The Community Land Model: Biogeophysics

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with input from lots of LMWGers

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What distinguishes a land model within an Earth System Model that consists of so many important pieces?

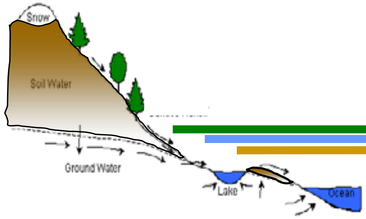
The land is a critical interface

through which climate, and climate change impacts humans and ecosystems

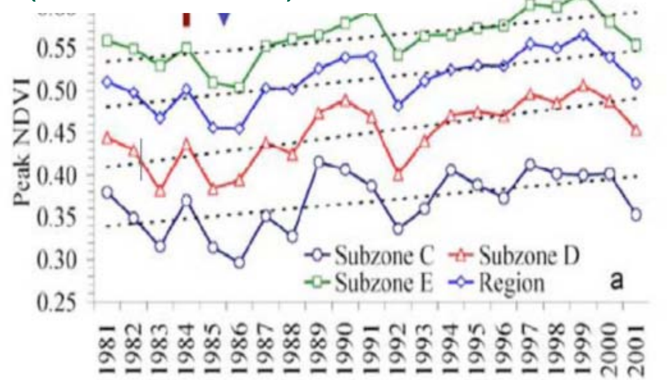
and

through which humans and ecosystems can effect global environmental and climate change

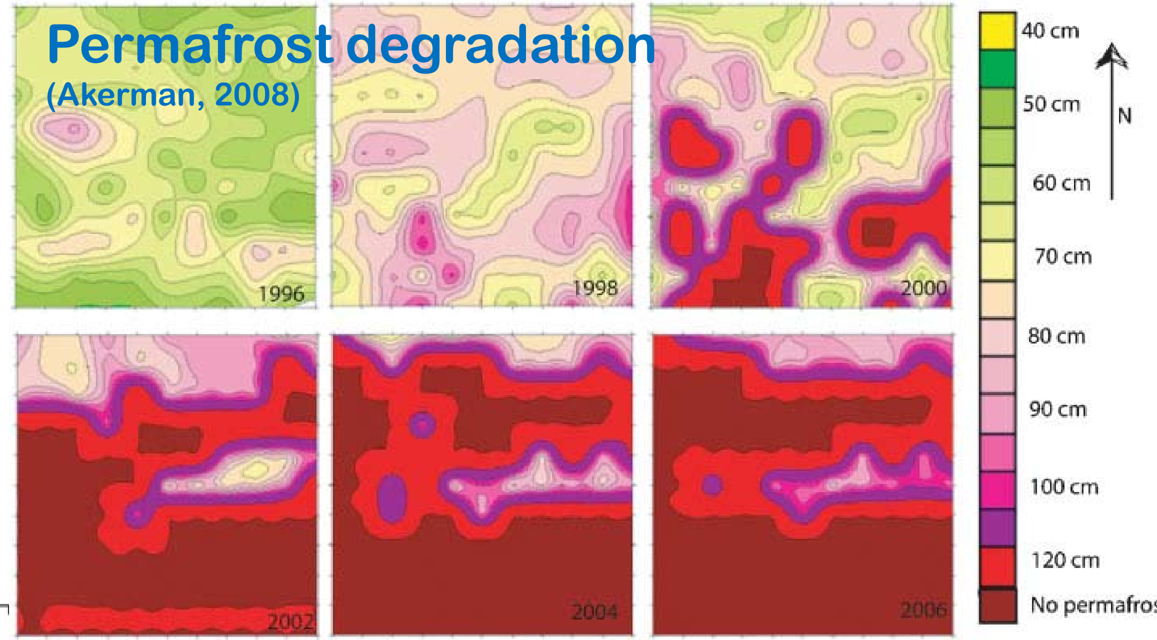
Observed terrestrial change



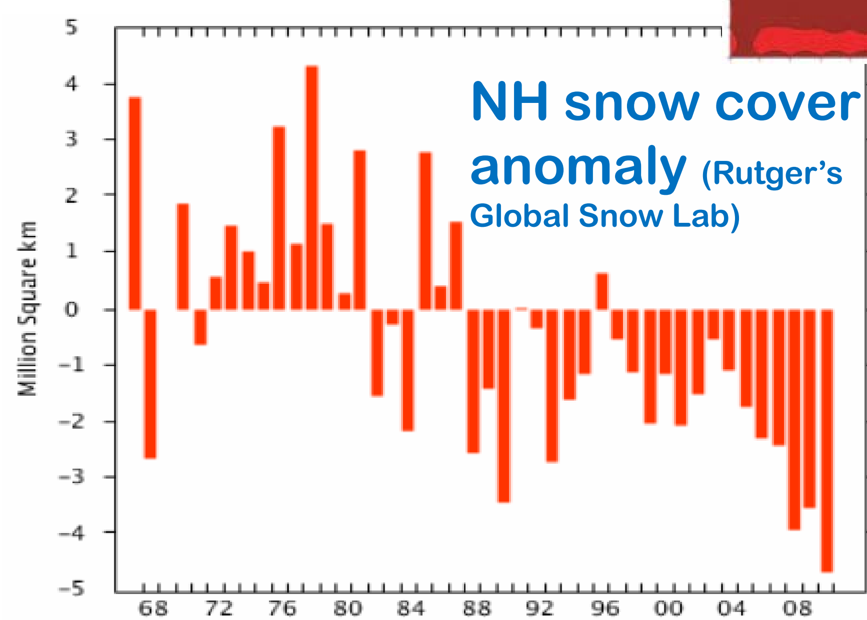
Arctic greening
(Bunn et al. 2007)



Permafrost degradation
(Akerman, 2008)



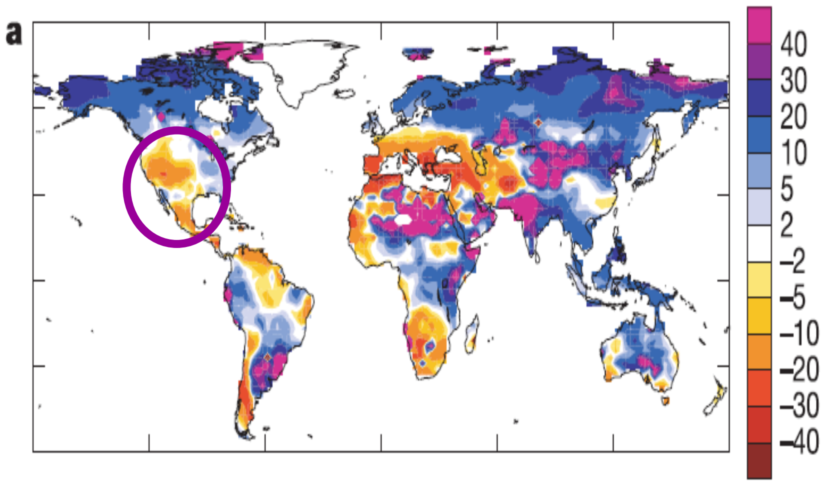
NH snow cover anomaly (Rutger's Global Snow Lab)



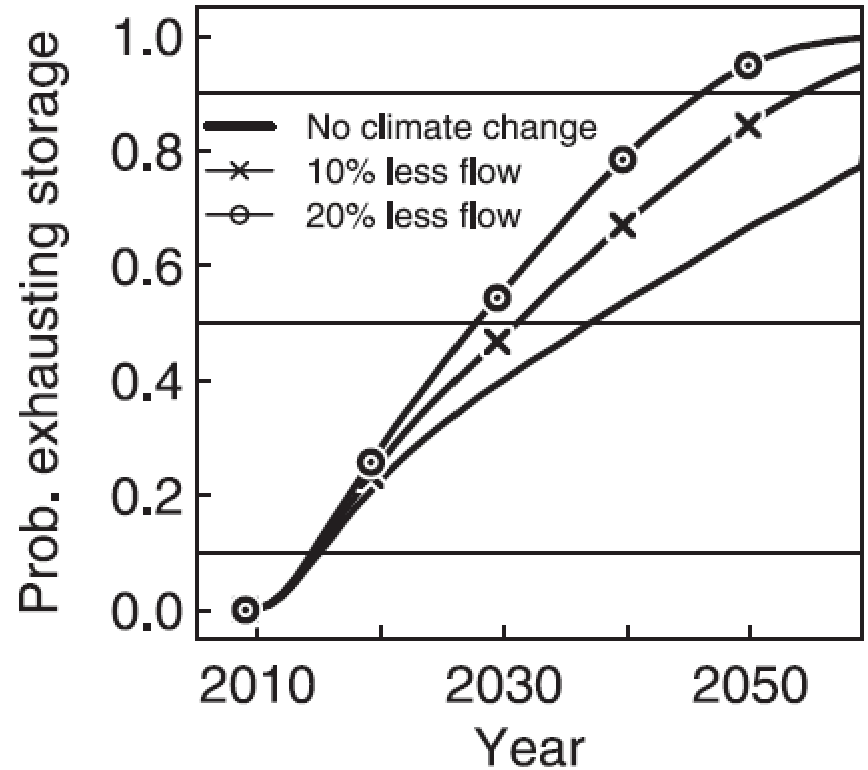
Deforestation

Water resources: When will Lake Mead go dry?

% Change in Runoff by 2050 (A1B)



Milly et al., 2005



Barnett et al., 2008

Soil moisture – Precipitation feedback

How much does a precipitation-induced soil moisture anomaly influence the overlying atmosphere and thereby the evolution of weather and the generation of precipitation?

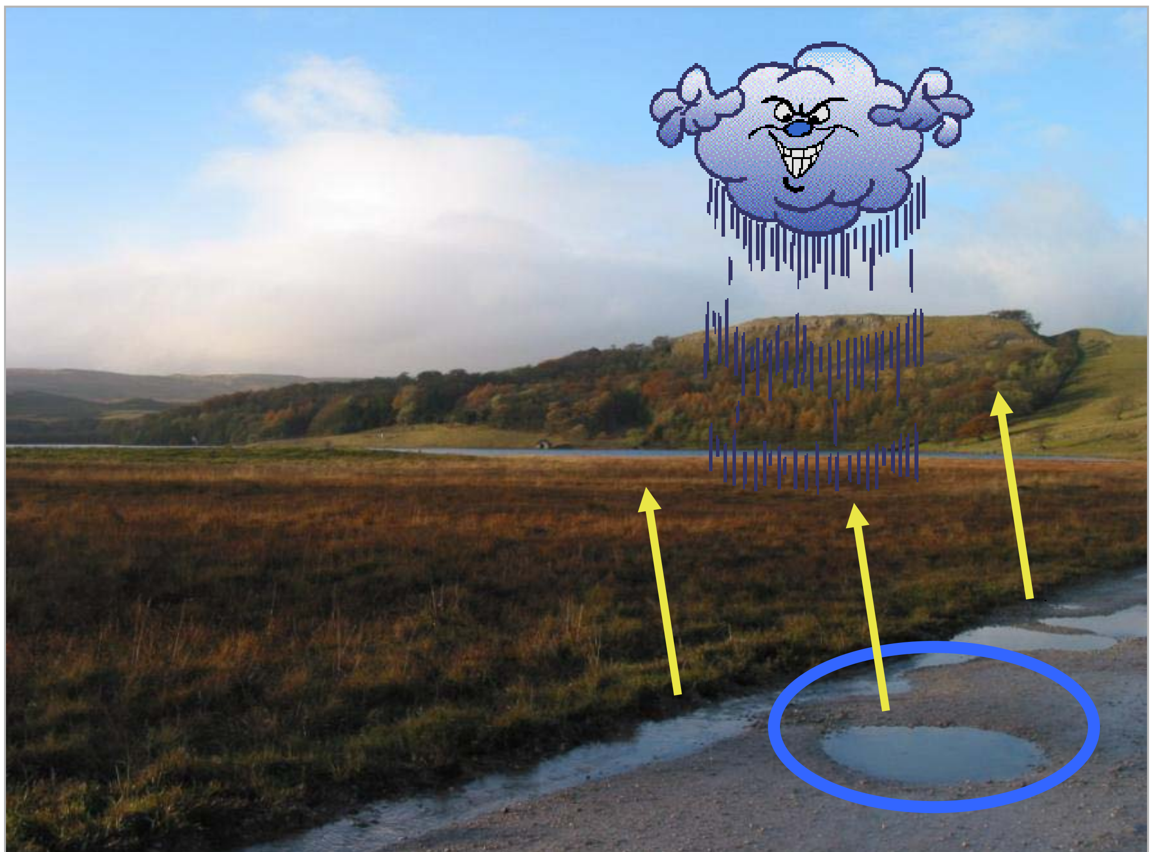
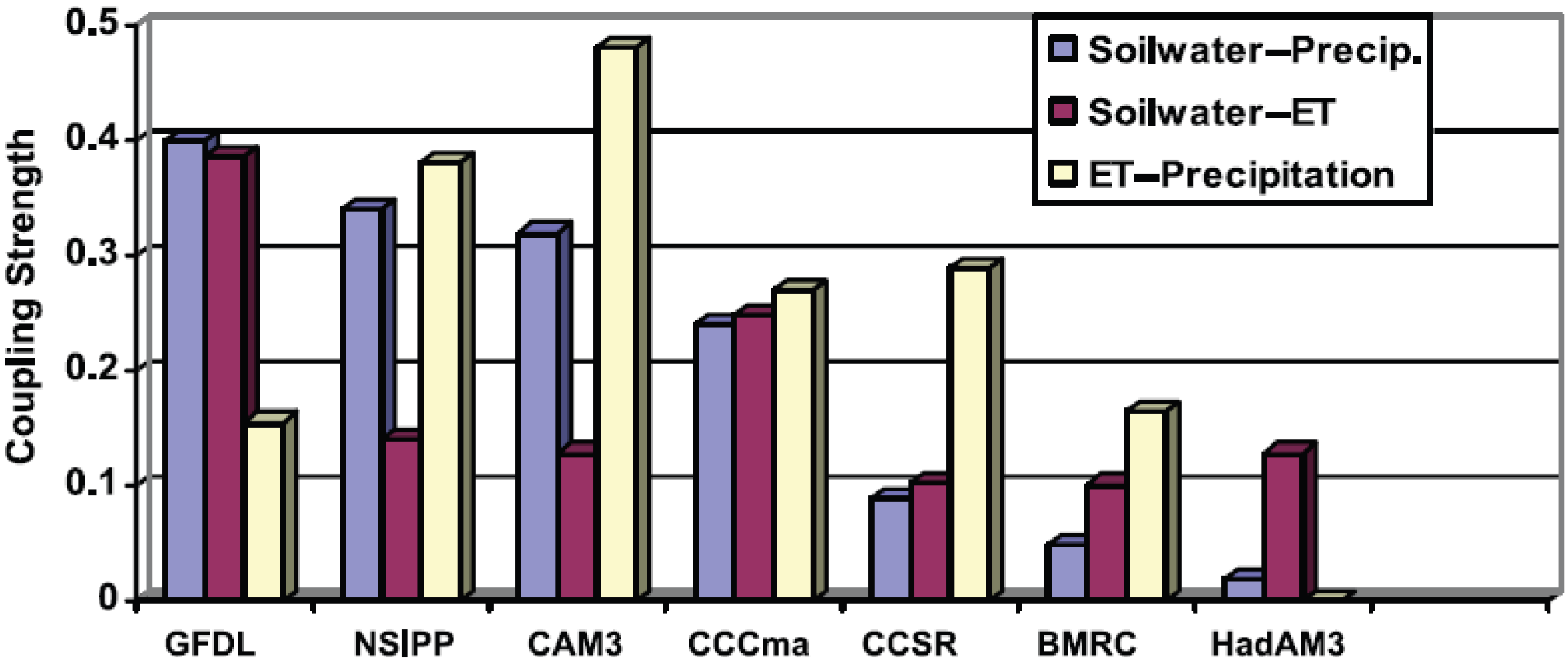


Photo by D. Fritz

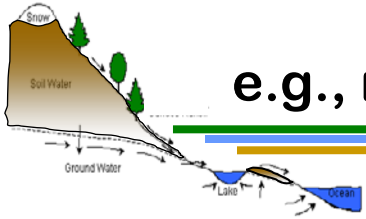
Land-atmosphere interactions

GLACE: To what extent does soil moisture influence the overlying atmosphere and the generation of precipitation?

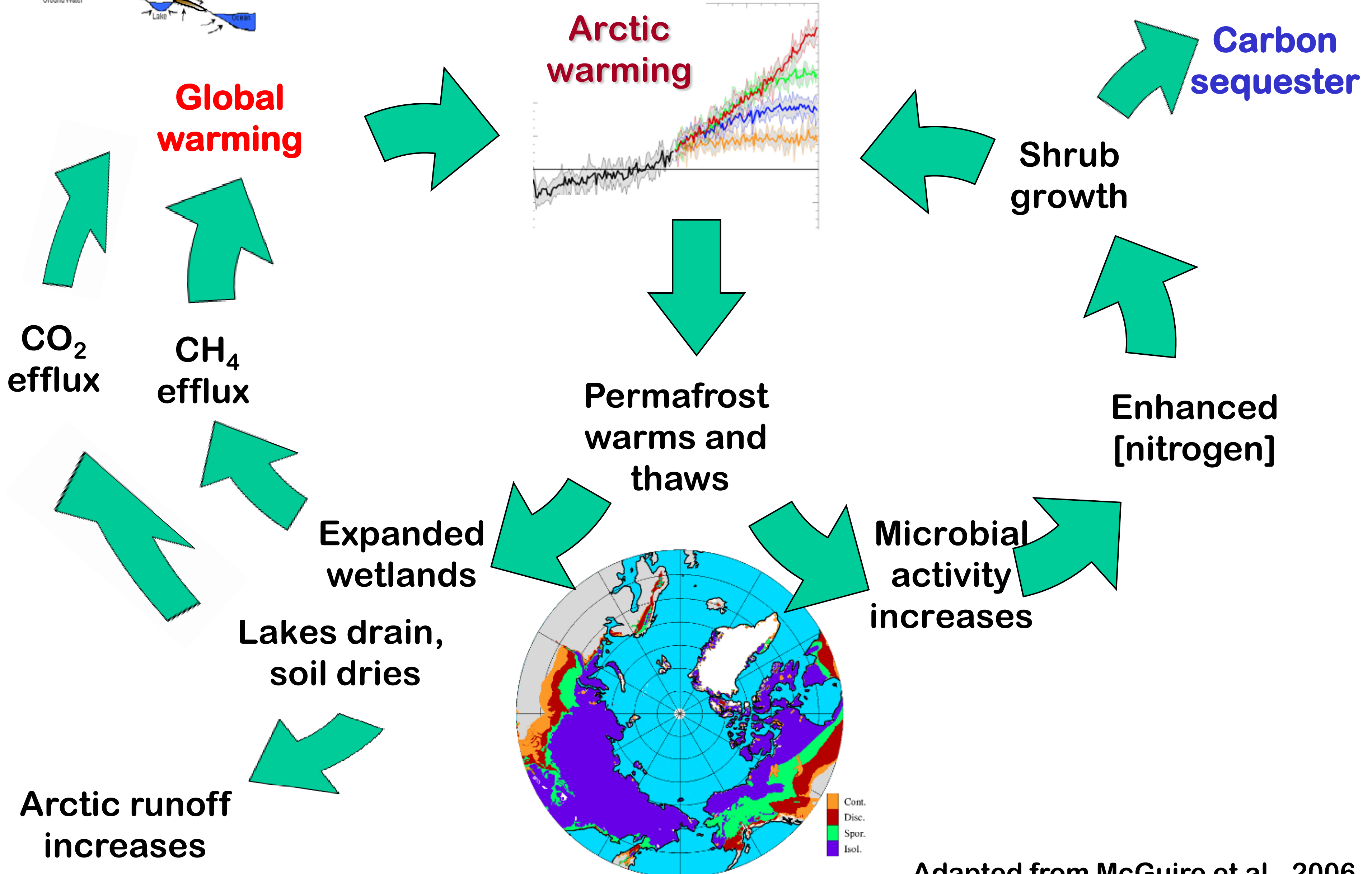


How does the representation of land-atmosphere interactions affect simulation of droughts, floods, extremes?

