The Community Land Model (CLM)

Representing terrestrial processes in the Earth System

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NCAR is sponsored by the National Science Foundation

The Community Terrestrial Systems Model (CTSM)

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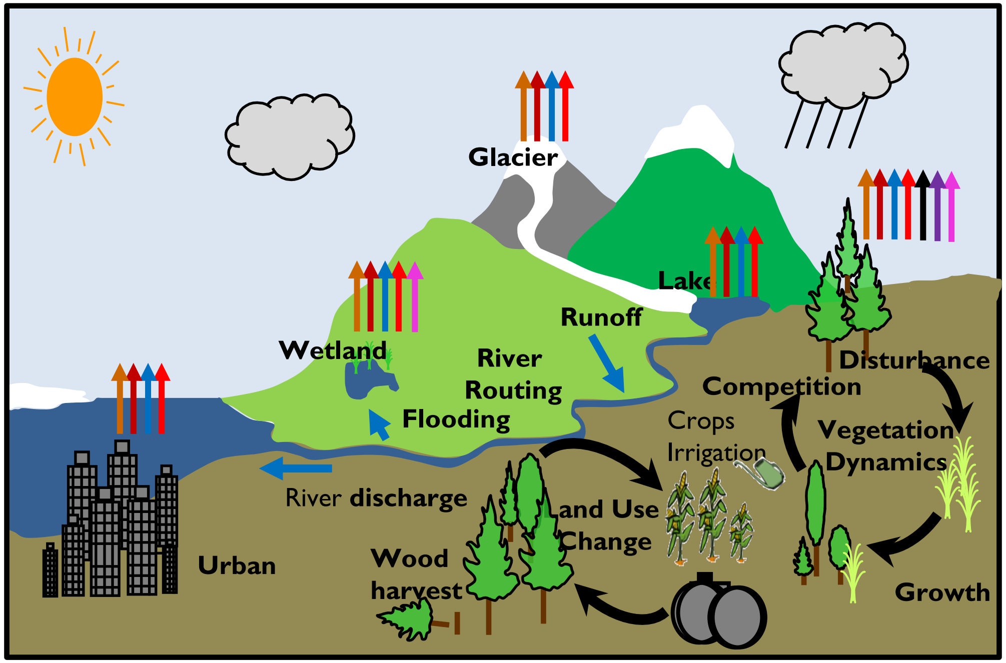
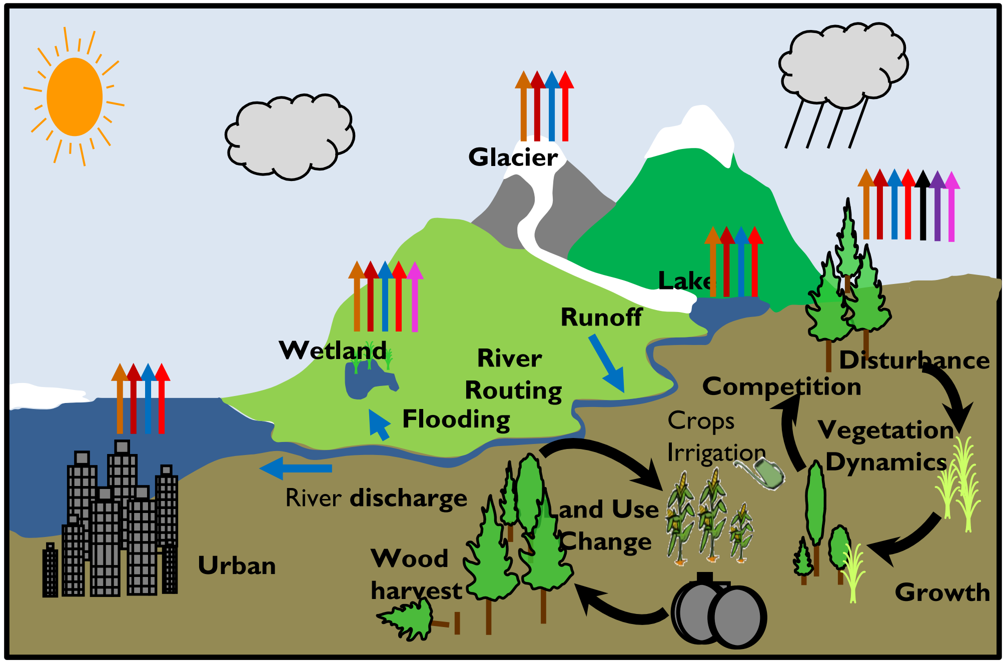
Land Modeling



"Why?"

"Are you sure this is necessary?"

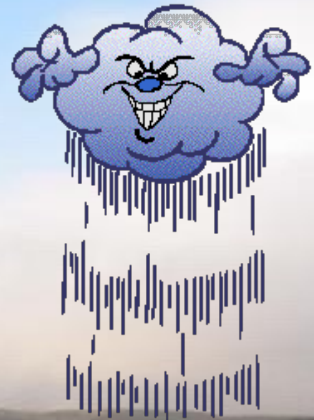
Land Modeling



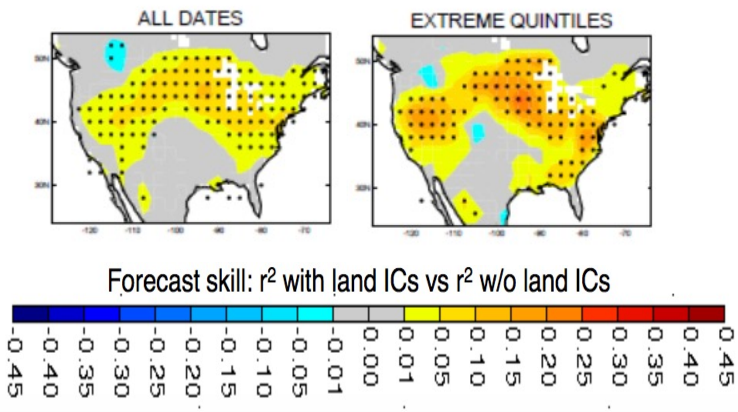
<u>Yes!</u>

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

Land modelling, why?   Land-atmosphere interactions



30-45 day forecast conditioned on SM

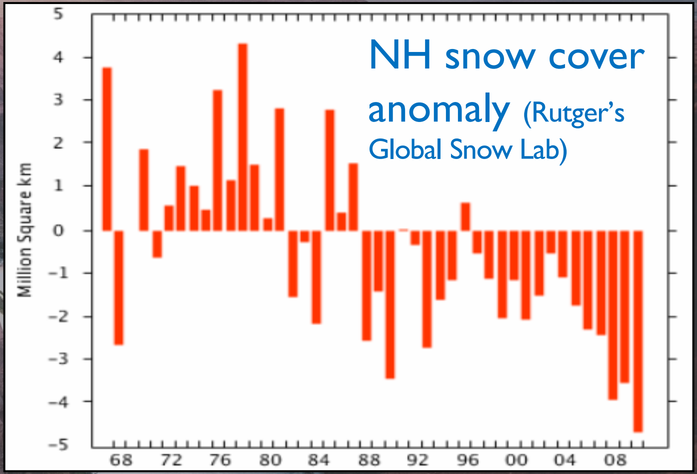


Koster et al., 2010

- When, where, and by how much do land fluxes influence atmosphere, surface temperature, clouds, precipitation, etc.?
- Land-driven predictability
  - Significant skill, especially when conditioned on amplitude of initial soil moisture anomaly
  - Increased land-atmosphere coupling in future warmer climate, increased land-driven skill?
- Land influence on extremes

Land modeling, why? Water

- Land feedbacks on droughts and floods
- Snow-albedo and snow-soil T feedbacks
- Water and food security
  - >1/6th world population dependent on water from seasonal snowpacks
- Water – plant interactions
  - Plant water use efficiency likely to increase with CO_2
- Streamflow prediction



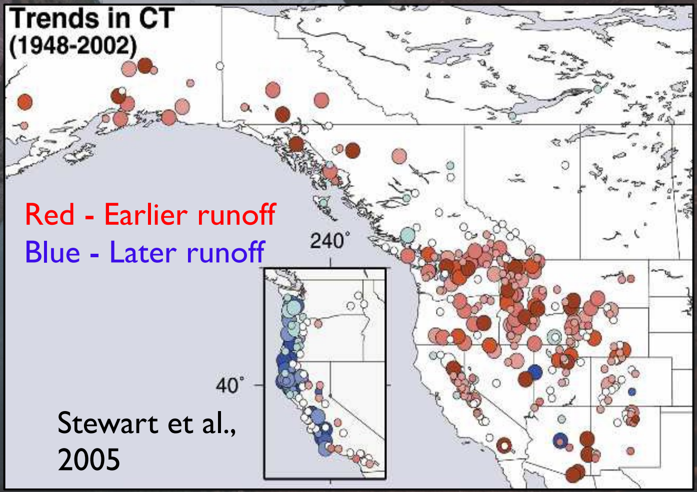
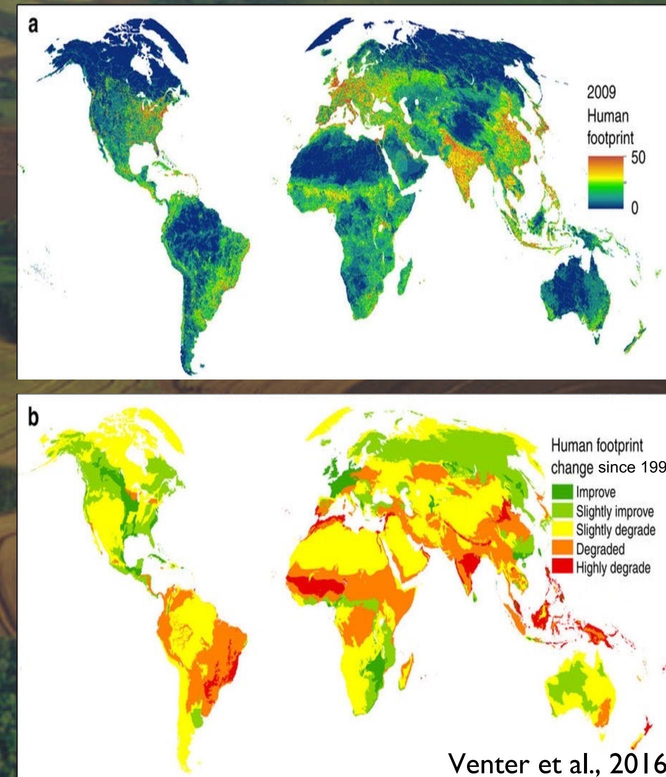


Image: Kimon Maritz

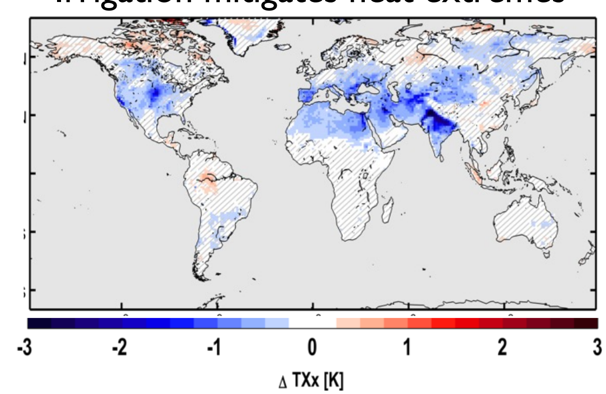
Land modeling why? Land-use and land-cover change

- ~25% non-ice land area undergone anthropogenic land-cover change
- ~80% non-ice land area under some form of land management
- Regionally, LULCC as impactful on surface climate as greenhouse gases
- ~1/3 of direct historic carbon emissions (180 ± 80PgC from land use, ~400 PgC from fossil fuel and cement),
- Deforestation: loss of Additional Sink Capacity yields indirect C impact
- Effectiveness of afforestation and biofuels for CO_2 mitigation
- Urban-rural differences in climate change impacts, e.g. ,heat stress



Venter et al., 2016

Irrigation mitigates heat extremes



Thierry, Lawrence, et al., 2017

Image: Frans Lanting/Robert Harding Picture Library

Land modeling, why? Carbon and ecology

- Carbon and nitrogen cycle interactions and their impact on long term trajectory of terrestrial carbon sink
- High uncertainty in projected land C sink
  - Emissions driven RCP8.5: 795 to 1140 ppm (source of ±1.2C uncertainty on top of 3.7C projected change)
- Vulnerability of ecosystems to climate change as well as natural and human disturbances
- Ecosystem services
- Ecosystem management to mitigate climate change

Image: Joel Vodell

The interdisciplinary evolution of land models

The interdisciplinary evolution of land models

Land as a lower boundary to the atmosphere → **Land as an integral component of the Earth System**

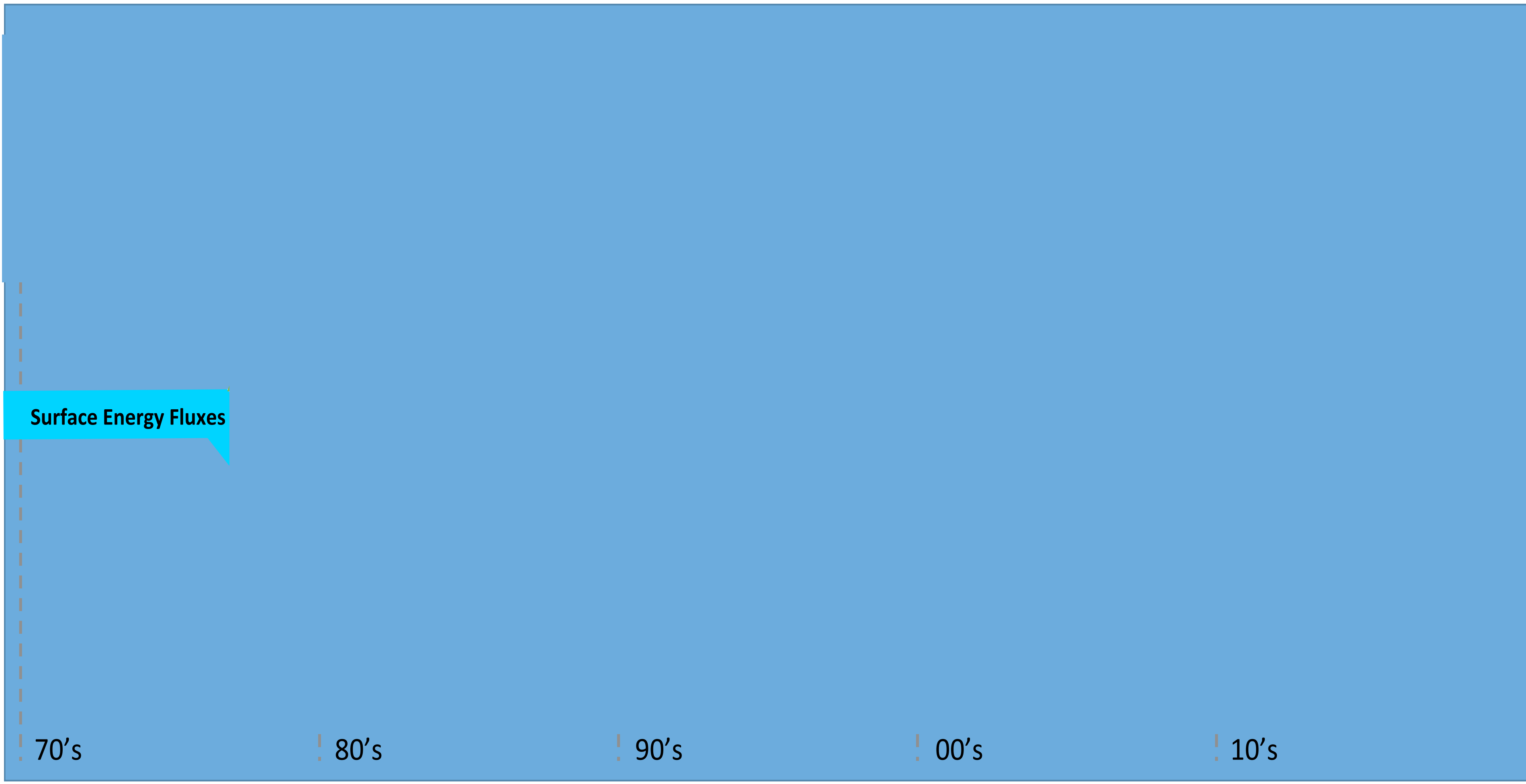
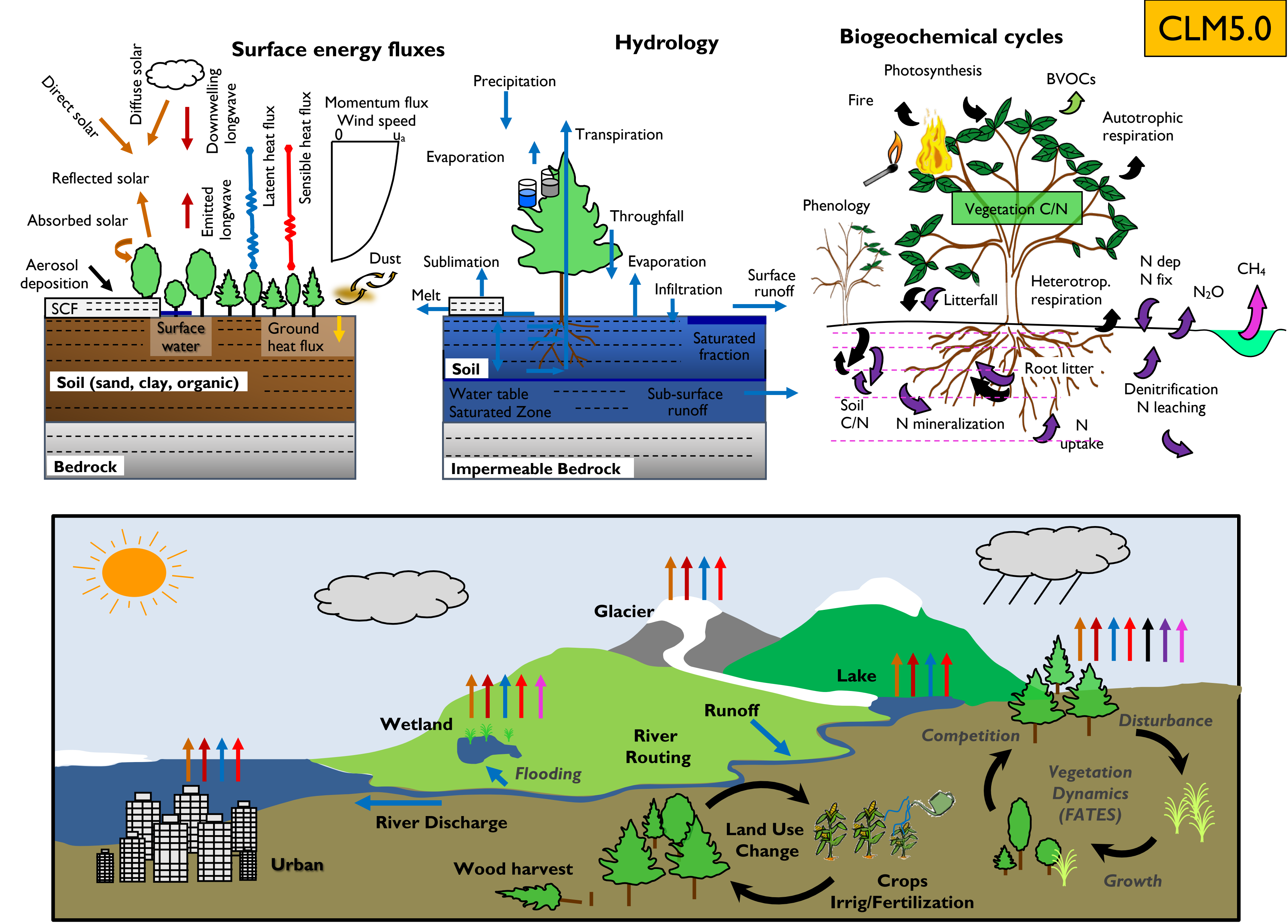
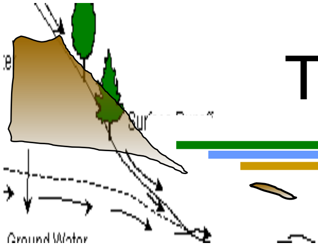


Figure: Fisher, Lawrence, Bonan, Clark, unpublished



Lawrence et al., 2011; Lawrence et al., 2019

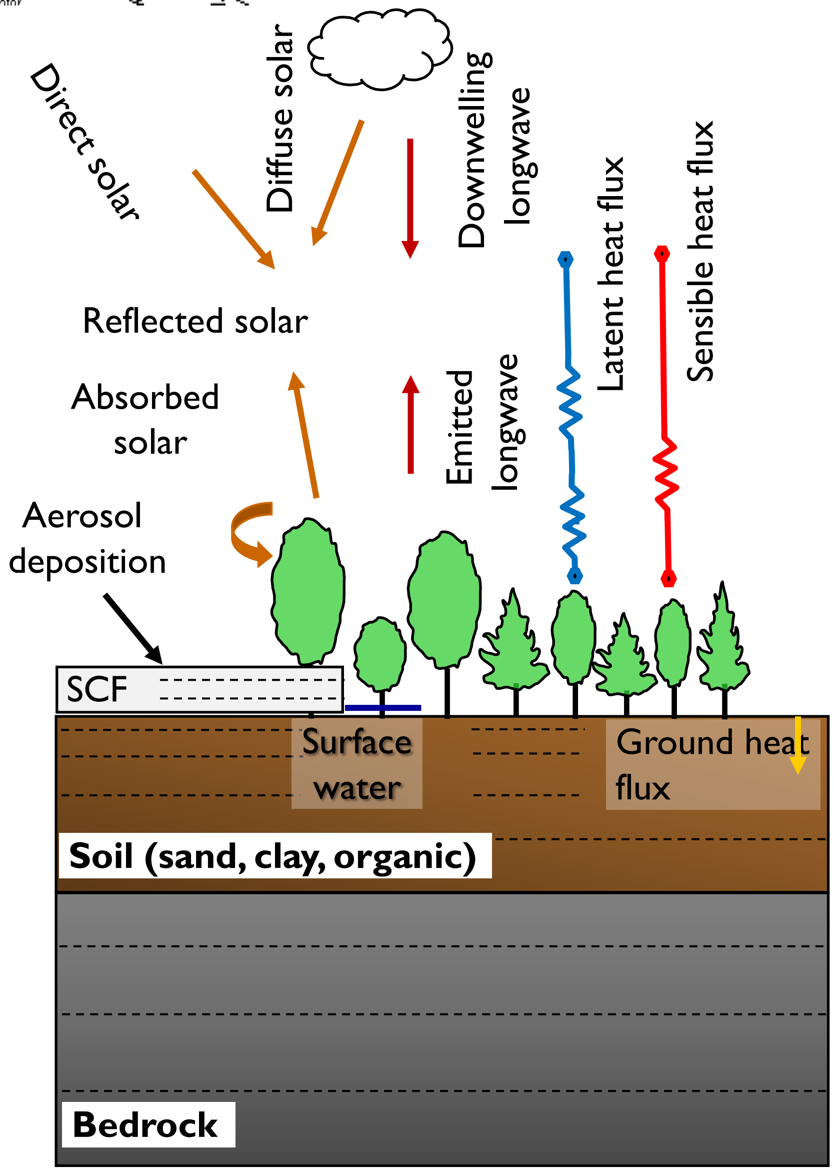


The role of a land model within an Earth System Model

– Simulate exchanges of momentum, energy, water vapor, CO_2, dust, and other trace gases/materials between land surface and the overlying atmosphere (and routing of runoff to the ocean)

– Prognose land states (soil moisture, soil temperature, canopy temperature, snow water equivalent, carbon and nitrogen stocks in vegetation and soil)

At each time step the land model solves Surface Energy Balance



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

$S\uparrow$, $S\downarrow$ are down(up)welling solar radiation,

$L\uparrow$, $L\downarrow$ are up(down)welling longwave rad,

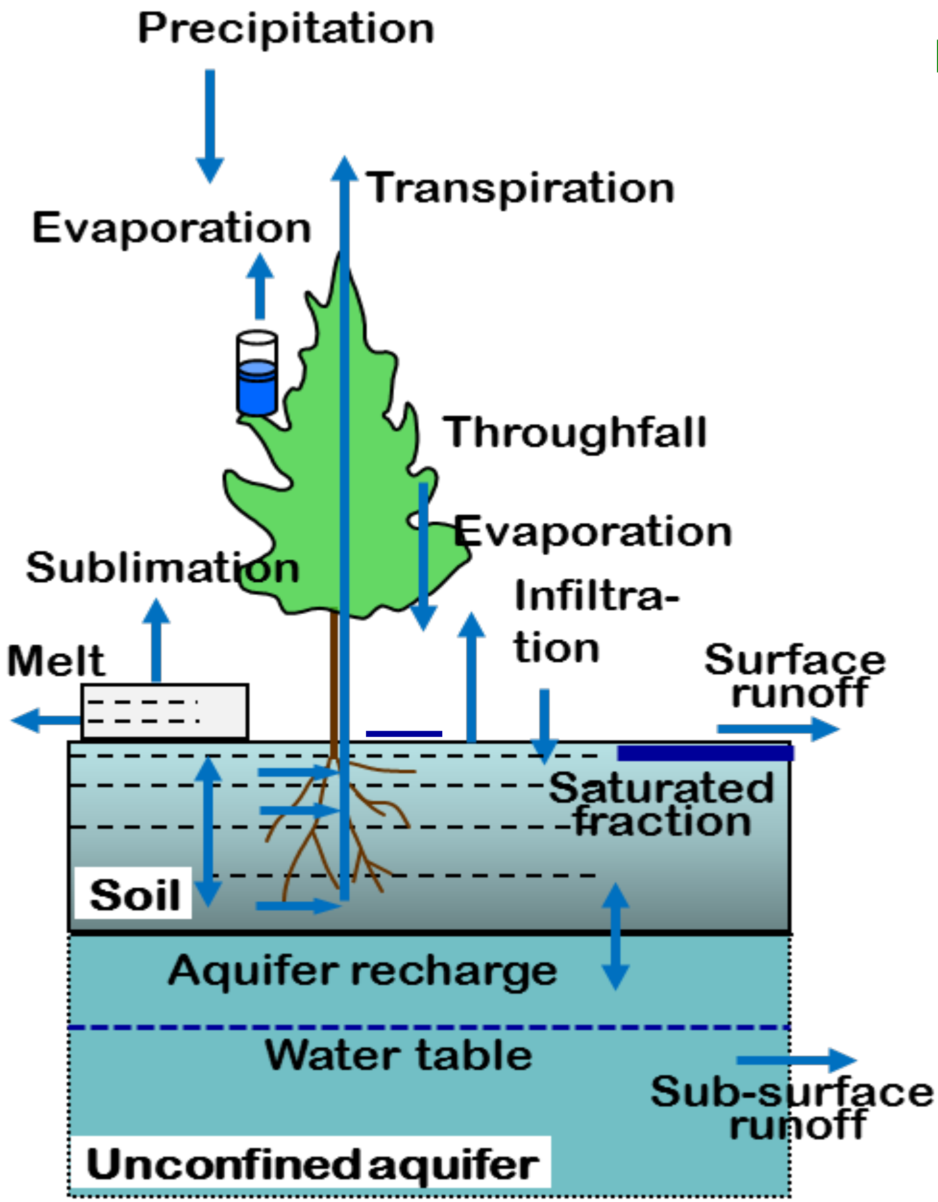
λ is latent heat of vaporization,

E is evaporation,

H is sensible heat flux

G is ground heat flux

… and the Surface Water Balance



$$P = E_S + E_T + E_C + R + (\Delta W_{soi} + \Delta W_{snw} + \Delta W_{sfcw} + \Delta W_{can}) \,/\, \Delta t$$

