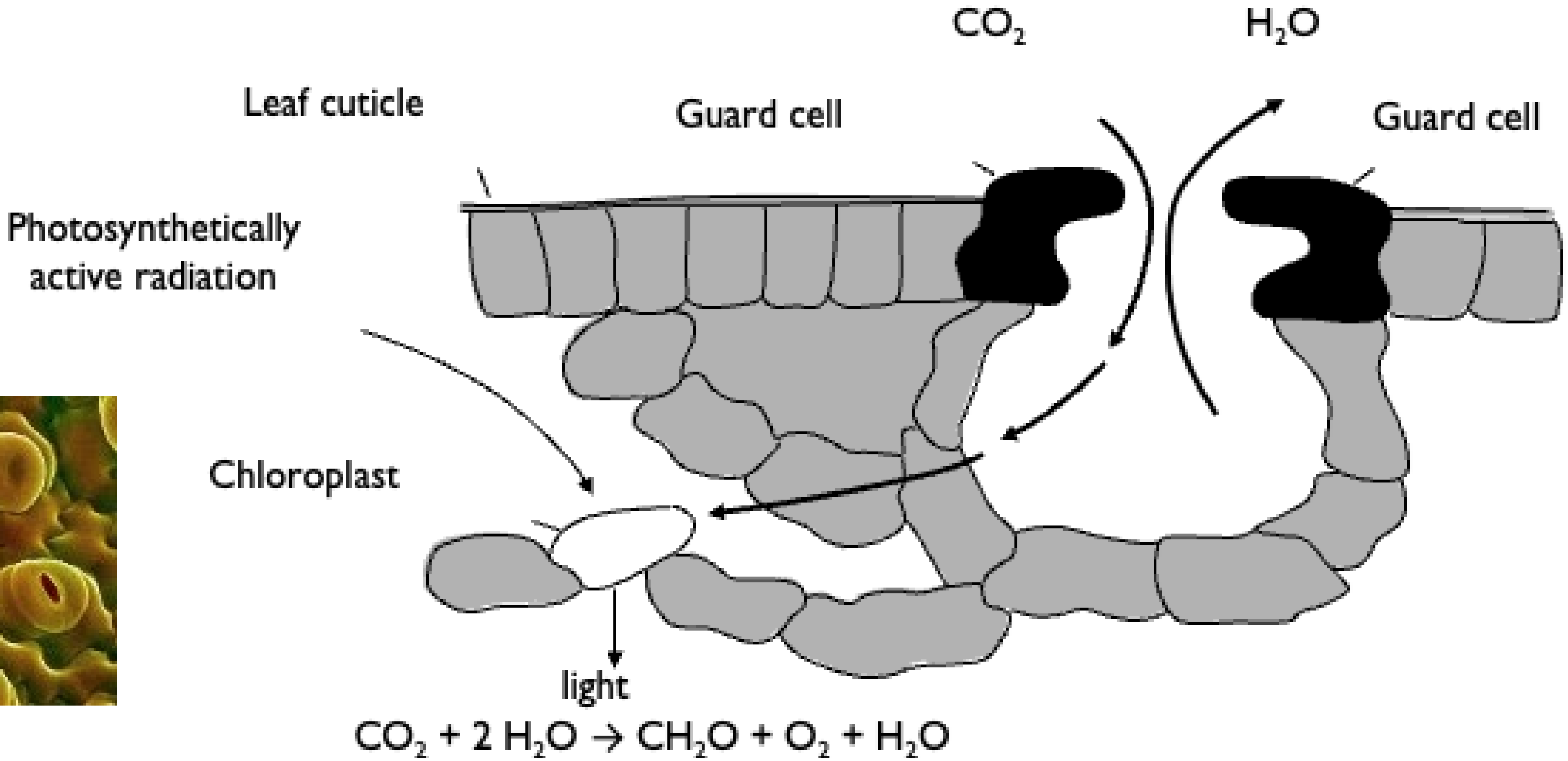
Blue marble…

…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



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

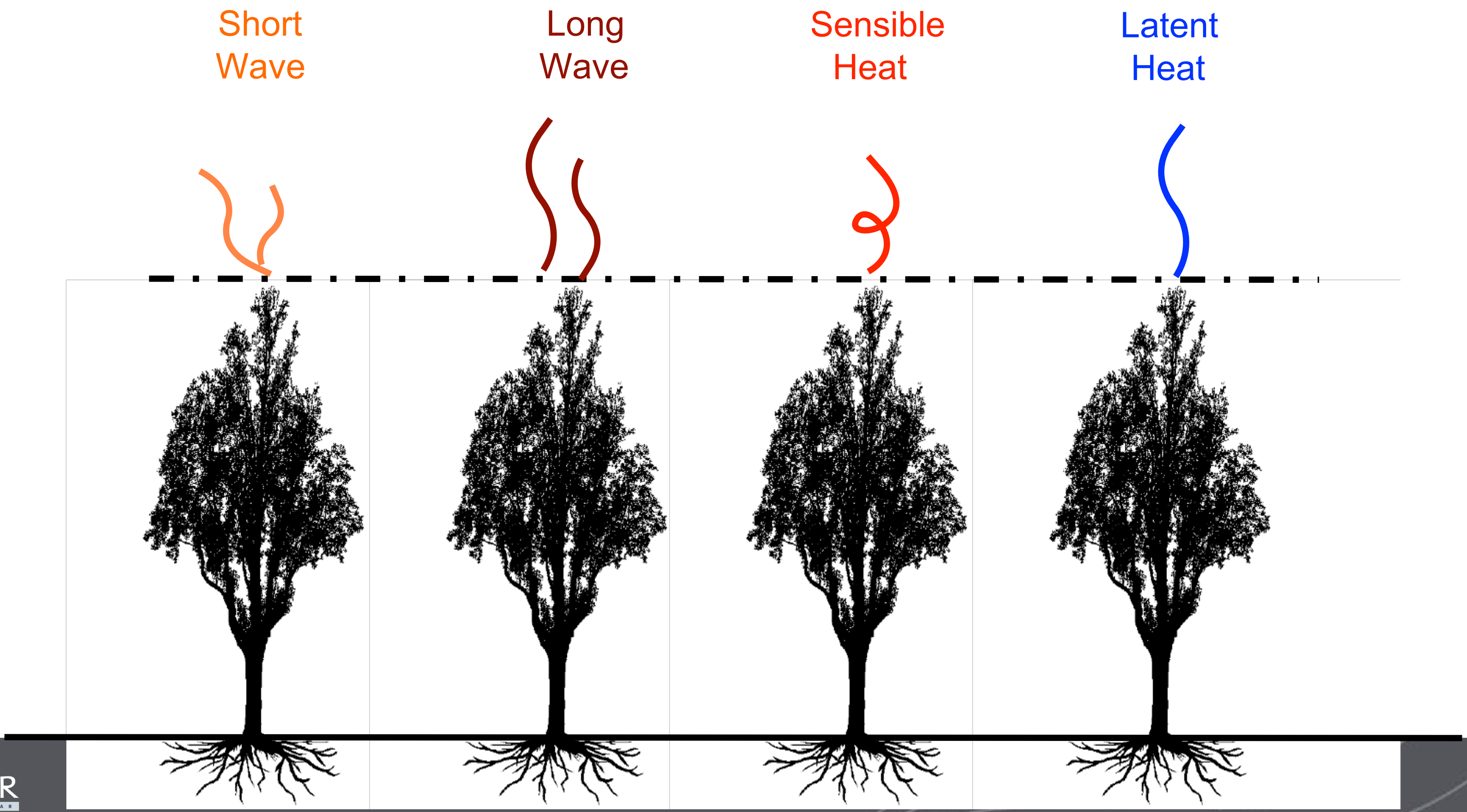
And…

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