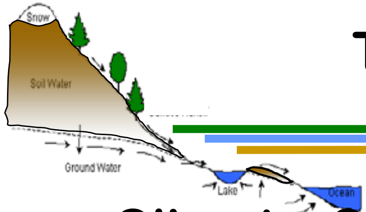
Koster et al., 2004; IPCC



Terrestrial Feedbacks:
e.g., representing Arctic climate-change feedbacks in CESM



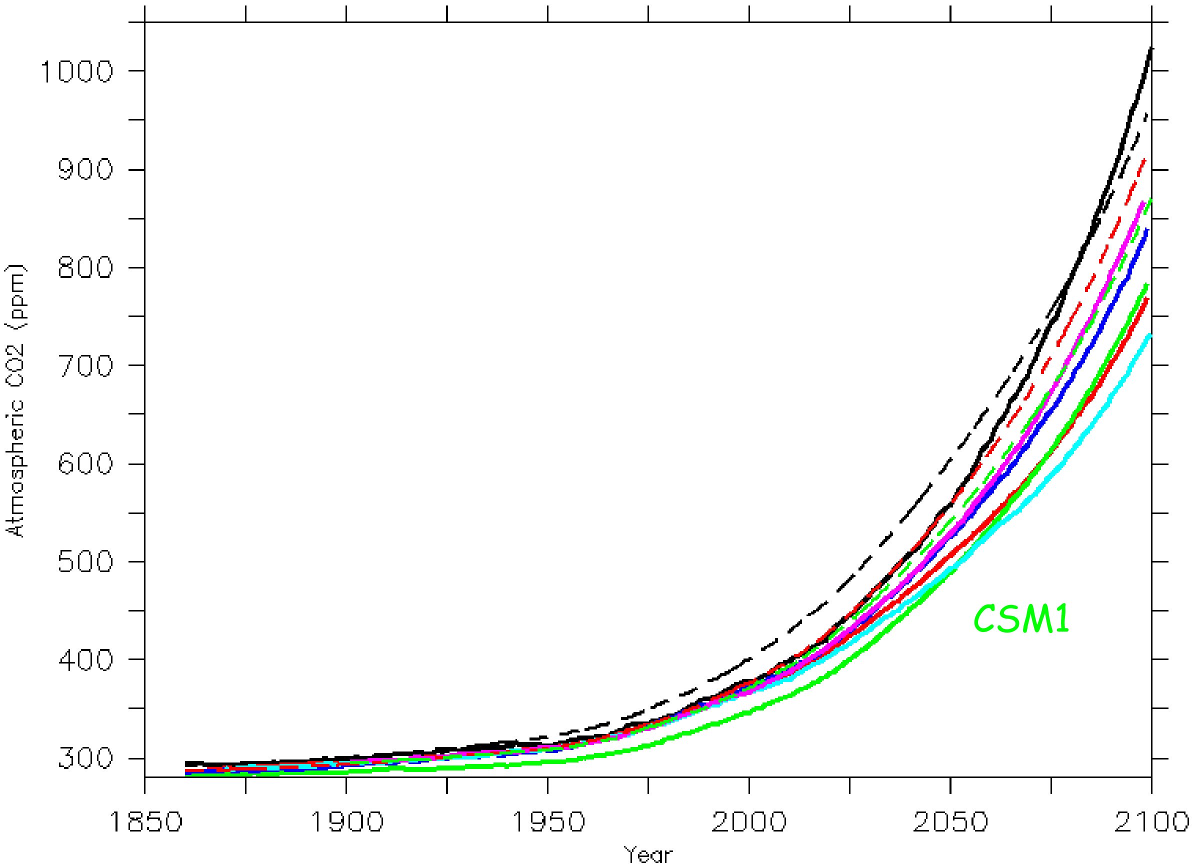
Adapted from McGuire et al., 2006



Terrestrial carbon cycle impact on atmospheric CO_2

Climate-Carbon model intercomparison (C_4MIP):

Nine climate models of varying complexity with active carbon cycle



Large range in simulated atmospheric CO_2 at 2100

max is > 1000 ppm
min is < 750 ppm

Most of the difference can be attributed to land processes

Courtesy of Pierre Friedlingstein

The role of the land model in an Earth System Model

- Provide energy, water, and momentum fluxes to atmosphere
  - Partition turbulent fluxes into latent vs sensible heat
  - Calculate absorbed solar radiation, surface albedo
- Runoff to ocean

- Trace gas and particle exchange with atmosphere
  - CO_2 fluxes to atmosphere
  - Dust emissions
  - Biogenic Volatile Organic Compound emissions

- Surface mass balance to ice sheet

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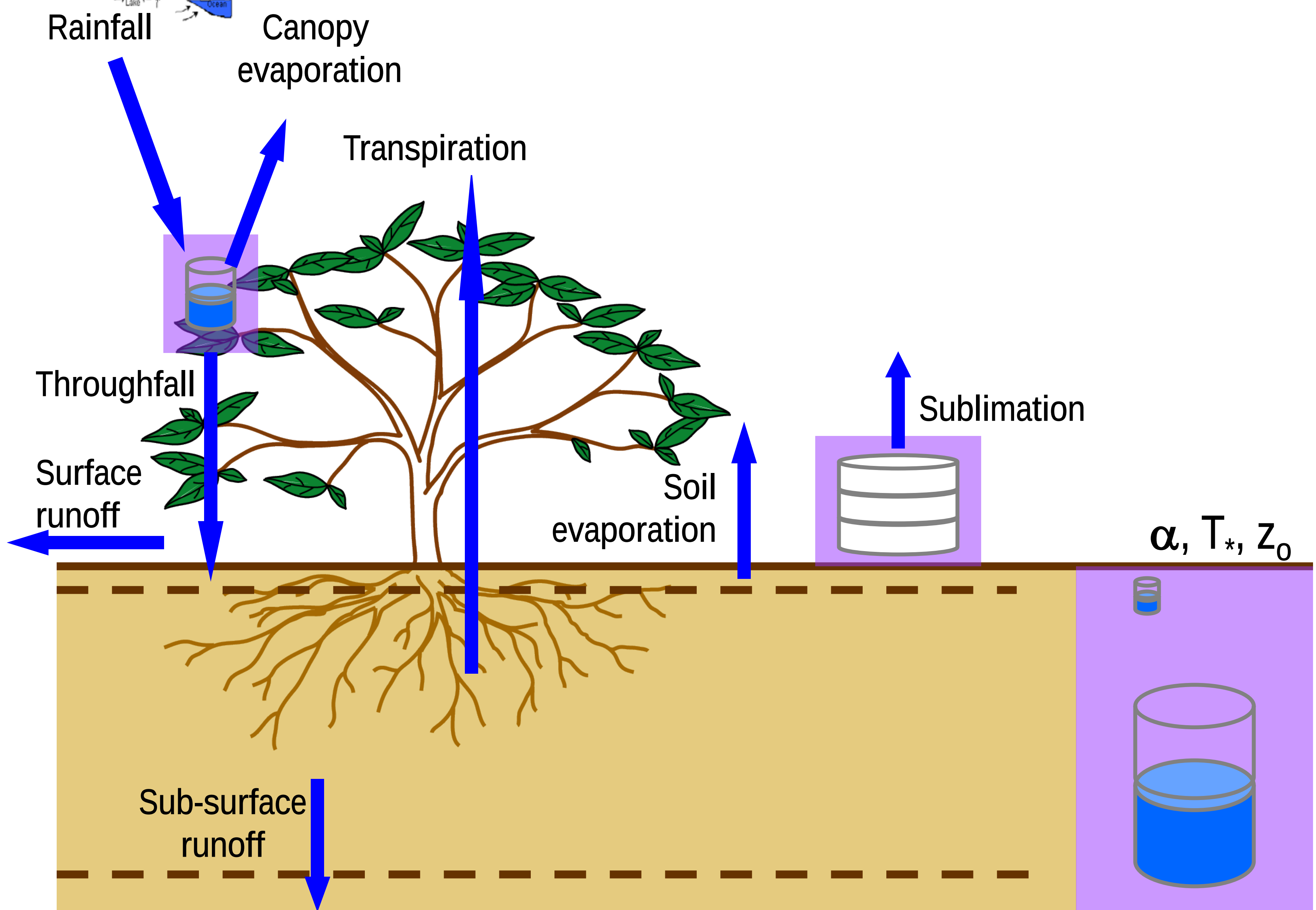
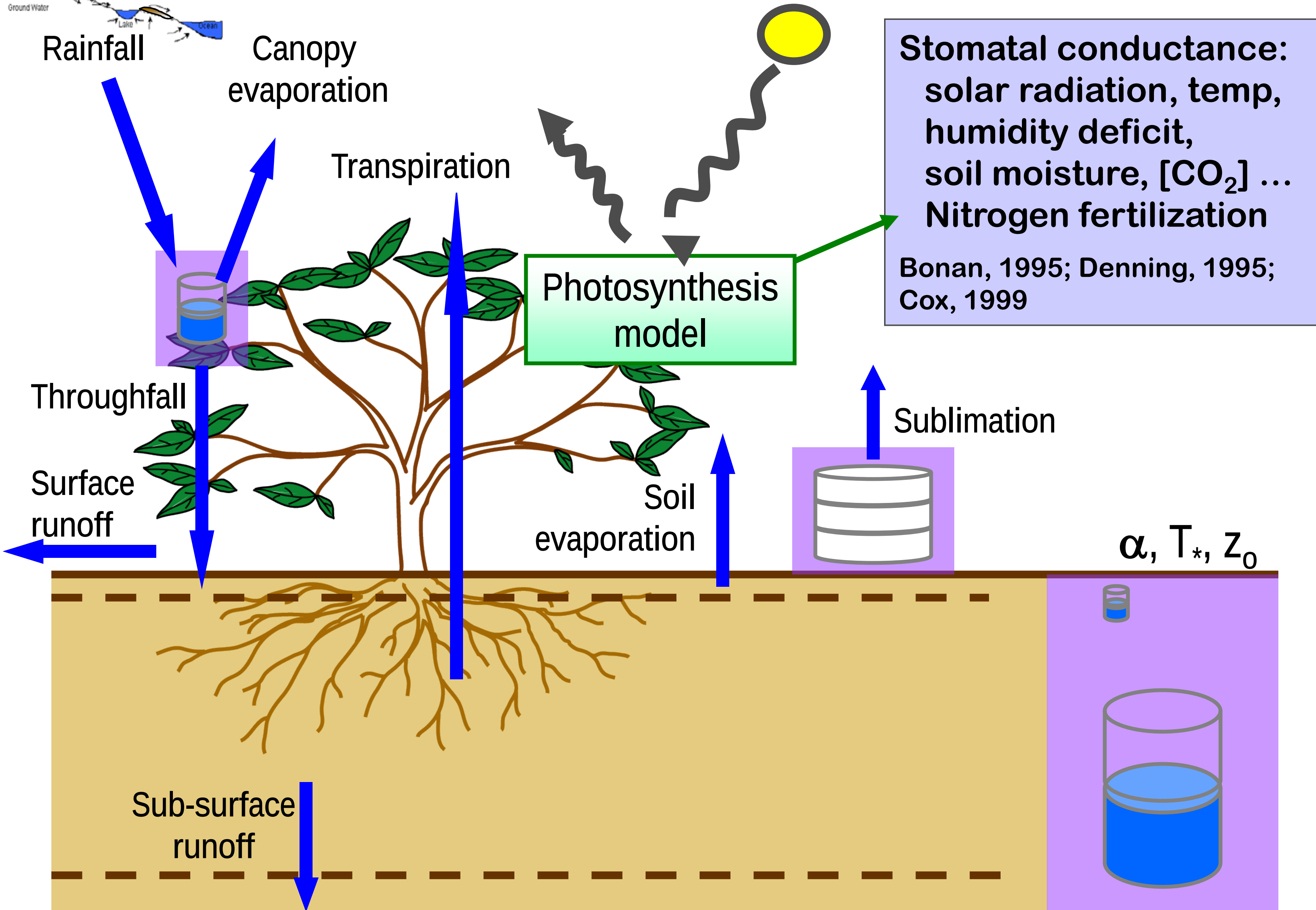
  - Dust emissions
  - Biogenic Volatile Organic Compound emissions
  - CH_4, N_2O emissions
- Surface mass balance with ice sheet

To model these fluxes, need to model the state variables of the land (i.e., soil moisture, soil T, snowpack, veg type, height, leaf area, C and N stocks in veg and soil)