P is rainfall/snowfall,

E_S is soil evaporation,

E_T is transpiration,

E_C is canopy evaporation,

R is runoff (surf + sub-surface),

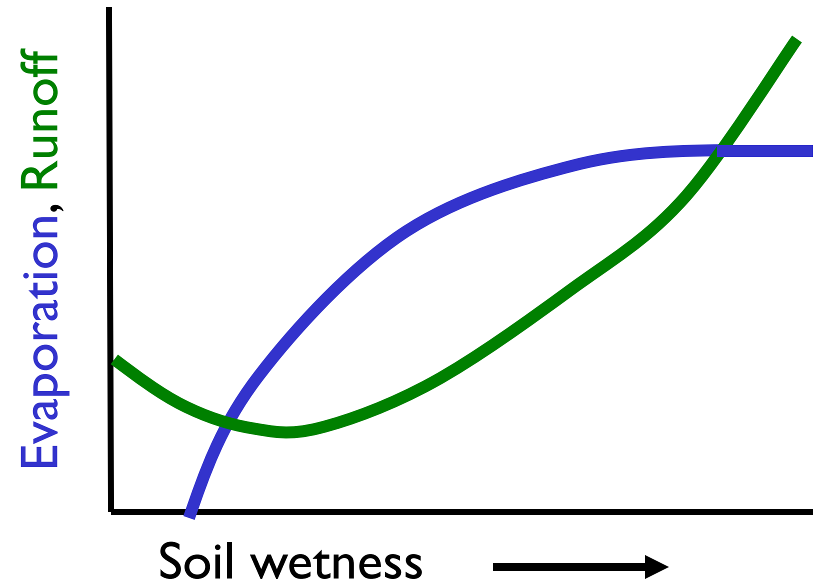
$\Delta W_{soi} / \Delta t$, $\Delta W_{snw} / \Delta t$, $\Delta W_{sfcw} / \Delta t$, $\Delta W_{can} / \Delta t$, are the changes in soil moisture, surface water, snow, and canopy water over a timestep

Terrestrial water and energy cycles intricately linked

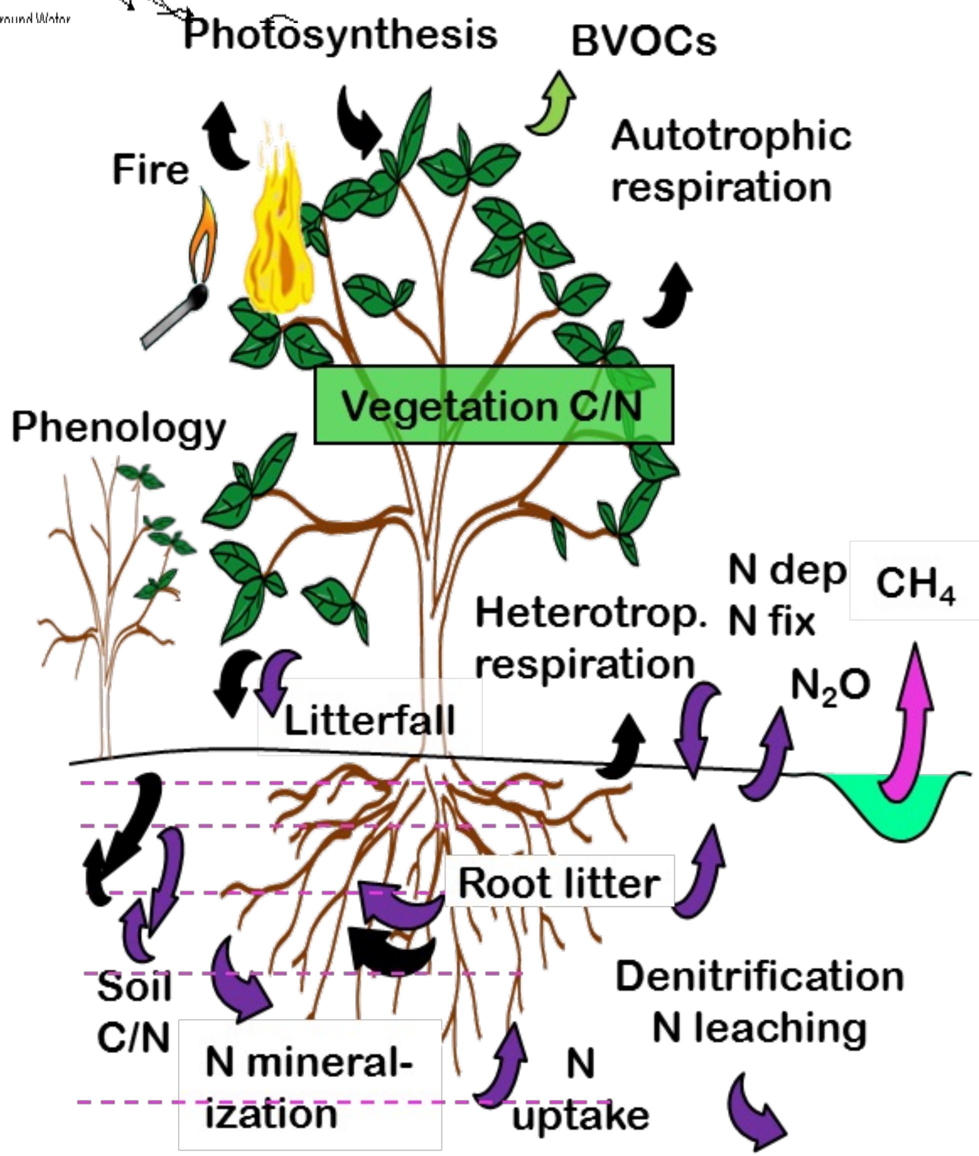
"The ability of a land-surface scheme to model evaporation correctly depends crucially on its ability to model runoff correctly. The two fluxes are intricately related through soil moisture."

(Koster and Milly, 1997).

Runoff and evaporation both vary non-linearly with soil moisture



… and Surface Carbon Exchange



$$\mathbf{NEE = GPP - HR - AR - Fire - LUC}$$

NEE is net ecosystem exchange

GPP is gross primary productivity

HR is heterotrophic respiration

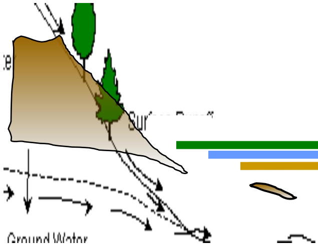
AR is autotrophic respiration

Fire is carbon flux due to fire

LUC is C flux due to land use change

Land complexity: Submodels of CLM

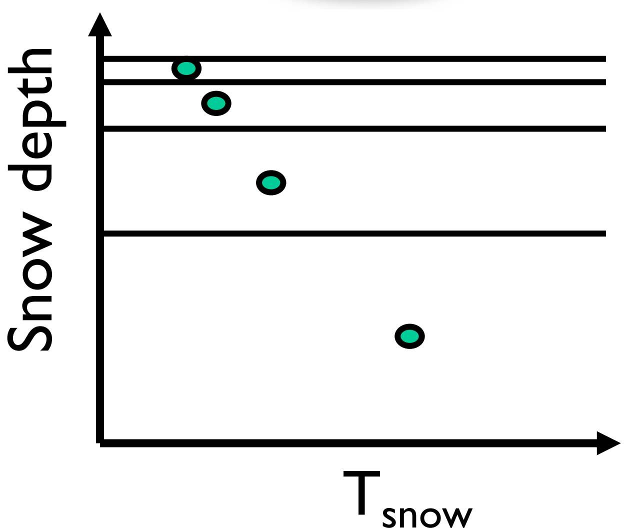
- Biogeophysics
  - Photosynthesis and stomatal resistance
  - Hydrology
  - Snow
  - Soil thermodynamics
  - Surface albedo and radiative fluxes
- Biogeochemistry
  - Carbon / nitrogen pools, allocation, respiration
  - Vegetation phenology
  - Decomposition
  - Plant mortality
  - External nitrogen cycle
  - Methane production and emission
- Vegetation dynamics
- Urban
- Crop and irrigation
- Lakes
- Glaciers and ice sheets
- Fire and fire emissions
- Dust emissions
- River flow
- Biogenic Volatile Organic Compound emissions



Land model complexity: Snow model example

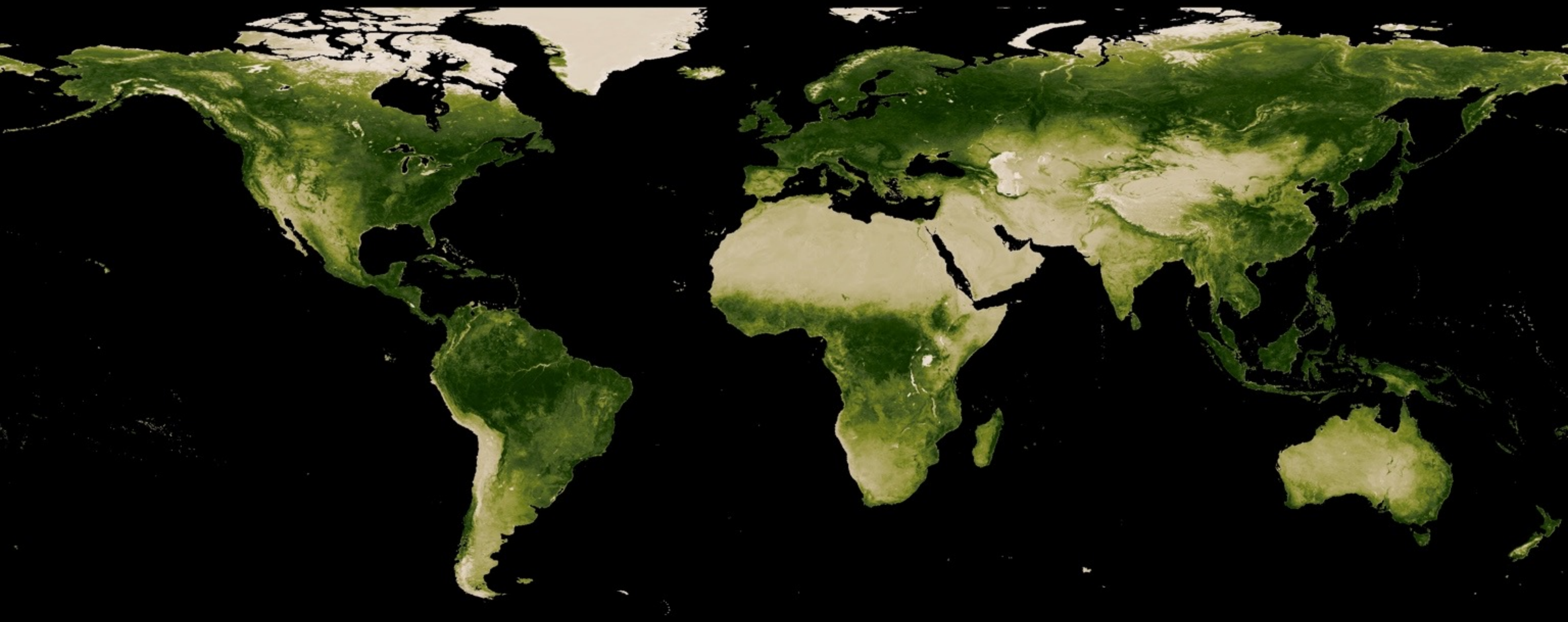
State Variables

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

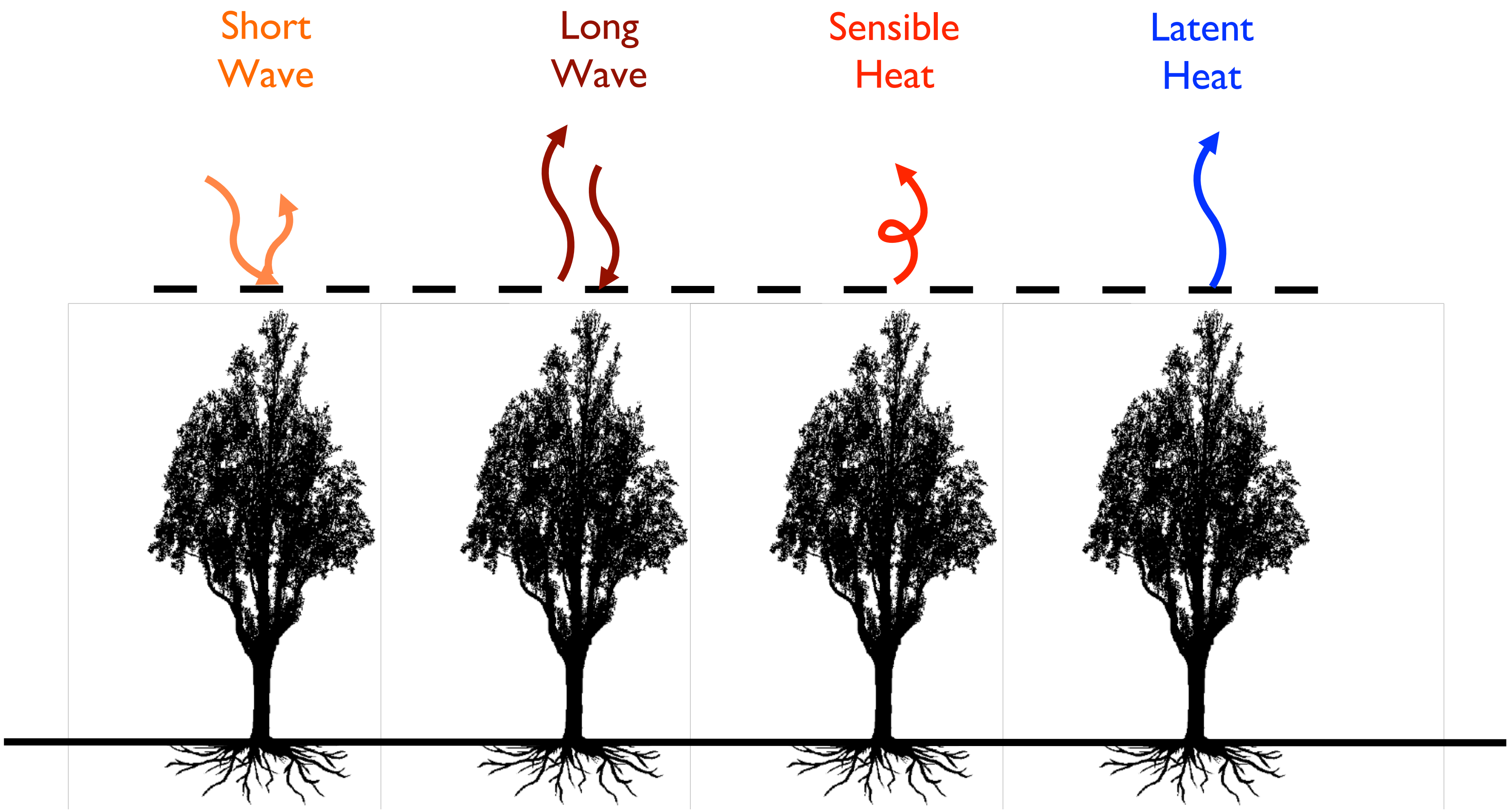


- Up to 10-layers of varying thickness
- Represented processes
  - Accumulation and fresh snow density *f* (T, wind)
  - Snow melt and refreezing
  - Snow aging
  - Water and energy transfer across snow layers
  - Snow compaction
    - destructive metamorphism due to temperature and wind
    - overburden
    - melt-freeze cycles
  - Sublimation
  - 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 depths
  - Depth hoar

Plants ⟷ Climate

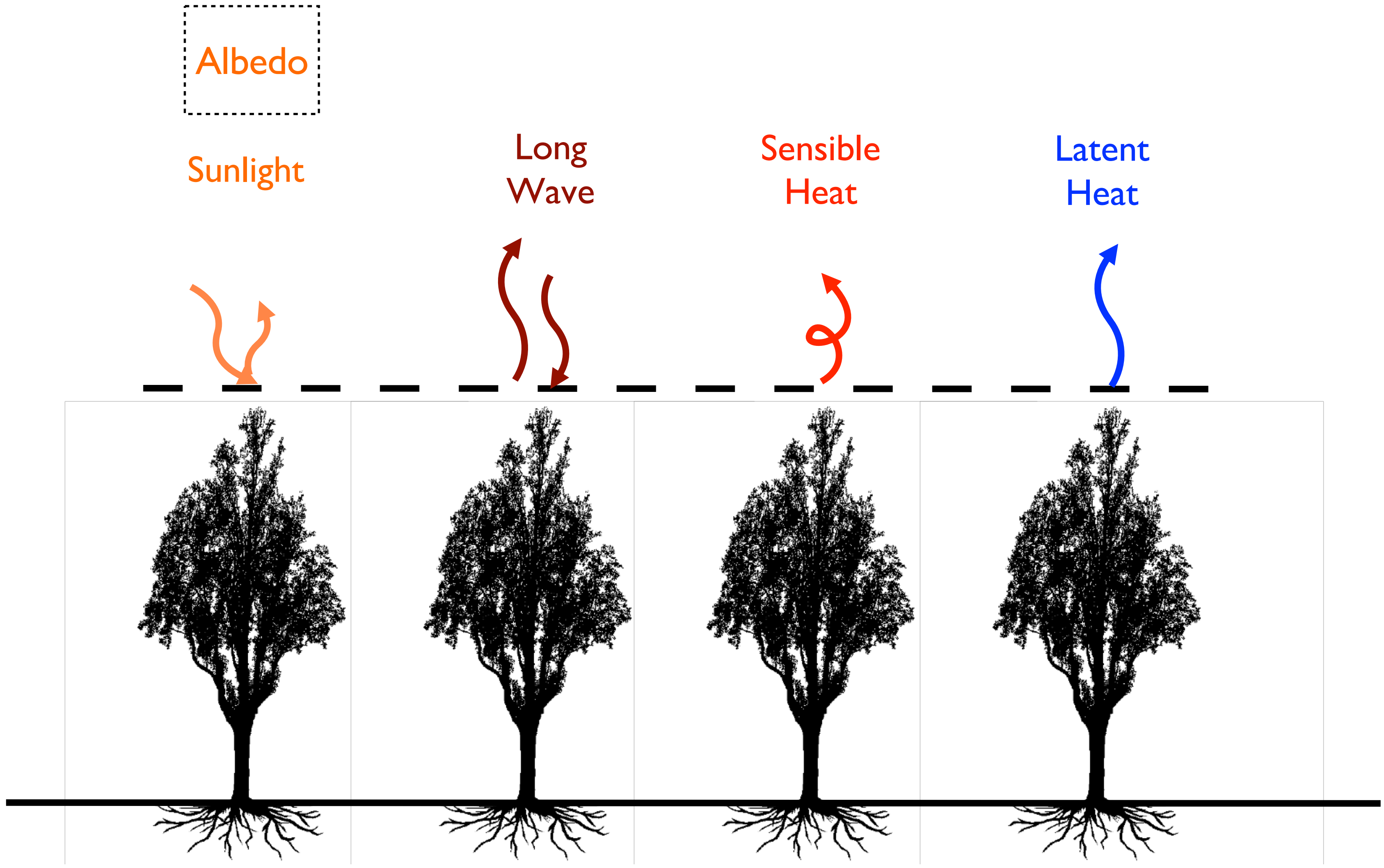


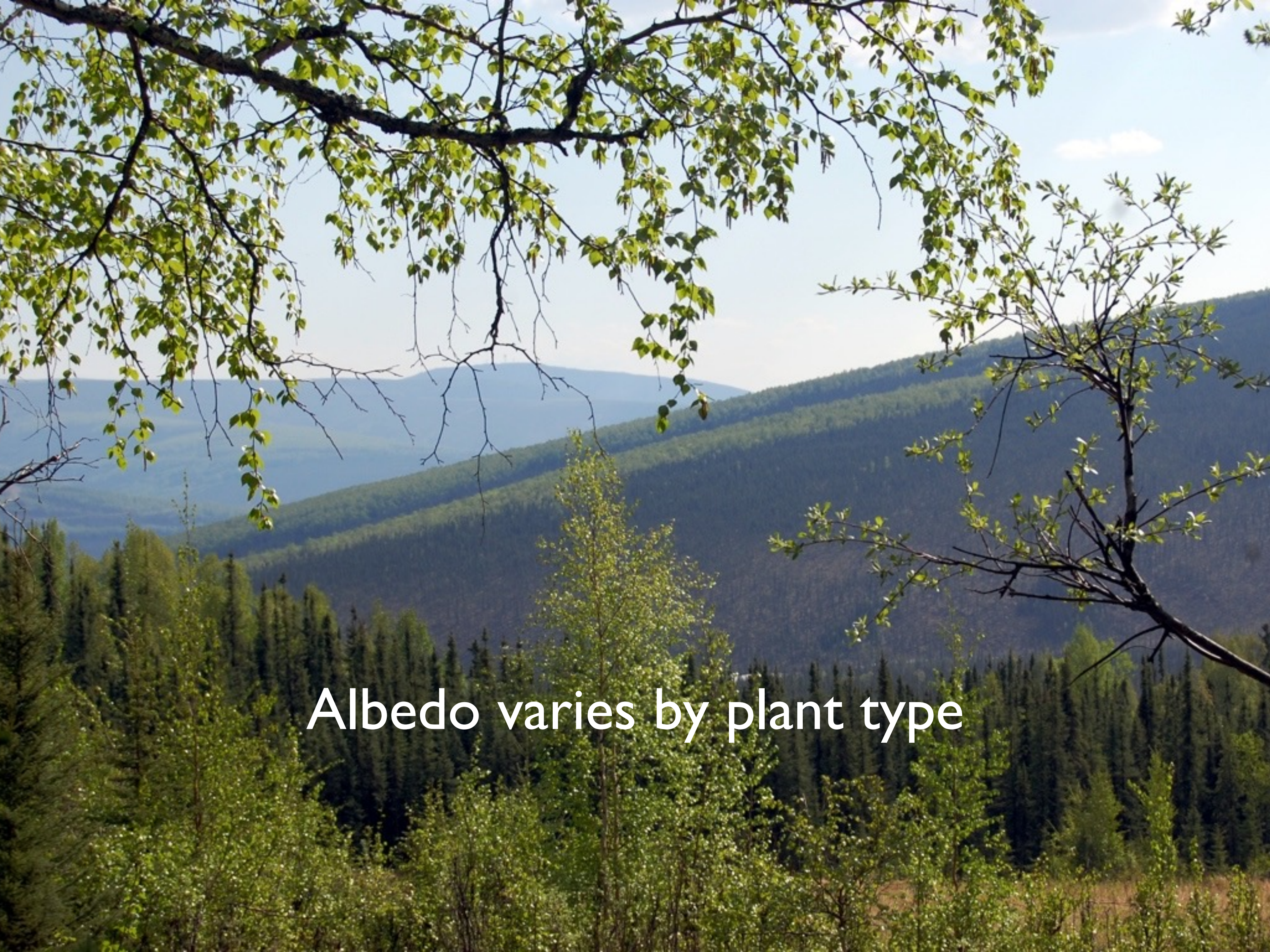
How do Plants and Climate Interact?