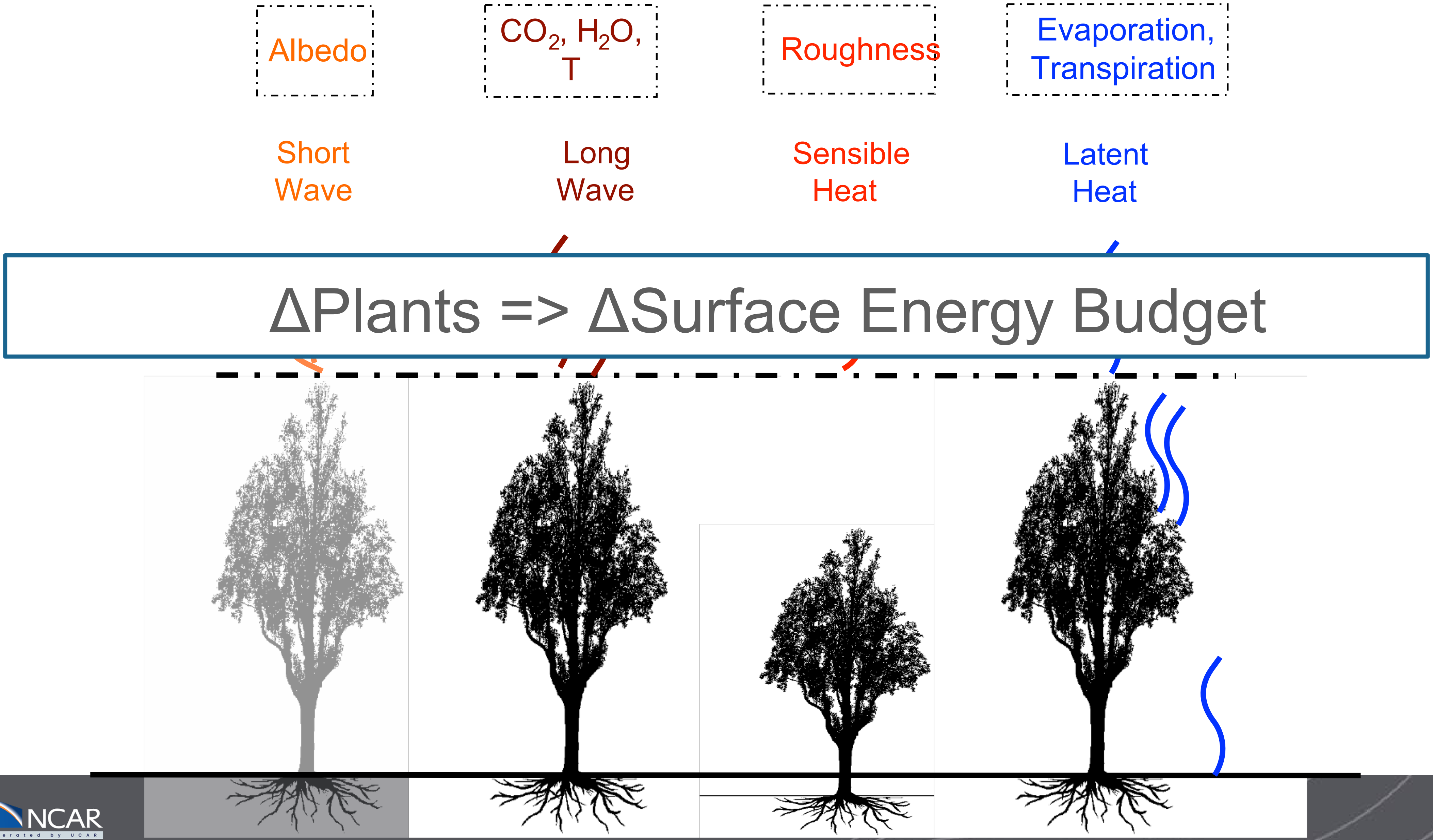
Lawrence et al. 2019

How do plants and climate interact?

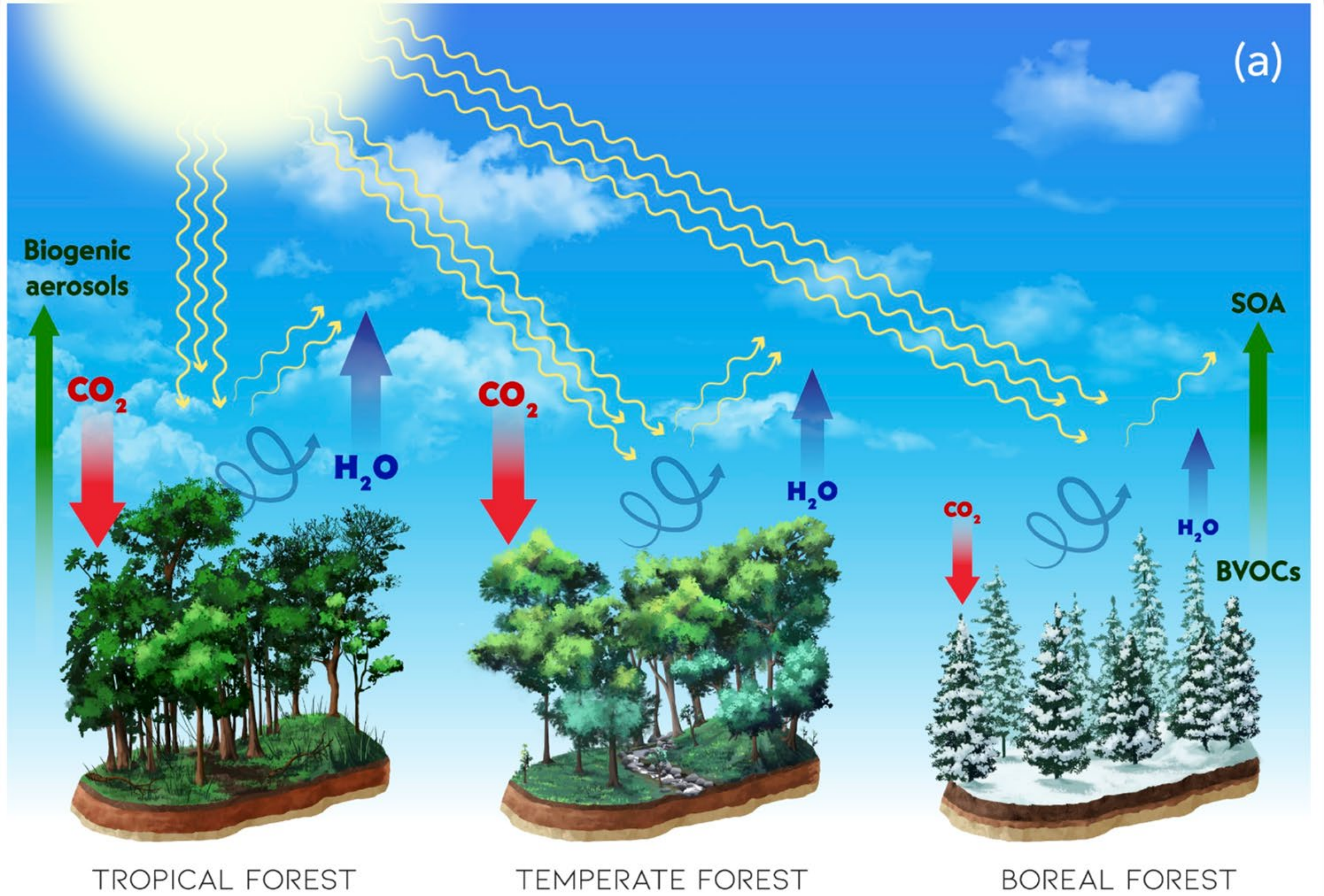
Terrestrial surface energy budget



How do plants and climate interact?