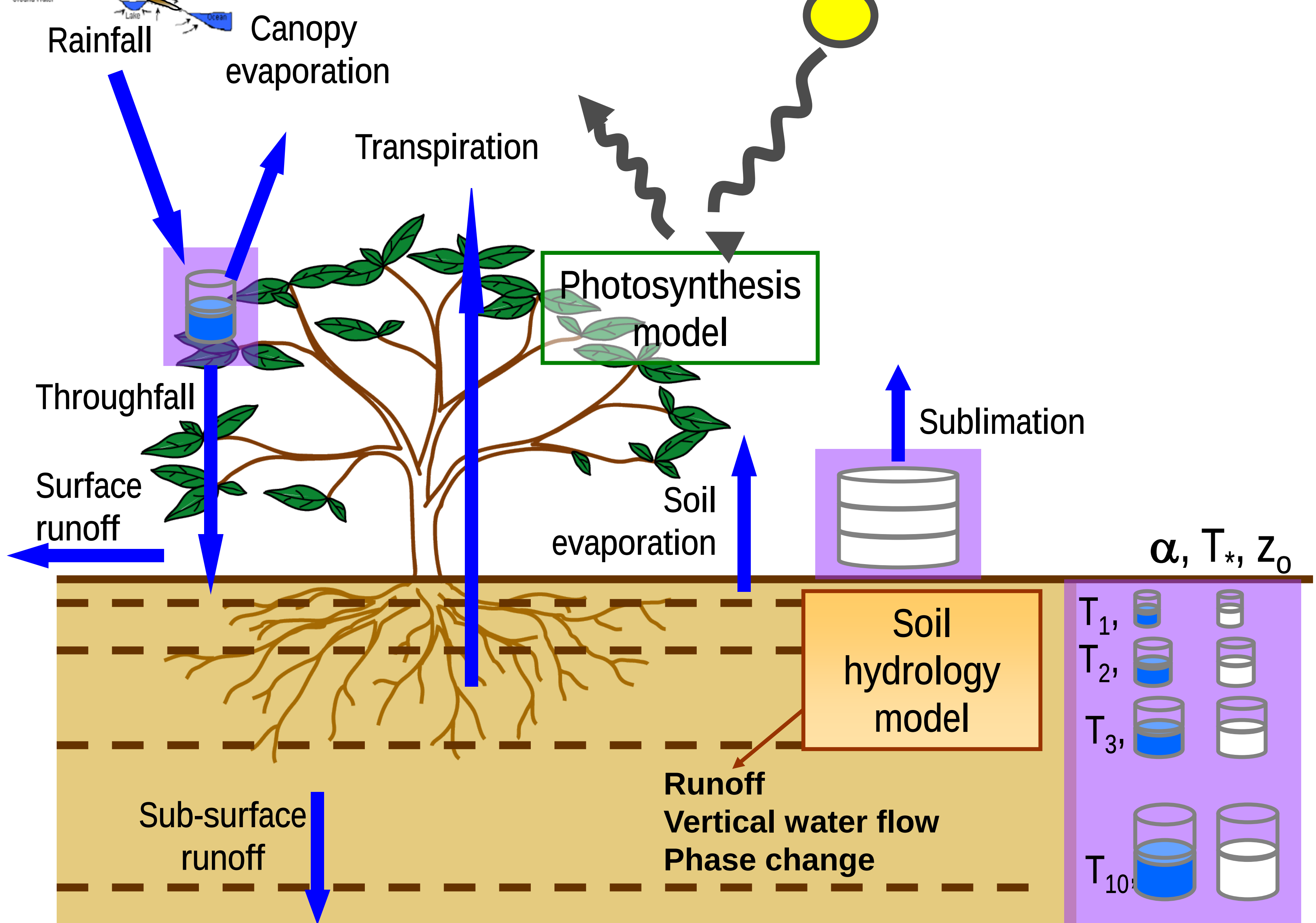
Land model processes

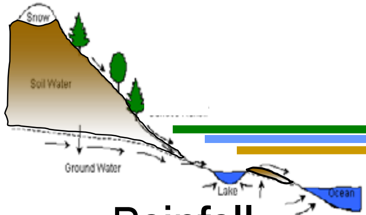


Land model processes

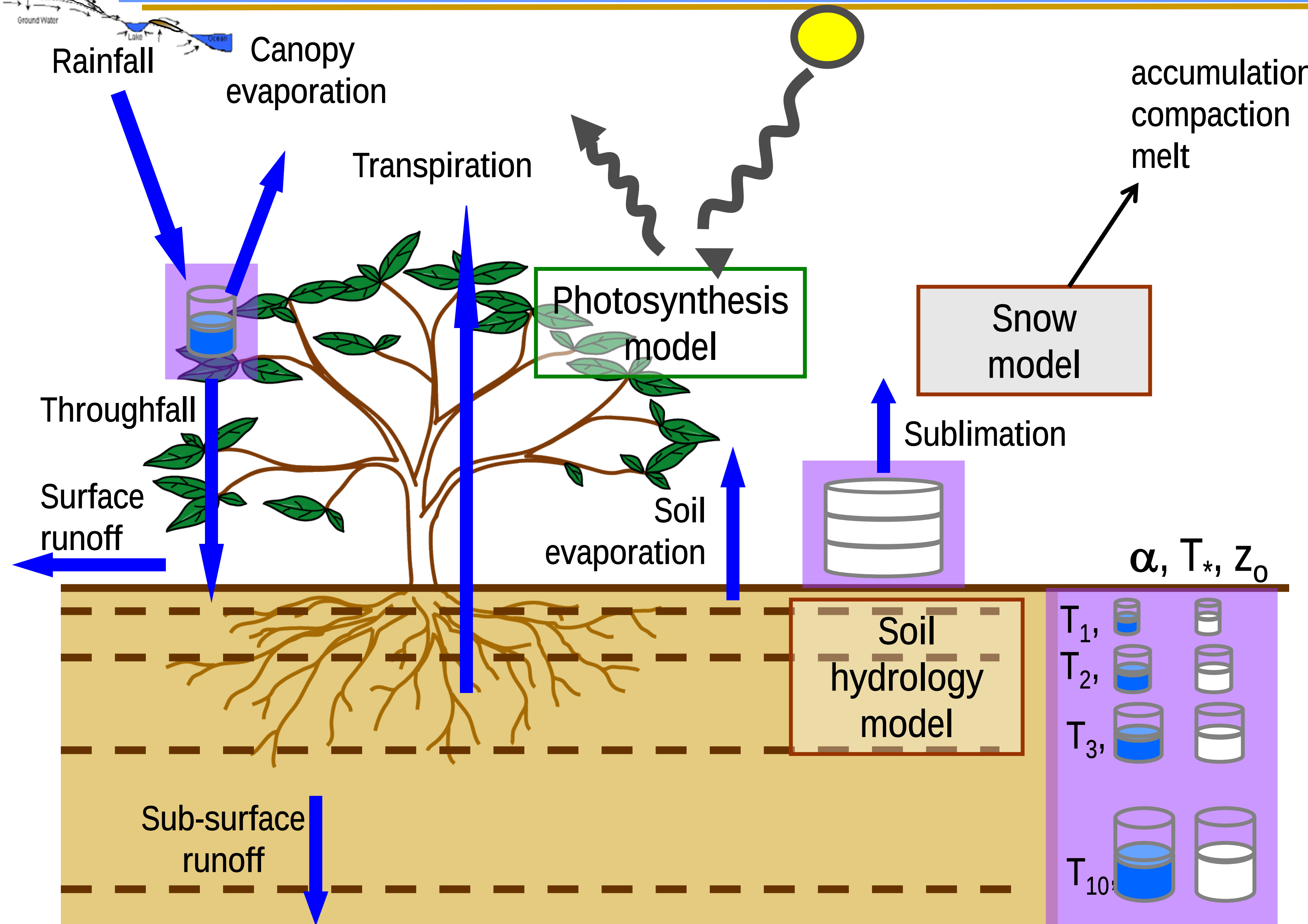


Land model processes





Land model processes



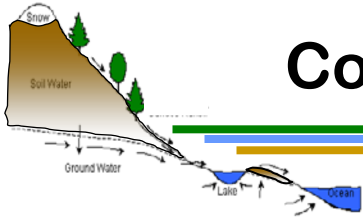
Main Features of the Community Land Model

- **Structural aspects (surface dataset and input datasets)**

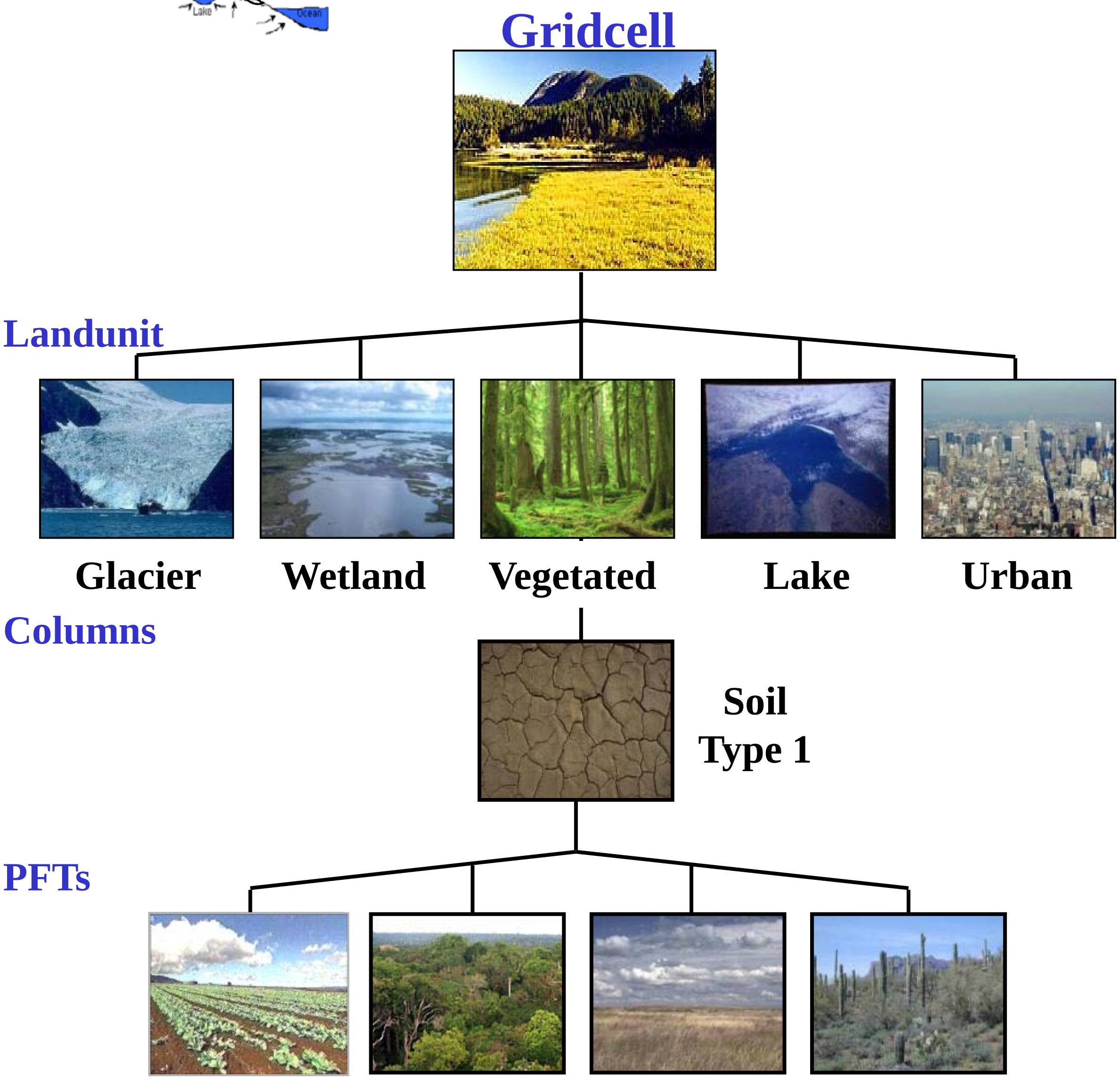
- **Component submodels**

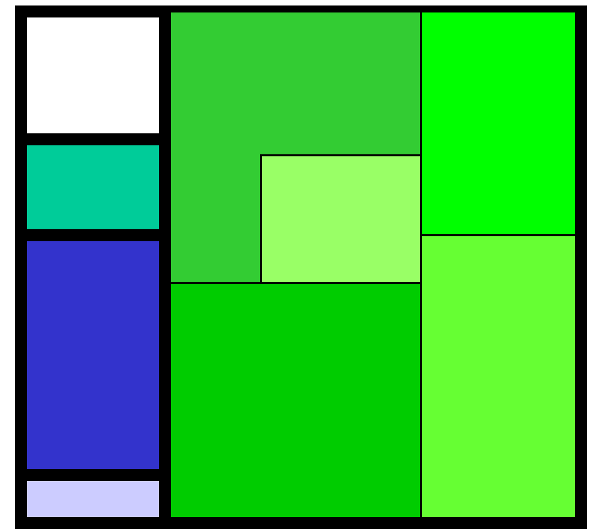
Main Features of the Community Land Model

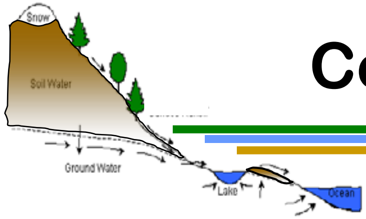
- **Structural aspects (surface dataset and input datasets)**
  - Heterogeneity of landscape, tiling
  - Plant Functional Types - vegetation types
  - Soil texture
  - River routing
  - Aerosol and nitrogen deposition



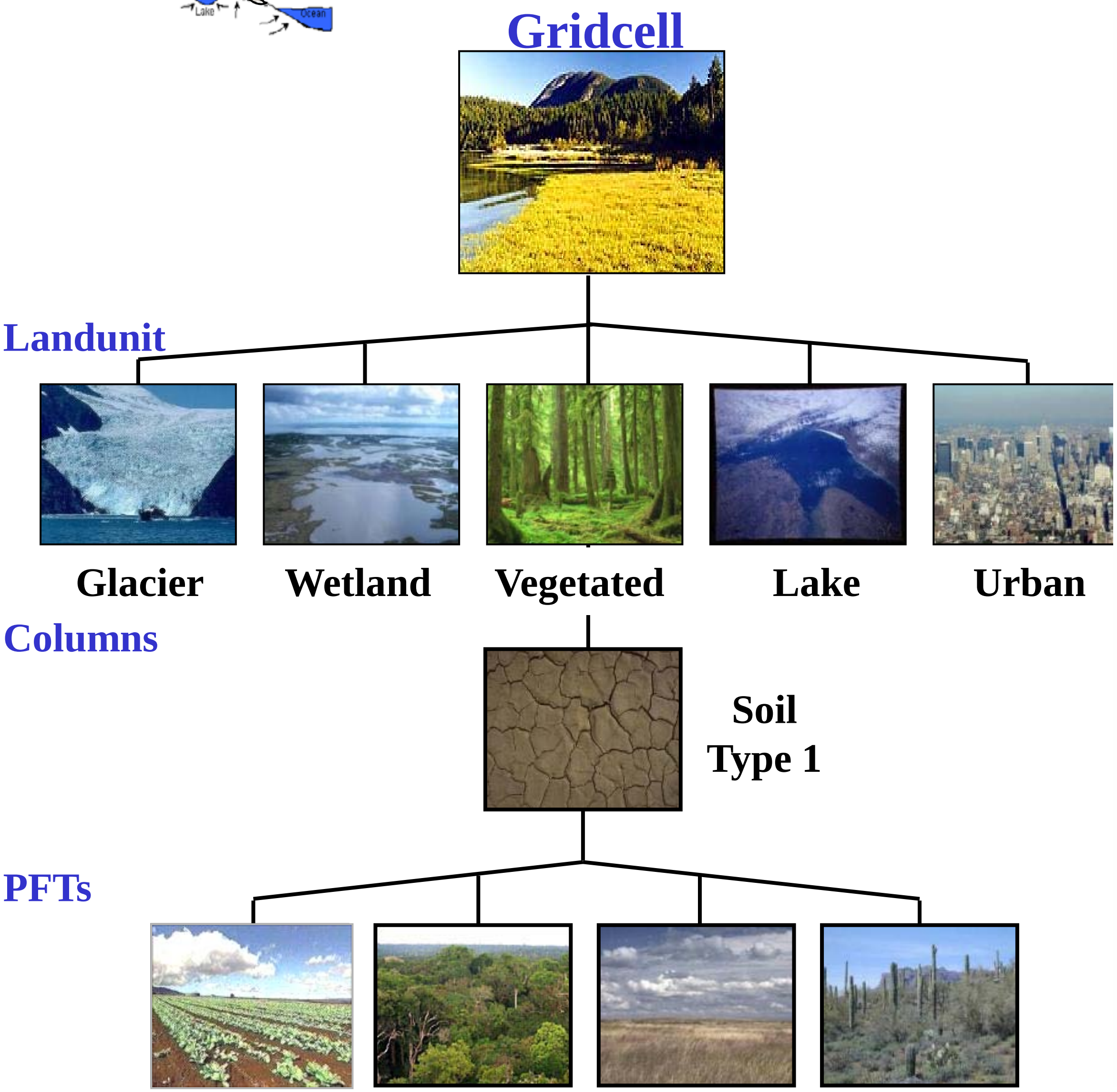
Community Land Model subgrid tiling structure







Community Land Model subgrid tiling structure



Plant Functional Types:

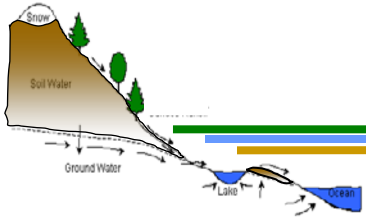
0. Bare

Tree:

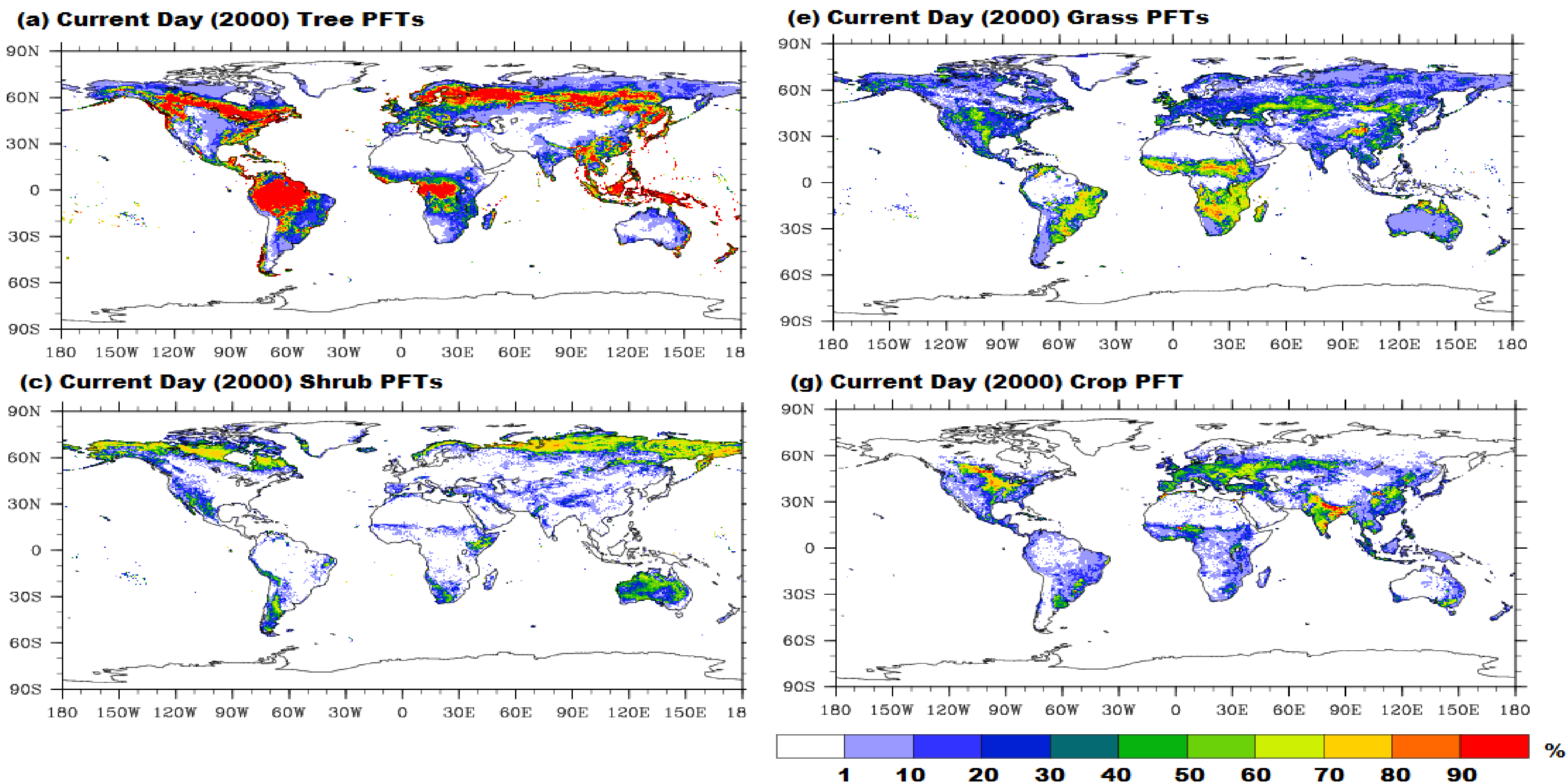
1. Needleleaf Evergreen, Temperate
2. Needleleaf Evergreen, Boreal
3. Needleleaf Deciduous, Boreal
4. Broadleaf Evergreen, Tropical
5. Broadleaf Evergreen, Temperate
6. Broadleaf Deciduous, Tropical
7. Broadleaf Deciduous, Temperate
8. Broadleaf Deciduous, Boreal

Herbaceous / Understorey:

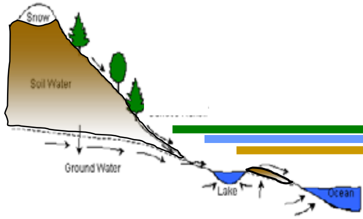
9. Broadleaf Evergreen Shrub, Temperate
10. Broadleaf Deciduous Shrub, Temperate
11. Broadleaf Deciduous Shrub, Boreal
12. C3 Arctic Grass
13. C3 non-Arctic Grass
14. C4 Grass
15. Crop