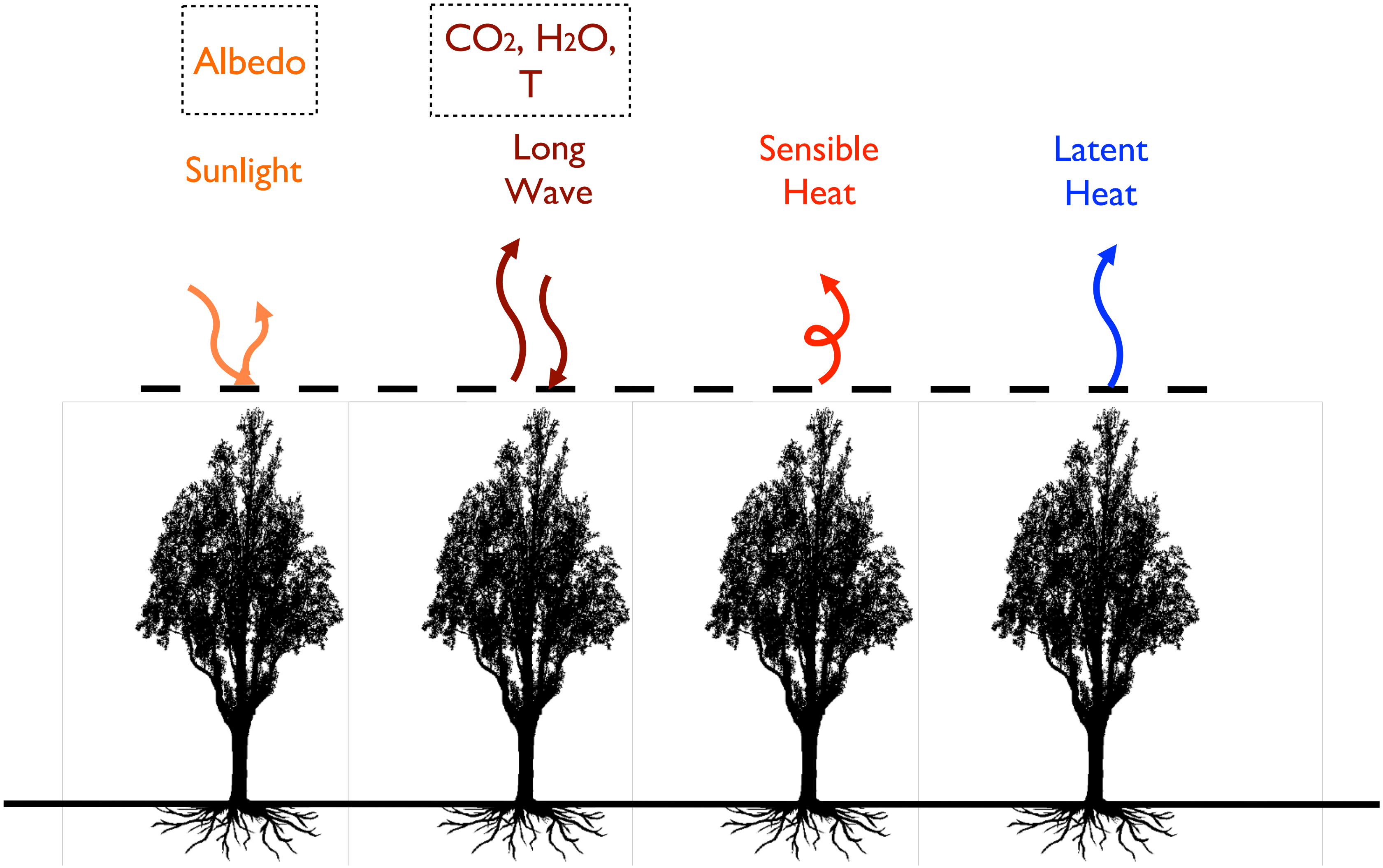
Terrestrial Surface Energy Budget

How do Plants and Climate Interact?

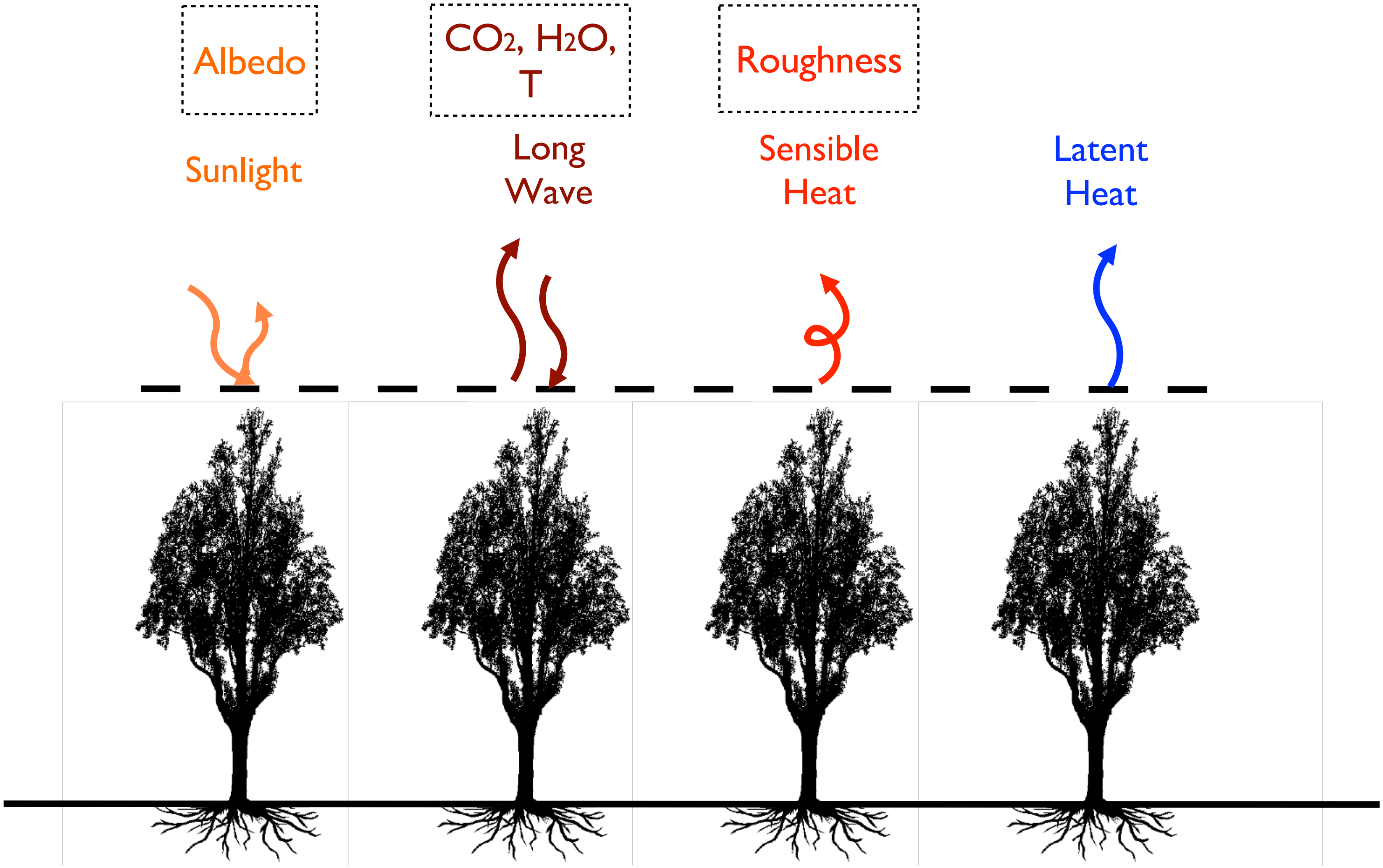



Albedo varies by plant type

How do Plants and Climate Interact?



How do Plants and Climate Interact?



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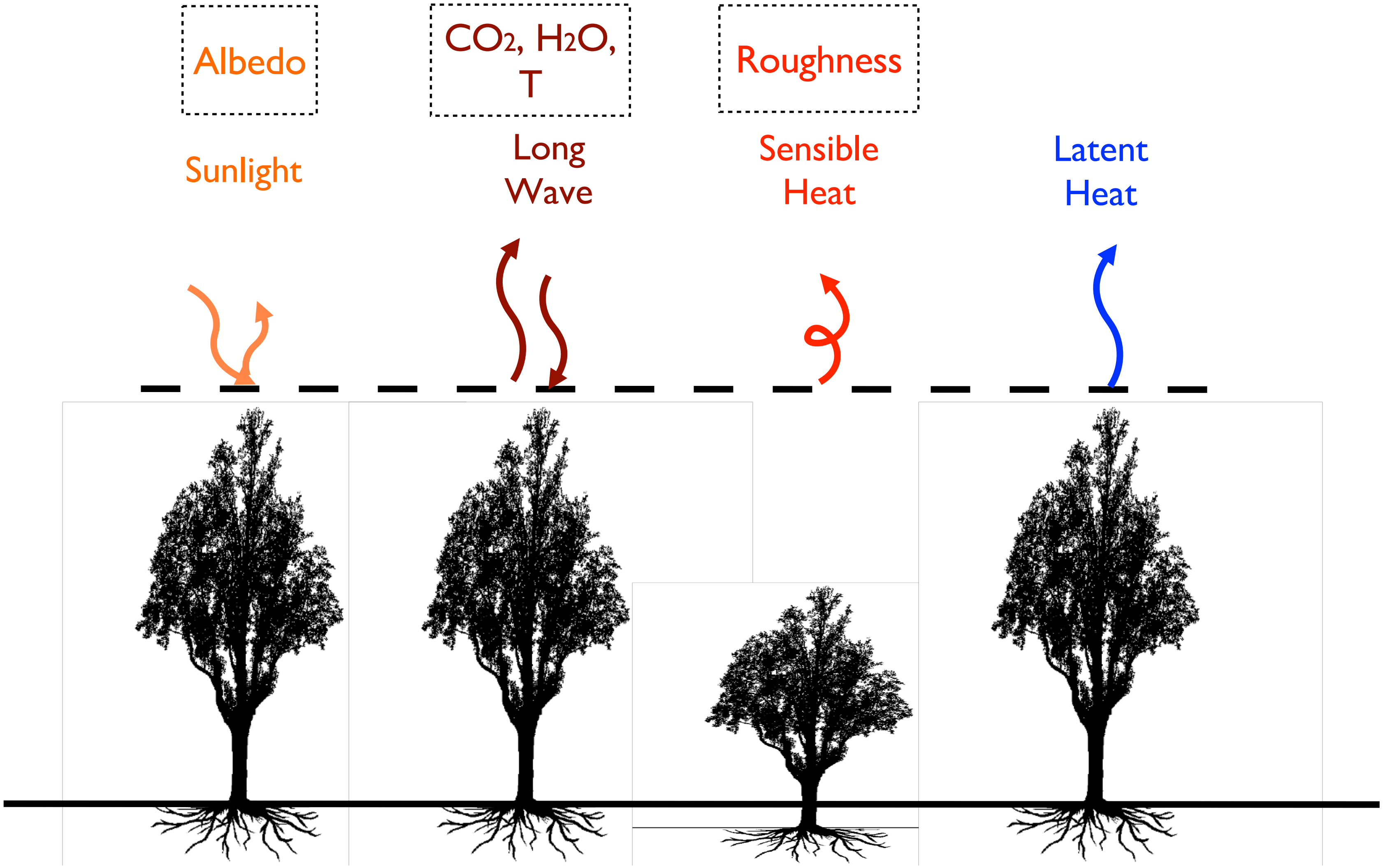

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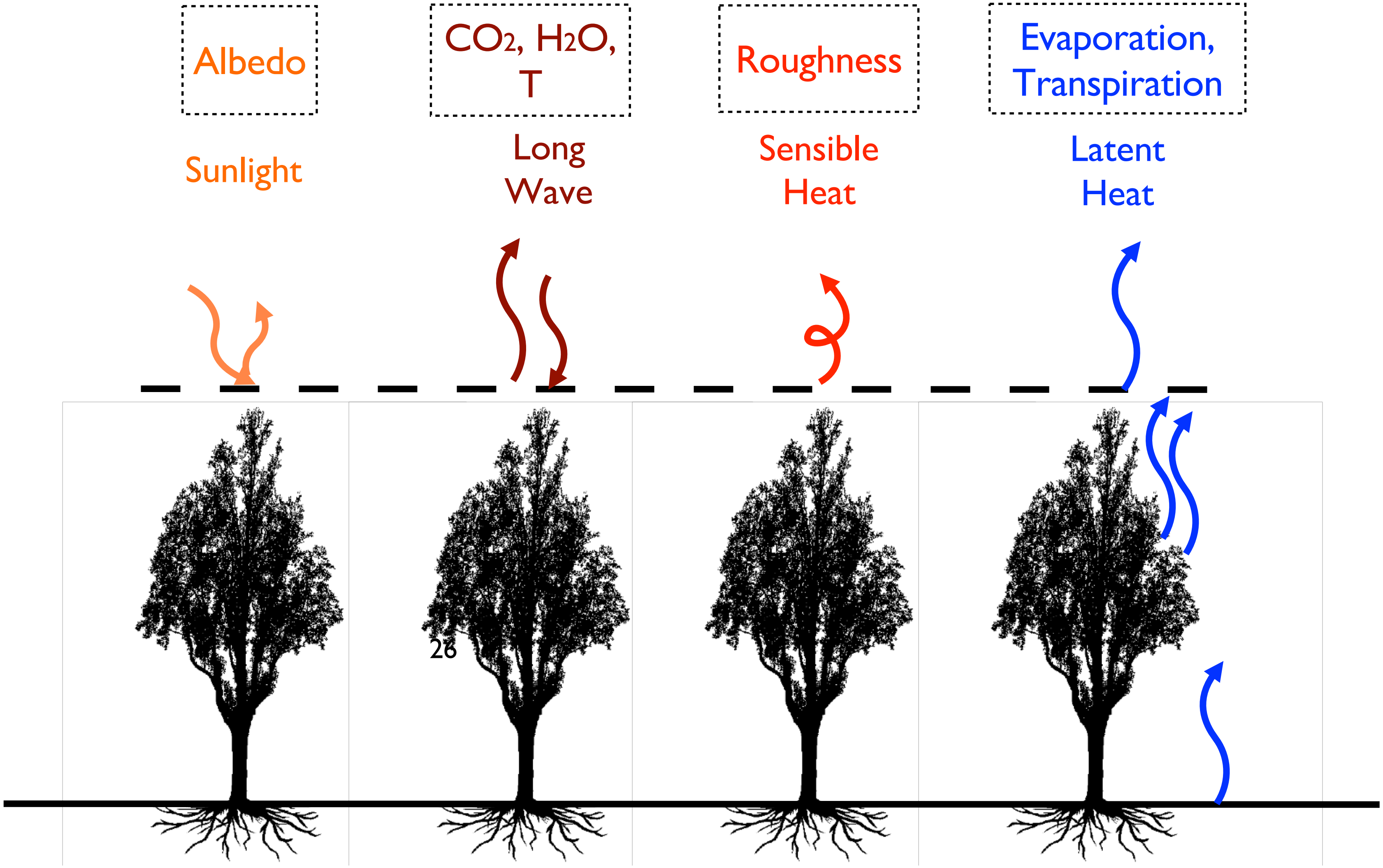
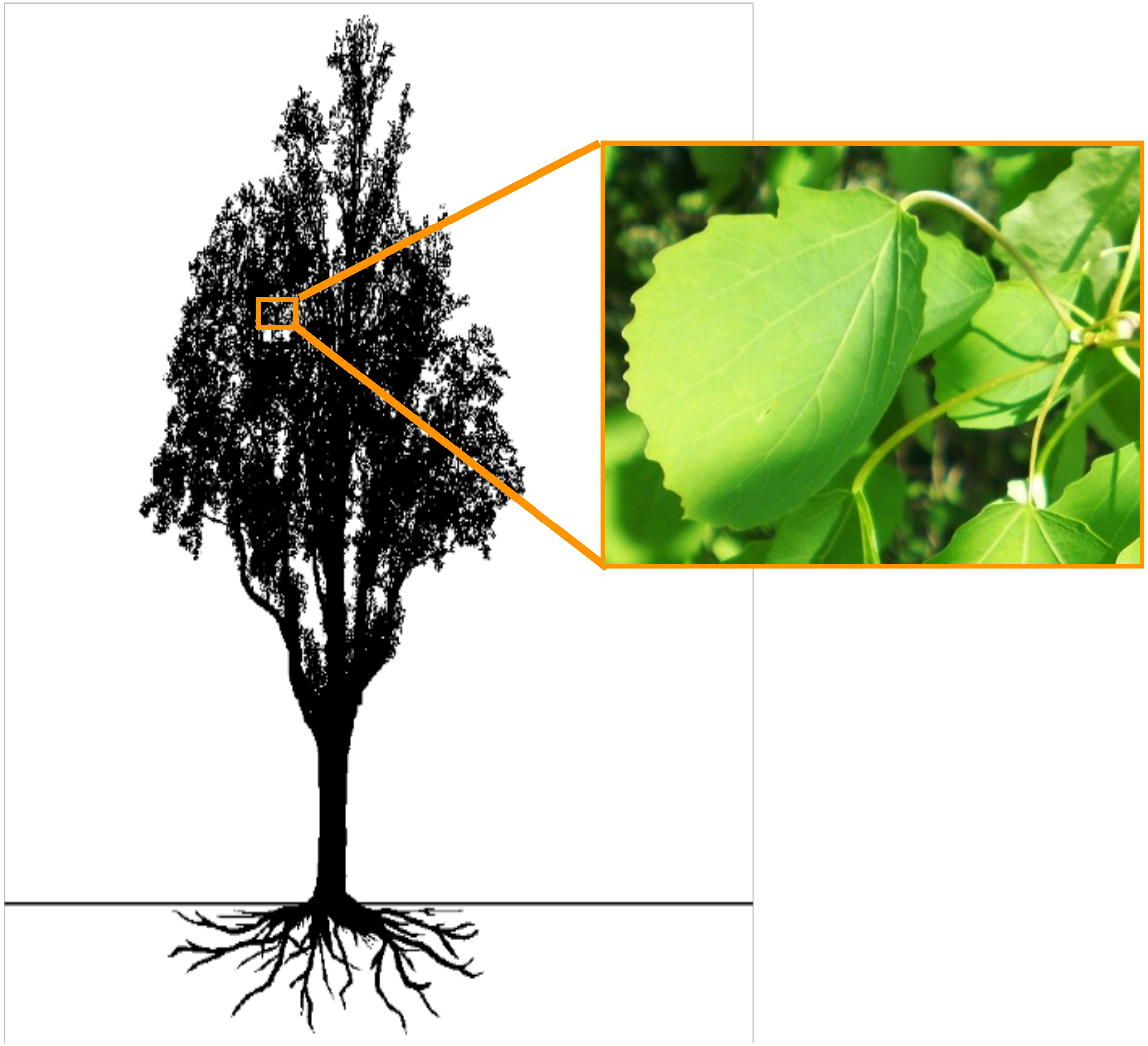
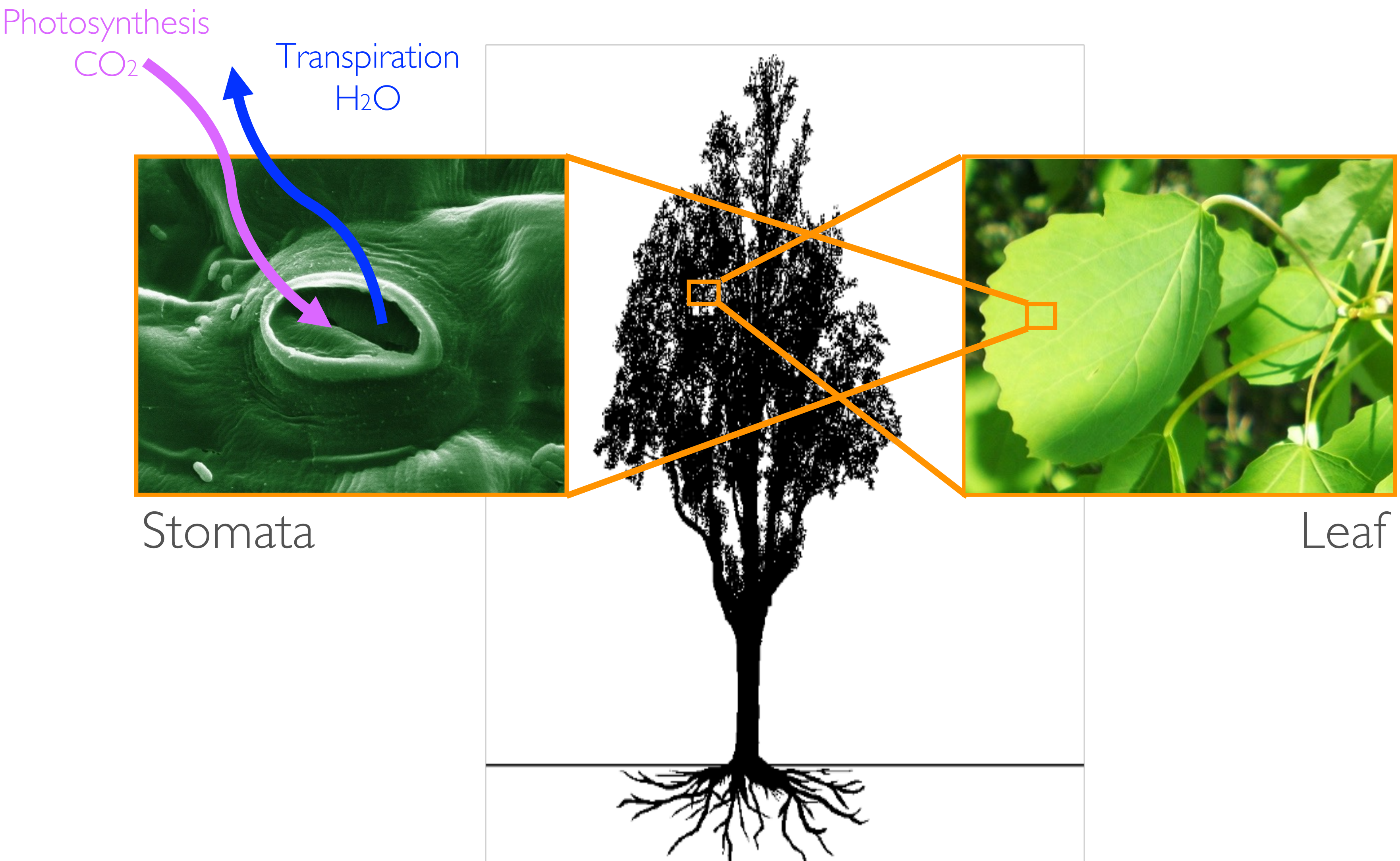


Transpiration flux of water



Photos: Wikimedia Commons

Carbon in, water out



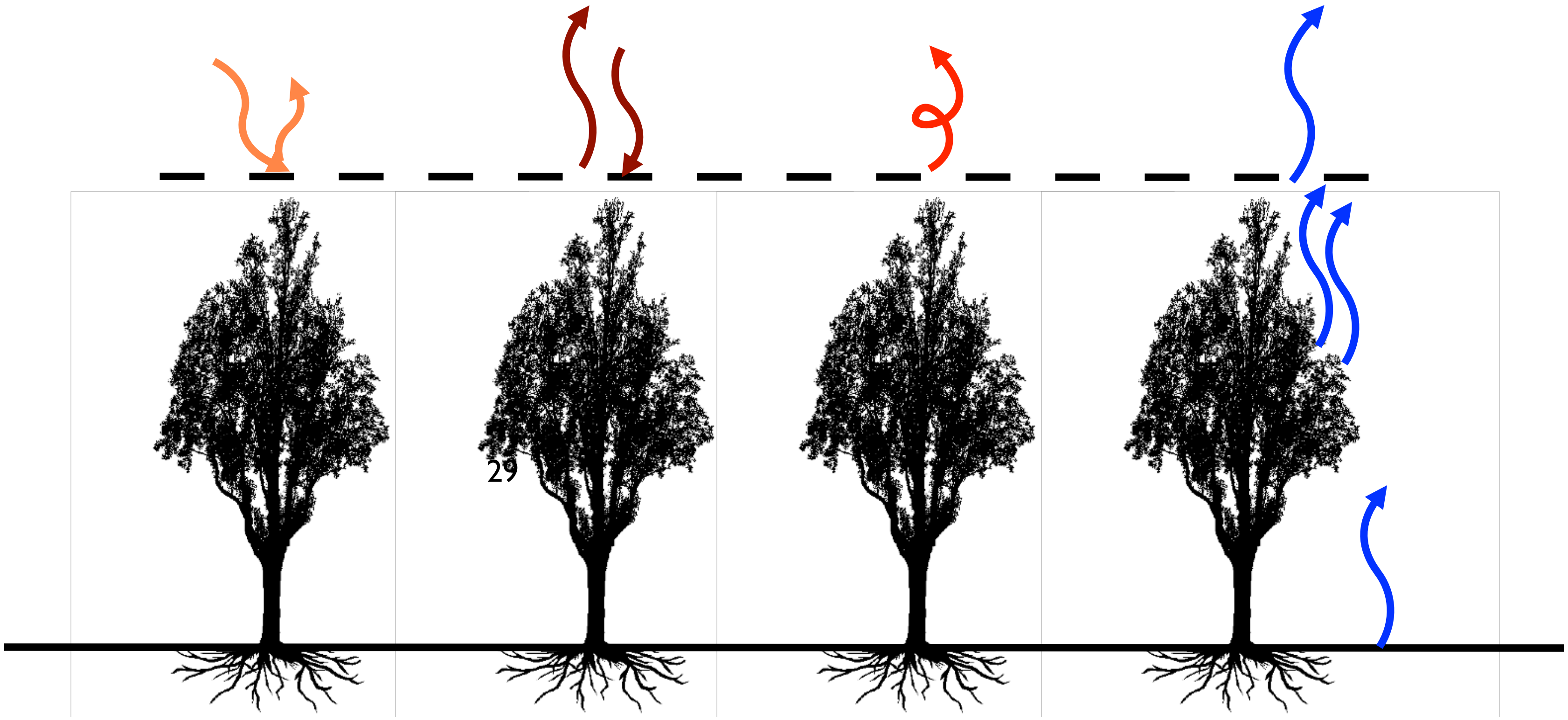
Plant physiological controls on CO_2 exchange and transpiration