Not all forests have the same climate impact



Bonan 2008
Bonan et al. 2024

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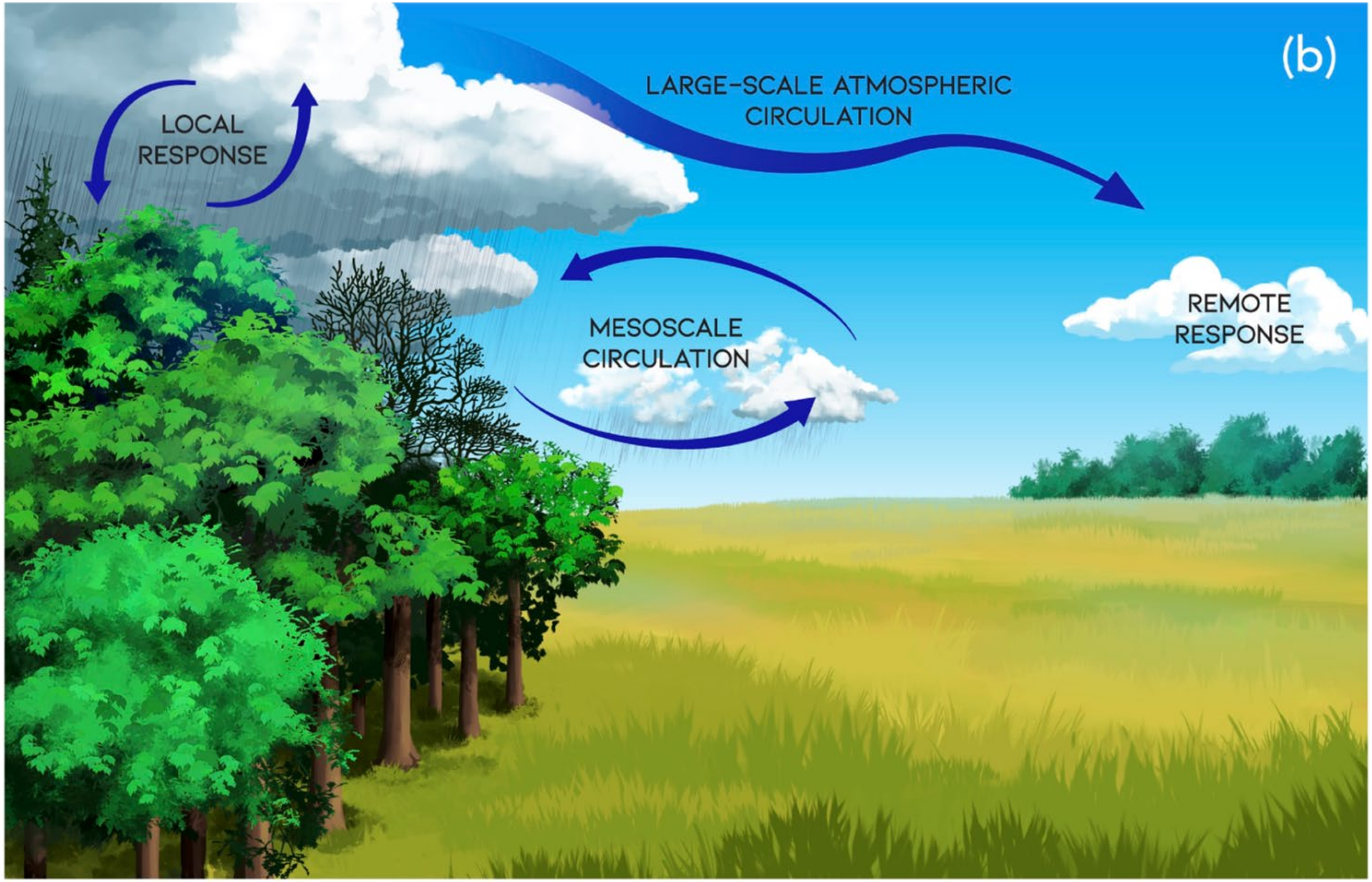

Bonan 2008
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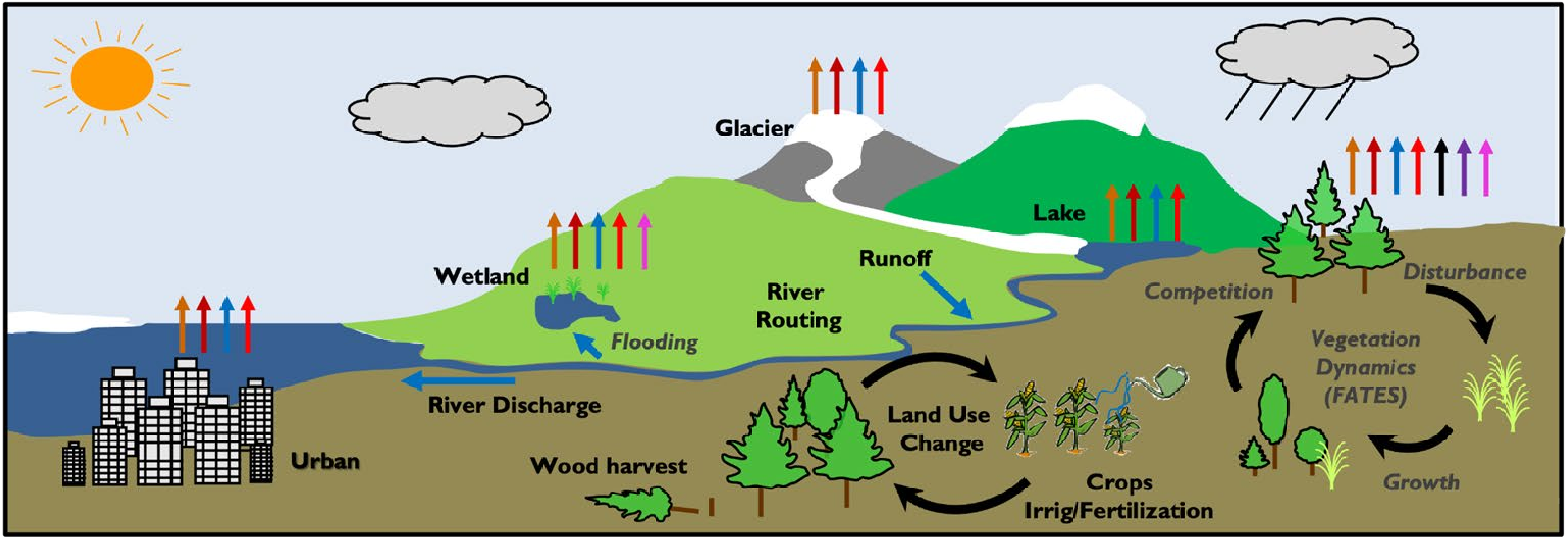
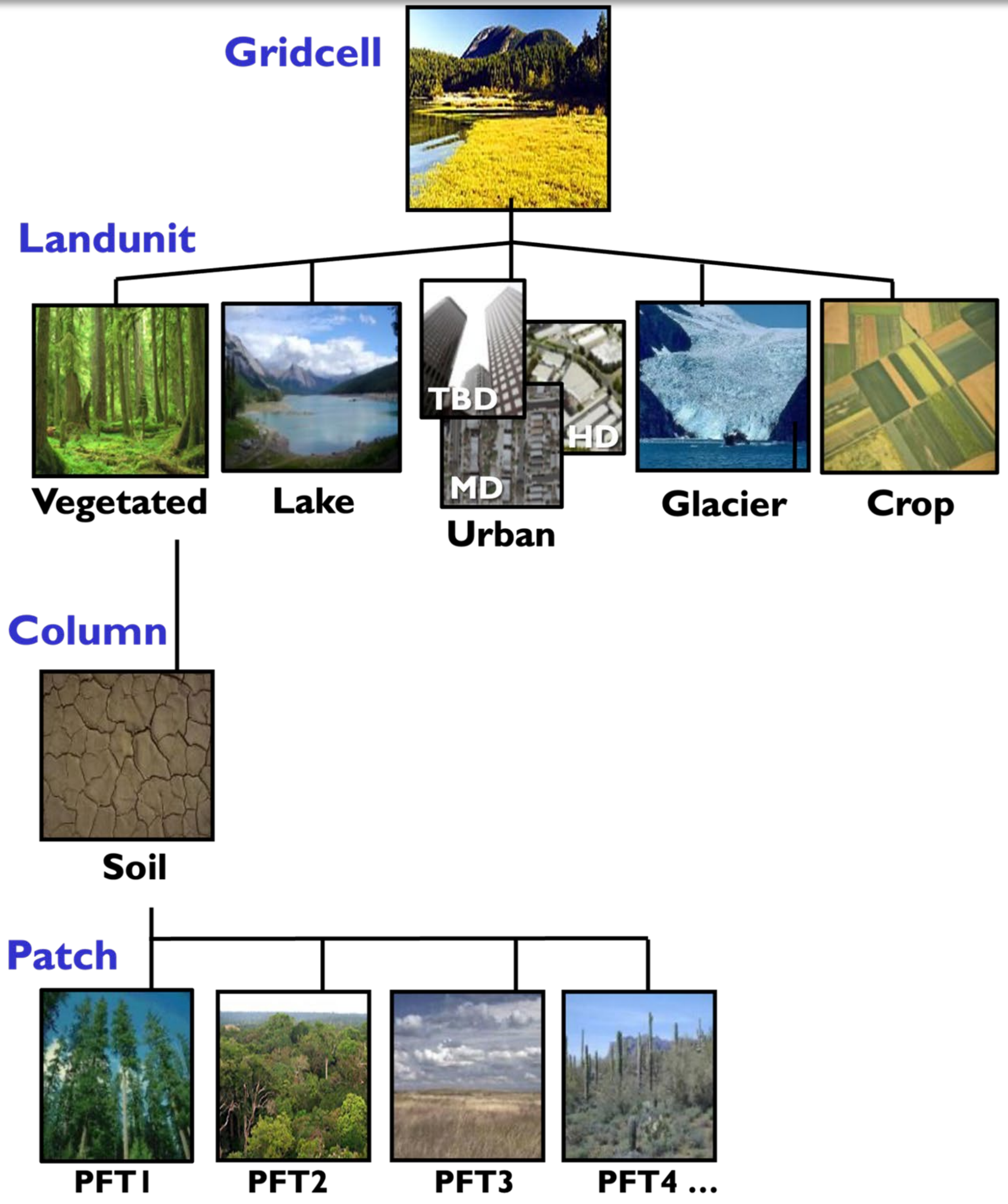
Land Surface Heterogeneity