Plant Function Type distribution in CLM4 based on MODIS/Crop datasets



Lawrence and Chase, 2007

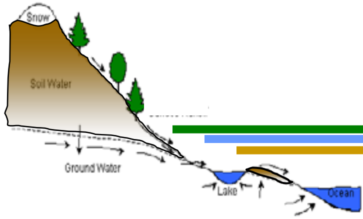


Plant Functional Type Parameters (CLM)

- Optical properties (visible and near-infrared):
  - Leaf angle
  - Leaf reflectance
  - Stem reflectance
  - Leaf transmittance
  - Stem transmittance

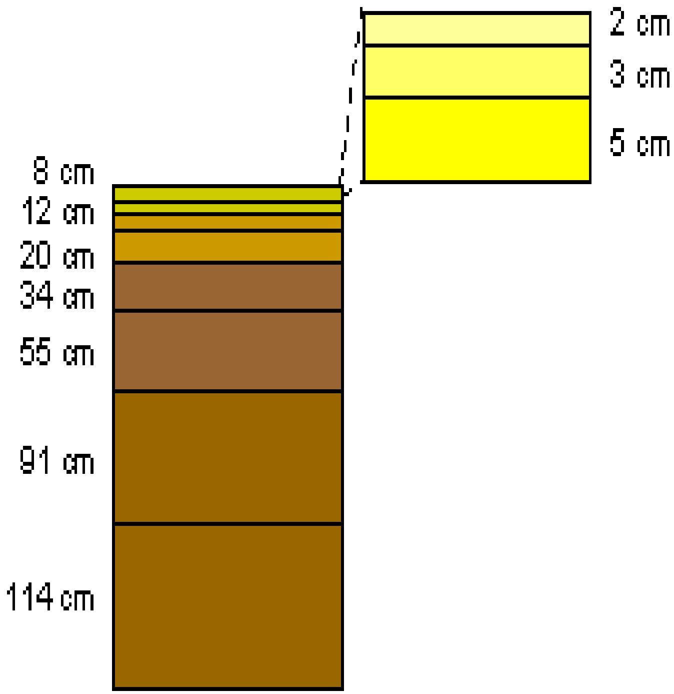
- **Land-surface models are parameter heavy!!!**

- Morphological properties:
  - Leaf area index (annual cycle)
  - Stem area index (annual cycle)
  - Leaf dimension
  - Canopy height
  - Root distribution
- Photosynthetic parameters:
  - quantum efficiency (mmol CO_2 mmol $photon^{-1}$)
  - m (slope of conductance-photosynthesis relationship)

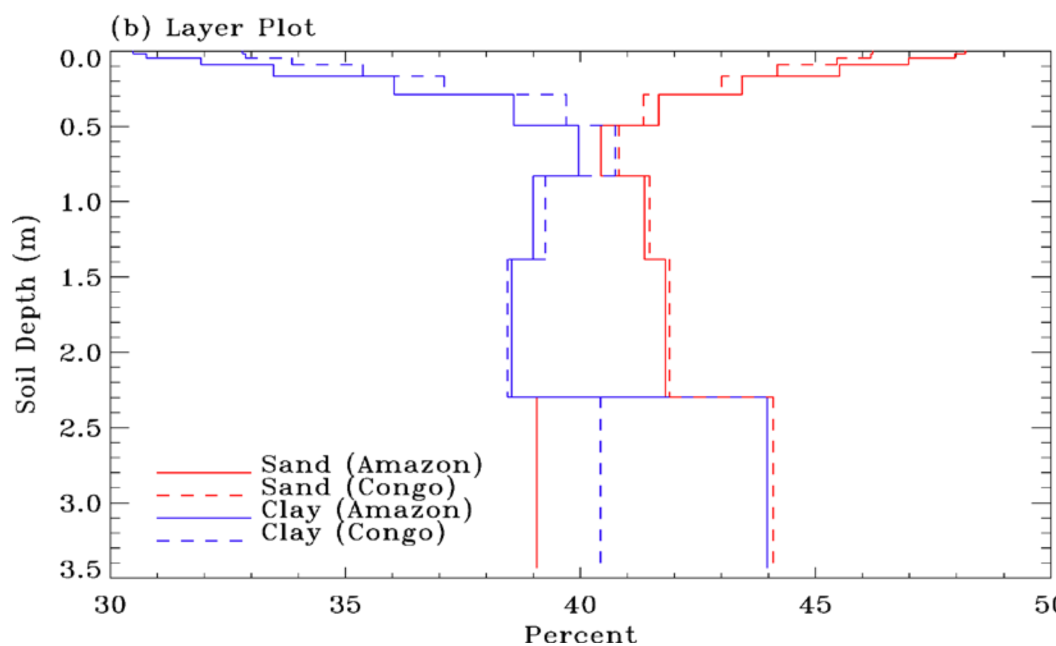


Soil Properties

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

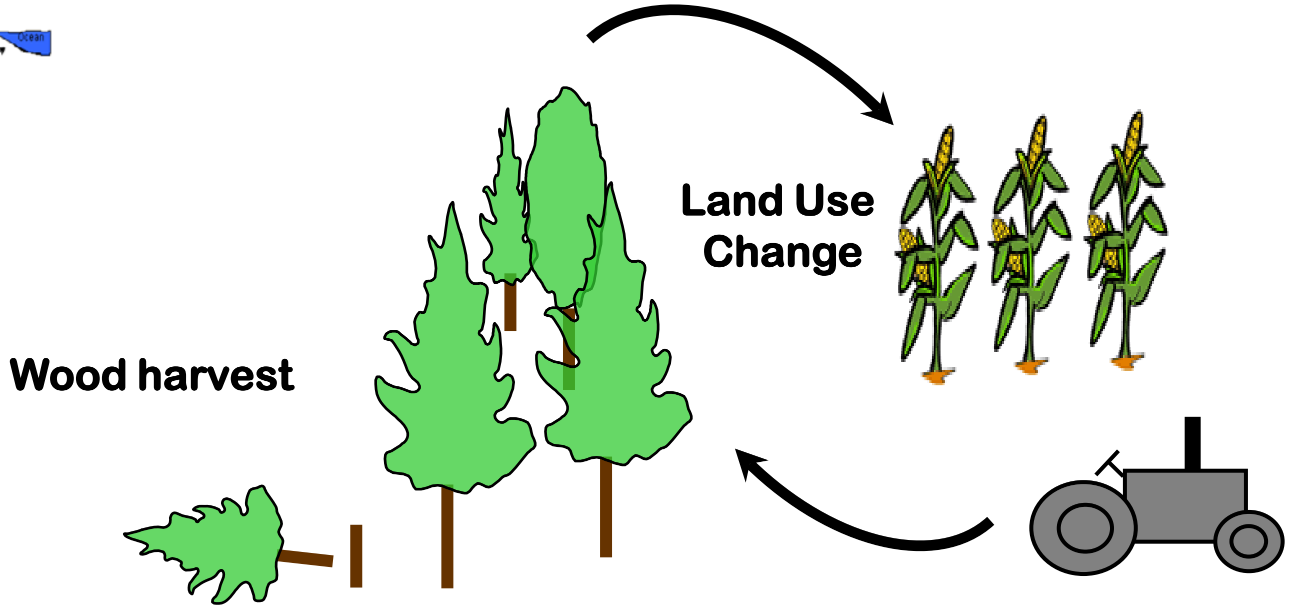


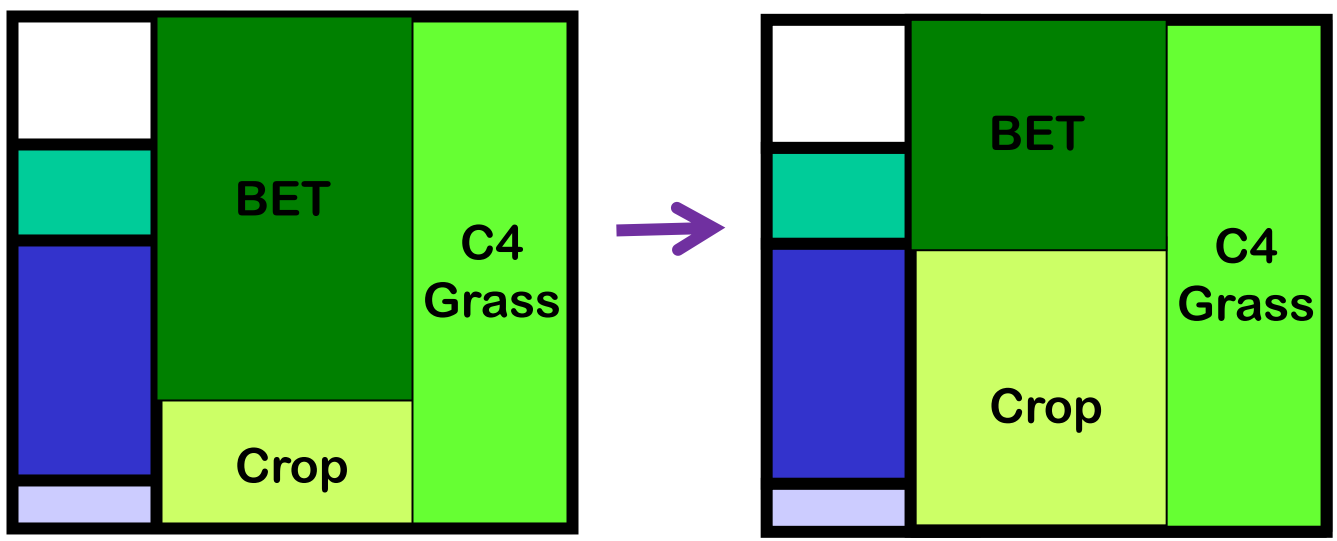
- Soil moisture concentration at saturation
- Soil moisture concentration at wilting point
- Hydraulic conductivity at saturation
- Saturated soil suction
- Thermal conductivity
- Thermal capacity

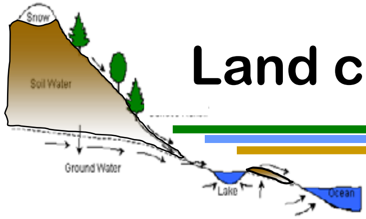


Soil profile
10 soil levels (~3.5m)
5 bedrock levels (~50m)

Land cover / land use change

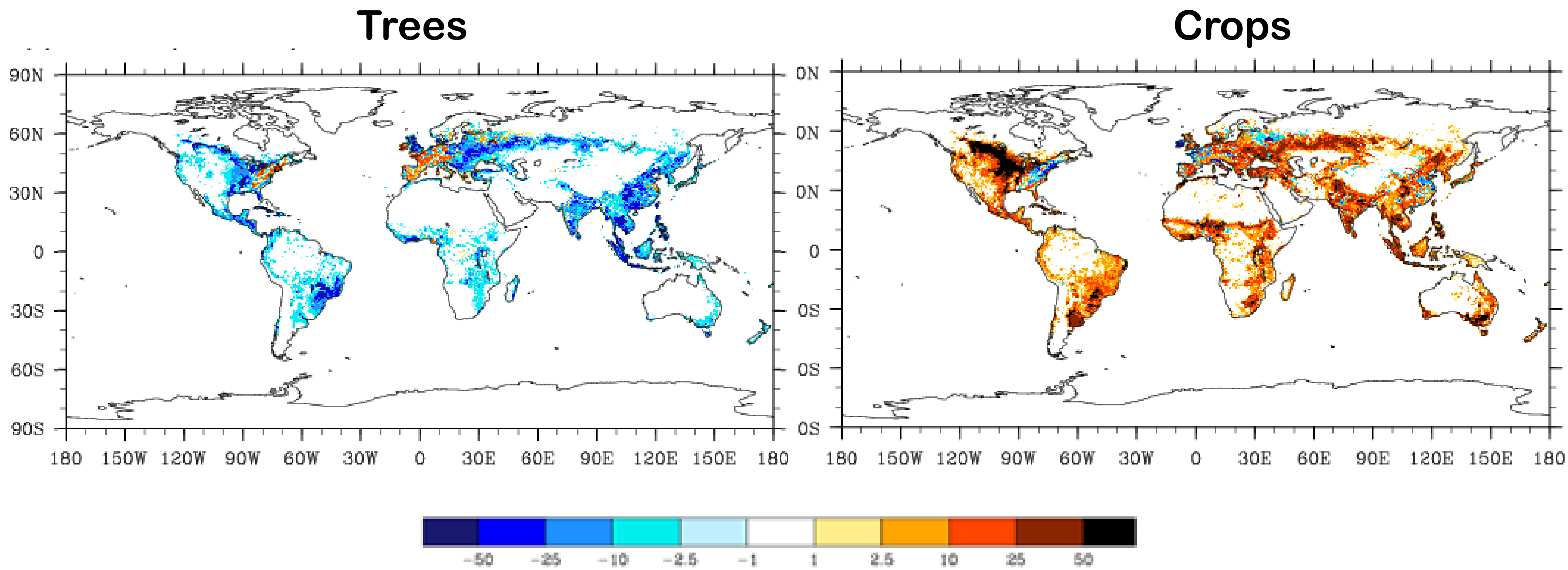






Land cover change (prescribed changes in distribution of PFTs)

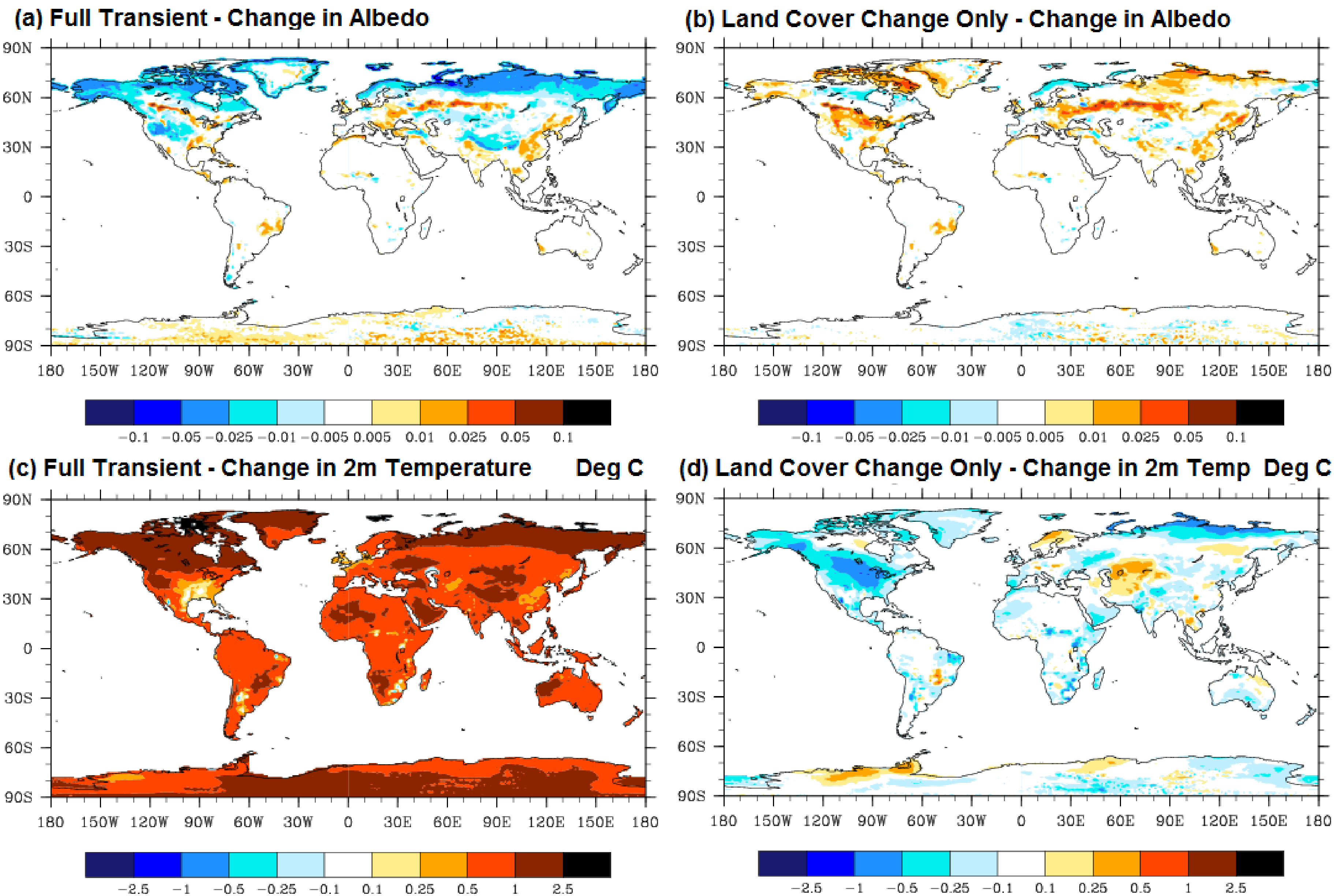
2005 – 1850



Deforestation across Eastern North America, Eastern Europe, India, China, Indonesia, SE South America for Crops

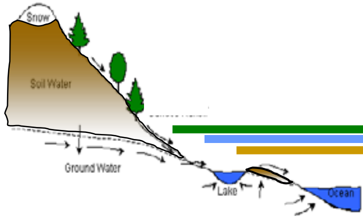
Lawrence, P et al. J. Climate, 2011

Impact of historic land cover change on climate



Main Features of the Community Land Model

- Component submodels
  - Soil hydrology and thermodynamics model
  - Snow model
  - Photosynthesis model
  - Radiation and albedo model
  - River Transport model
  - Lake model
  - Urban model
  - Vegetation dynamics model
  - Carbon and nitrogen cycle model
  - Volatile Organic Compound emissions model
  - Dust emissions model

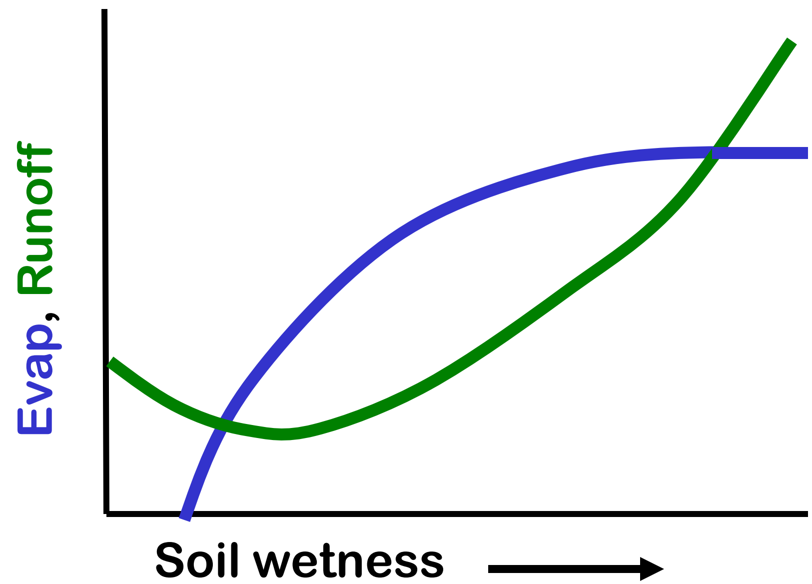


Modeling evaporation and runoff

"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."