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

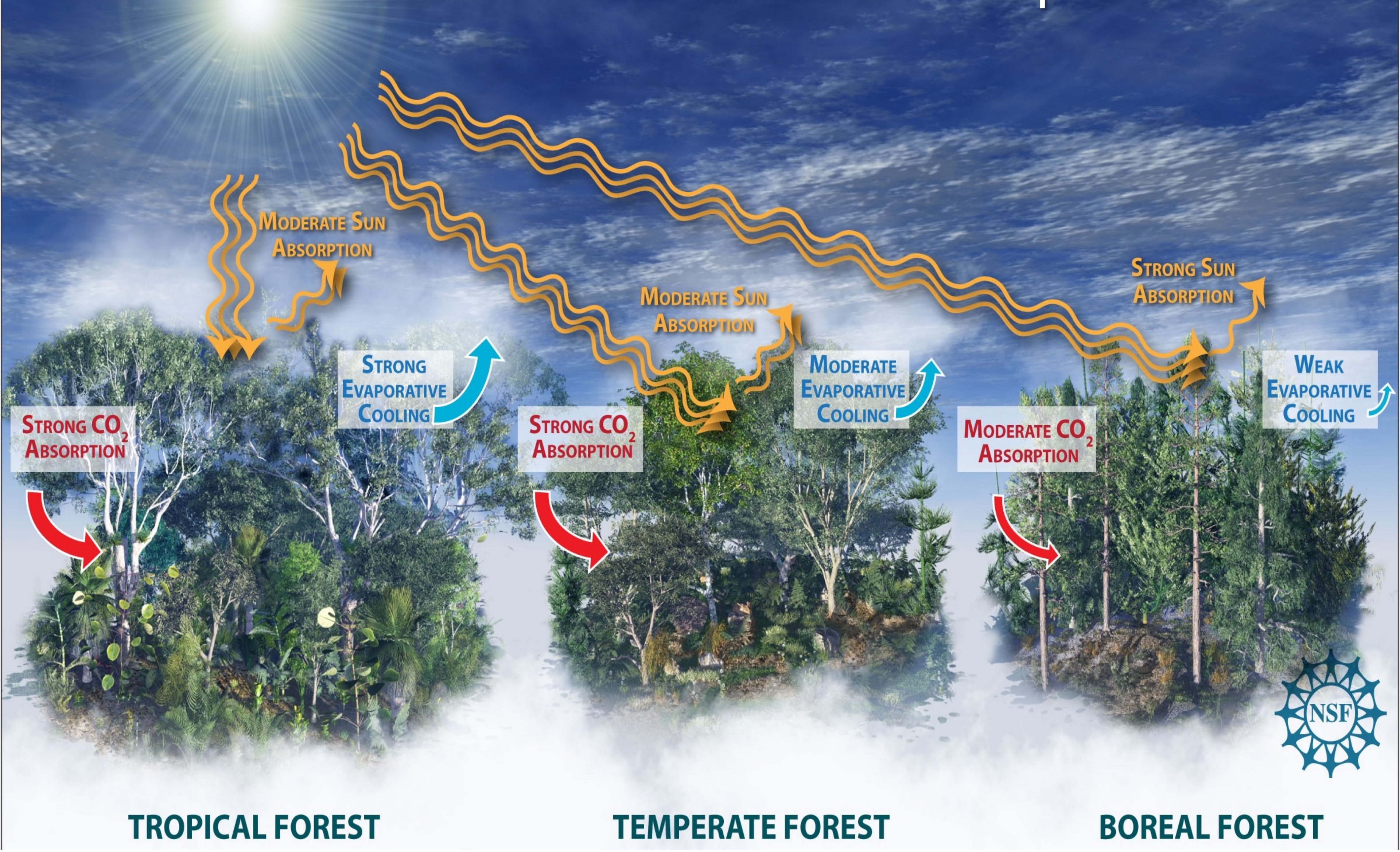
Photos: Wikimedia Commons

ΔPlants => ΔSurface Energy Budget

Albedo	CO_2, H_2O, T	Roughness	Evaporation, Transpiration
Sunlight	Long Wave	Sensible Heat	Latent Heat



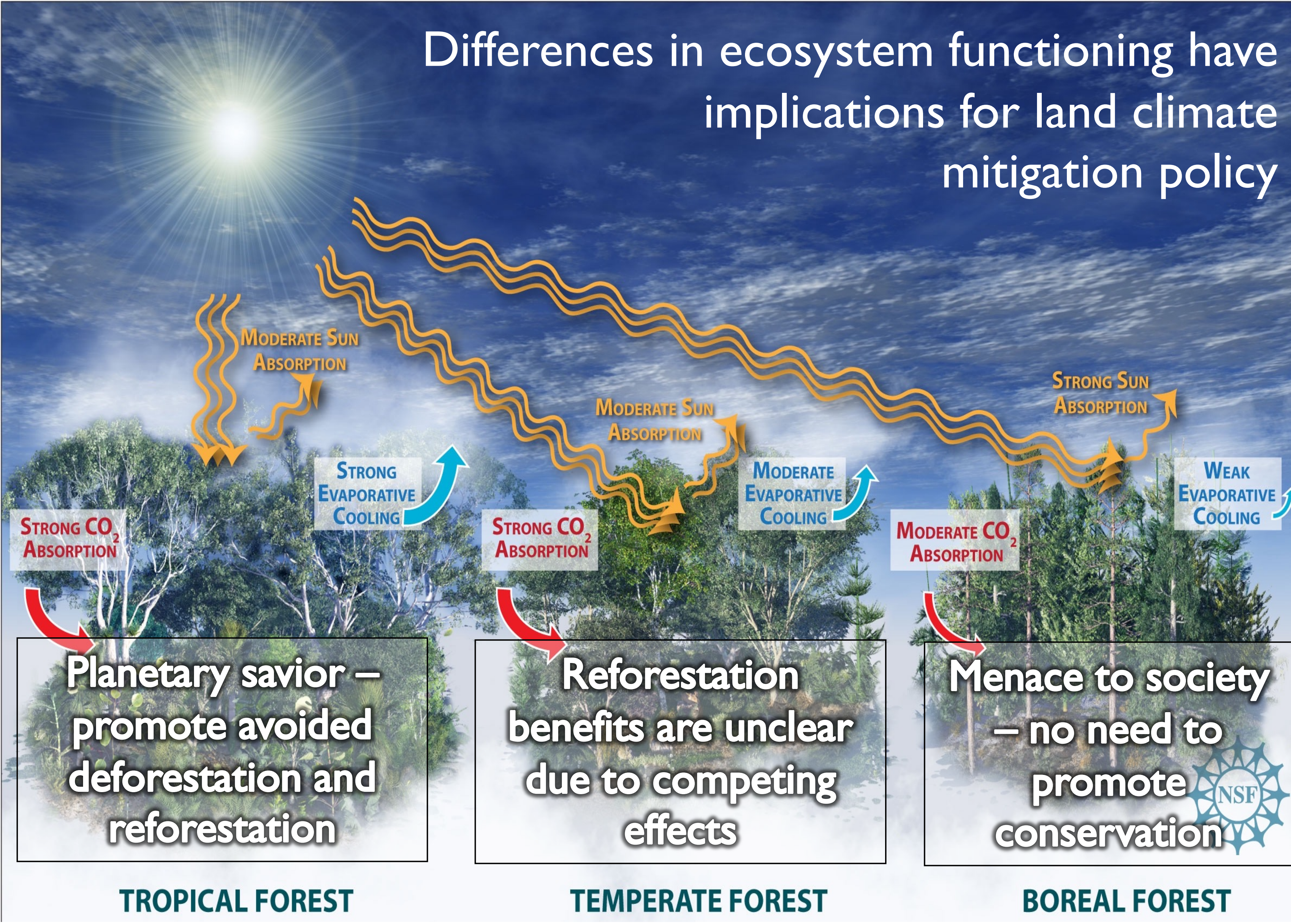
Not all forest ecosystems have the same impact on climate



Bonan (2008) Science 320:1444-1449

Credit: *Nicolle Rager Fuller, National Science Foundation*

Differences in ecosystem functioning have implications for land climate mitigation policy

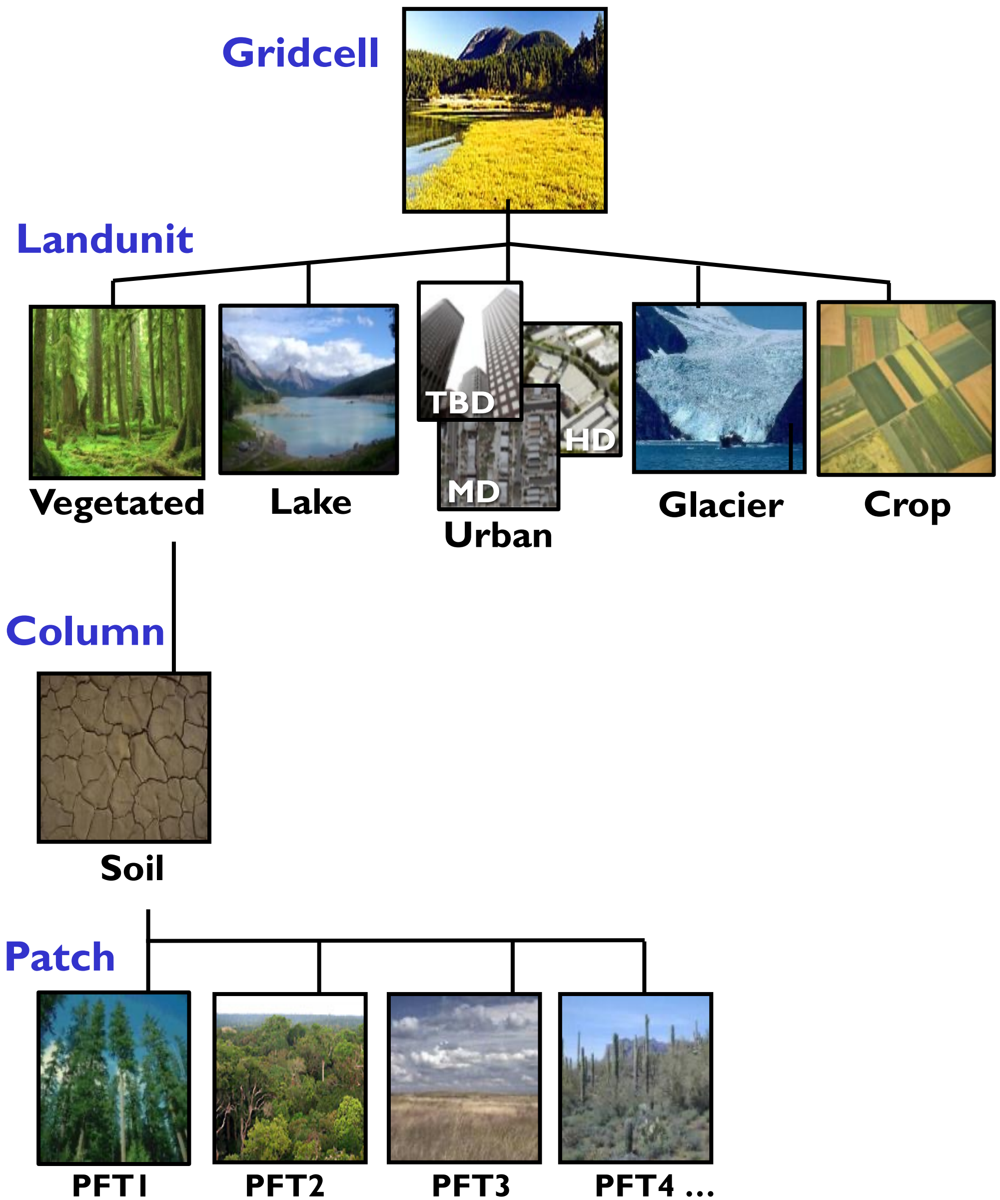


Bonan (2008) Science 320:1444-1449

Credit: *Nicolle Rager Fuller, National Science Foundation*

Land Modeling Challenges: Land surface heterogeneity

Land surface heterogeneity: Subgrid tiling



Plant Functional Types:

0. Bare

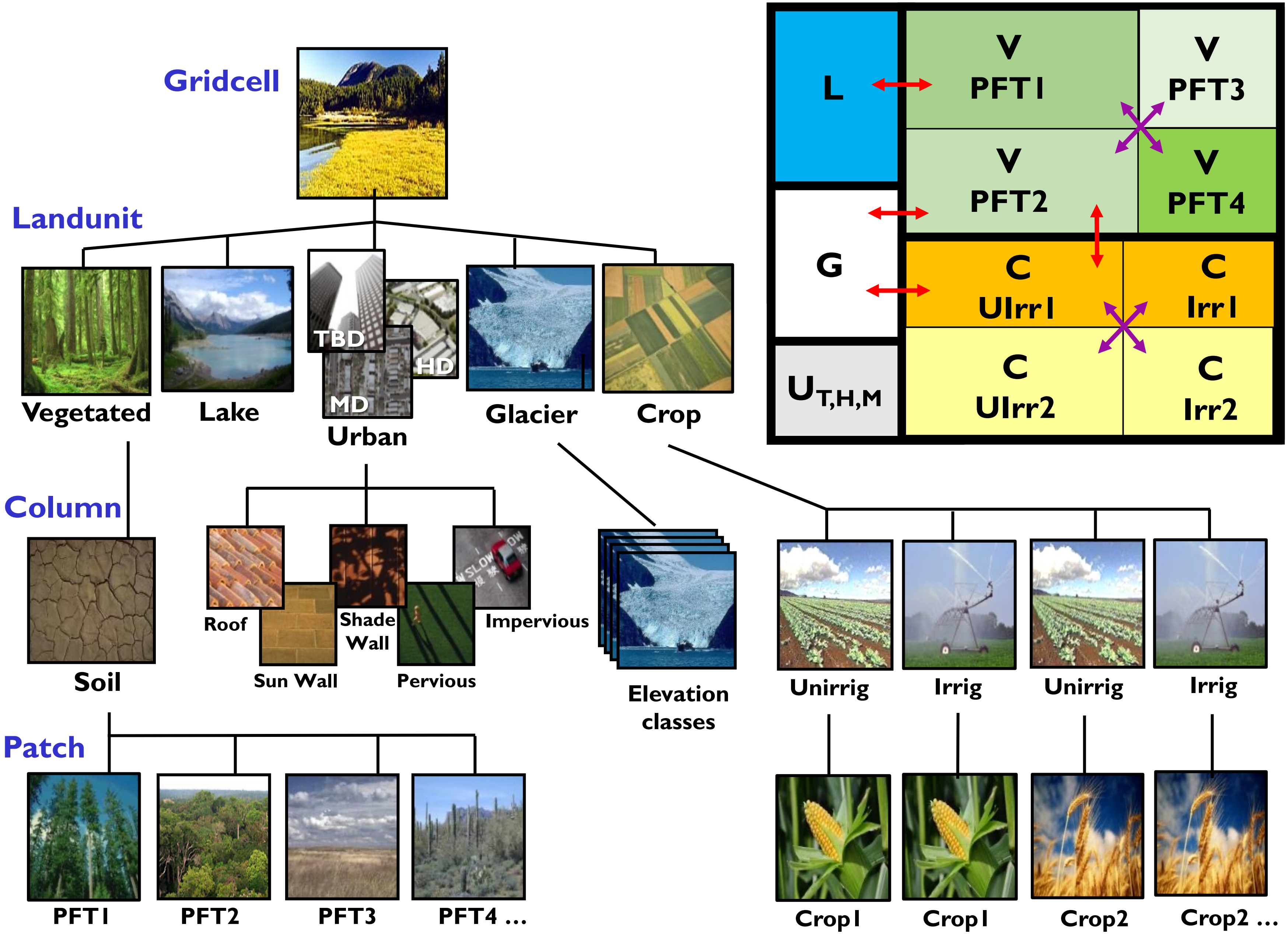
Tree:

1. Needleleaf Evergreen, Temperate
2. Needleleaf Evergreen, Boreal
3. Needleleaf Deciduous, Boreal
4. Broadleaf Evergreen, Tropical
5. Broadleaf Evergreen, Temperate
6. Broadleaf Deciduous, Tropical
7. Broadleaf Deciduous, Temperate
8. Broadleaf Deciduous, Boreal

Herbaceous / Understorey:

9. Broadleaf Evergreen Shrub, Temperate
10. Broadleaf Deciduous Shrub, Temperate
11. Broadleaf Deciduous Shrub, Boreal
12. C3 Arctic Grass
13. C3 non-Arctic Grass
14. C4 Grass
15. Crop

Land surface heterogeneity: Subgrid tiling



Land management in CLM5

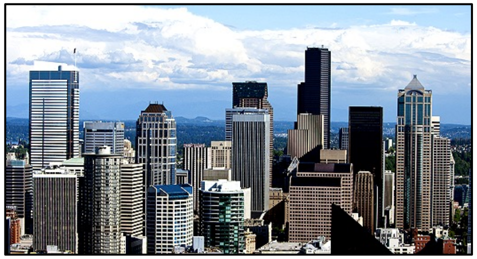
<u>Included in default CLM5</u>

- Global crop model with 8 basic crop types; planting, grain fill, harvest
- Crop irrigation
- Crop industrial fertilization
- Wood harvest
- Urban environments
- Anthropogenic fire ignition and suppression

Corn* Winter wheat Sugarcane

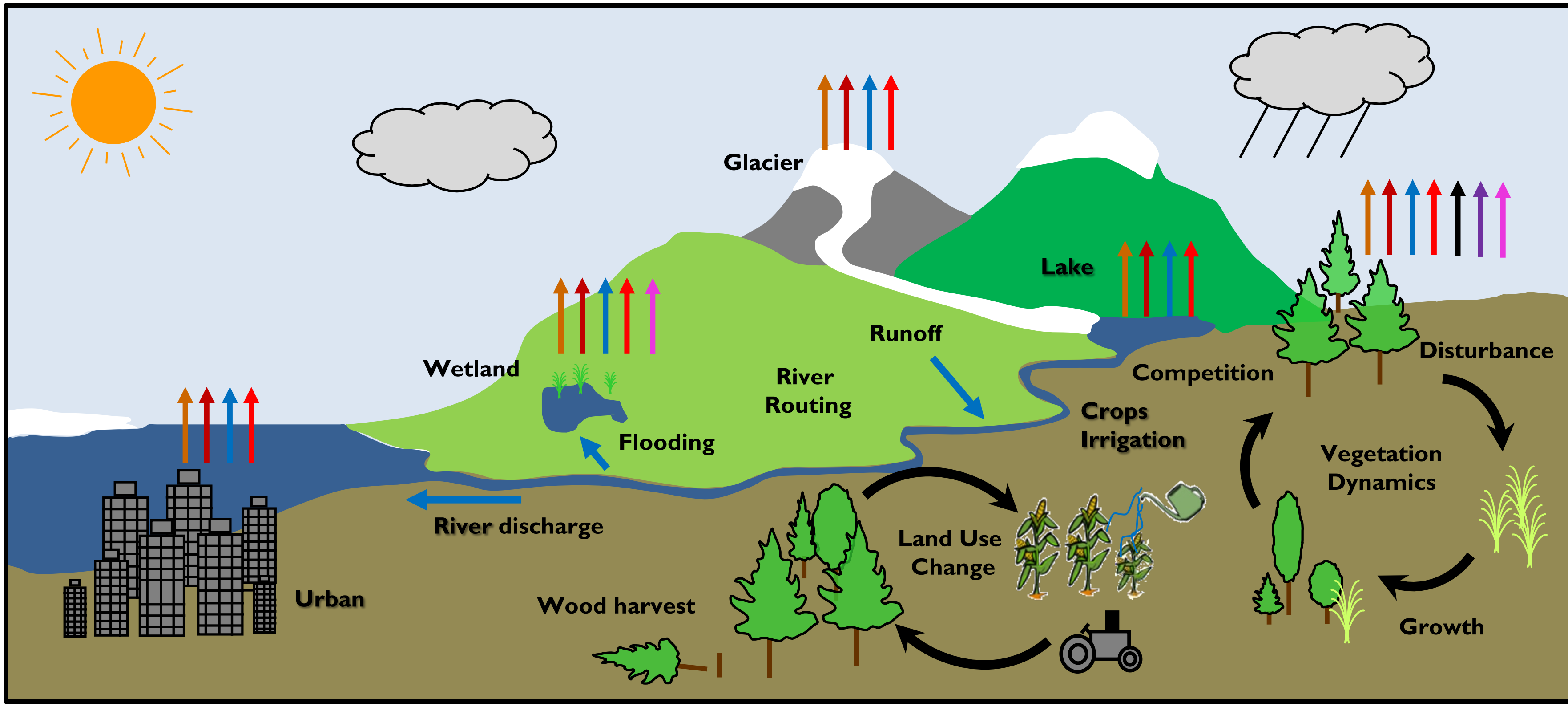
Soy* Cotton Rice

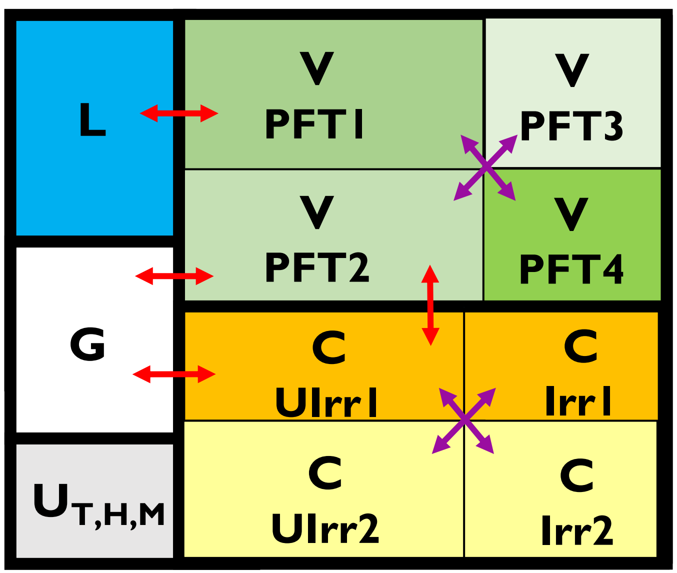
** Temperate and tropical varieties*



Fertilization

Irrigation

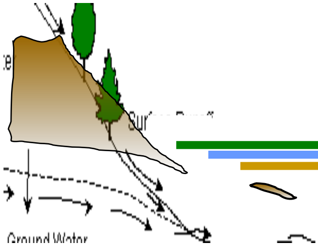


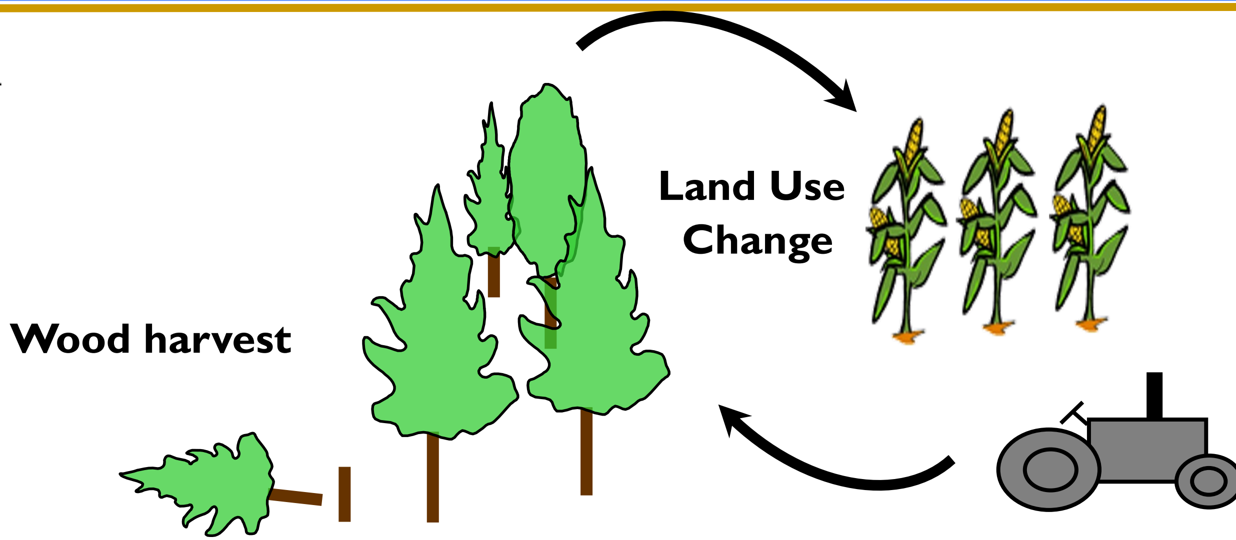


Landscape-scale dynamics

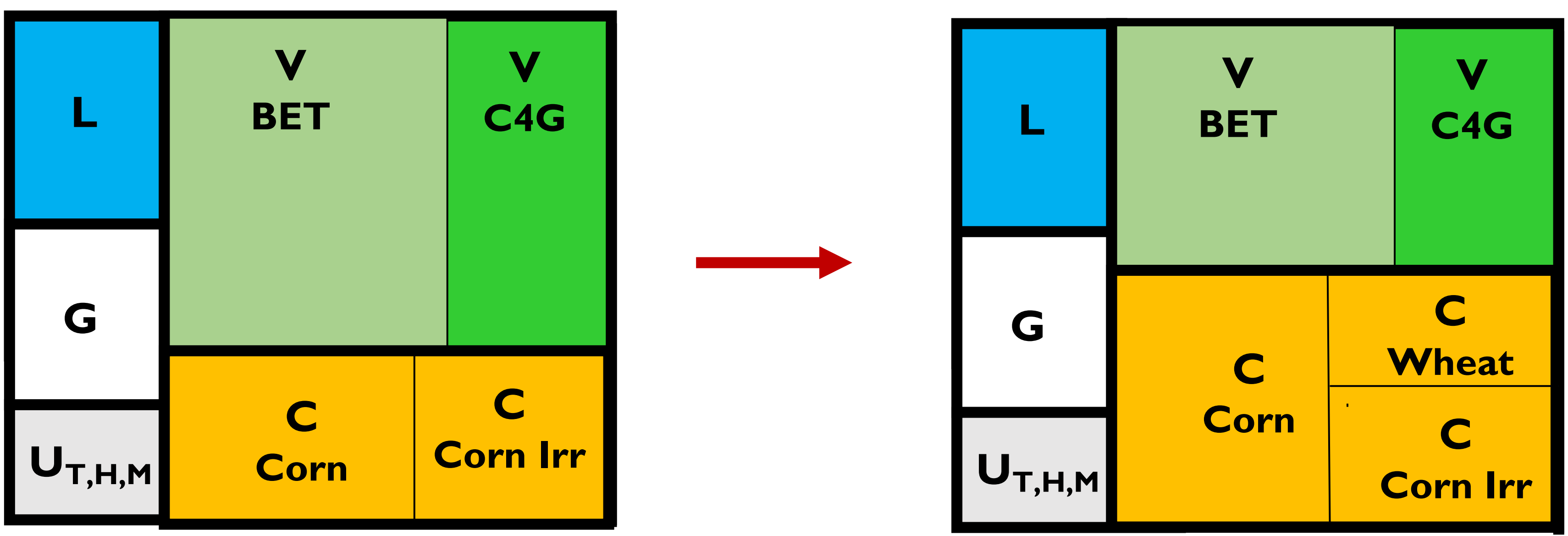
Long-term dynamical processes that affect fluxes in a changing environment (disturbance, land use, succession)

Land-cover / land-use change (prescribed)





Deforestation example

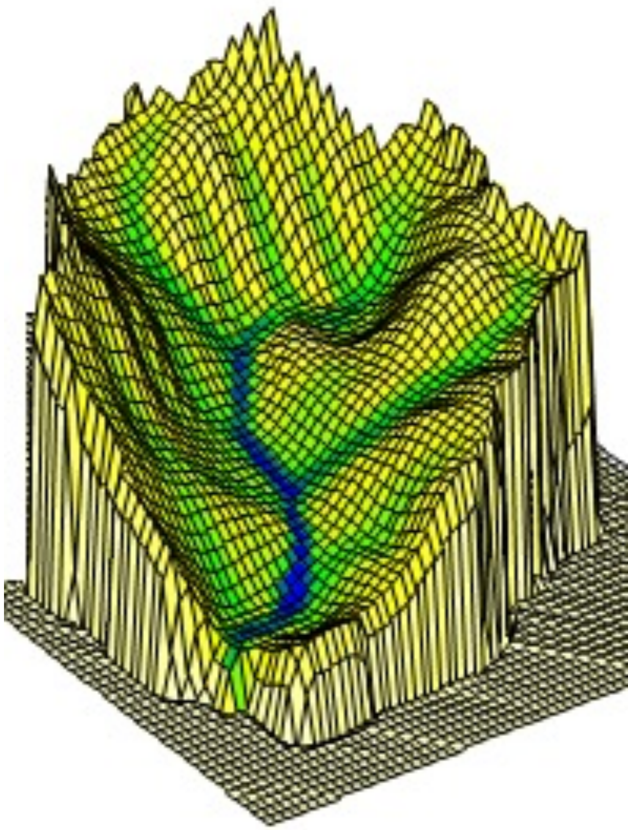


Land Modeling Challenges: Land surface heterogeneity

Parameterize impact of subgrid-scale soil moisture heterogeneity

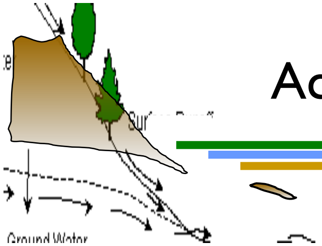
A major control on soil moisture heterogeneity and thus runoff is topography.