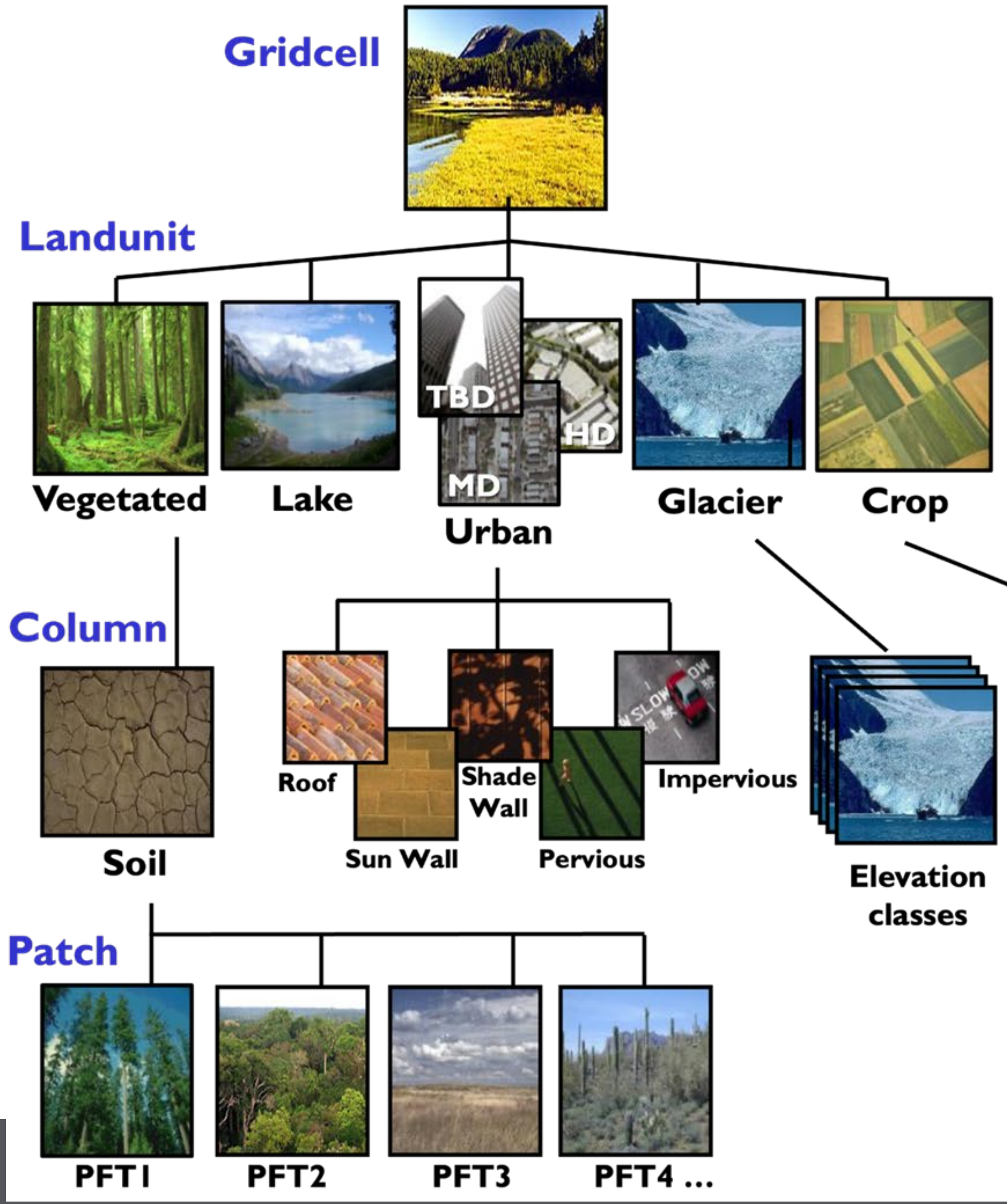
Lawrence et al. 2019

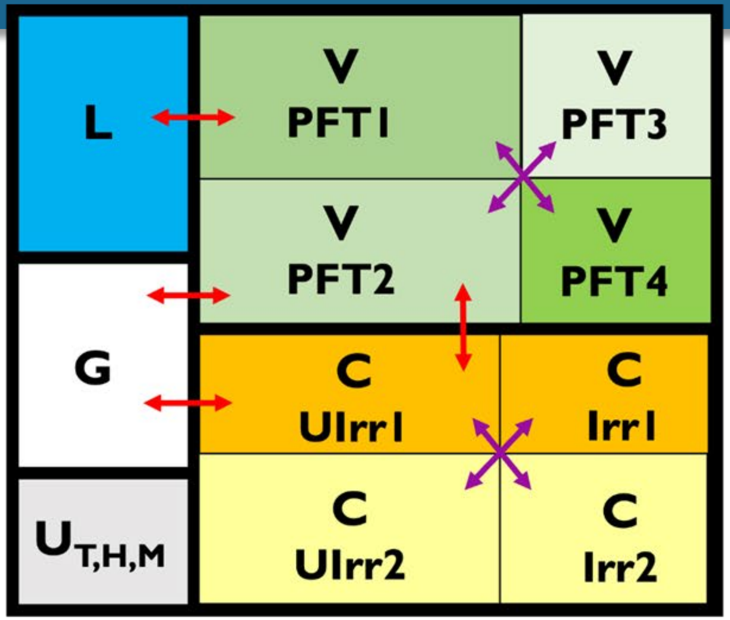
Changing Land Surface Heterogeneity

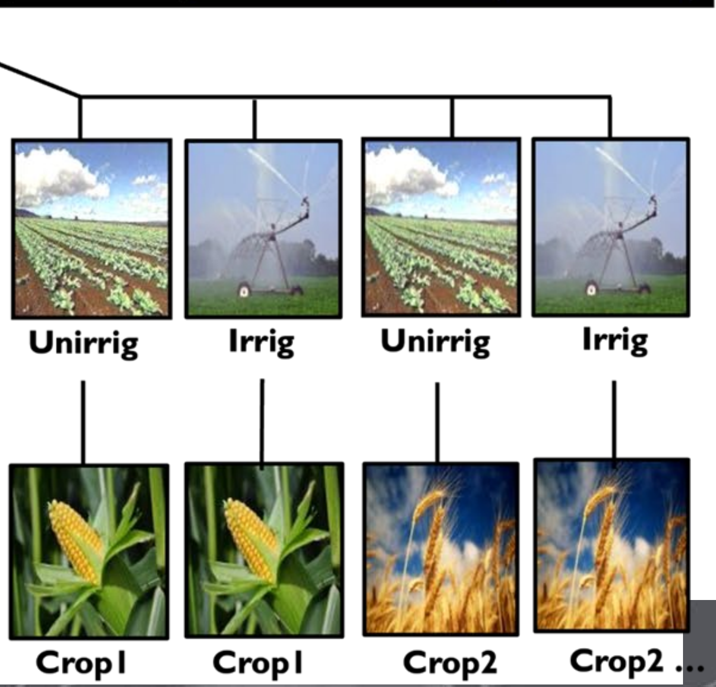


Lawrence et al. 2019

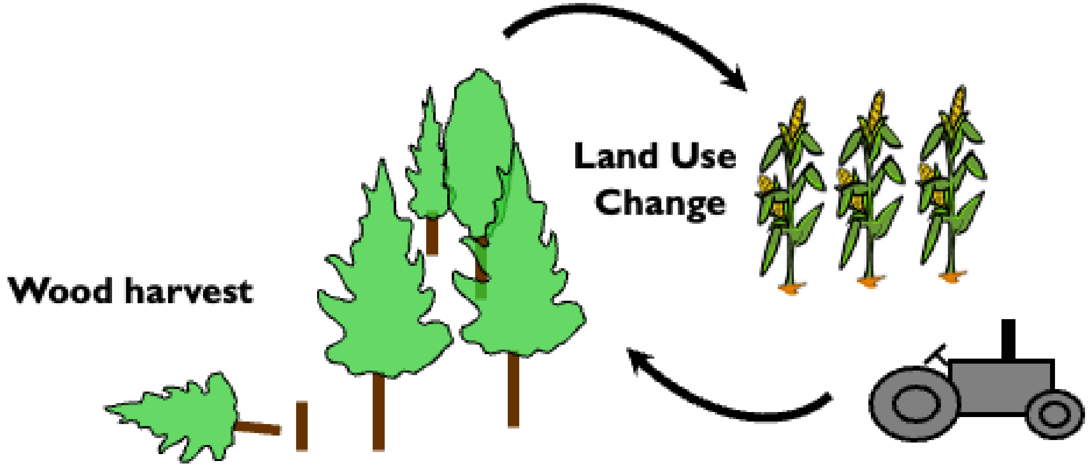
Changing Land Surface Heterogeneity



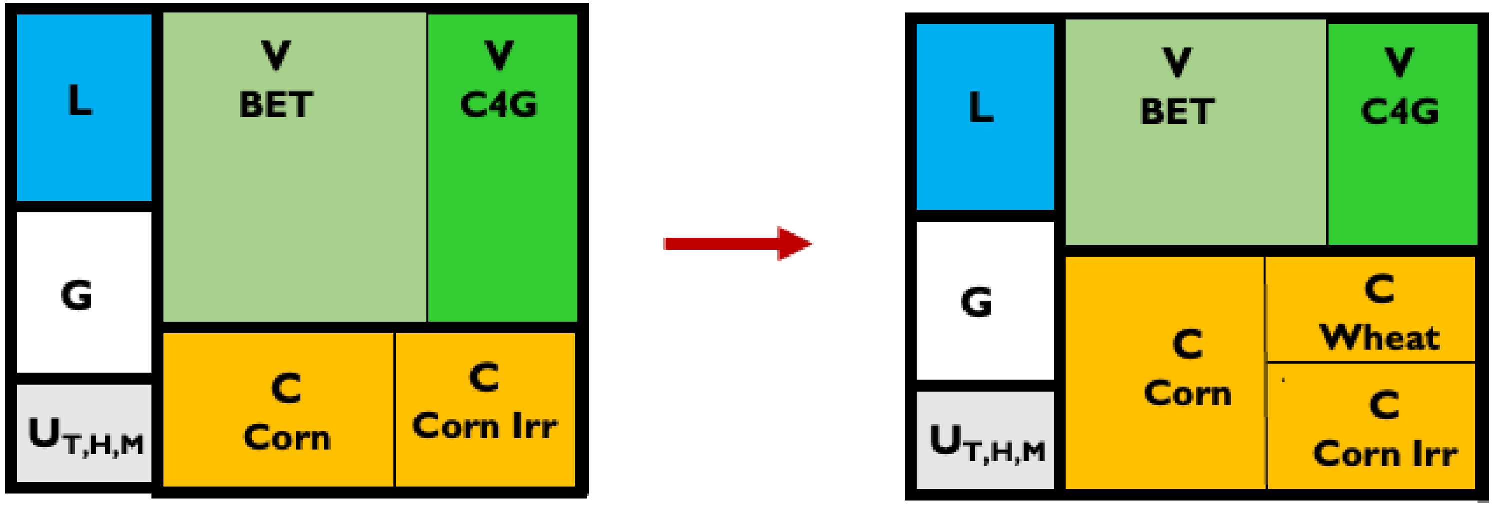




Lawrence et al. 2019



Deforestation example



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: Future Directions

Ecosystems:
FATES

Food:
Crop Model

Water:
Hillslope
Hydrology

Urban: CLM -U

Abbreviated list of land biophysical features in CESM3+