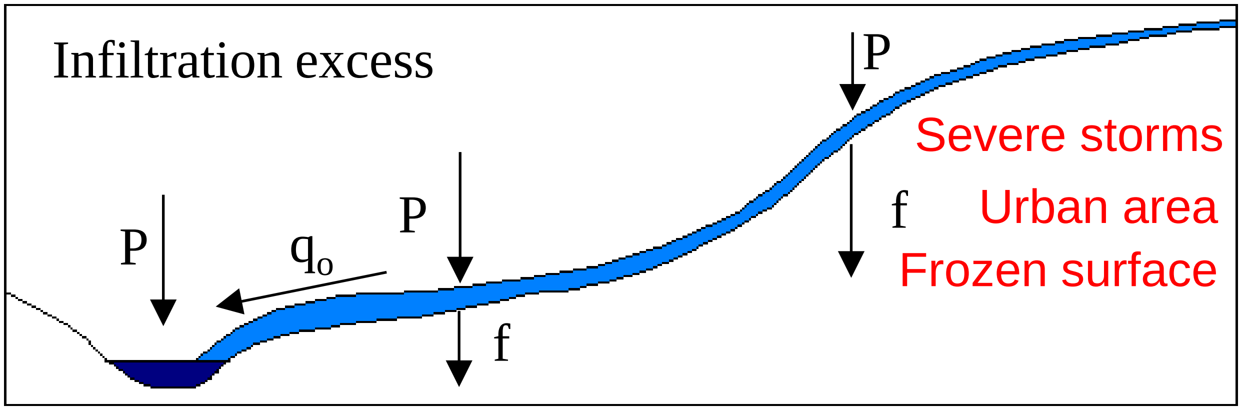
(Koster and Milly, 1997).

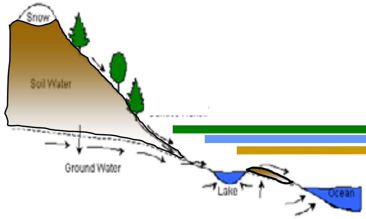
Runoff and evaporation vary non-linearly with soil moisture



Runoff processes

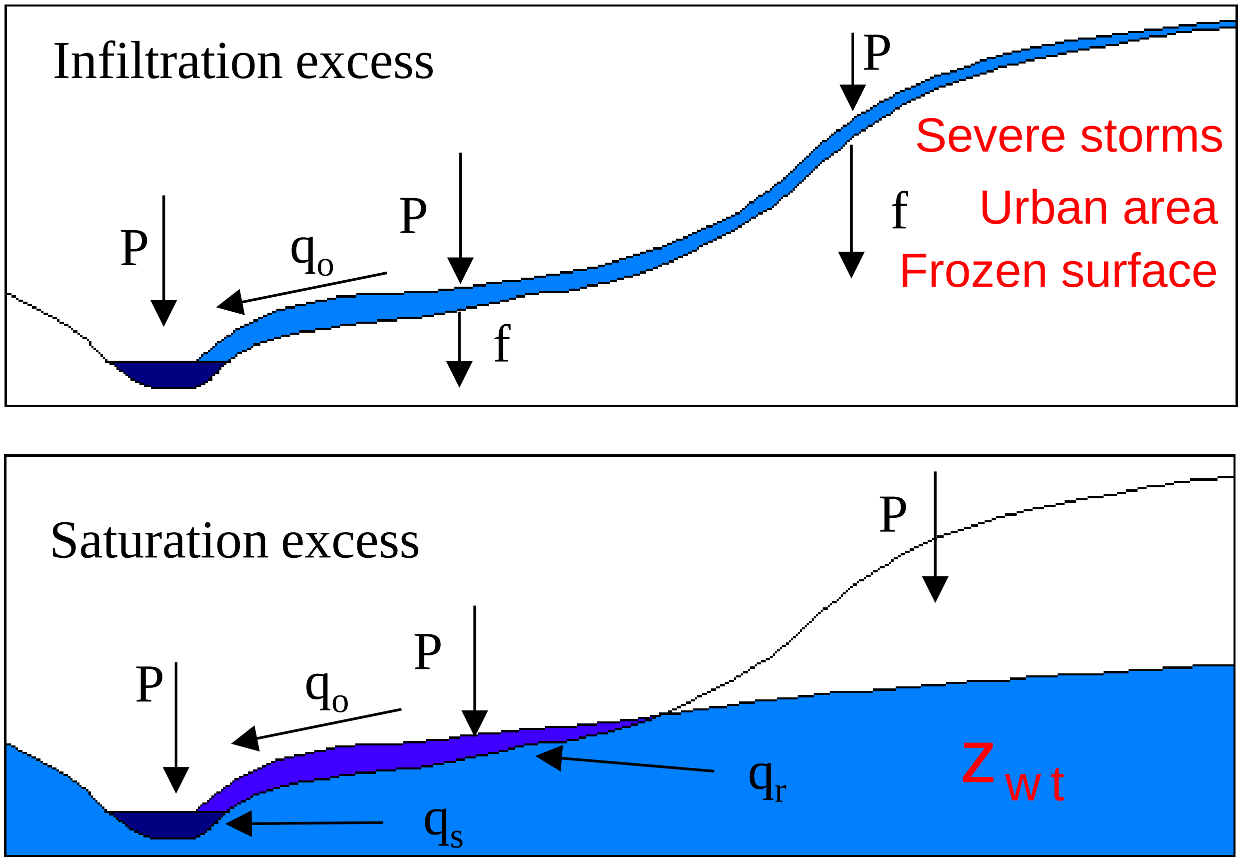
SIMTOP: TOPMODEL-based runoff

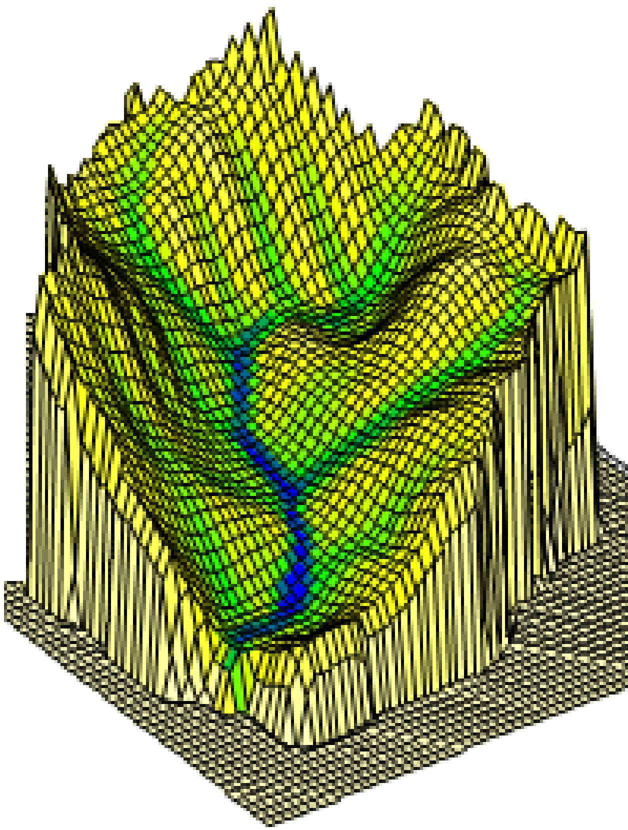


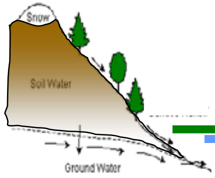


Subgrid-scale soil moisture heterogeneity

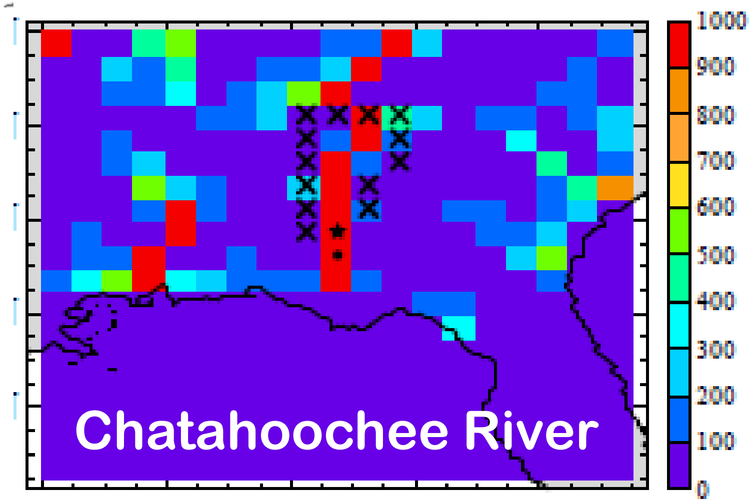
SIMTOP: TOPMODEL-based runoff

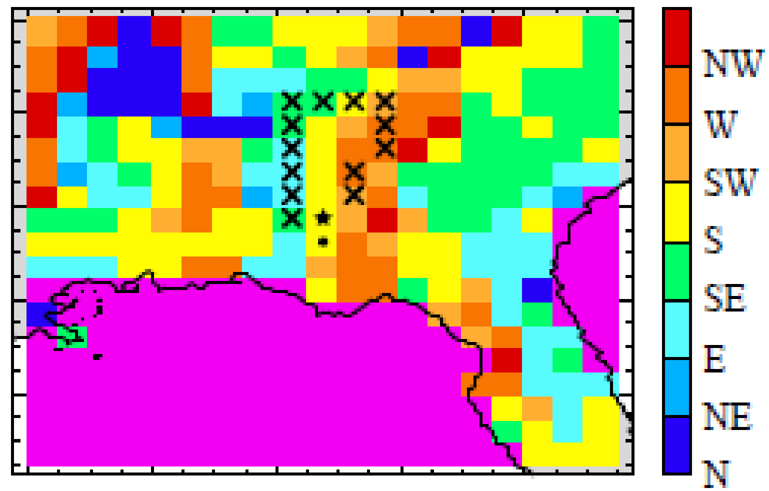


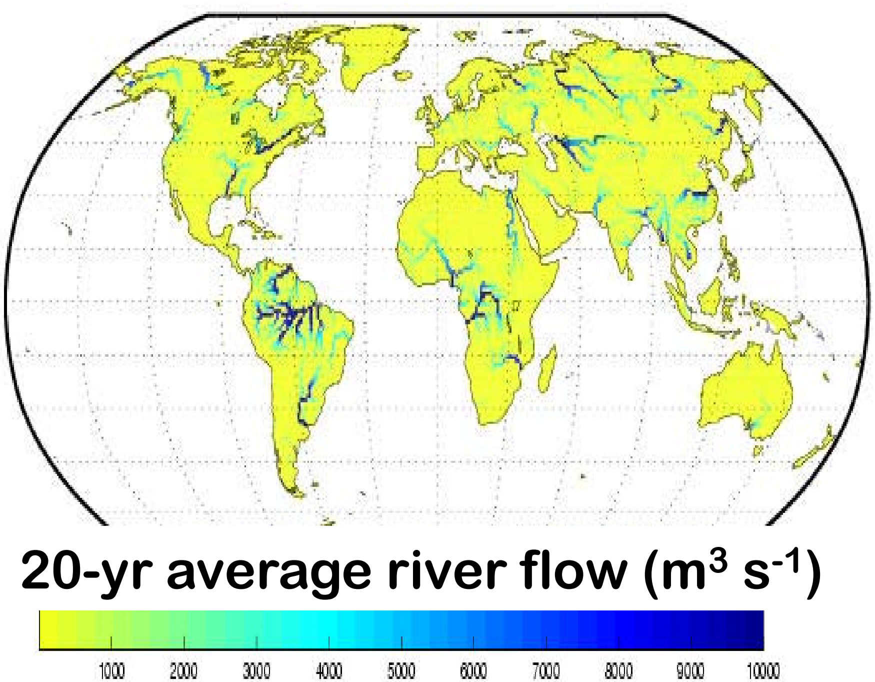


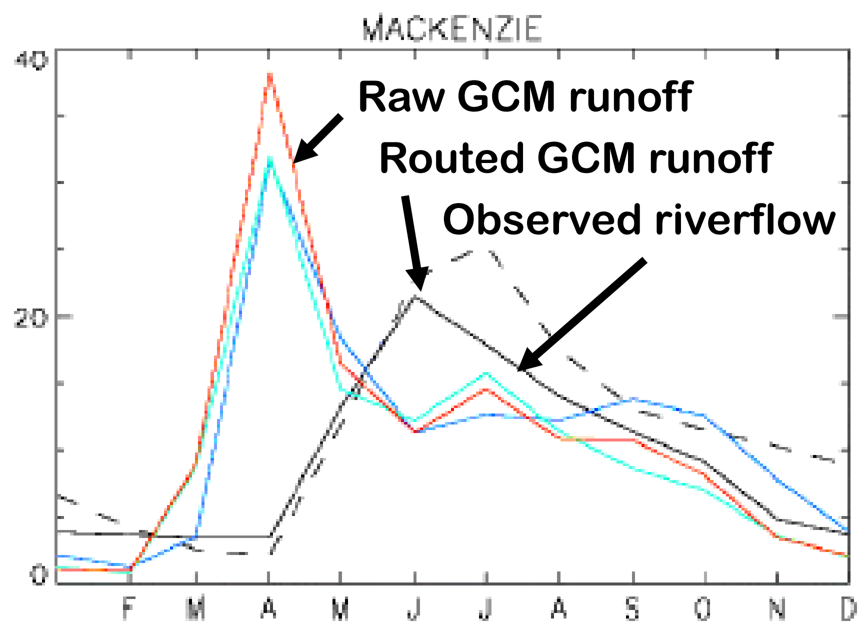


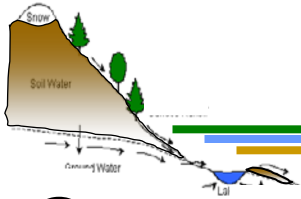
River Transport Model





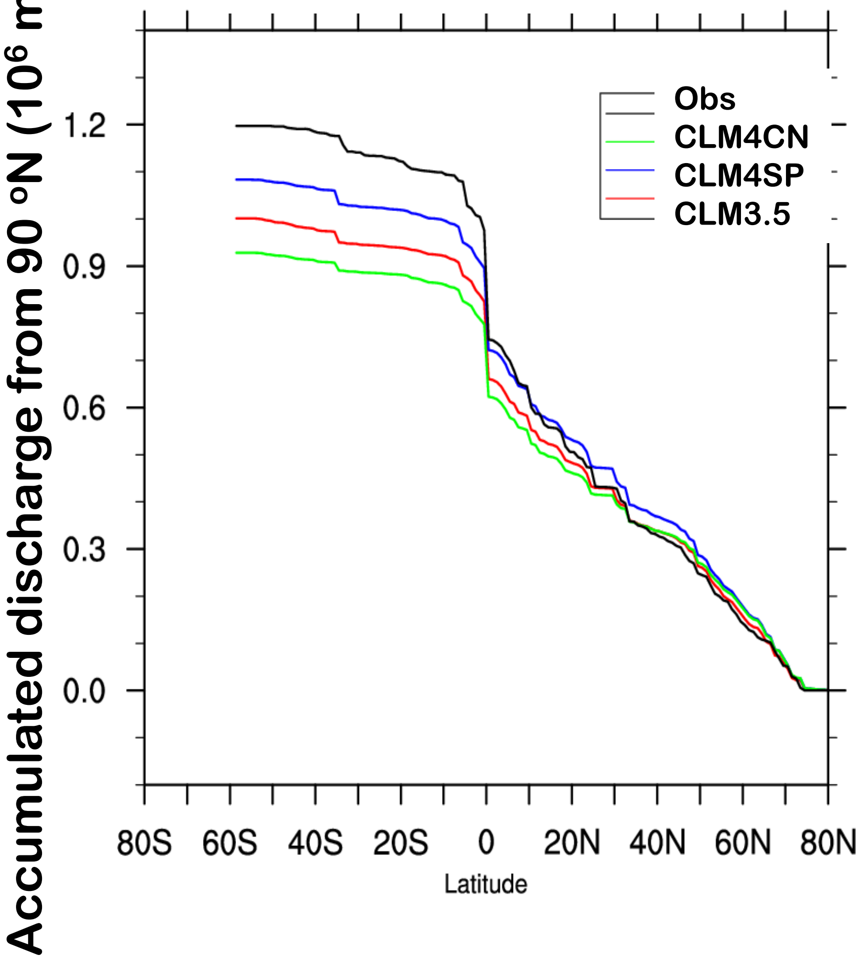




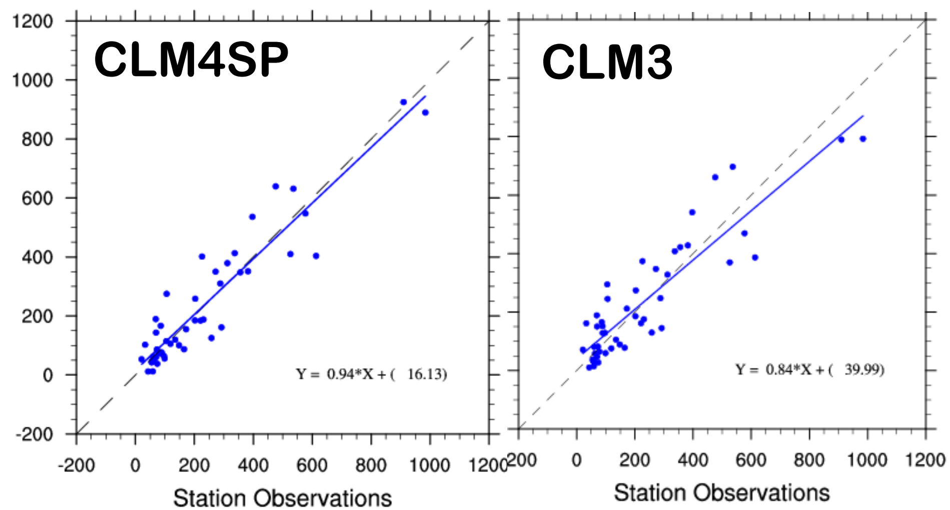


River Discharge

Annual discharge into Global ocean



River flow at outlet Top 50 rivers (km^3 yr^{-1})