Lowland soils tend to be zones of high soil moisture content, while upland soils tend to be progressively drier.



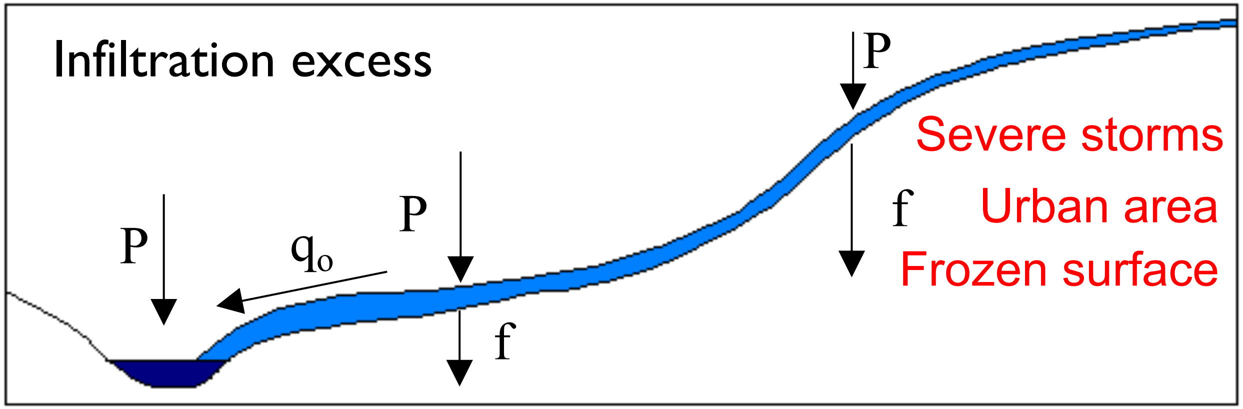
Three main sources of runoff:

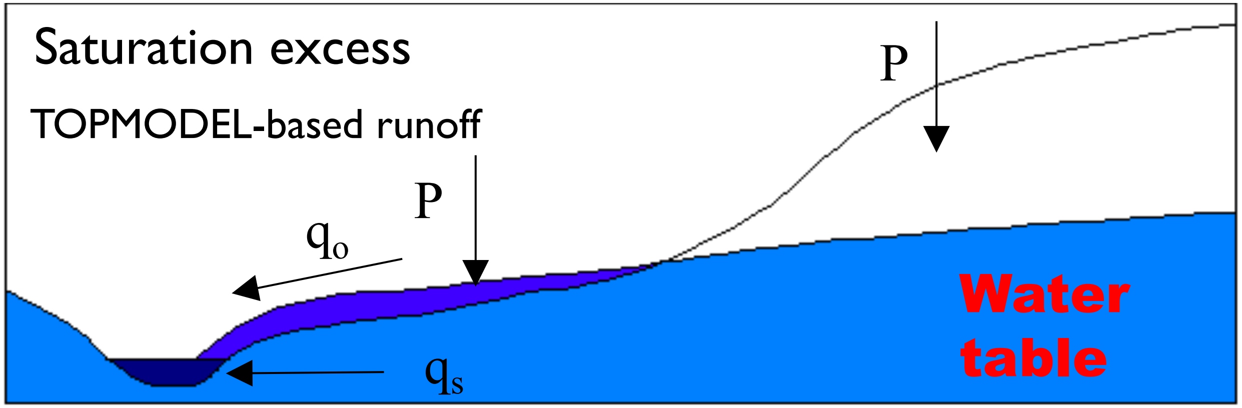
- Infiltration excess
- Saturation excess
- Baseflow (drainage)

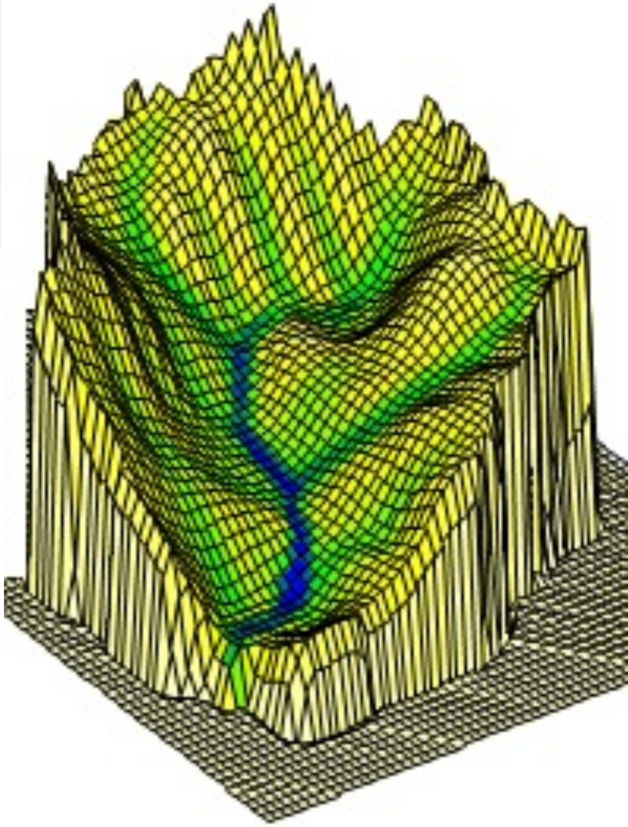


Accounting for subgrid soil moisture heterogeneity impacts on runoff

Surface runoff arises in two ways:





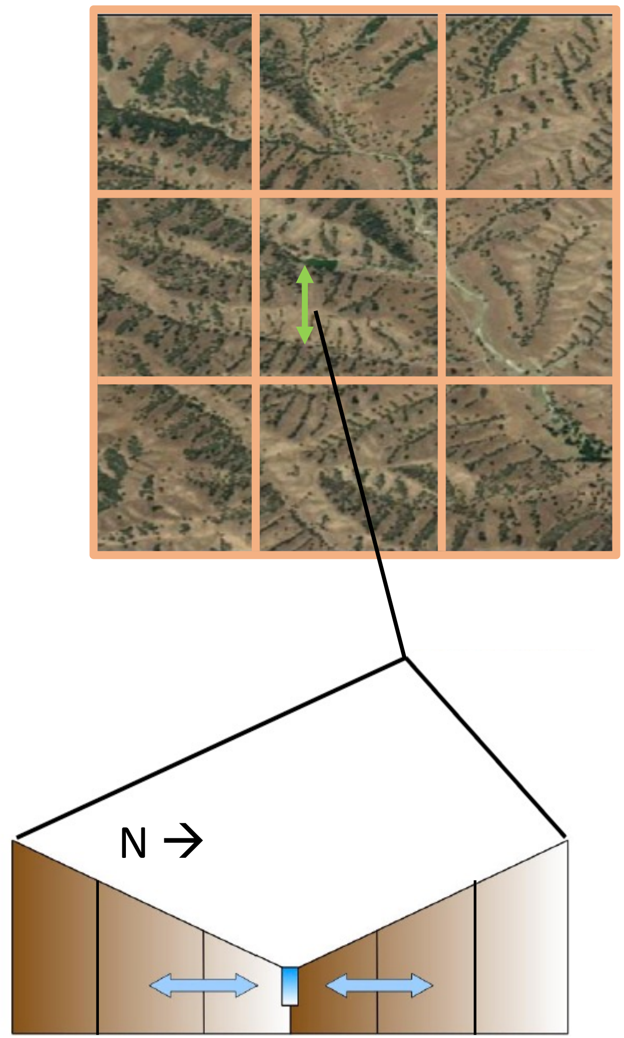


Subgrid hillslope processes

Implementing concept of 'representative hillslopes' into CLM

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

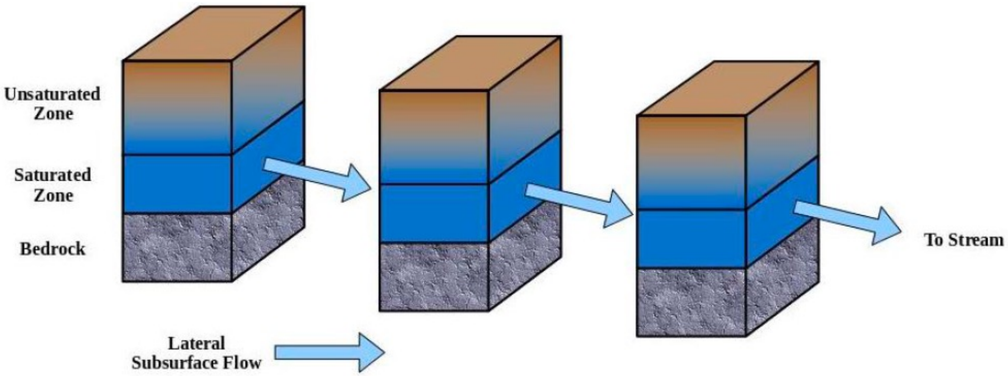
CLM grid cell (~1°x1°)



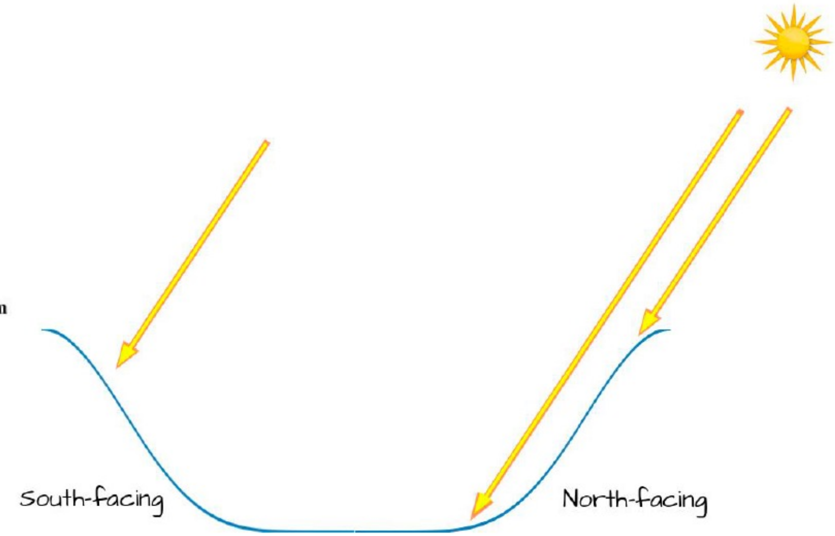
Sub-grid hillslope processes

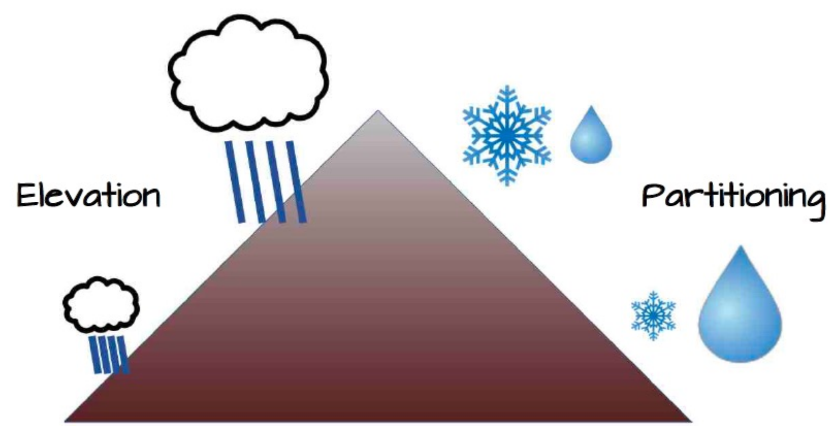
Implementing concept of subgrid 'representative hillslopes' into CLM

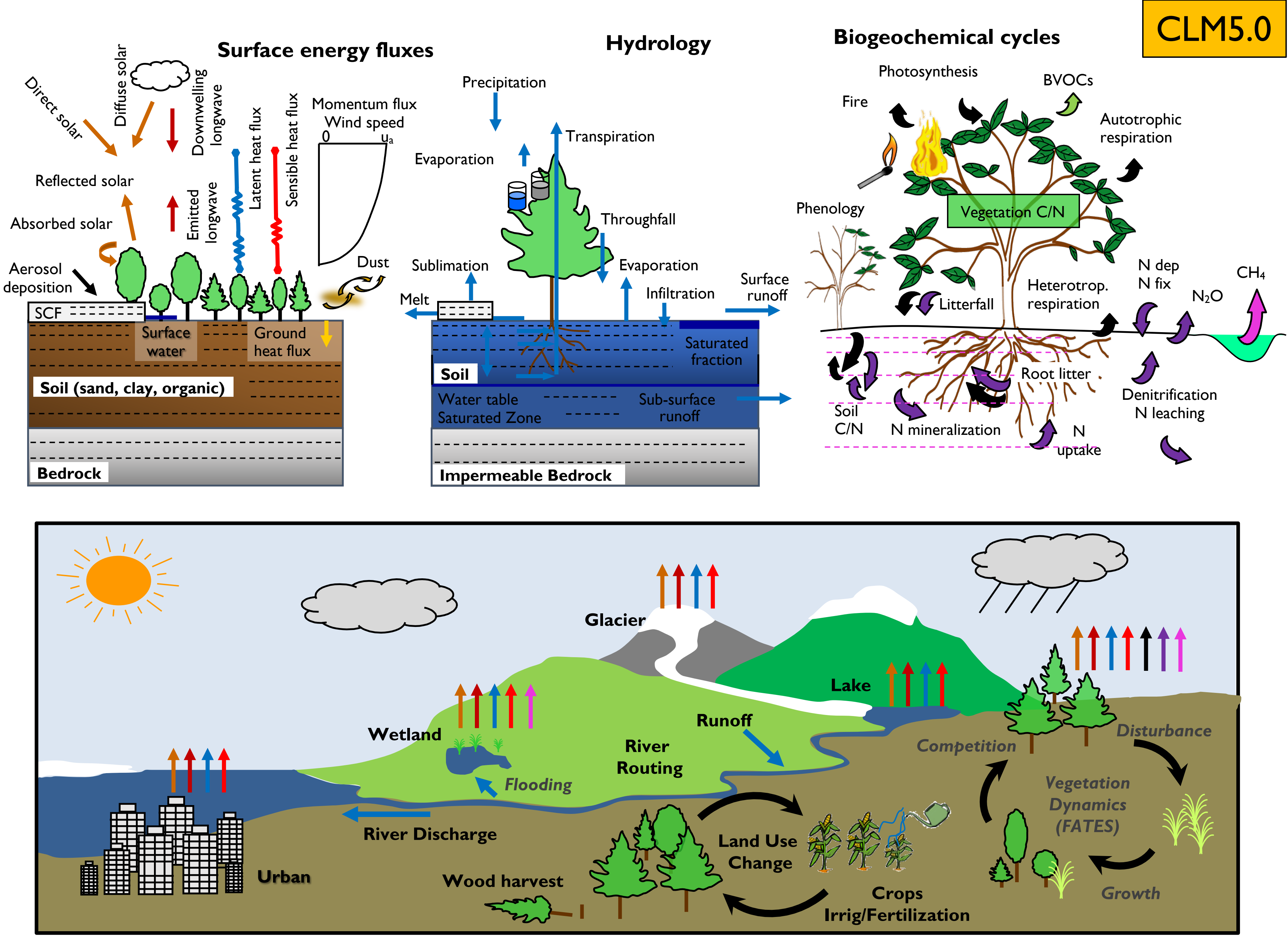
Explicit Lateral Flow Within Gridcell



Downscaled Meteorology

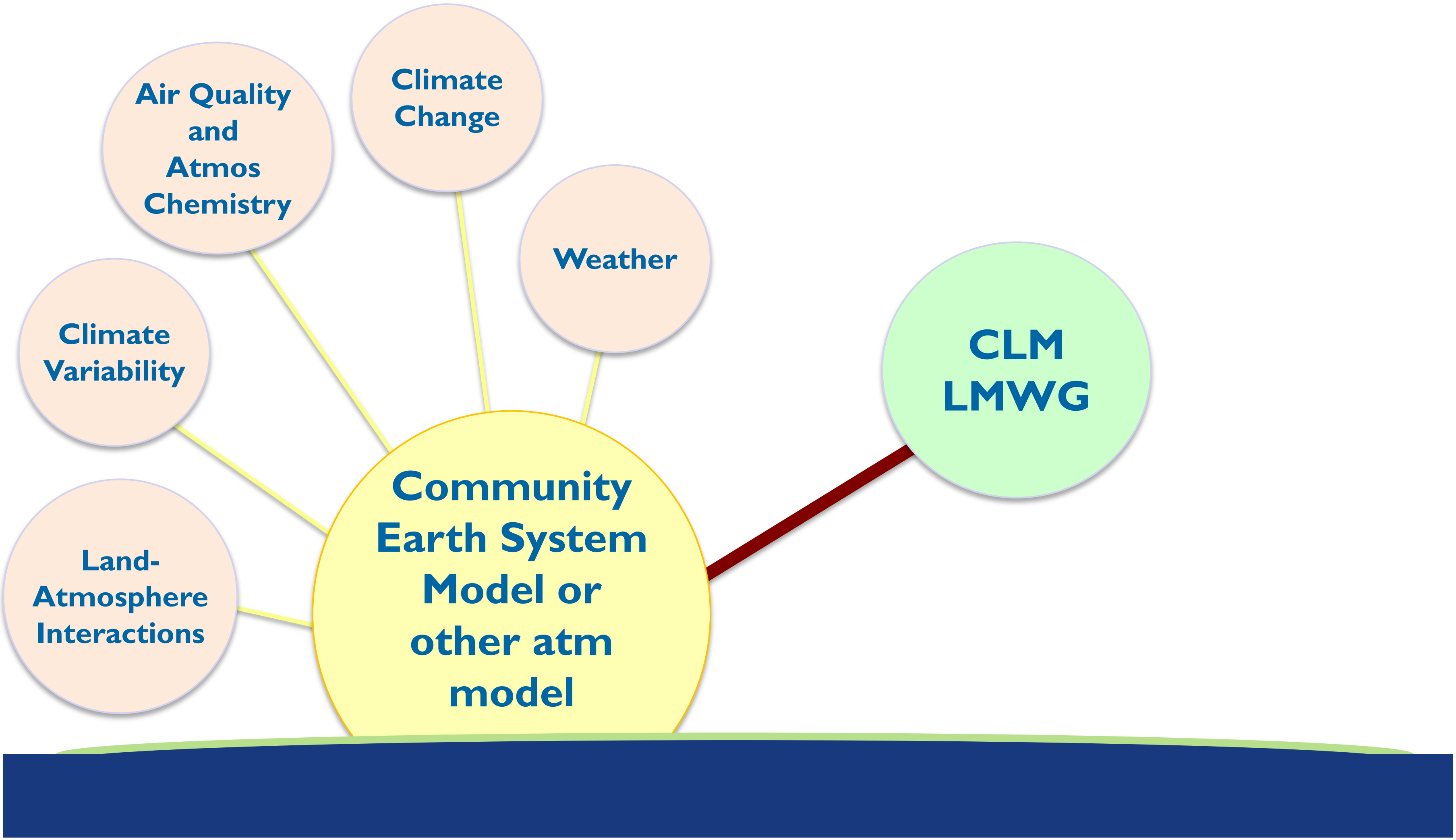




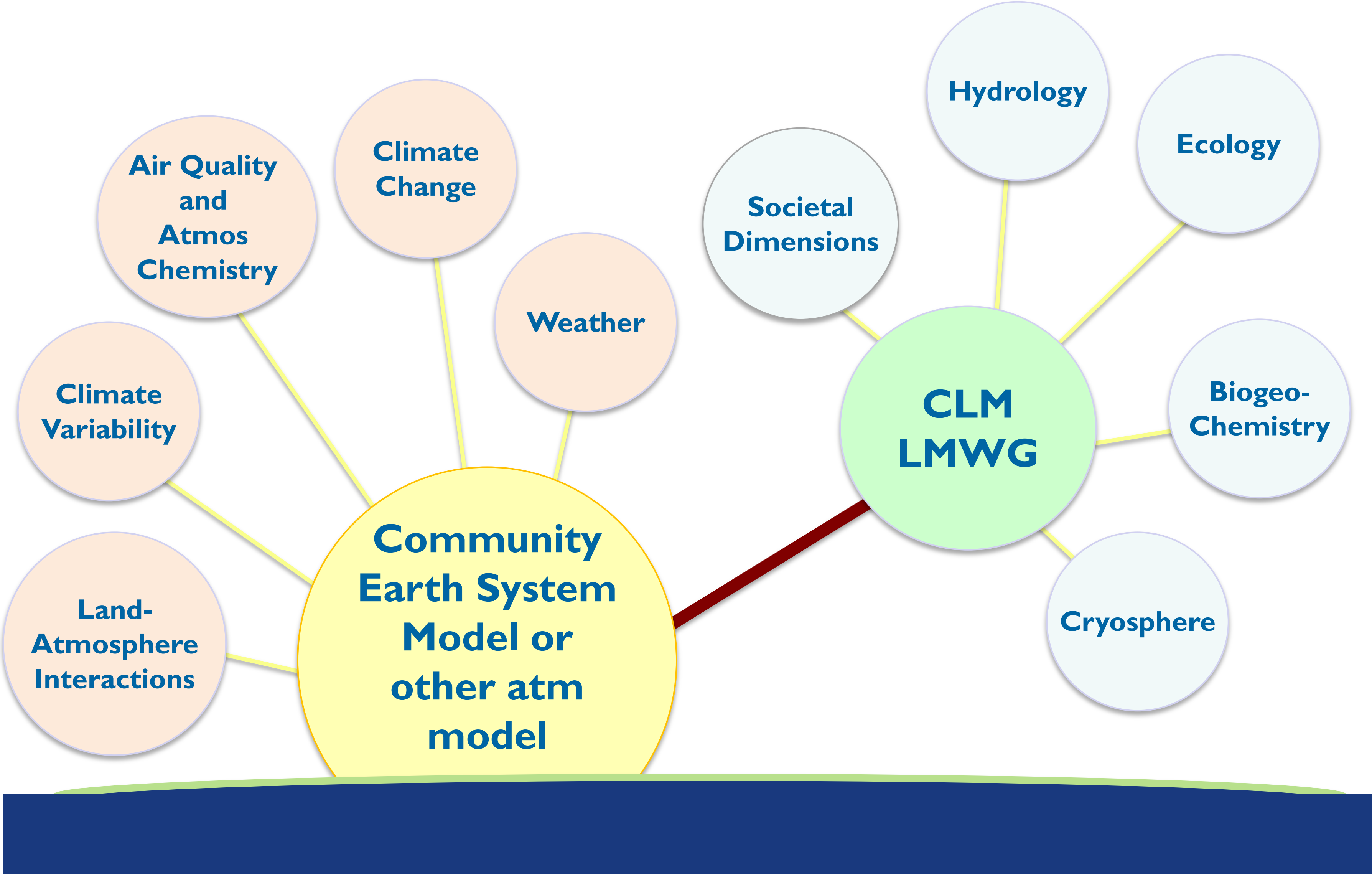


Lawrence et al., 2011; Lawrence et al., 2019

CLM as a community modeling tool



CLM as a community modeling tool



What's New for CLM5

https://github.com/ESCOMP/ctsm

A LOT!