Emission Driven Focus

Interactive Fires

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

Calibration Capabilities & Parameter Uncertainty

Transient Urban Extent

Transient Hillslope Capabilities

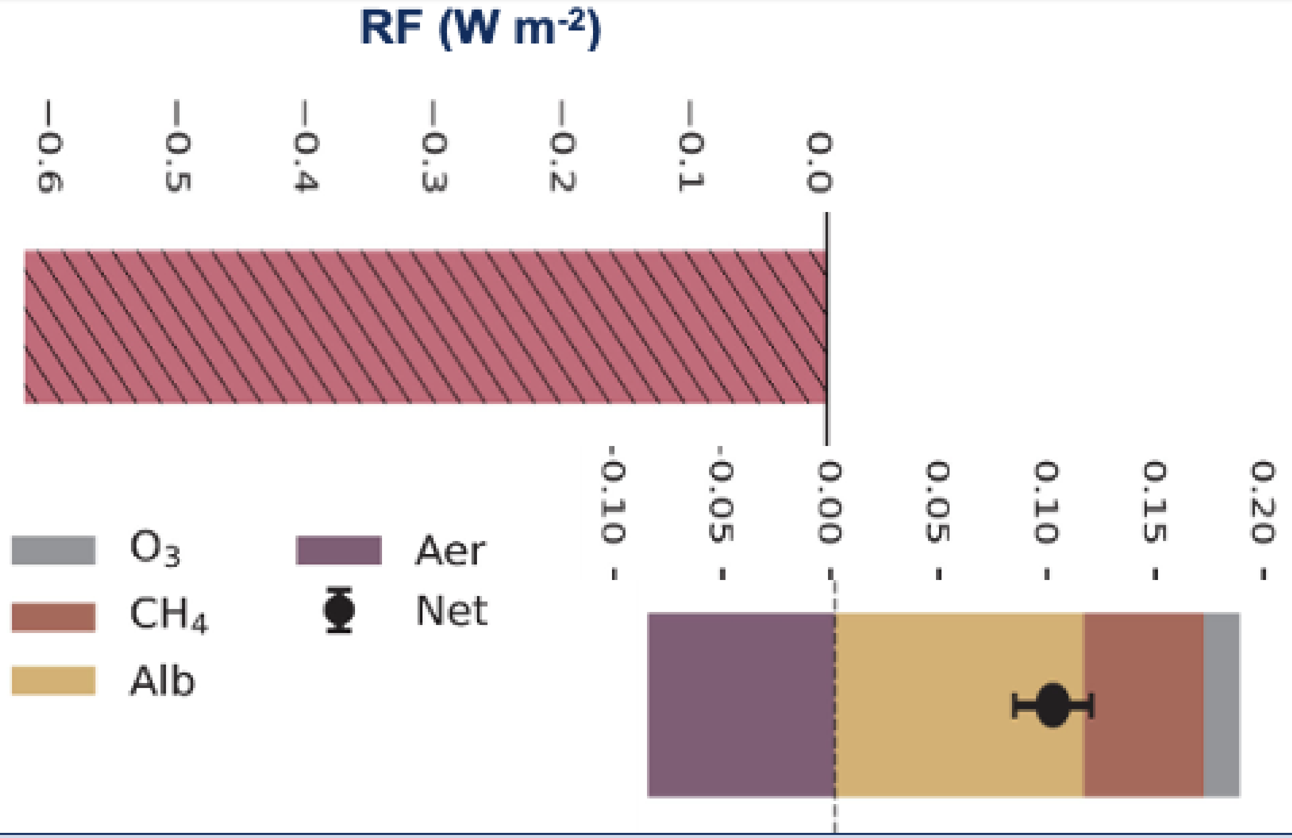
Transient FATES with LULCC

Questions & Discussion

Earth system to reforestation

RF from CO_2 removal

RF from other sources



Full understanding of climate impacts from reforestation requires ESMs

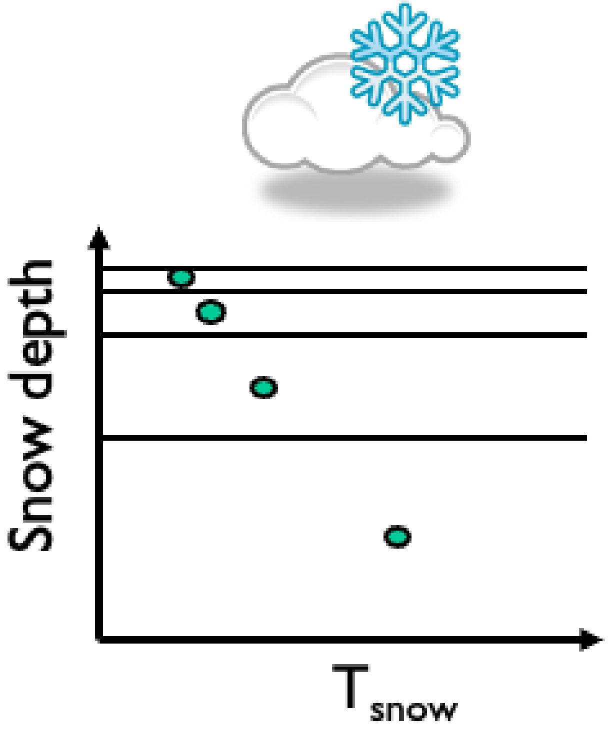
Changes in albedo and BVOC emissions from reforestation offset ⅓ of radiative forcing (RF) from CO_2 removal in CESM2