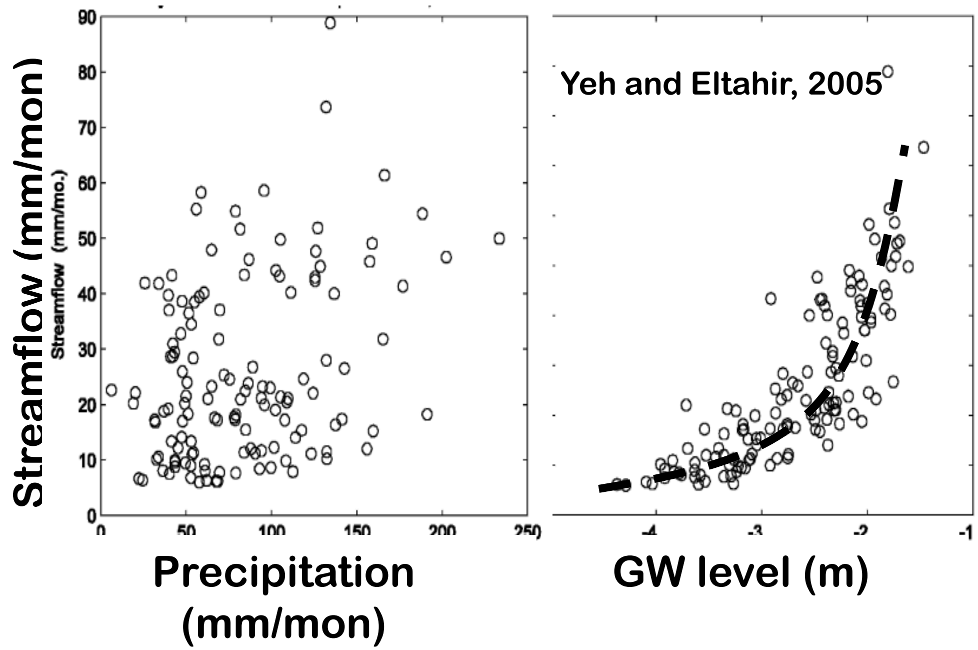


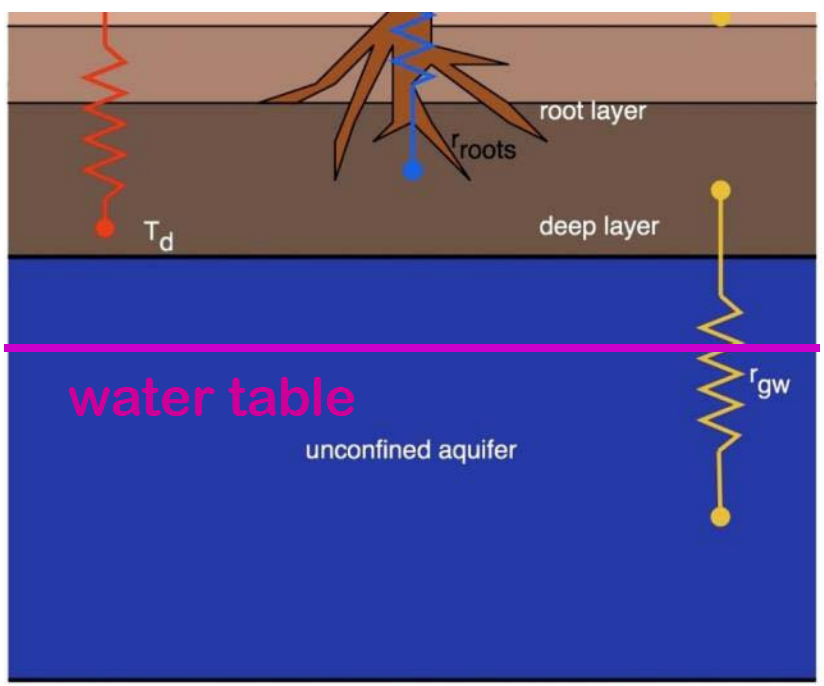
CLM3: r = 0.86
CLM3.5: r = 0.87
CLM4SP: r = 0.94
CLM4CN: r = 0.77

Groundwater in CLM

Groundwater controls runoff (Yeh and Eltahir, 2005)

Groundwater affects soil moisture and ET (Gutowski et al, 2002; York et al., 2002)

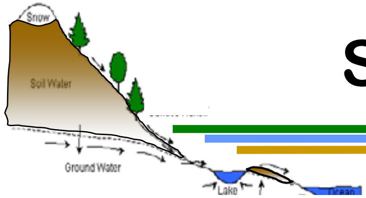




Groundwater model (SIMGM) determines water table depth

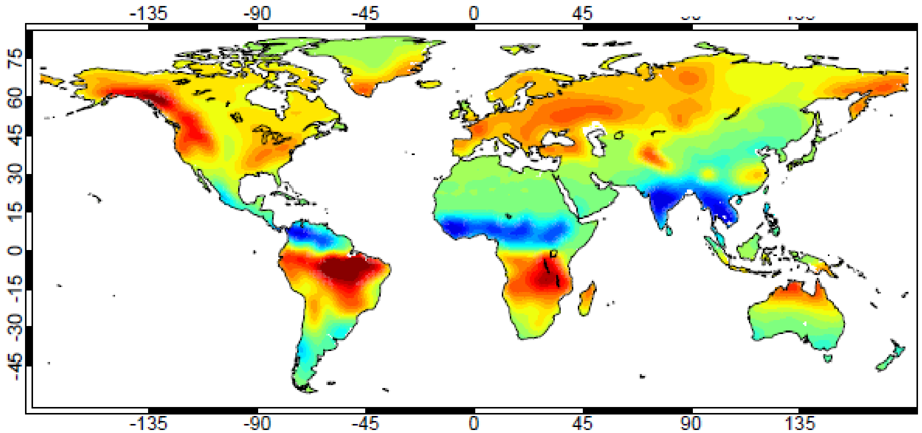
Subsurface runoff is exponential function of water table depth

Niu and Yang, 2005

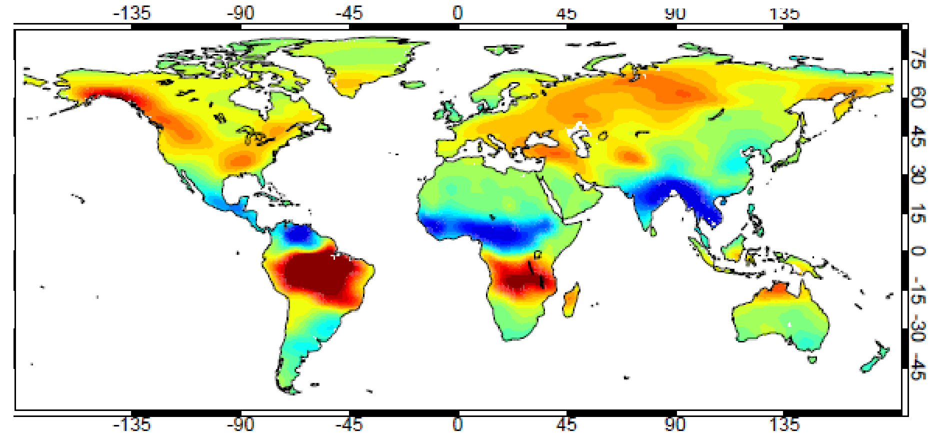


Soil (and snow) water storage (MAM – SON)

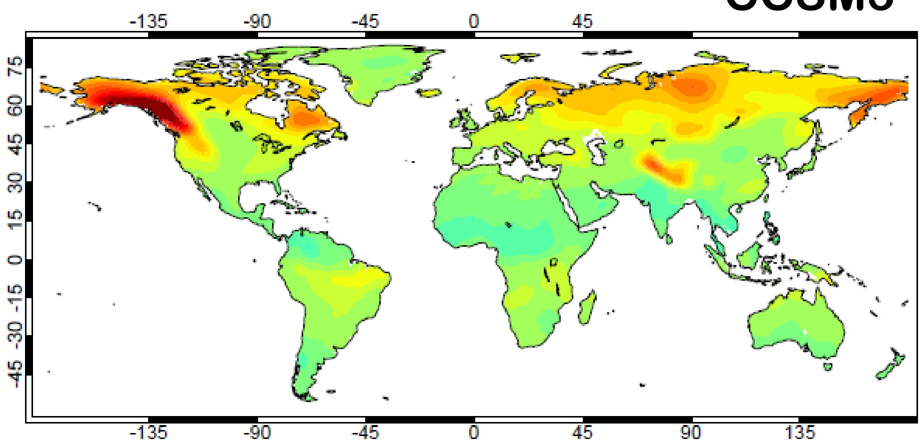
CCSM4



GRACE (obs)



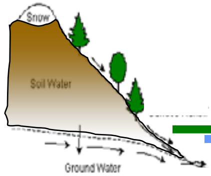
CCSM3



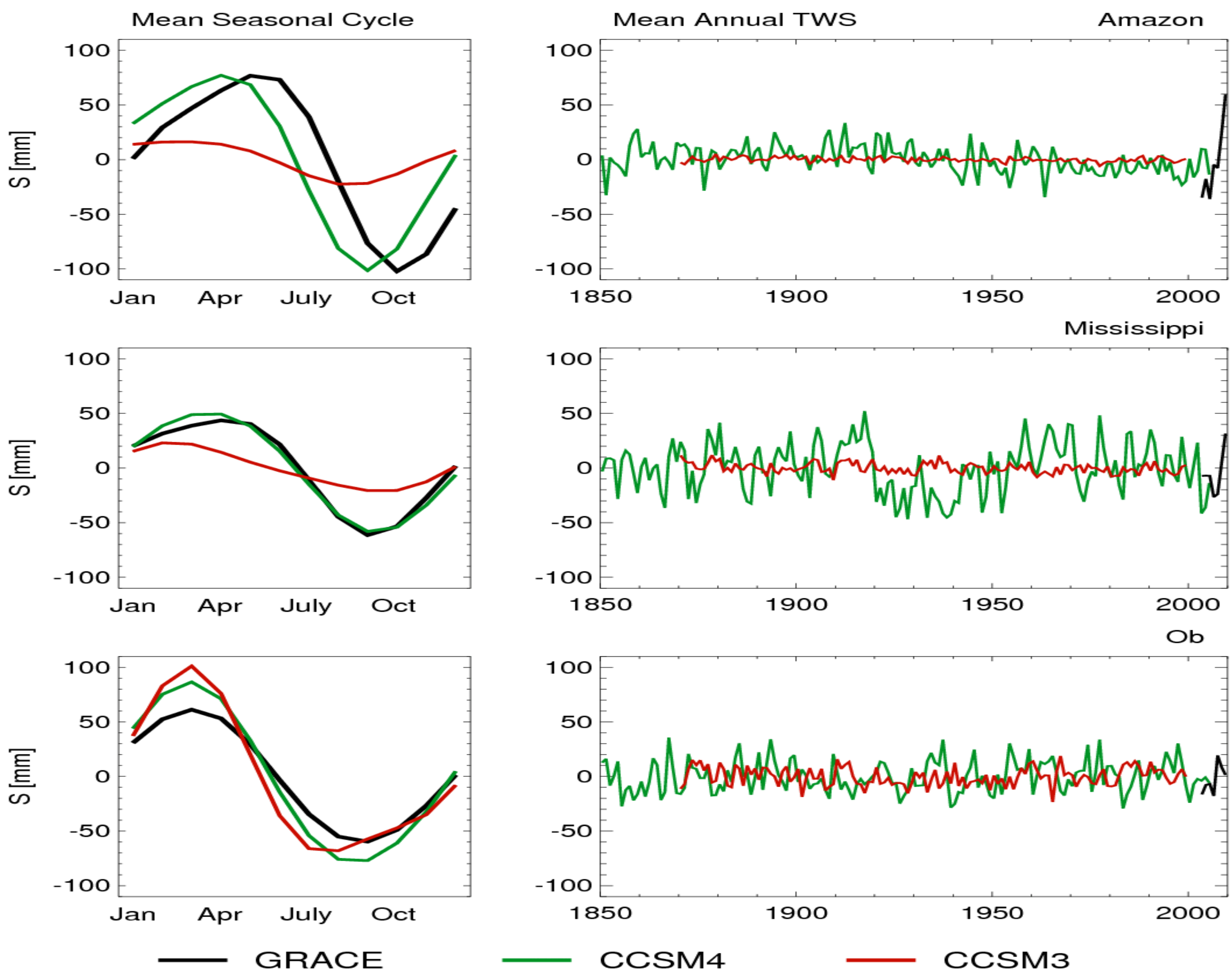
300 200 100 0 -100 -200 -300 (mm)

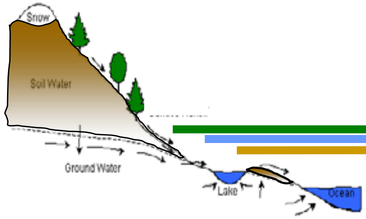
GRACE satellite measures small changes in gravity which on seasonal timescales are due to variations in water storage

CCSM3 and CCSM4 data from 1870 and 1850 control



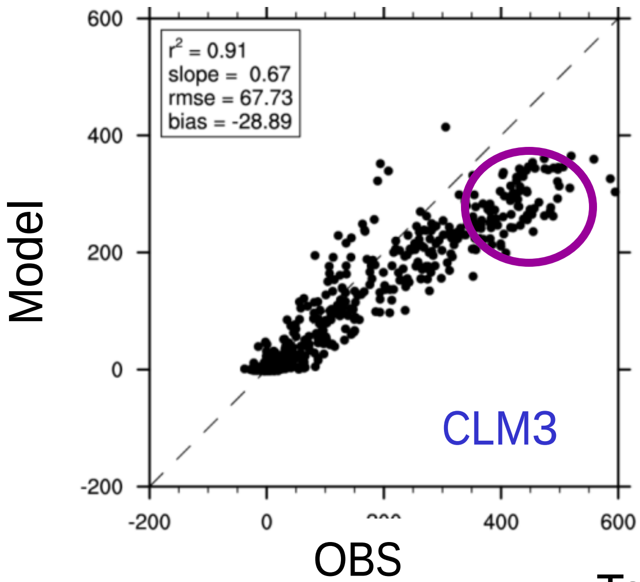
Total Land Water Storage (CCSM vs GRACE)



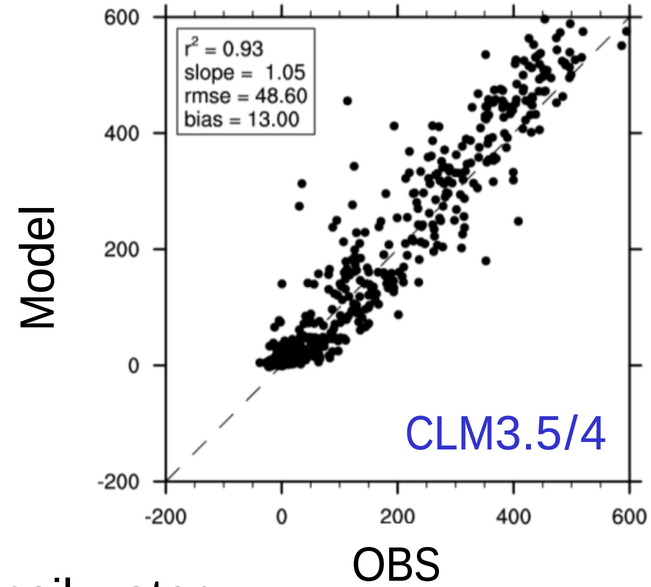


Abracos tower site (Amazon)