More than 50 researchers from 15 different institutions were involved in development of CLM5

Parallel focus on mechanistic improvements and expansion of capabilities

- hydrology more consistent with state-of-art understanding
- more ecologically relevant plant nutrient, carbon, and water dynamics
- land management including global crop model, wood harvest, urban environments
- prognostic Greenland ice sheet model

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The Community Land Model Version 5: Description of New Features, Benchmarking, and Impact of Forcing Uncertainty

David M. Lawrence, Rosie A. Fisher, Charles D. Koven, Keith W. Oleson, Sean C. Swenson
... See all authors

First published: 19 October 2019 | https://doi.org/10.1029/2018MS001583 | Citations: 307

CTSM as a research tool

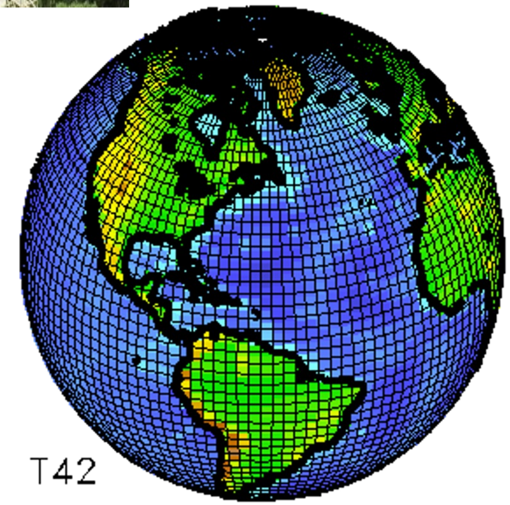
http://www.cesm.ucar.edu/models/cesm2/land/

Model configurations

- SP (satellite phenology, prescribed vegetation)
- BGC (prognostic carbon, vegetation)
- BGC-crop (default in CESM2, same as BGC with crops)
- BGC no-anthro
- FATES
- + many options for individual parameterizations (i.e., can revert to CLM4.5)

Spatial configurations

- Global (low and high resolution)
- Regional
- Single point (tower site)
- Irregular grids (cubed sphere, *catchment*)



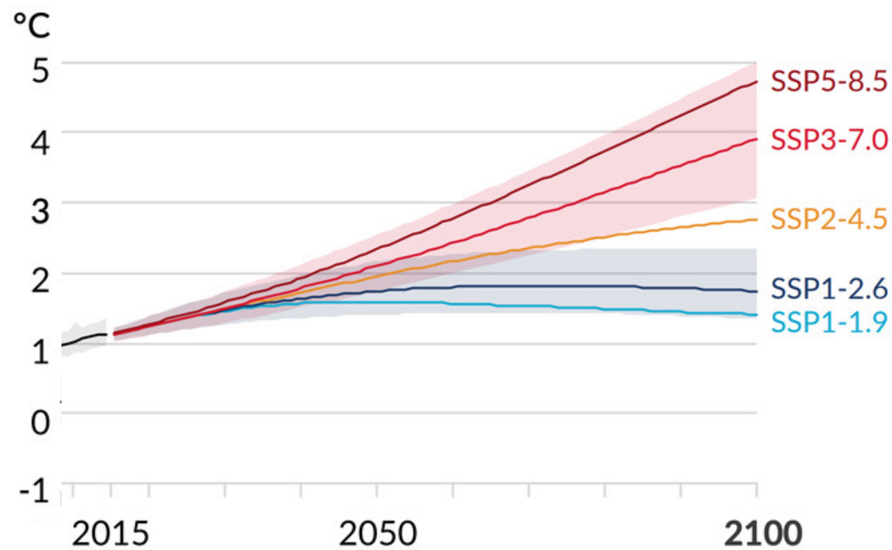
CTSM as a research tool

http://www.cesm.ucar.edu/models/cesm2/land/

Modes of forcing

- Anomaly forcing
  - monthly anomalies added to cycled reanalysis
  - four SSPs available 'out-of-box'
  - enables land-only simulations forced by climate change
- Forcing datasets (GSWP3, CRUJRA, Princeton, WATCH, NLDAS)
- Prescribed soil moisture
- Alternate LULCC

- And, obviously, coupled to CAM, CESM, and also WRF
- Ensembles of simulations
- Data assimilation with DART



CTSM as a research tool

Options to reduce complexity

- CH_4 emissions
- Carbon isotopes
- Land-use change
- VOC emissions
- Plant Hydraulics
- Fewer landunits and PFTs per gridcell
- Soil structure (15-level vs 25-level)

Options to increase complexity

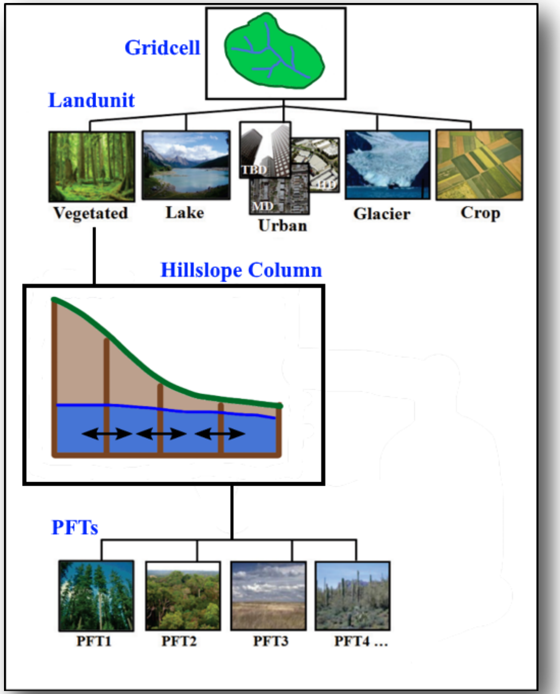
- Representative hillslopes
- FATES (Ecosystem dynamics)
- Fire trace gas emissions
- Additional land management
- Flooding
- Ozone damage to plants

Resources:

- CLM5 release webpage: www.cesm.ucar.edu/models/cesm2/land/
- CLM code repository: github.com/ESCOMP/ctsm
- Lawrence et al. (2019), in review *JAMES*

Some priorities and plans for next generation CLM

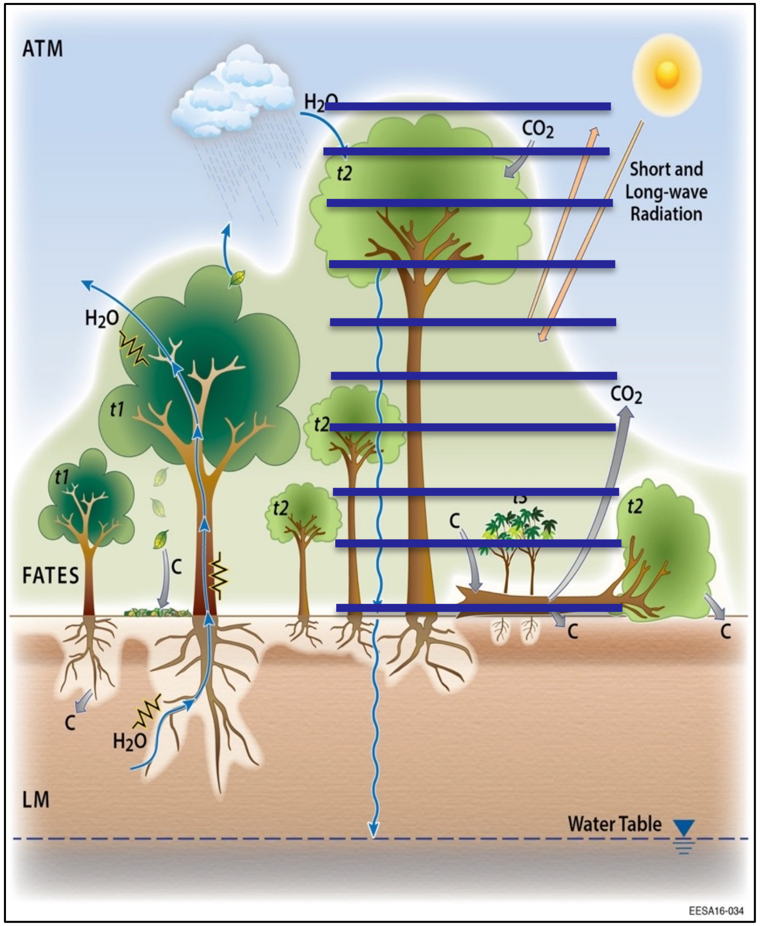
- Water and food security in context of climate variability, change, and extreme weather
- Ecosystem vulnerability and impacts on carbon cycle and ecosystem services
- Sources of predictability from land processes
- Impacts of land use and land-use change on climate, carbon, water, and extremes



Lateral fluxes of water

Water and land management

Ecosystem Demography / Multi-layer canopy



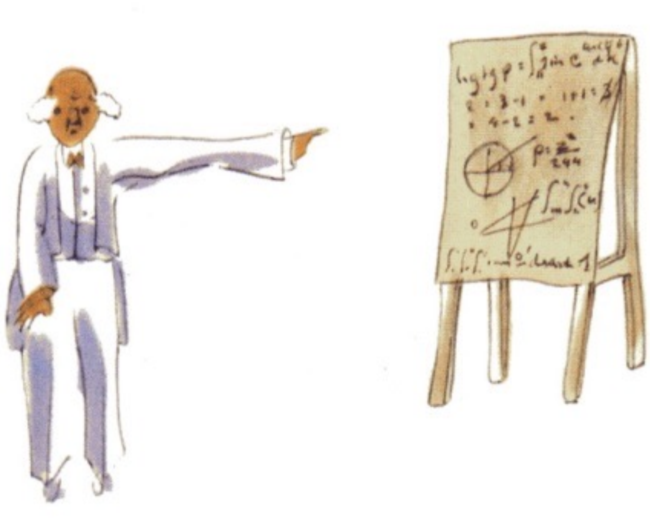
Questions?

Extra slides

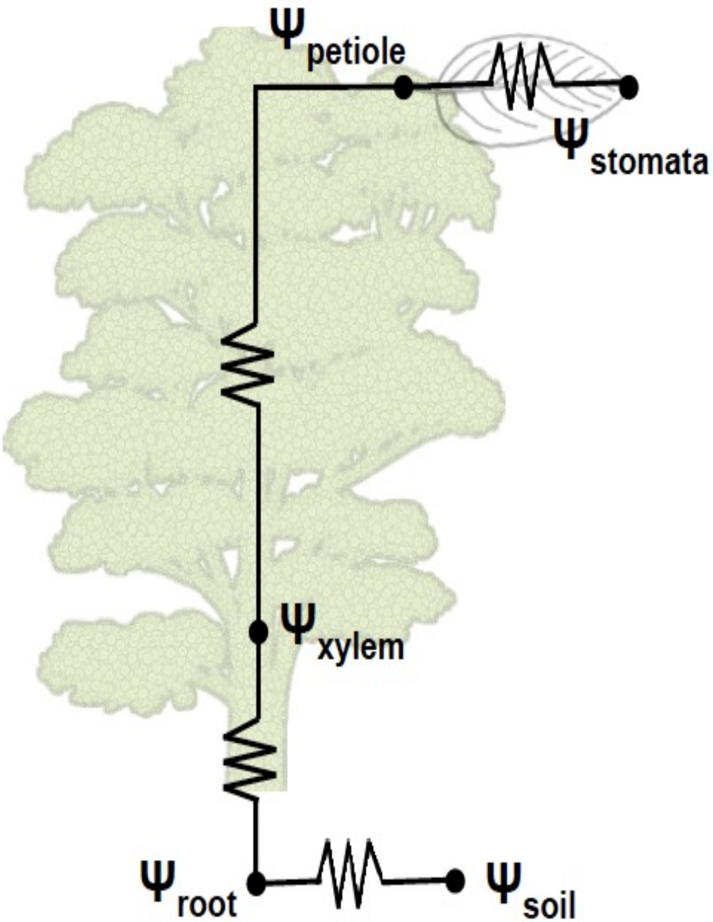
Modeling caveats

CLM (CESM) is just a starting point for the science. It is not the science itself

- Easy to run the model and get an answer
- Much harder to understand why you got that answer
- CLM is a very complex, multidisciplinary model

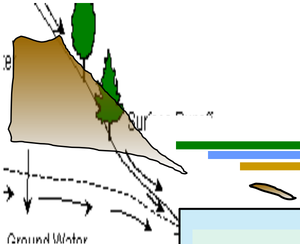


CLM5: Plant Hydrodynamics

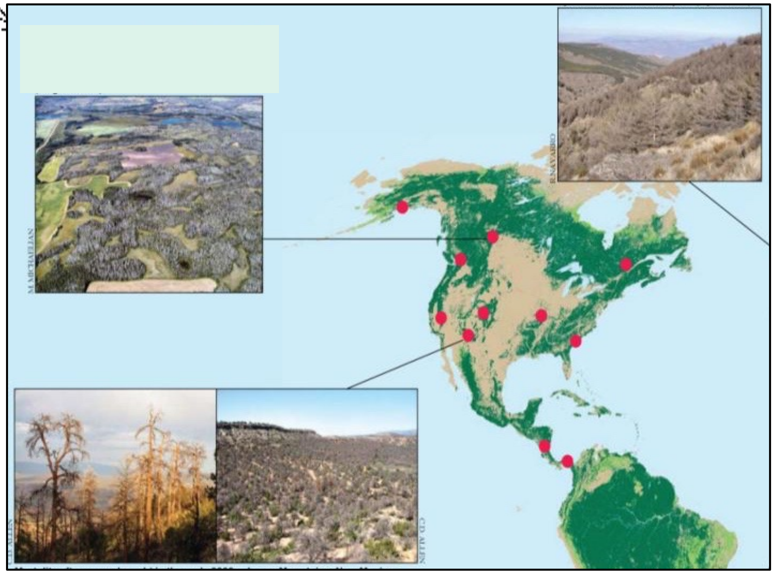


Why plant hydrodynamics

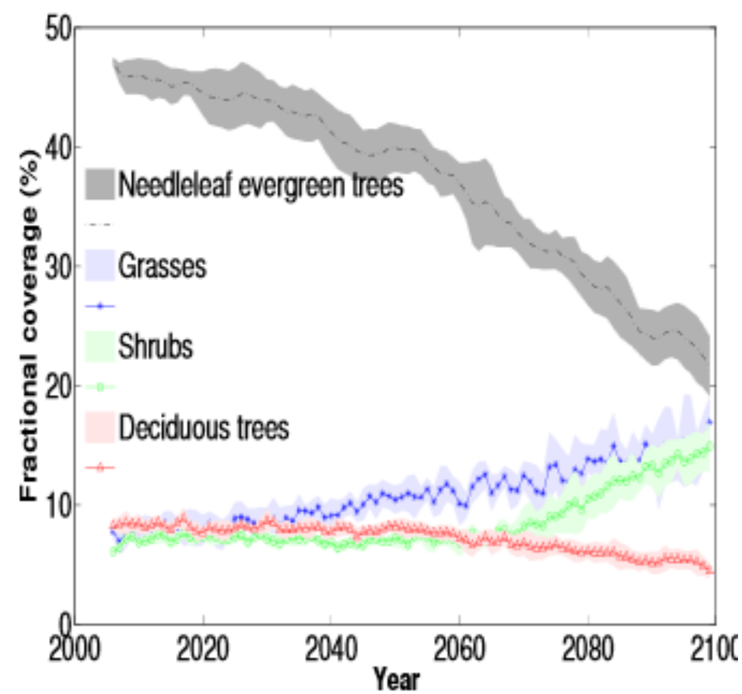
- BTRAN (soil moisture stress), and it's parameters, θ_{crit} and θ_{wilt}, have no physical meaning and cannot be measured.
- Flux tower ET convolutes transpiration with canopy and soil evap making it difficult to use for process-level assessment. With plant hydrodynamics, sap flow measurements could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



Ecosystem vulnerability to climate change
e.g., how vulnerable are western US forests to climate change?



CLM4(DGVM), suggests widespread die-off of forests by 2100, but simple representation of hydrology, plant water use, mortality, ecosystem dynamics

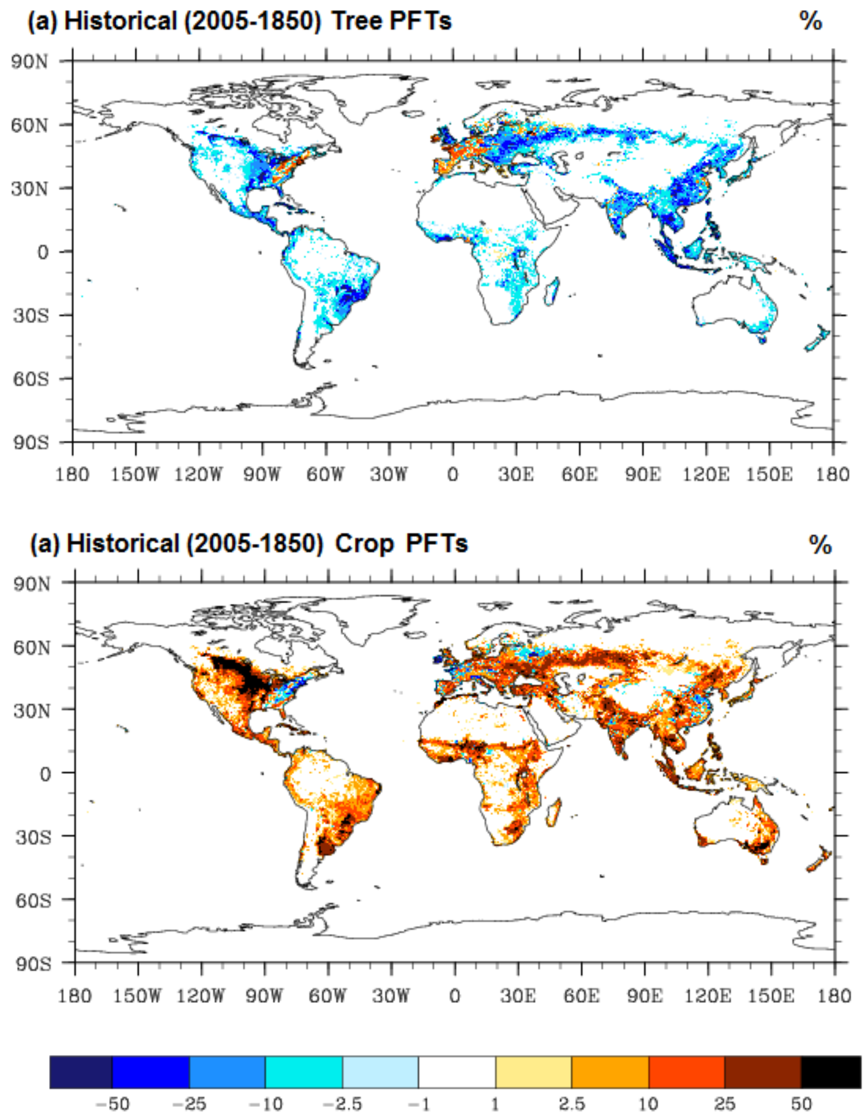


But … these results are likely unreliable; tree response to soil moisture deficits represented in ad hoc way in land models. Forest loss is complex problem that requires combined consideration of climate, hydrology, ecology, and plant physiology and diversity

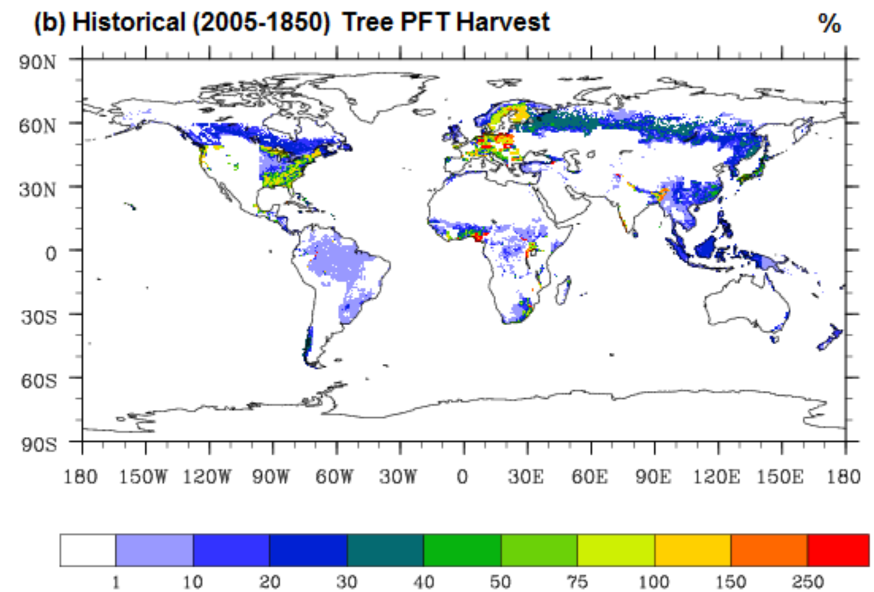
Jiang et al. 2013

Historical land use & land cover change, 1850-2005

Change in tree and crop cover (% of grid cell)



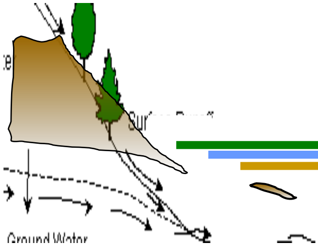
Cumulative percent of grid cell harvested



Historical LULCC

- ❑ Loss of tree cover and increase in cropland
- ❑ Farm abandonment and reforestation in eastern U.S. and Europe
- ❑ Extensive wood harvest

P. Lawrence et al. (2012) J Climate 25:3071-3095



Many paths to improve models and reduce model uncertainty

Model intercomparisons (MIPs)
- CMIP6: carbon cycle, land use, land-atmosphere coupling, …
- Range of plausible outcomes, but more models ≠ better results

Model benchmarking
- Comprehensive model evaluation against observations

Real-world experiments and models
- FACE, N addition

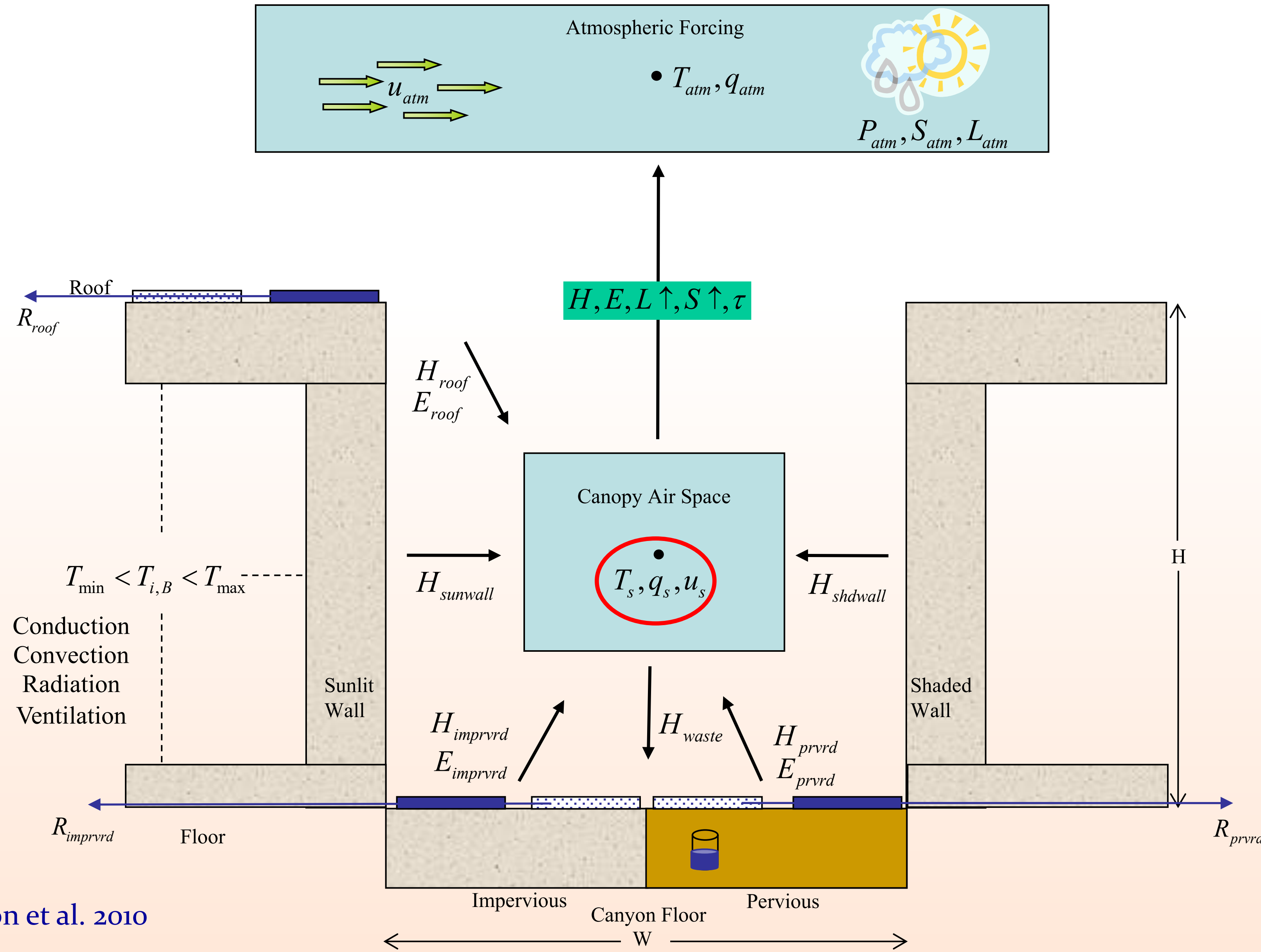
Model-data fusion
- Data assimilation, parameter estimation

“Discover” critical missing process
- Add another process that is ecologically or hydrologically important but poorly known at the global scale. Tune a key parameter to get a good simulation.