Weber et al. Science 2024

Land Model Complexity: Snow

State Variables

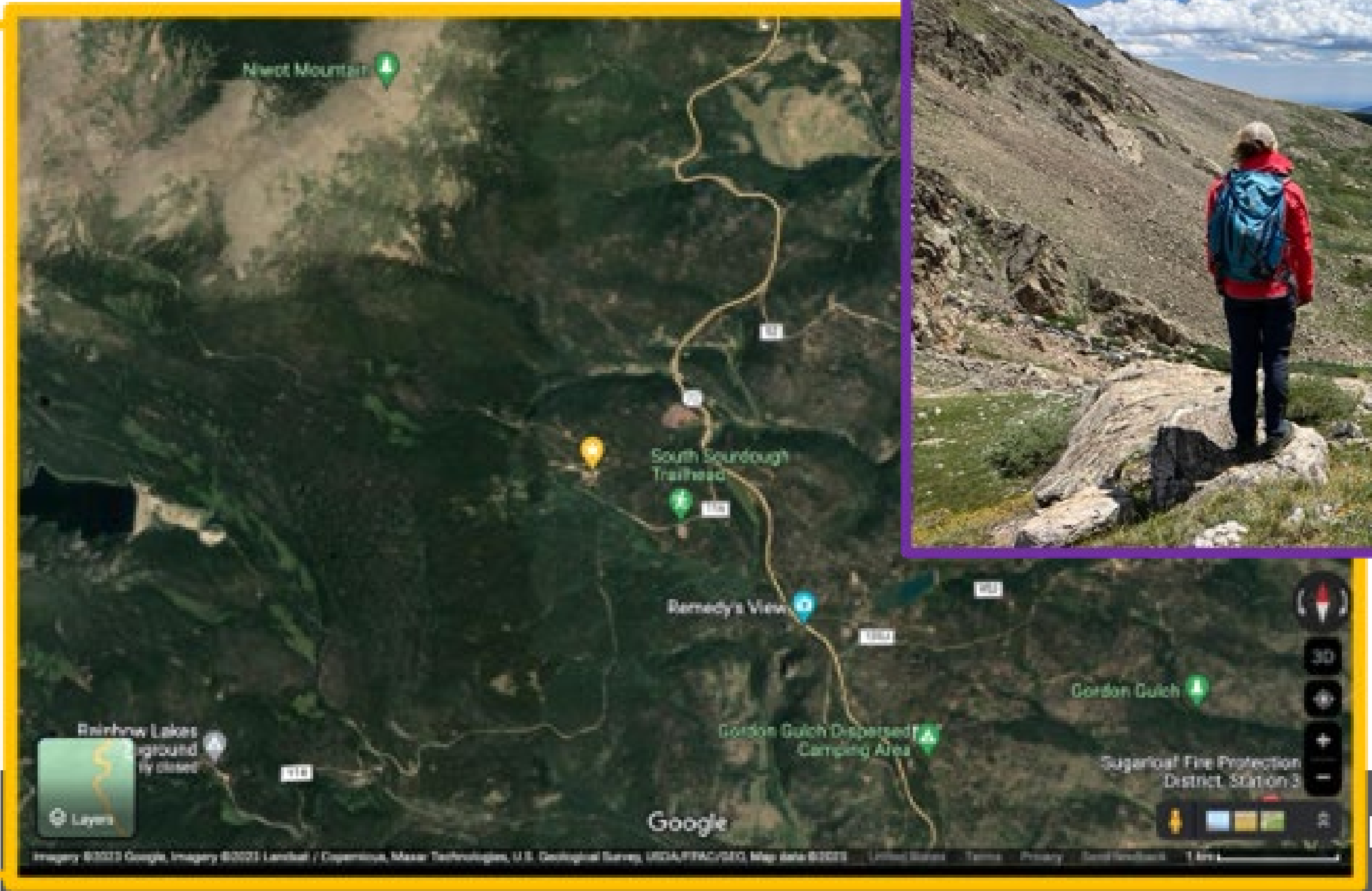
$N, w_{liq,i}, w_{ice,i}, \Delta z_i, T_i$

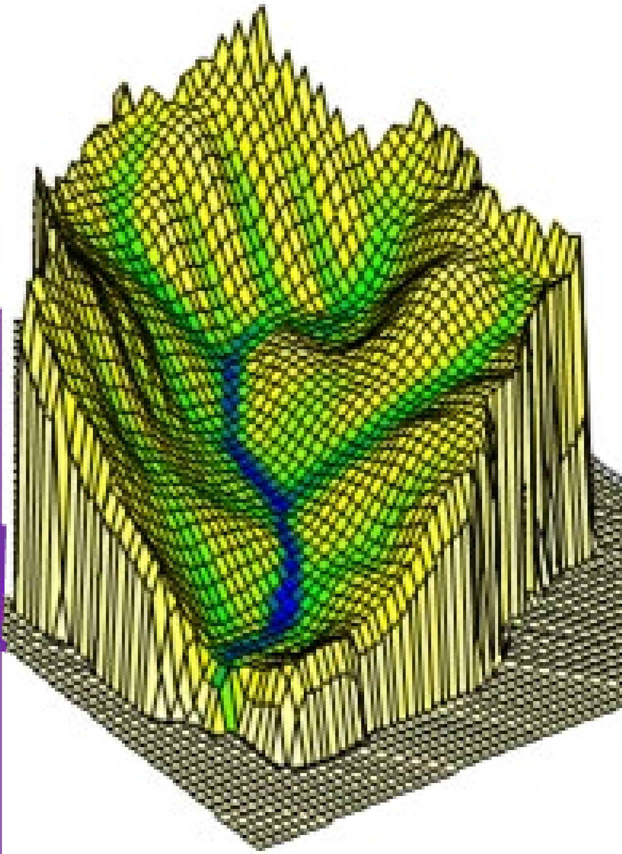


- Up to 10 layers of varying thickness
- **Represented processes**
  - Accumulation and fresh snow density *f*(T, wind)
  - Melt, refreezing, aging
  - Compaction
    - destructive metamorphism *f*(T, wind)
    - overburden
    - melt-freeze cycles
  - Sublimation
  - Water and energy transfer across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

Subgrid heterogeneity in soil moisture

25% CESM grid cell (~1^ox1^o)