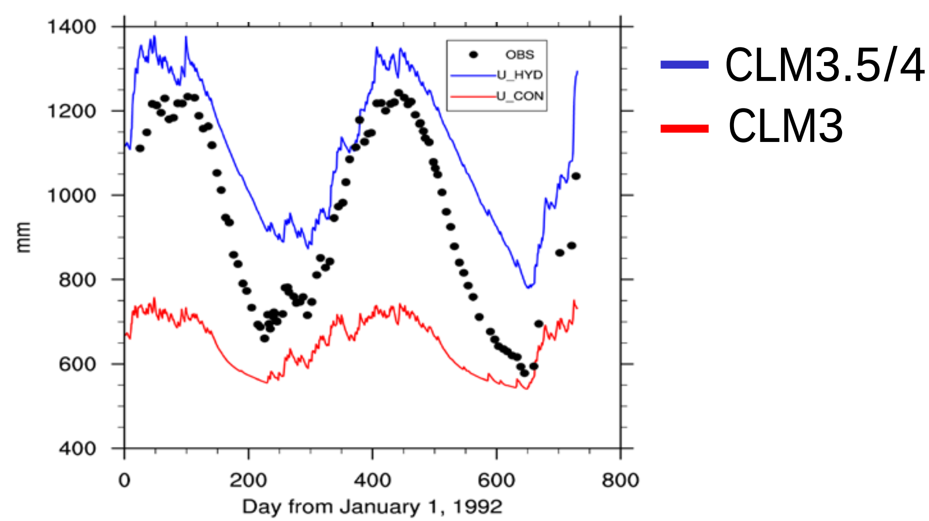
Latent Heat Flux



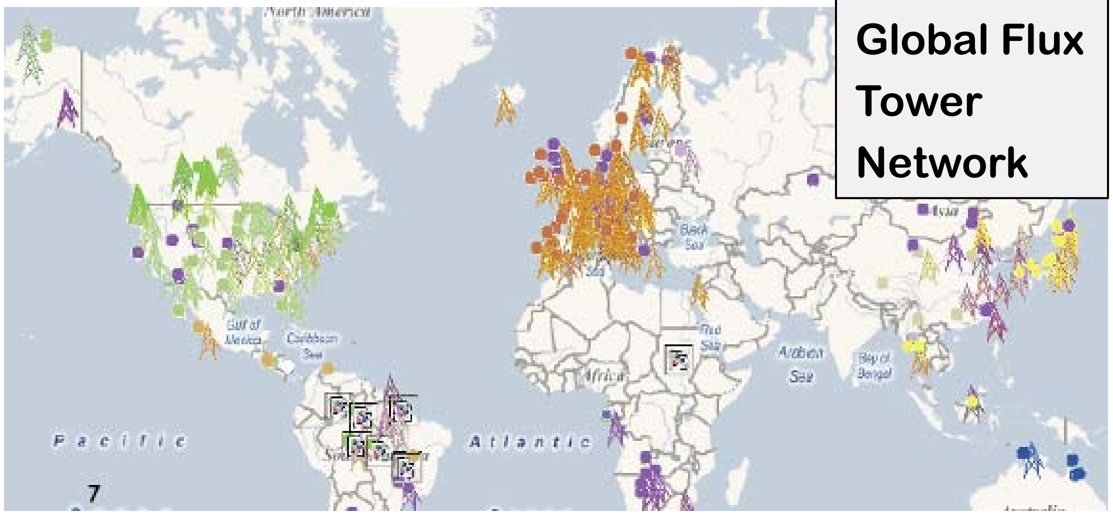
Latent Heat Flux



Total soil water

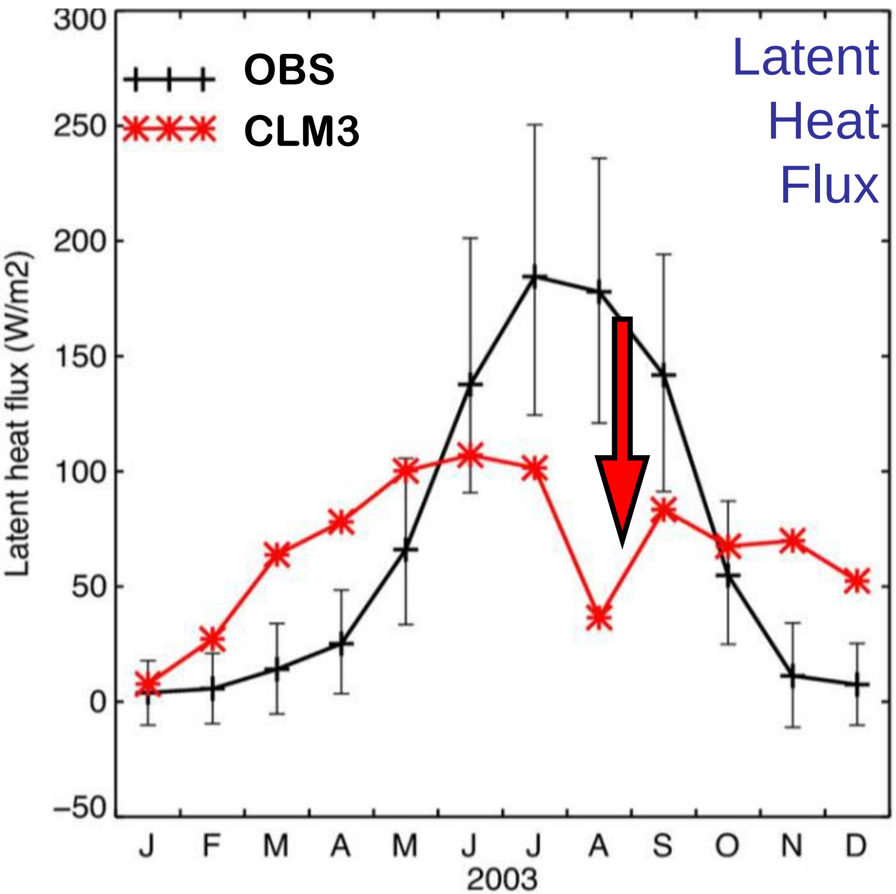


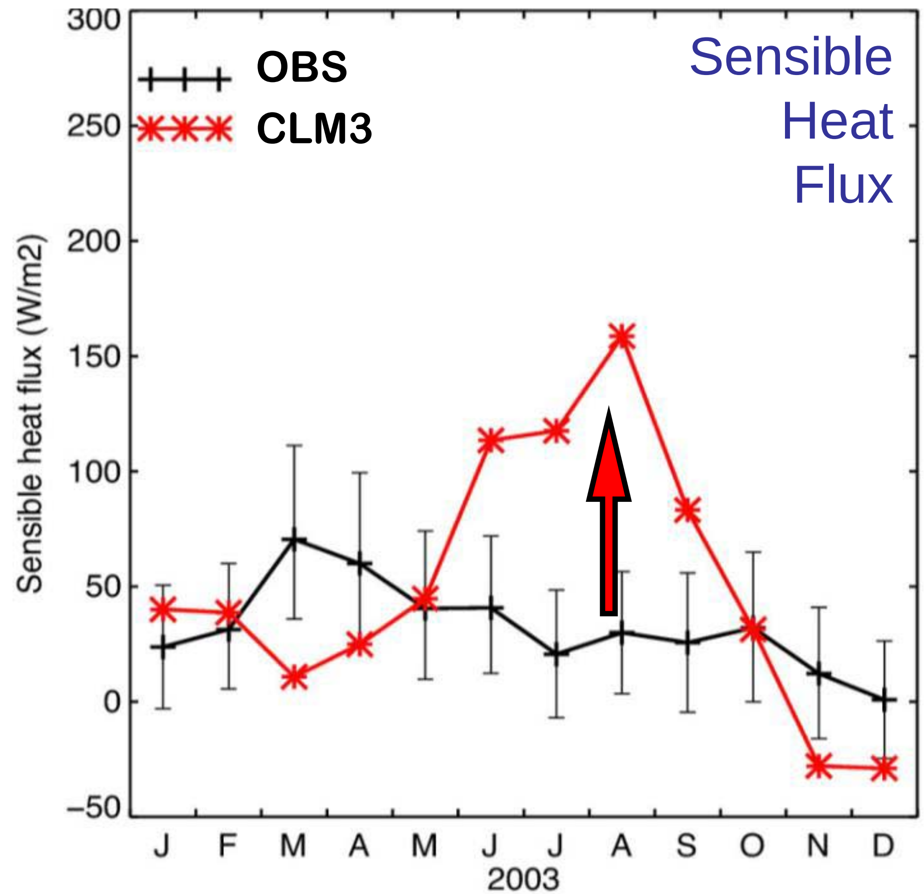
Evaluating and Improving the model with Tower Flux data



Global Flux Tower Network

Morgan Monroe State Forest tower site



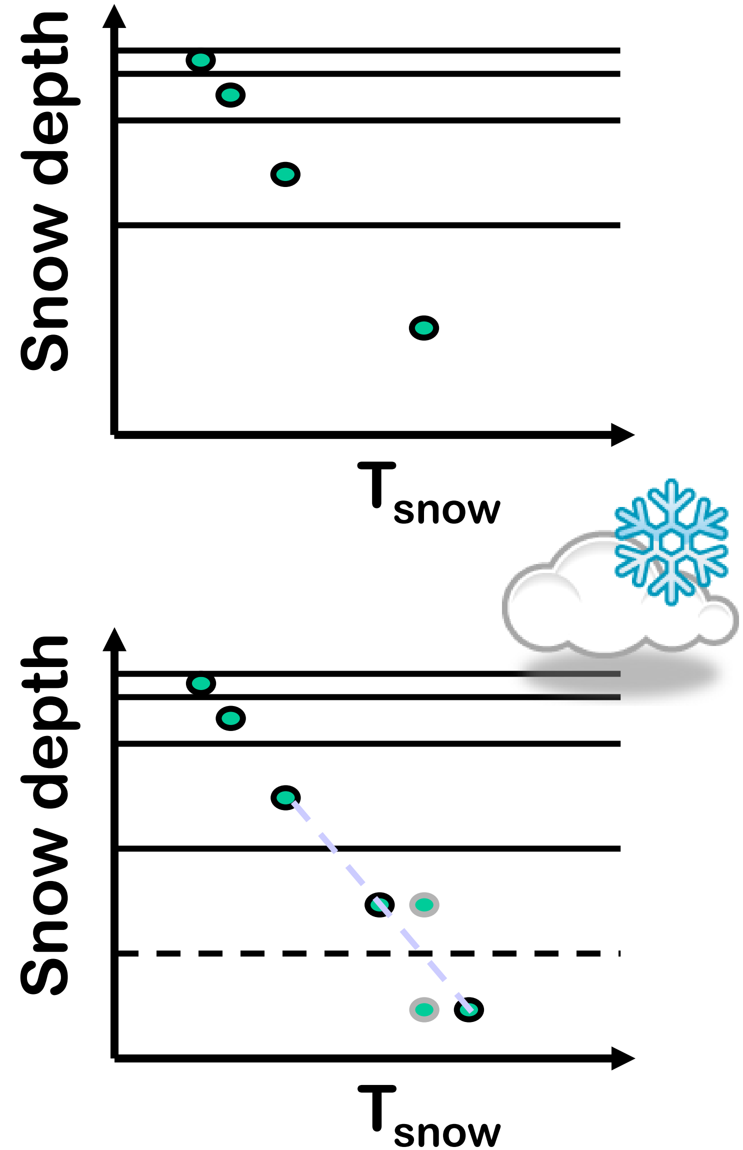


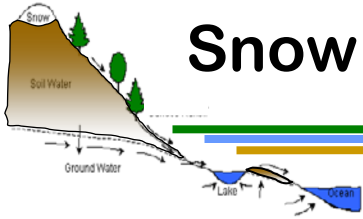
Tower flux statistics (15 sites incl. tropical, boreal, mediteranean, alpine, temperate; hourly)

	Latent Heat Flux		Sensible Heat Flux	
	r	RMSE (W/m^2)	r	RMSE (W/m^2)
CLM3	0.54	72	0.73	91
CLM3.5	0.80	50	0.79	65
CLM4SP	0.80	48	0.84	58

Model components: Snow Model

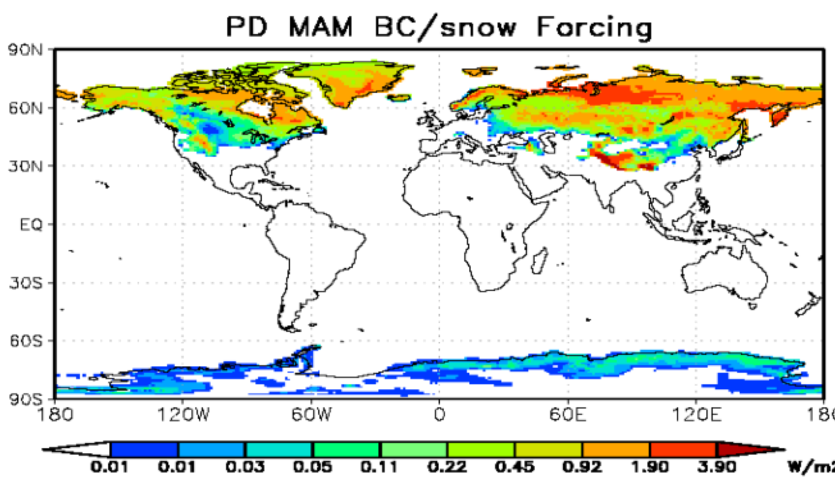
- Up to 5-layers of varying thickness
- Treats processes such as
  - Accumulation
  - Snow melt and refreezing
  - Snow aging
  - Water transfer across layers
  - Snow compaction
    - destructive metamorphism due to wind
    - overburden
    - melt-freeze cycles
  - Sublimation
  - Aerosol deposition

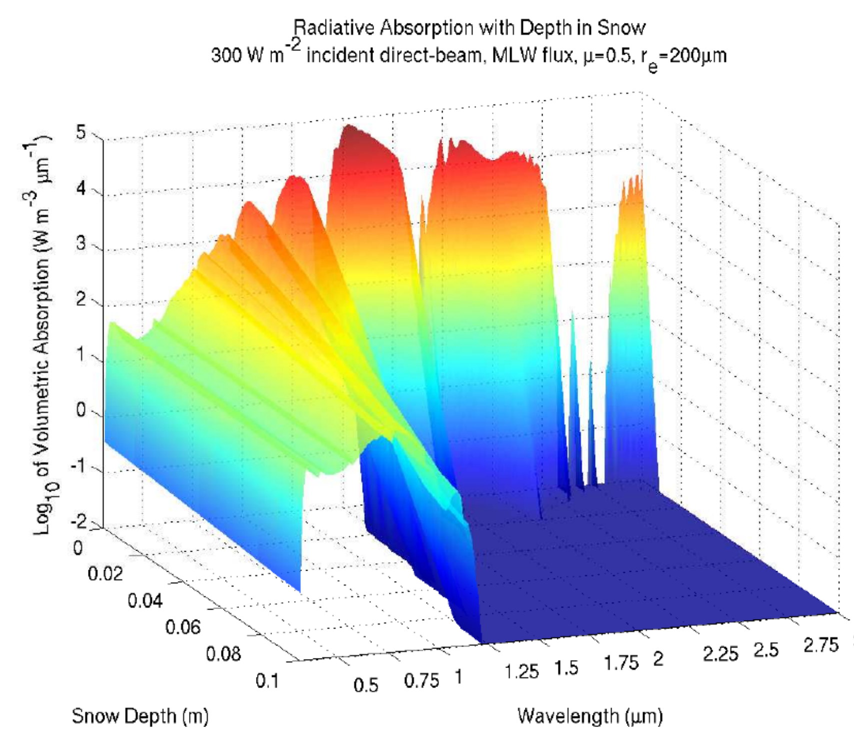




Snow, Ice, and Aerosol Radiative Model (SNICAR)

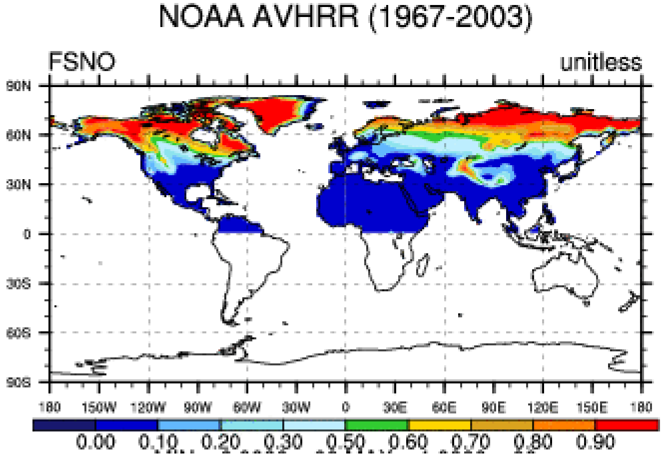
– Snow darkening from deposited black carbon, mineral dust, and organic matter
– Vertically-resolved solar heating in the snowpack
– Snow aging (evolution of effective grain size) based on:
  - Snow temperature and temperature gradient
  - Snow density
  - Liquid water content and
  - Melt/freeze cycling



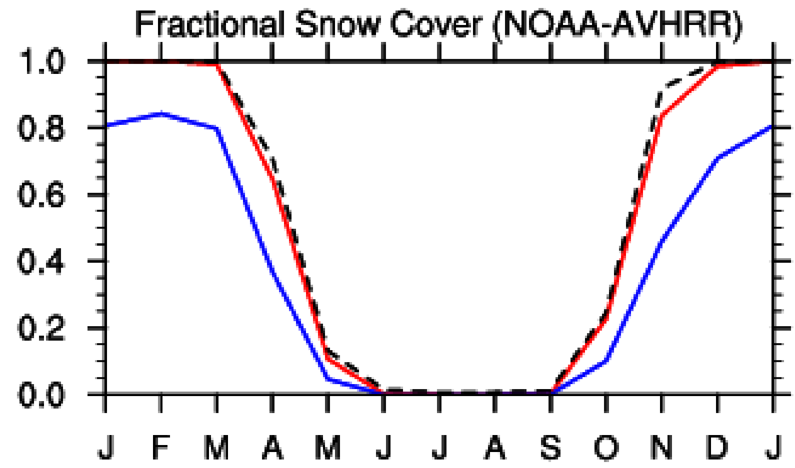


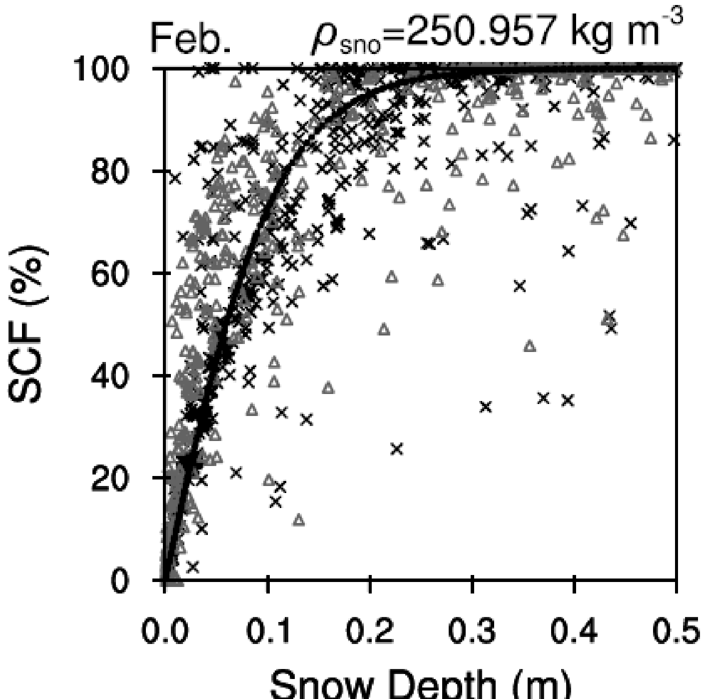
Flanner et al (2007), *JGR*
Flanner and Zender (2006), *JGR*
Flanner and Zender (2005), *GRL*