Model intracomparison
- Focus on model structural uncertainty to identify processes contributing to uncertainty

Model hierarchy
- CLM
- Process models (multilayer canopy, MIMICS)
- Simple land models (Marysa Lague)

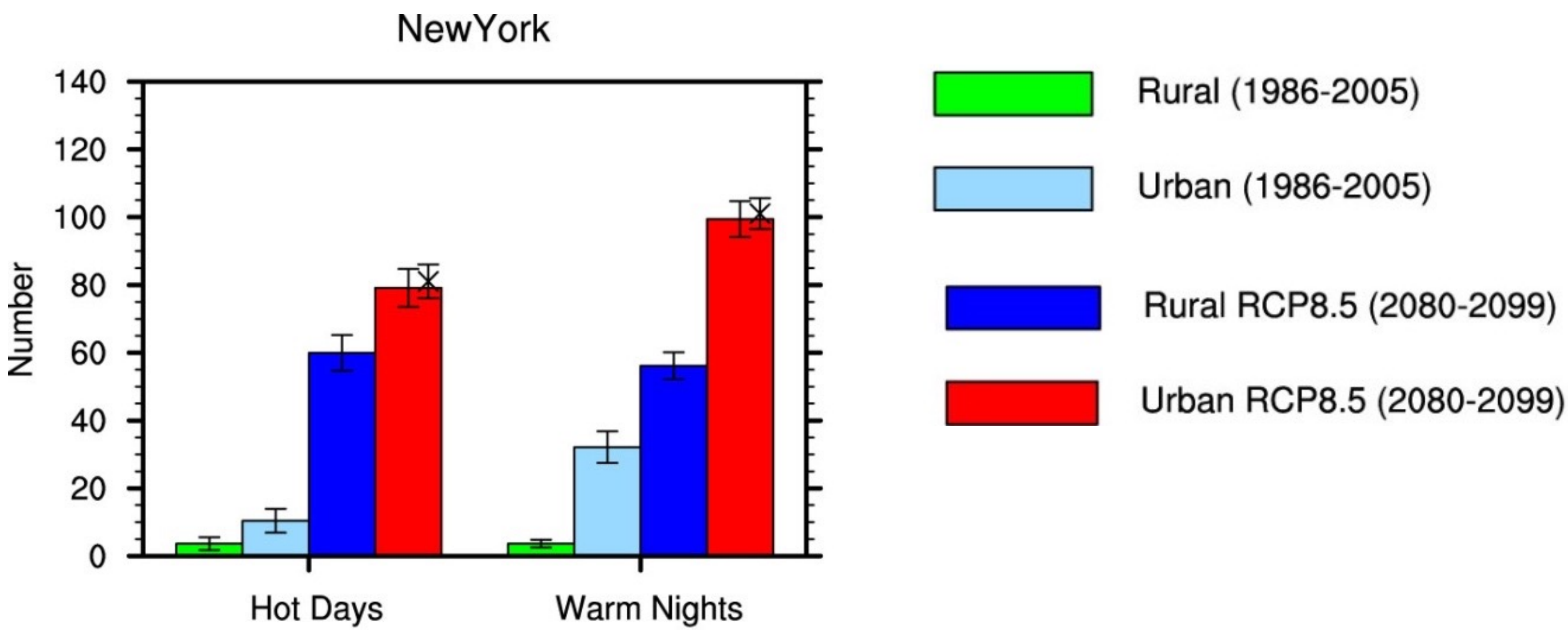
Urban Model



Oleson et al. 2010

Changes in hot days and warm nights – RCP8.5

Hot days (warm nights) – Number of days per year that daily TMAX (TMIN) exceeds 99th percentile of present day Rural daily TMAX (TMIN)



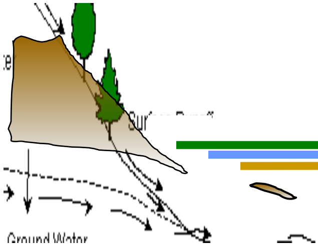
Present-day climate

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

Slide courtesy K. Oleson

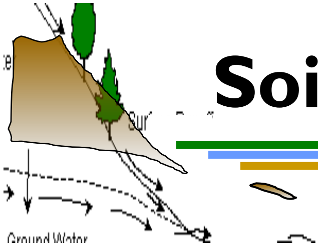


The role of CLM in CESM: Land to Atmosphere

[1]Latent heat flux	$\lambda_{vap} E_v + \lambda E_g$	W m^{-2}
Sensible heat flux	$H_v + H_g$	W m^{-2}
Water vapor flux	$E_v + E_g$	mm s^{-1}
Zonal momentum flux	τ_x	kg m^{-1} s^{-2}
Meridional momentum flux	τ_y	kg m^{-1} s^{-2}
Emitted longwave radiation	$L\uparrow$	W m^{-2}
Direct beam visible albedo	$I\uparrow_{vis}^{\mu}$	-
Direct beam near-infrared albedo	$I\uparrow_{nir}^{\mu}$	-
Diffuse visible albedo	$I\uparrow_{vis}$	-
Diffuse near-infrared albedo	$I\uparrow_{nir}$	-
Absorbed solar radiation	$\vec{S}$	W m^{-2}
Radiative temperature	T_{rad}	K
Temperature at 2 meter height	T_{2m}	K
Specific humidity at 2 meter height	q_{2m}	kg kg^{-1}
Snow water equivalent	W_{sno}	m
Aerodynamic resistance	r_{am}	s m^{-1}
Friction velocity	u_*	m s^{-1}
[2]Dust flux	F_j	kg m^{-2} s^{-1}
Net ecosystem exchange	NEE	$kgCO_2$ m^{-2} s^{-1}

The role of CLM in CESM: Atmosphere to Land

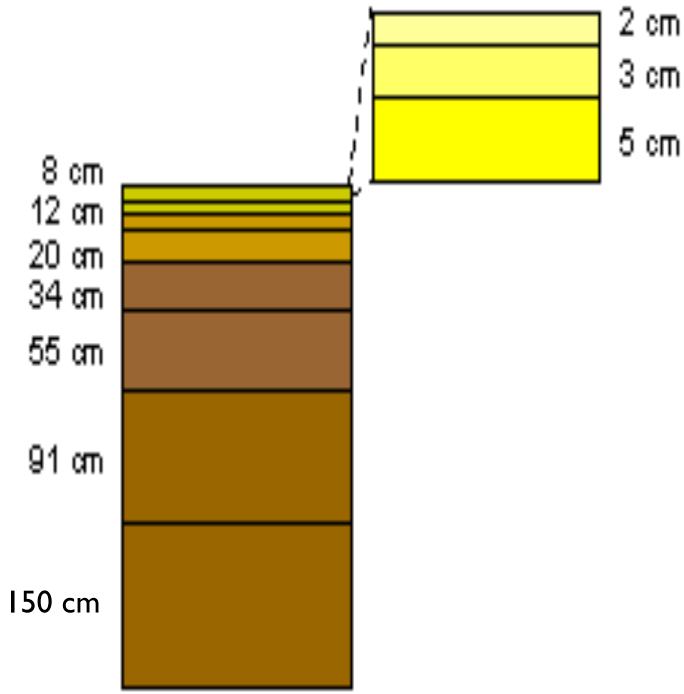
[1]Reference height	z'_{atm}	m
Zonal wind at z_{atm}	u_{atm}	m s^{-1}
Meridional wind at z_{atm}	v_{atm}	m s^{-1}
Potential temperature	$\overline{\theta_{atm}}$	K
Specific humidity at z_{atm}	q_{atm}	kg kg^{-1}
Pressure at z_{atm}	P_{atm}	Pa
Temperature at z_{atm}	T_{atm}	K
Incident longwave radiation	$L_{atm}\downarrow$	W m^{-2}
[2]Liquid precipitation	q_{rain}	mm s^{-1}
[2]Solid precipitation	q_{sno}	mm s^{-1}
Incident direct beam visible solar radiation	$S_{atm}\downarrow^{\mu}_{vis}$	W m^{-2}
Incident direct beam near-infrared solar radiation	$S_{atm}\downarrow^{\mu}_{nir}$	W m^{-2}
Incident diffuse visible solar radiation	$S_{atm}\downarrow_{vis}$	W m^{-2}
Incident diffuse near-infrared solar radiation	$S_{atm}\downarrow_{nir}$	W m^{-2}
Carbon dioxide (CO_2) concentration	c_a	ppmv
[3]Aerosol deposition rate	D_{sp}	kg m^{-2} s^{-1}
[4]Nitrogen deposition rate	NF_{ndep_sminn}	g (N) m^{-2} yr^{-1}
[5]Lightning frequency	I_l	flash km^{2} hr^{-1}



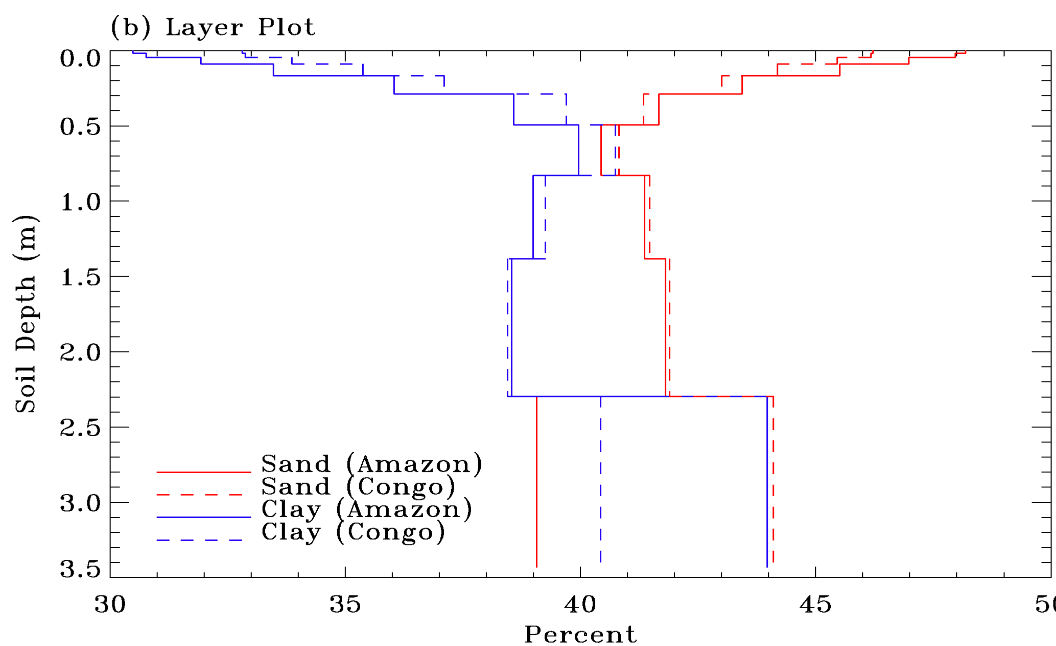
Soil Texture – thermal/hydrologic parameters

Soil parameters are derived from sand / clay percentage and soil organic matter content which is specified geographically and by soil level

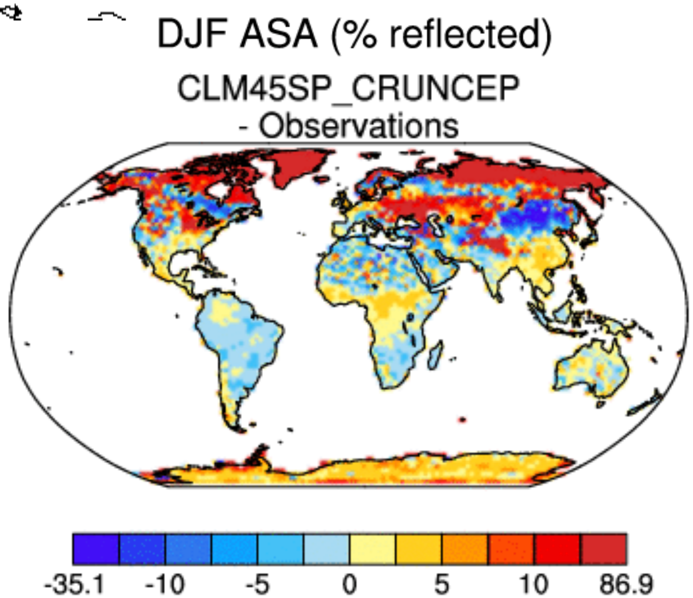
- Soil moisture concentration at saturation
- Soil moisture concentration at wilting point
- Hydraulic conductivity at saturation
- Saturated soil suction
- Thermal conductivity
- Thermal capacity

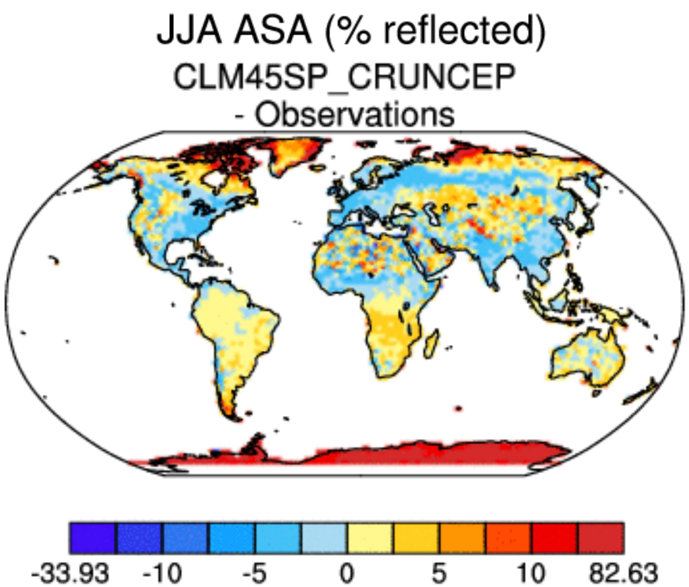


Soil profile
10 soil levels (~3.8m)
5 bedrock levels (~42m)



Modeling surface albedo



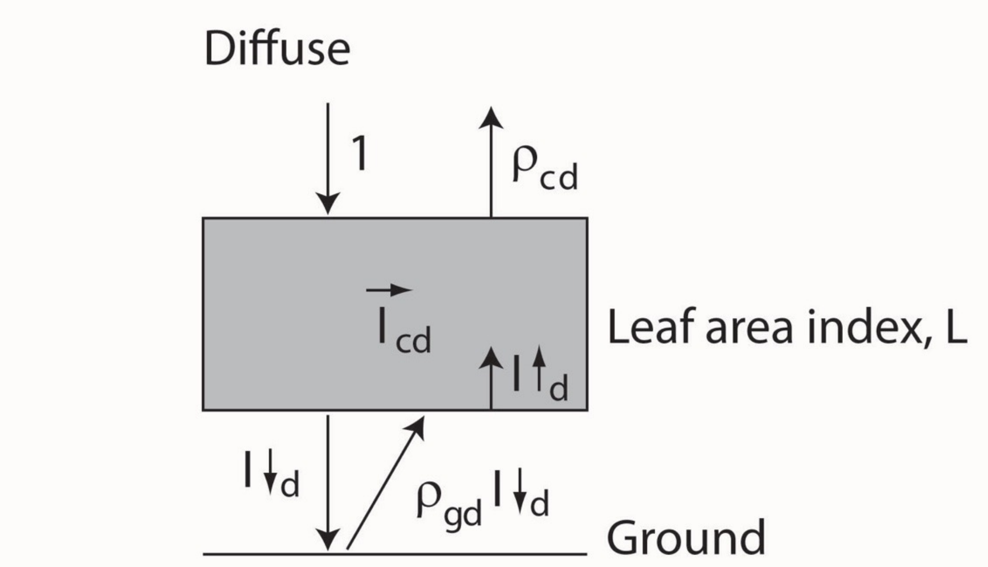


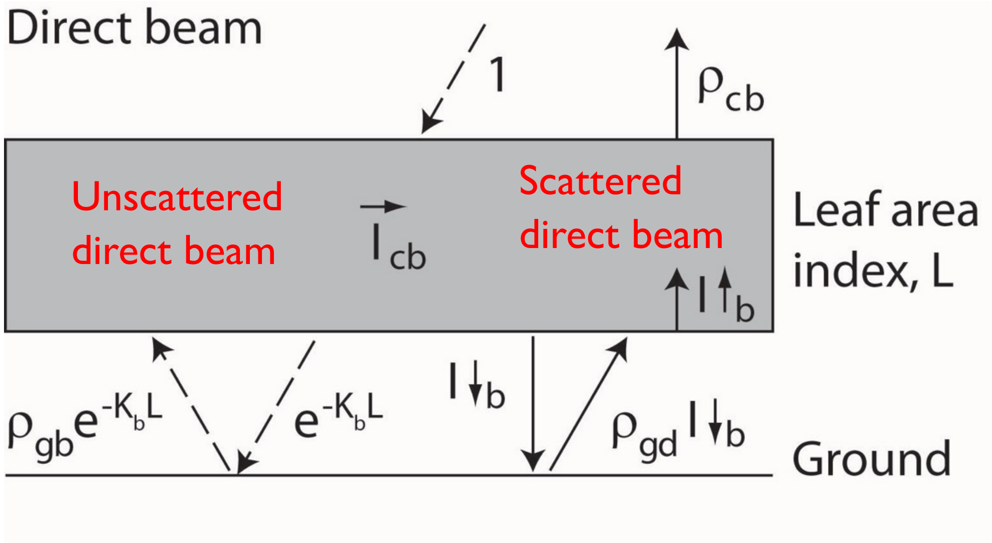
Surface albedo a function of

- Vegetation cover and type
- Snow cover
- Snow age
- Soil moisture
- Soil color
- Solar zenith angle
- Amount of direct vs diffuse solar radiation
- Amount of visible vs IR solar radiation

Note: MODIS albedo biased low for snow at high zenith angle
(Wang and Zender, 2010)

Two-stream radiative transfer





Radiative transfer uses the two-stream approximation (Dickinson, Sellers) to determine reflected and absorbed solar radiation

Slide courtesy G. Bonan

Momentum, and sensible heat and evaporation fluxes

Momentum flux

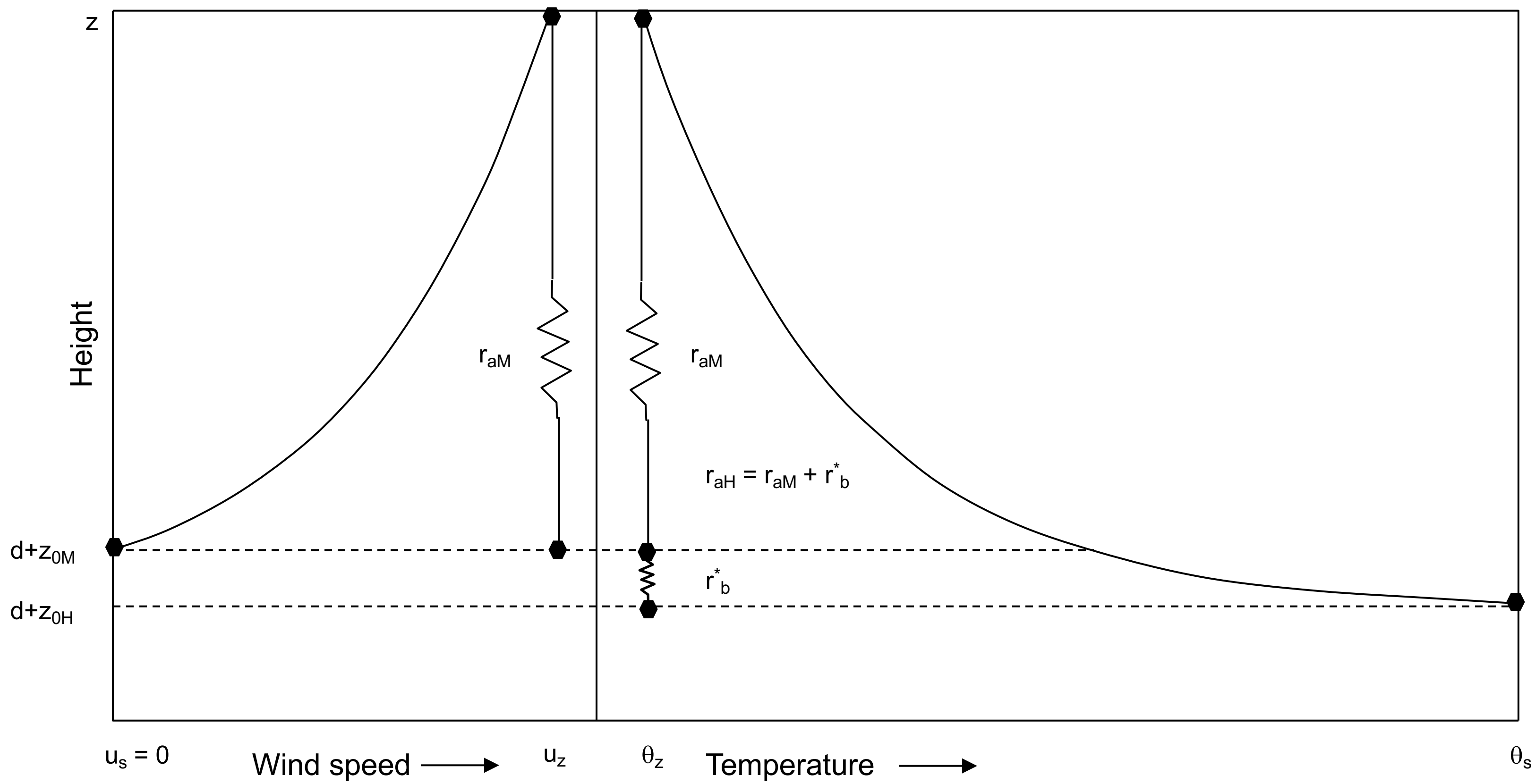
$u_* u_* = \tau / \rho$ and $\tau = \rho(u_a - u_s)/r_{aM} = \rho u / r_{aM}$ ➡ $r_{aM} = \frac{1}{k^2 u}\left[\ln\left(\frac{z-d}{z_{0M}}\right) - \psi_m(\zeta)\right]^2$

Sensible heat flux

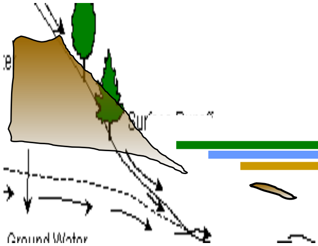
$\theta_* u_* = -H/(\rho c_p)$ and $H = -\rho c_p(\theta_a - T_s)/r_{aH}$ ➡ $r_{aH} = \frac{1}{k^2 u}\left[\ln\left(\frac{z-d}{z_{0M}}\right) - \psi_m(\zeta)\right]\left[\ln\left(\frac{z-d}{z_{0H}}\right) - \psi_h(\zeta)\right]$

Evaporation

$q_* u_* = -E/\rho$ and $E = -\rho(q_a - q_s)/r_{aW}$ ➡ $r_{aW} = \frac{1}{k^2 u}\left[\ln\left(\frac{z-d}{z_{0M}}\right) - \psi_m(\zeta)\right]\left[\ln\left(\frac{z-d}{z_{0W}}\right) - \psi_w(\zeta)\right]$