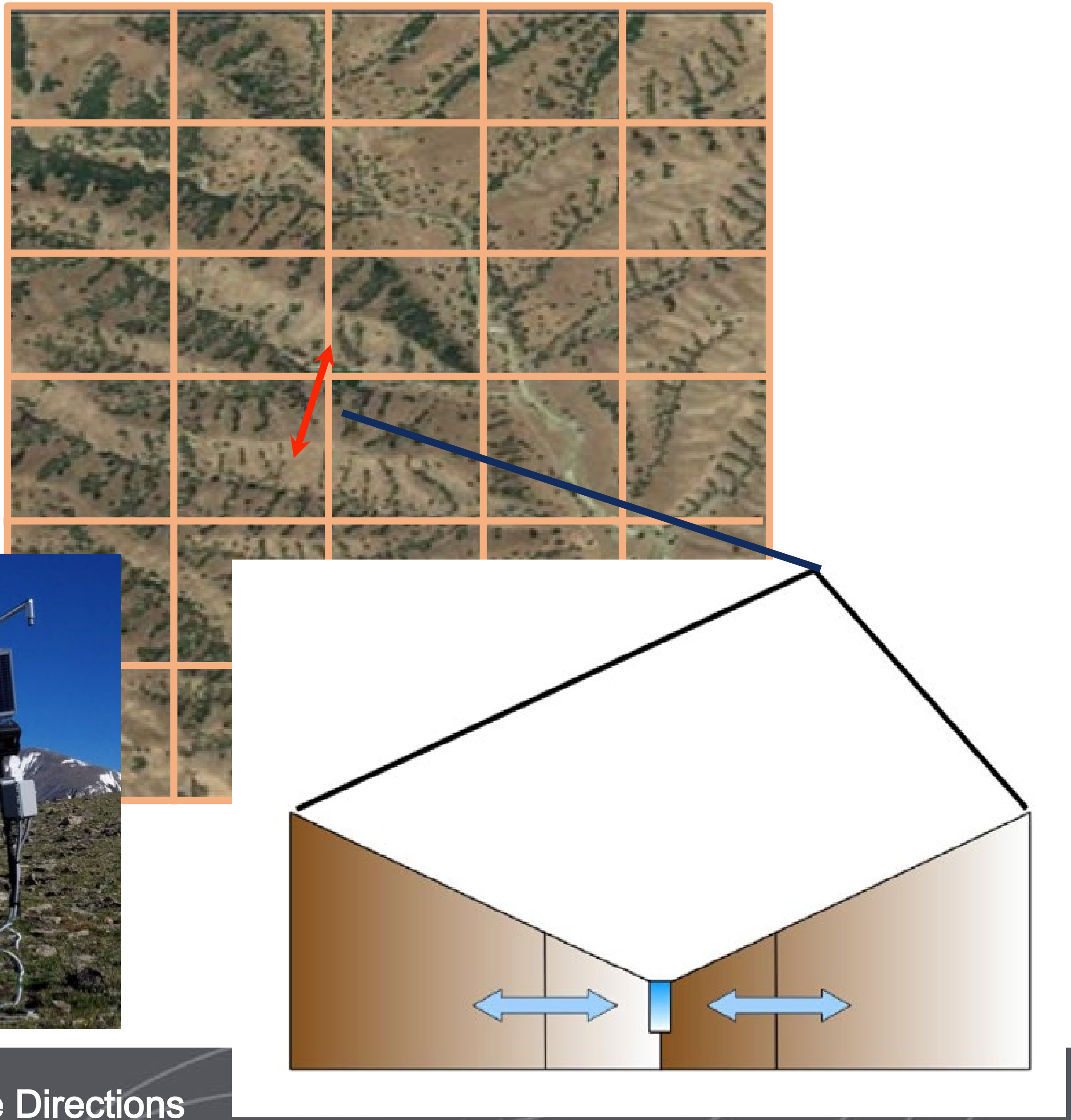


Swenson

Subgrid Hillslope Processes

CESM grid cell (~1°x1°)

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

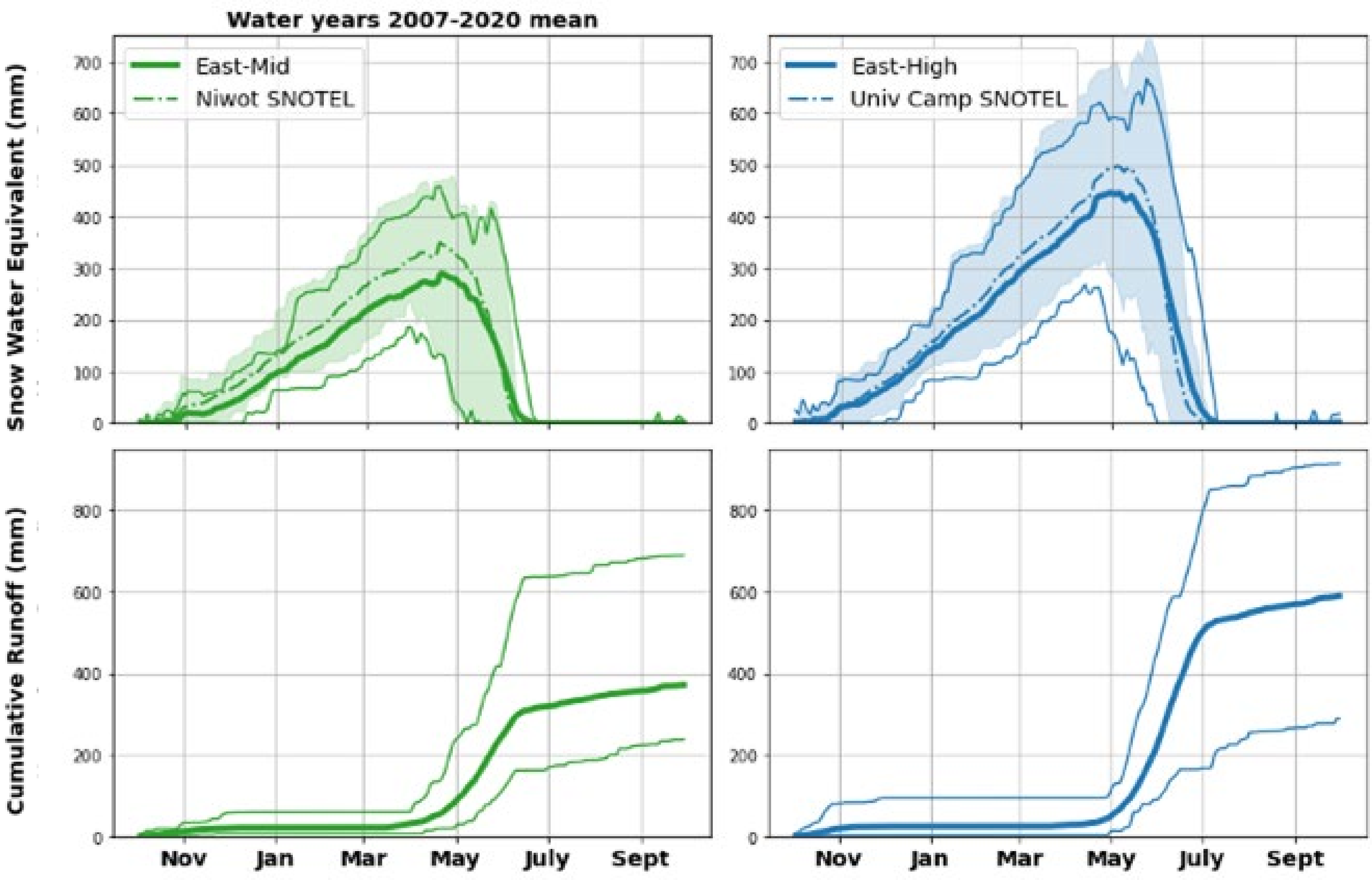


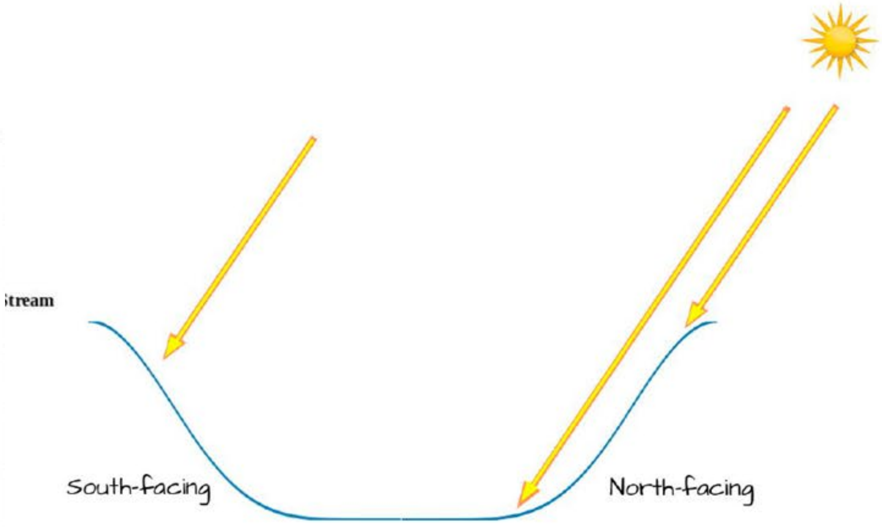
Fan et al. WRR, 2019
Swenson et al. JAMES 2019