Slide courtesy G. Bonan



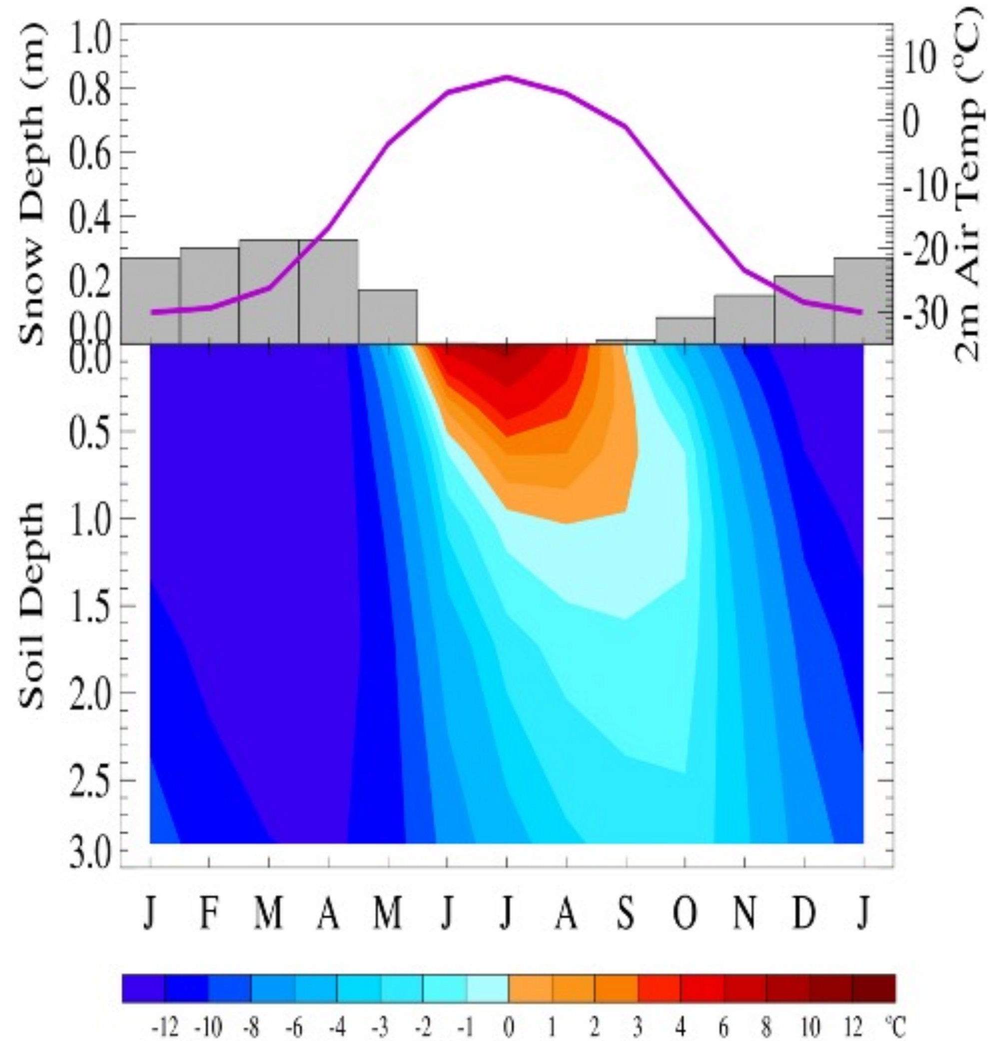
Snow/Soil thermodynamics

Solve the heat diffusion equation for multi-layer snow and soil model

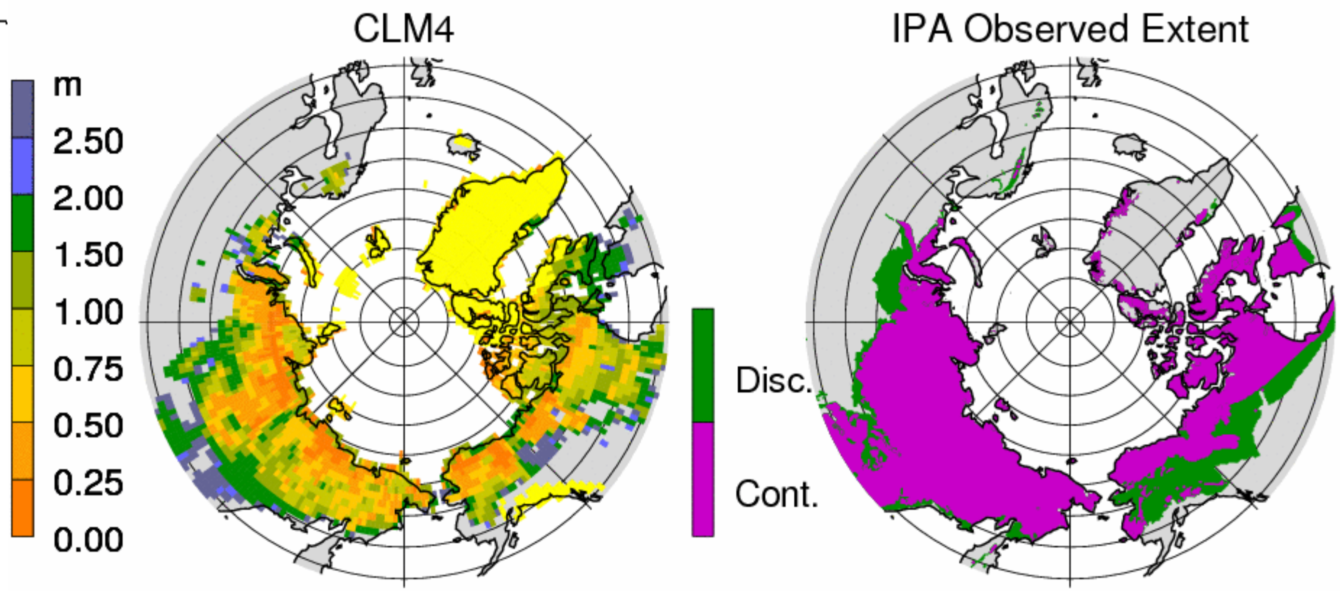
$$C_p \frac{\partial T}{\partial t} = \frac{\partial}{\partial z}\left(K \frac{\partial T}{\partial z} \right)$$

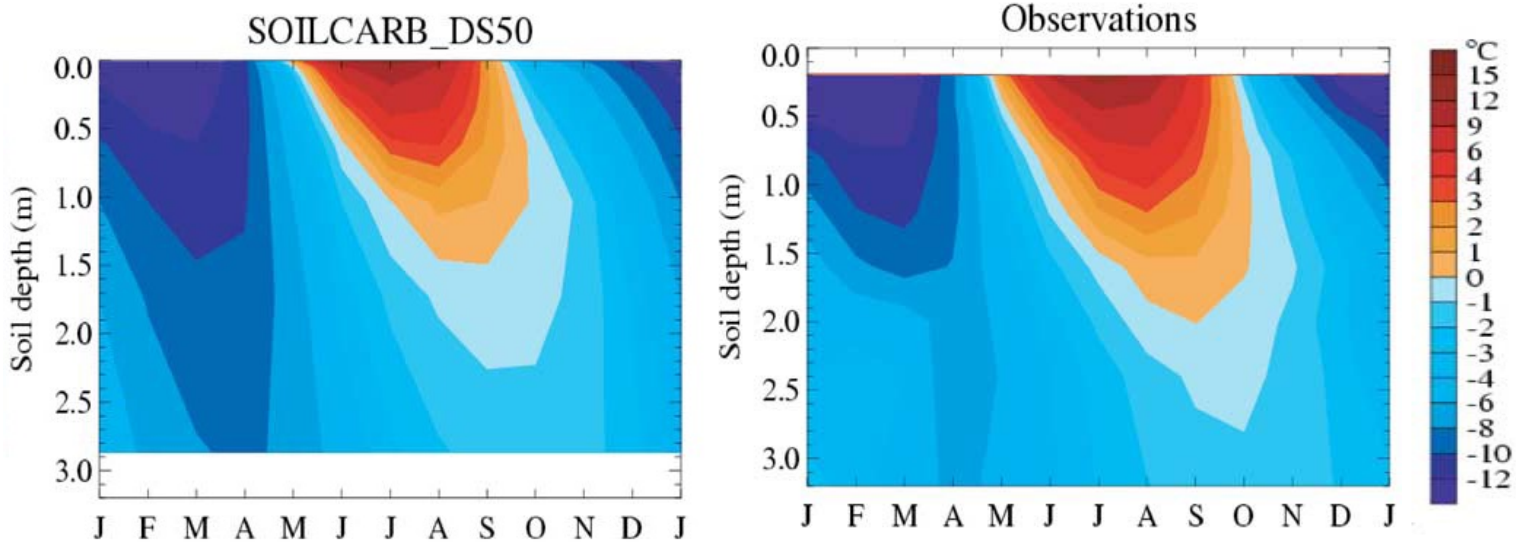
where C_p (heat capacity) and K (thermal conductivity) are functions of:

- temperature
- total soil moisture
- soil texture
- ice/liquid content



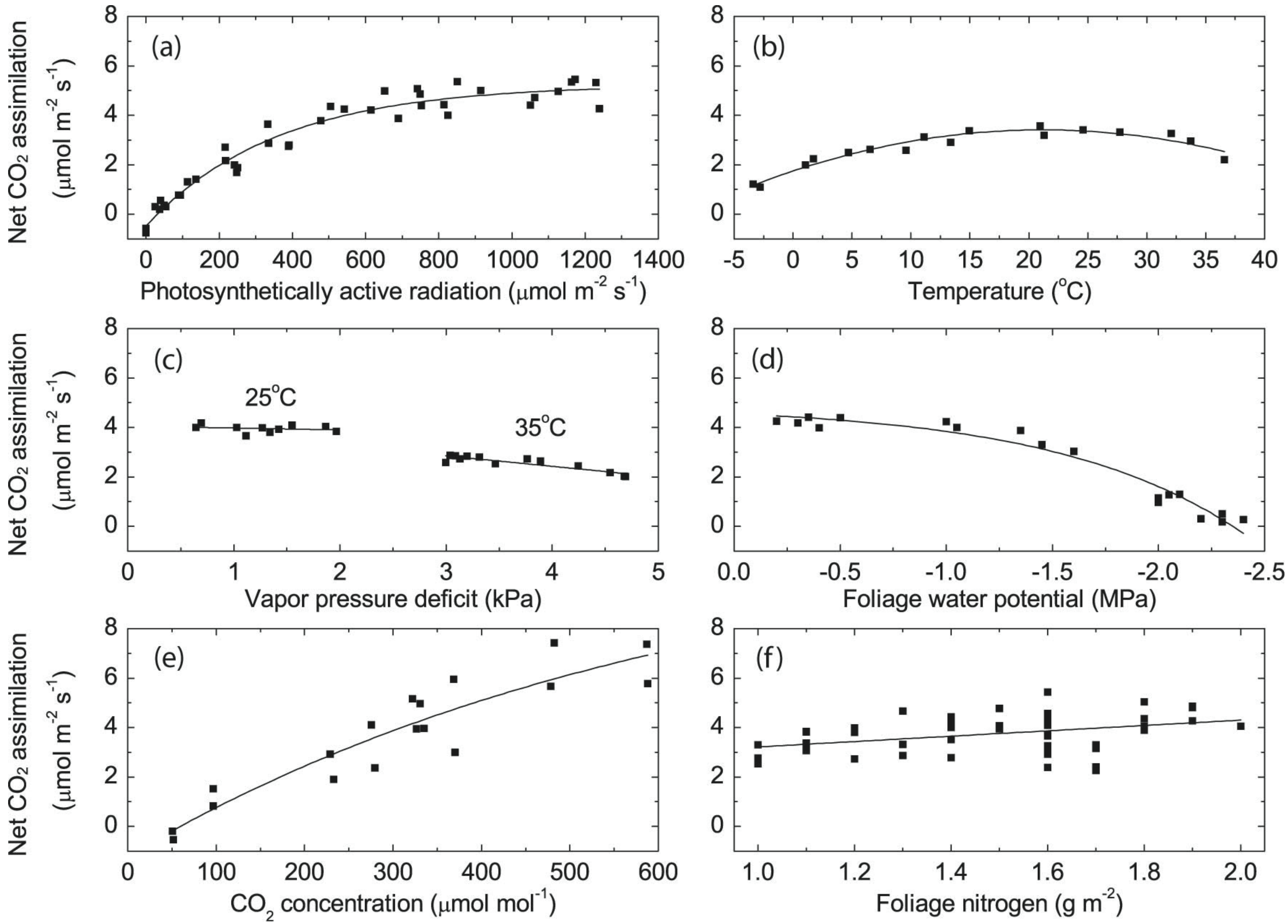
Modeling Permafrost in CLM





Lawrence et al., J. Climate, 2011

Leaf photosynthesis



Slide courtesy G. Bonan

Leaf photosynthesis and stomatal conductance

Farquhar photosynthesis model

$$A_n = \min(w_c, w_j, w_p) - R_d$$

w_c is the rubisco-limited rate of photosynthesis, w_j is light-limited rate allowed by RuBP regeneration, w_p is product limited rate of carboxylation

rubisco-limited rate is

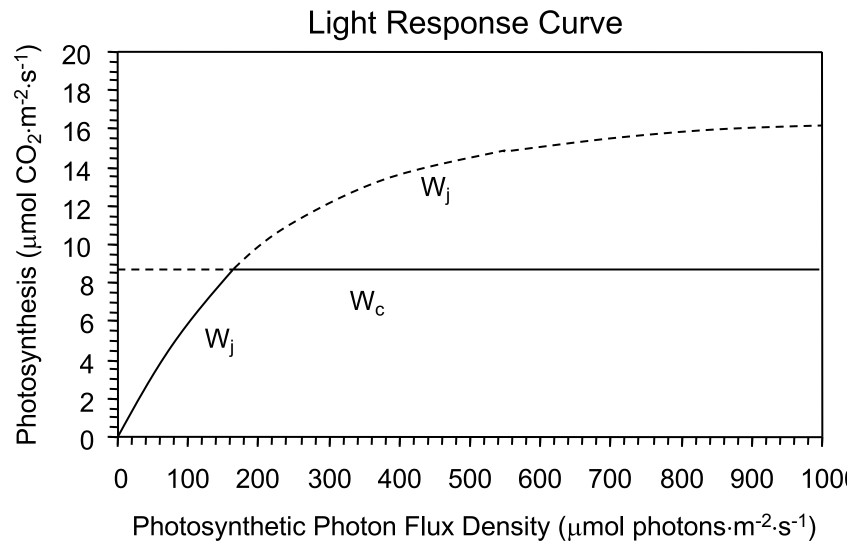
$$w_c = \frac{V_{c\max}(c_i - \Gamma_*)}{c_i + K_c(1 + O_i/K_o)}$$

RuBP regeneration-limited rate is

$$w_j = \frac{J(c_i - \Gamma_*)}{4(c_i + 2\Gamma_*)}$$

product-limited rate is

$$w_p = 3T_p$$

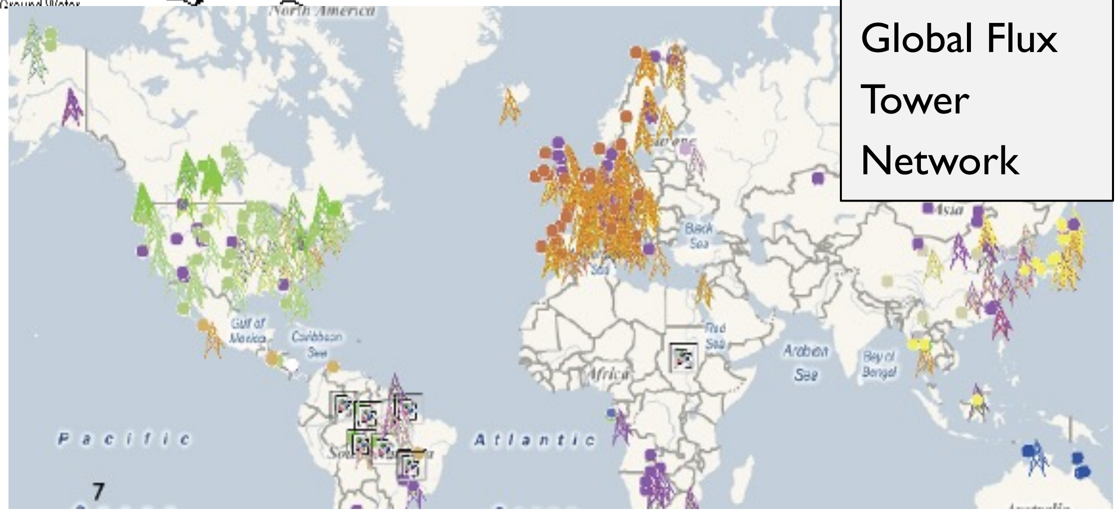


Ball-Berry stomatal conductance

$$\frac{1}{r_s} = g_s = g_1 \frac{A_n h_s}{c_s / P_{atm}} + g_0 \beta_t$$

Slide courtesy G. Bonan

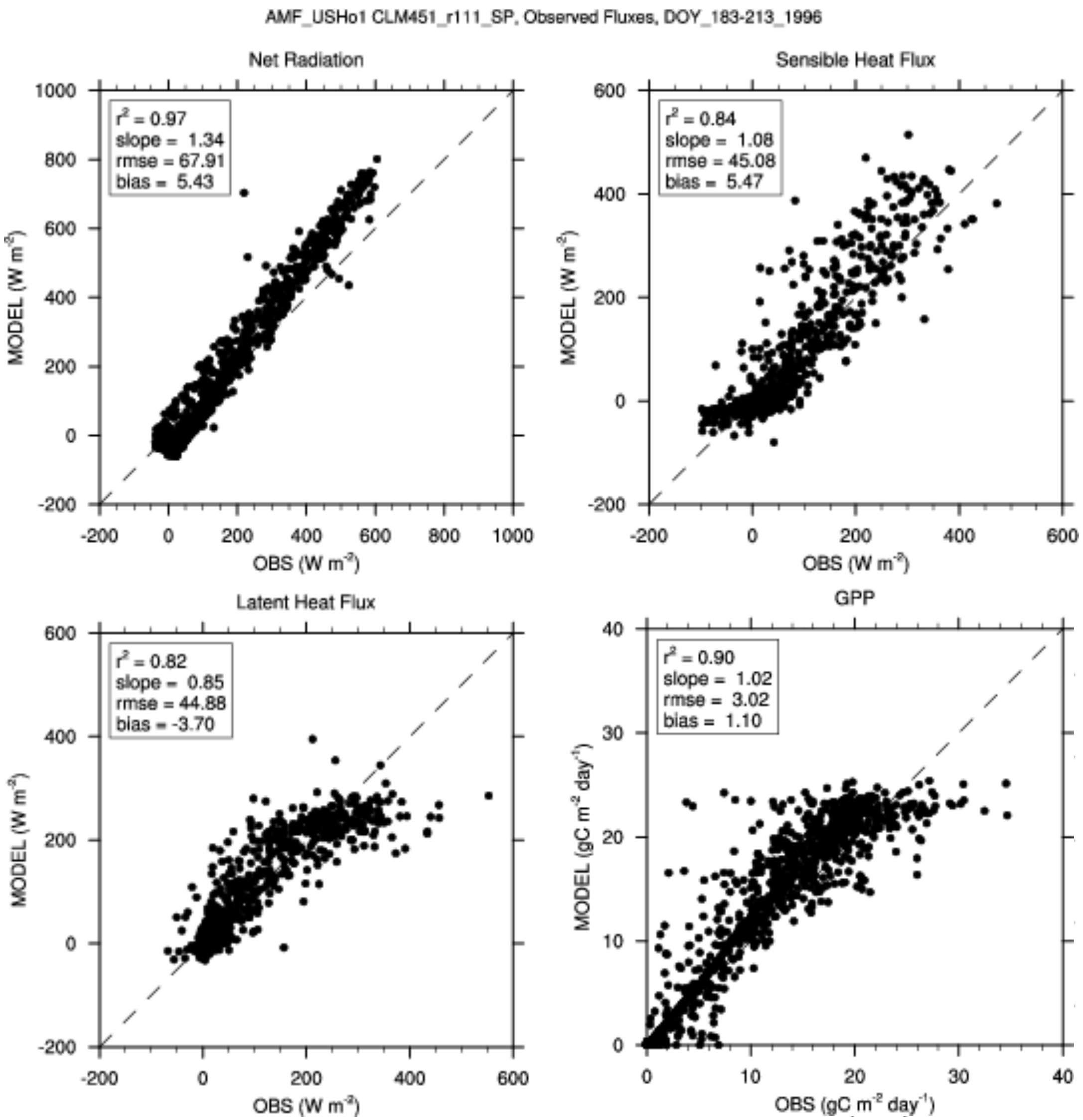
Evaluating the model with tower flux data



Global Flux Tower Network

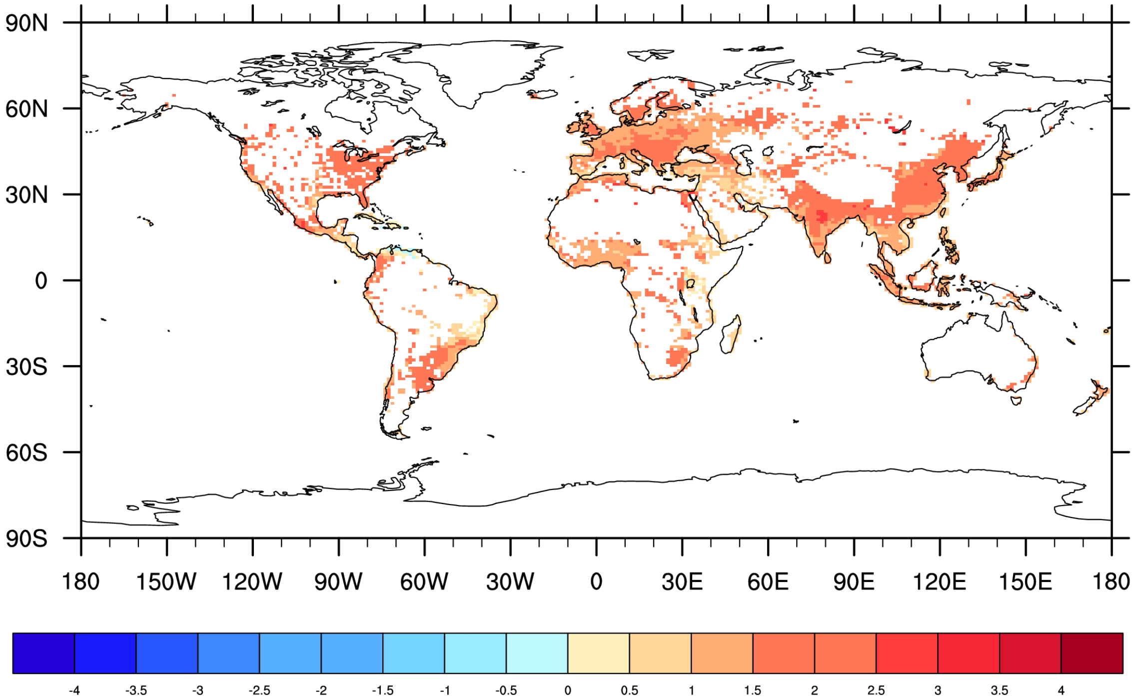
Evaluating CLM4.5 with tower flux data

Howland Forest, Maine, July, 1996

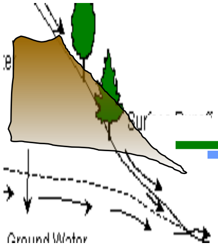


Urban Heat Island in CCSM4

Present day Urban Heat Island (UHI) simulated by CLM Urban (°C)

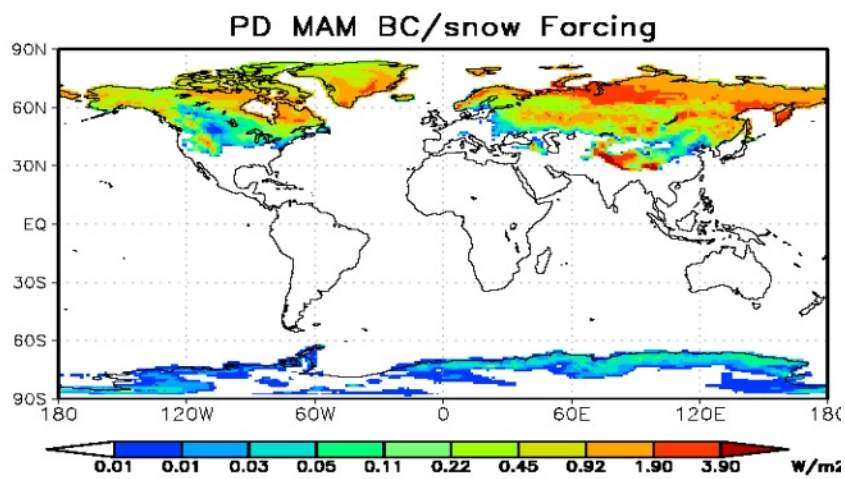


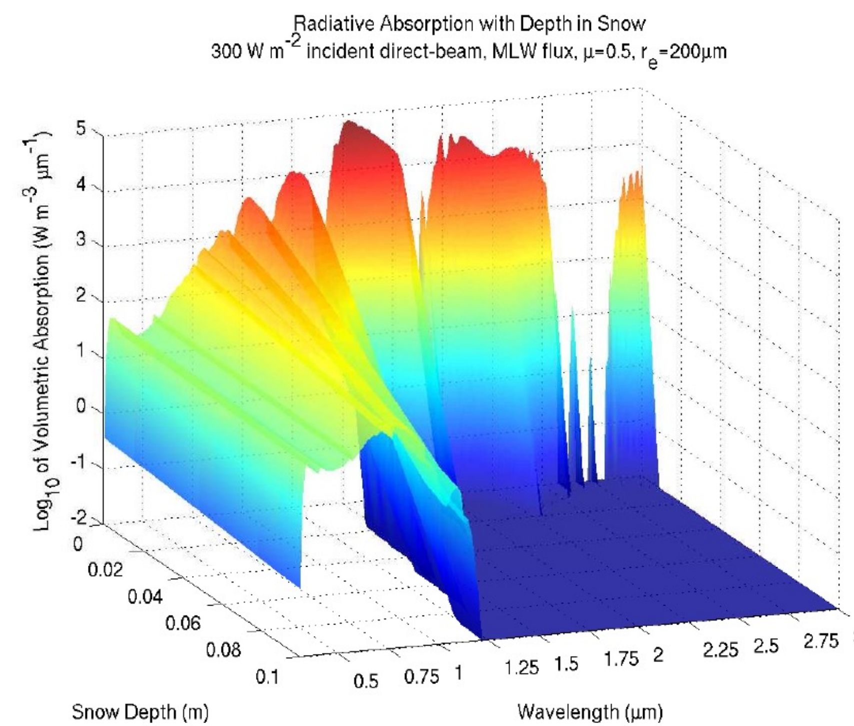
Modeled UHI ranges from near-zero up to 4°C with spatial and seasonal variability controlled by urban to rural contrasts in energy balance.



Snow, Ice, and Aerosol Radiative Model (SNICAR)

- Snow darkening from deposited black carbon, mineral dust, and organic matter
- Vertically-resolved solar heating in the snowpack
- Snow aging (evolution of effective grain size) based on:
  - Snow temperature and temperature gradient
  - Snow density
  - Liquid water content and
  - Melt/freeze cycling





Flanner et al (2007), *JGR*
Flanner and Zender (2006), *JGR*
Flanner and Zender (2005), *GRL*