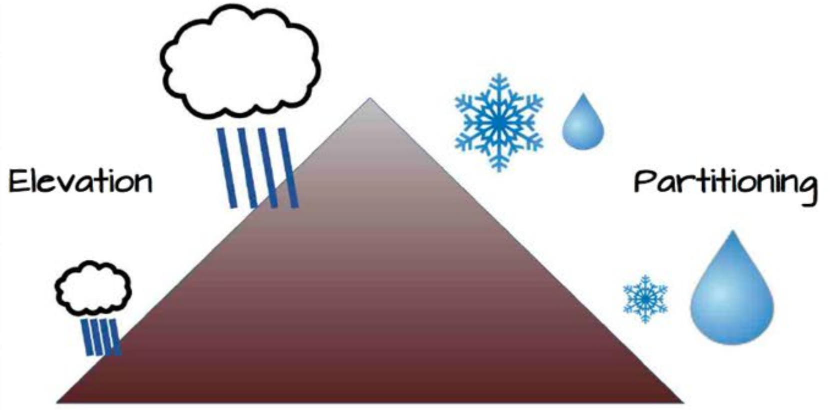
Hillslope Hydrology

Explicit Lateral Flow Within Gridcell

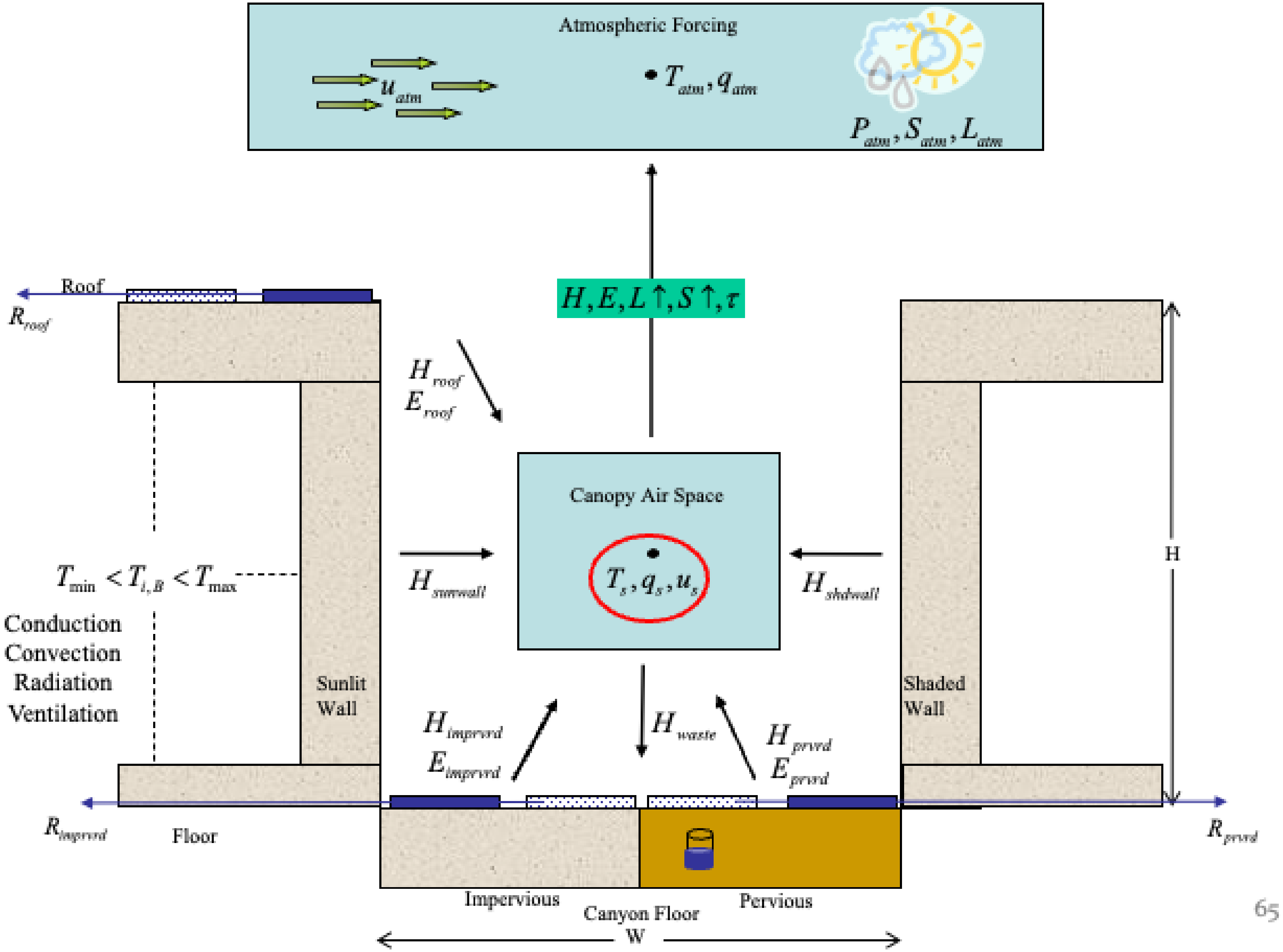
Downscaled Meteorology





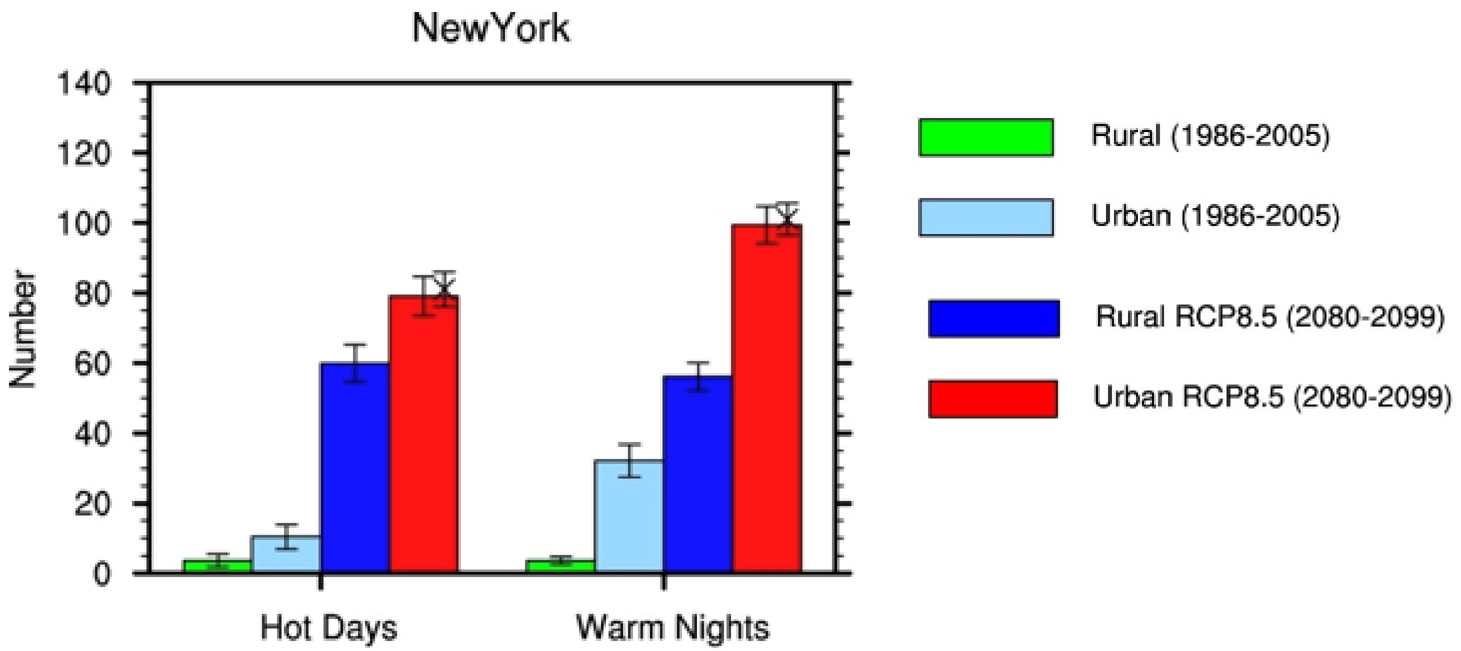


CLM-Urban Model (CLM-U)



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