Snow cover fraction



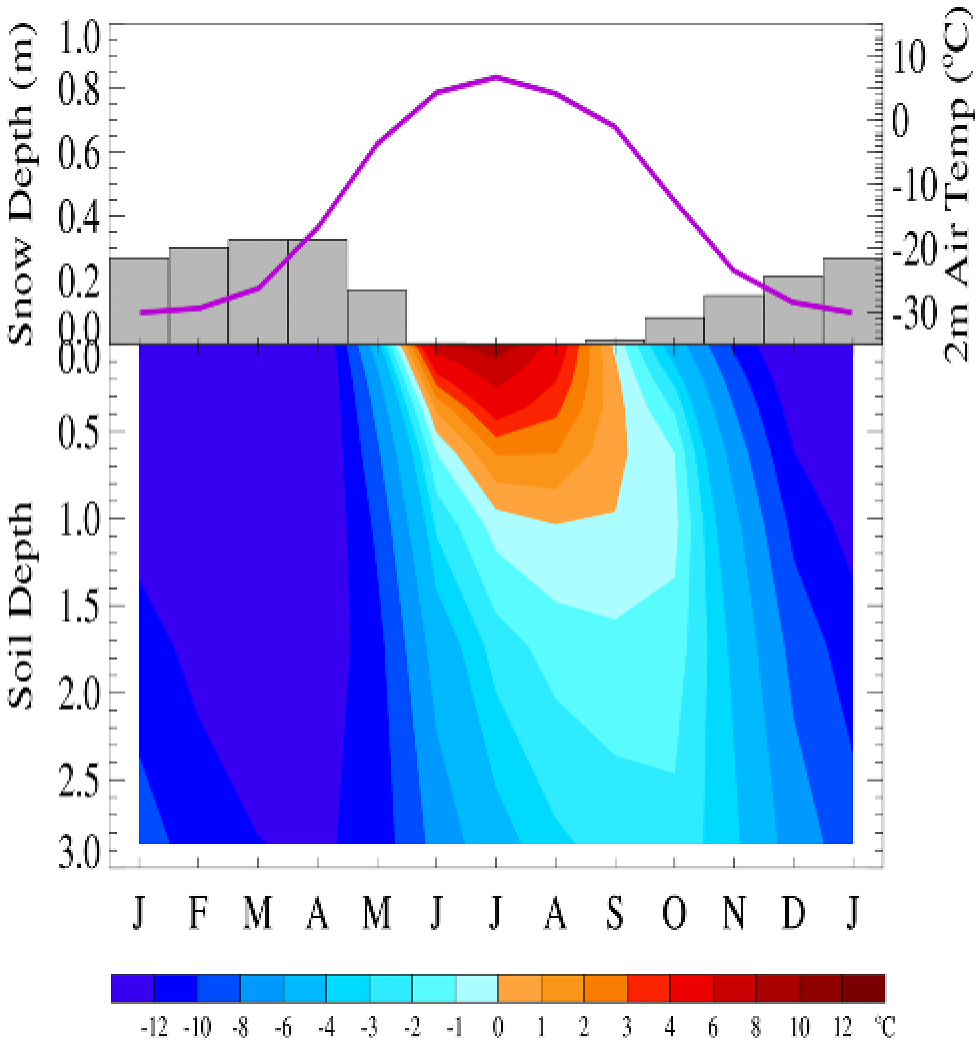
How much of a grid cell is covered with snow for a given snow depth?





Niu and Yang, JGR, 2006

Soil thermodynamics

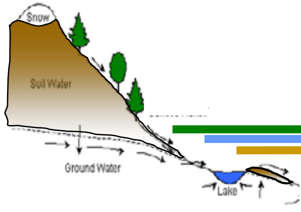


Solve the heat diffusion equation for multi-layer soil and snow model

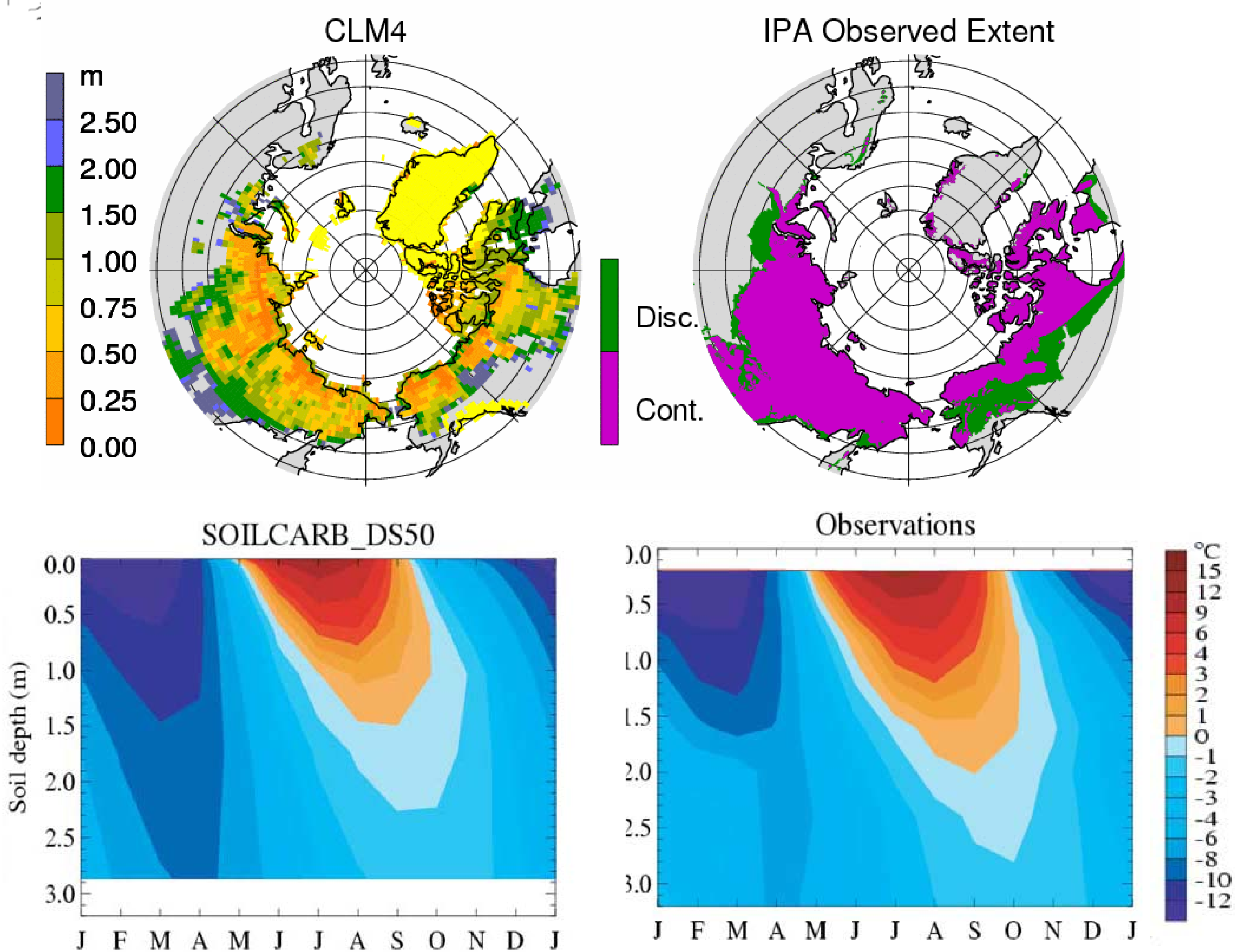
$$C_p \frac{\partial T}{\partial t} = \frac{\partial}{\partial z}\left(K \frac{\partial T}{\partial z} \right)$$

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

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

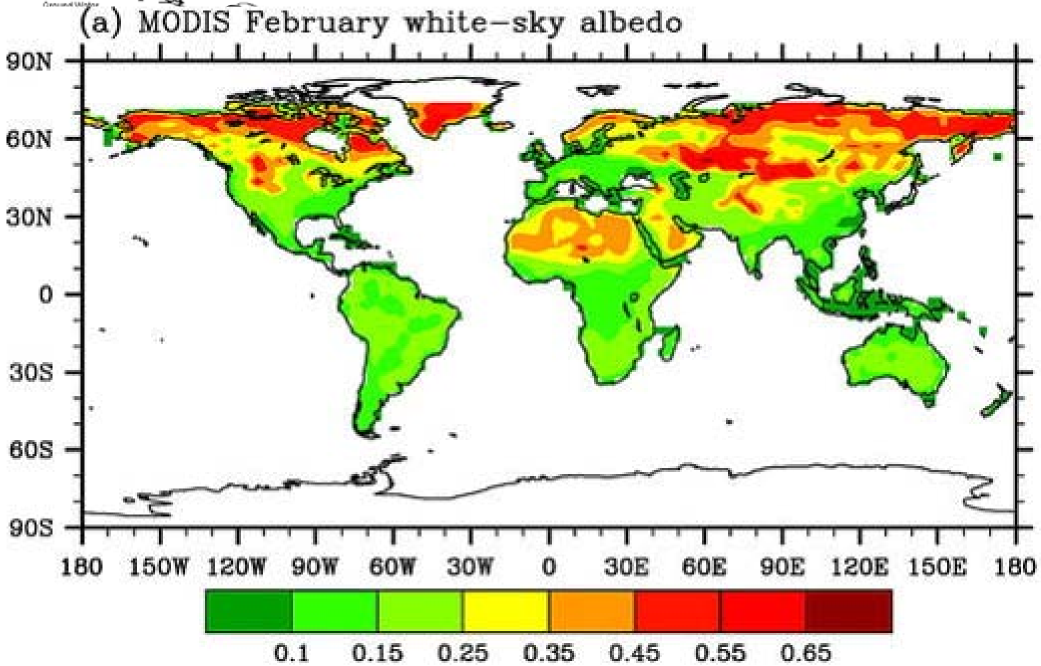


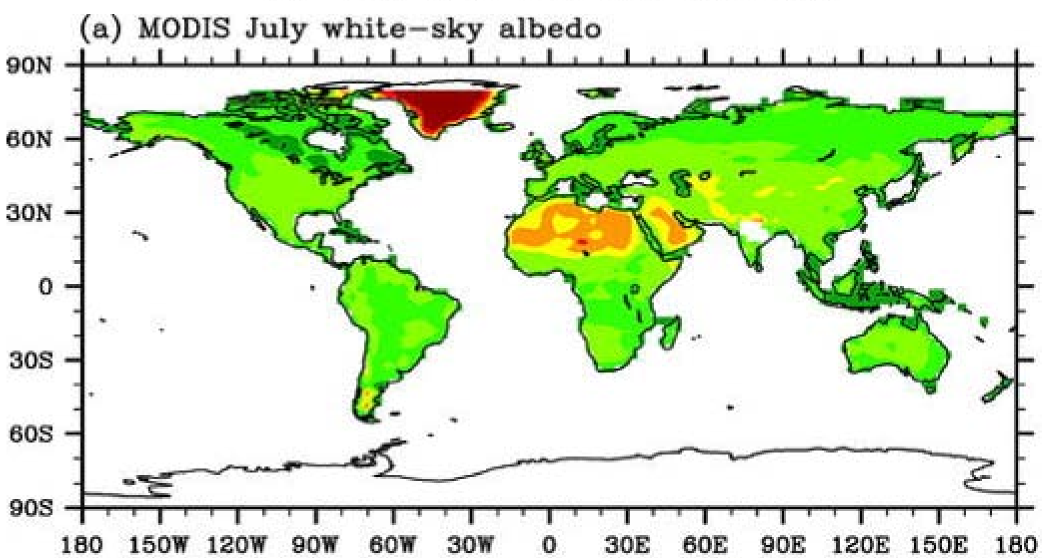
Modeling Permafrost in CLM



Lawrence et al., J. Climate, 2011

Modeling surface albedo



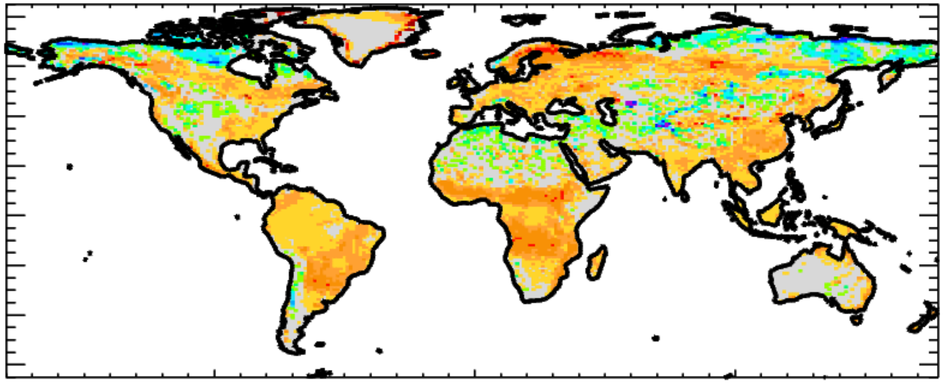


Surface albedo a function of

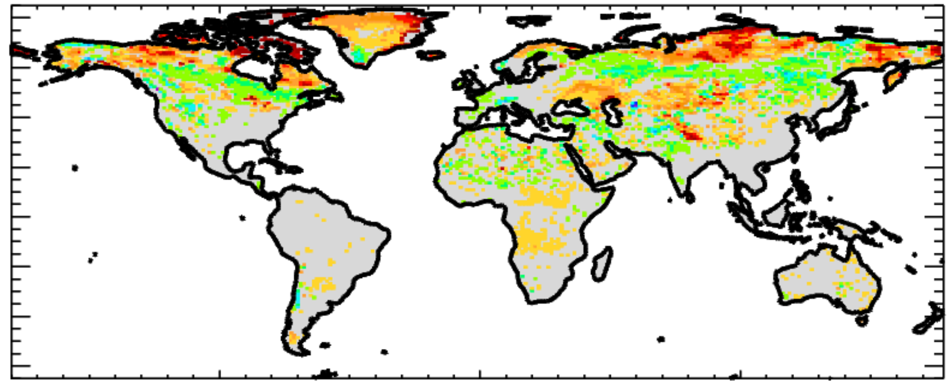
- Vegetation cover and type
- Snow cover
- Snow age
- Solar zenith angle
- Soil moisture
- Amount of direct vs diffuse solar radiation
- Amount of visible vs IR solar radiation

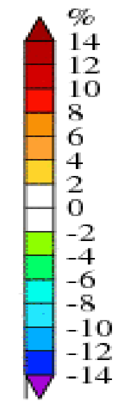
Surface albedo (CLM offline compared to MODIS)

CLM3.5 – Obs



CLM4SP – Obs



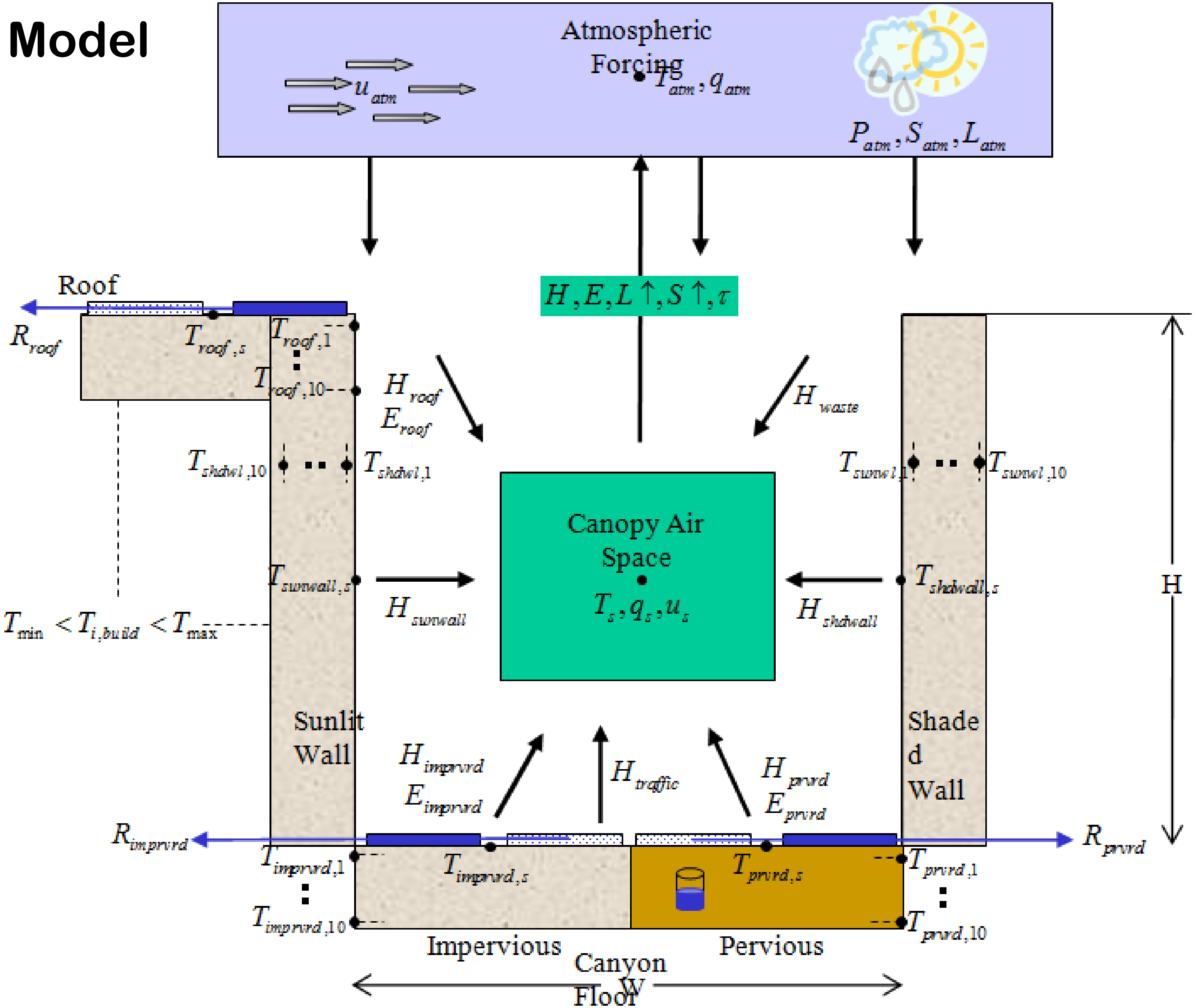


	Bias (%)		RMSE (%)	
Model	Snow-free	Snow depth> 0.2m	Snow-free	Snow depth > 0.2m
CLM3.5	2.7	-5.0	4.1	11.9
CLM4SP	0.4	2.9	2.0	13.2

Note: MODIS albedo biased low for snow at high zenith angle

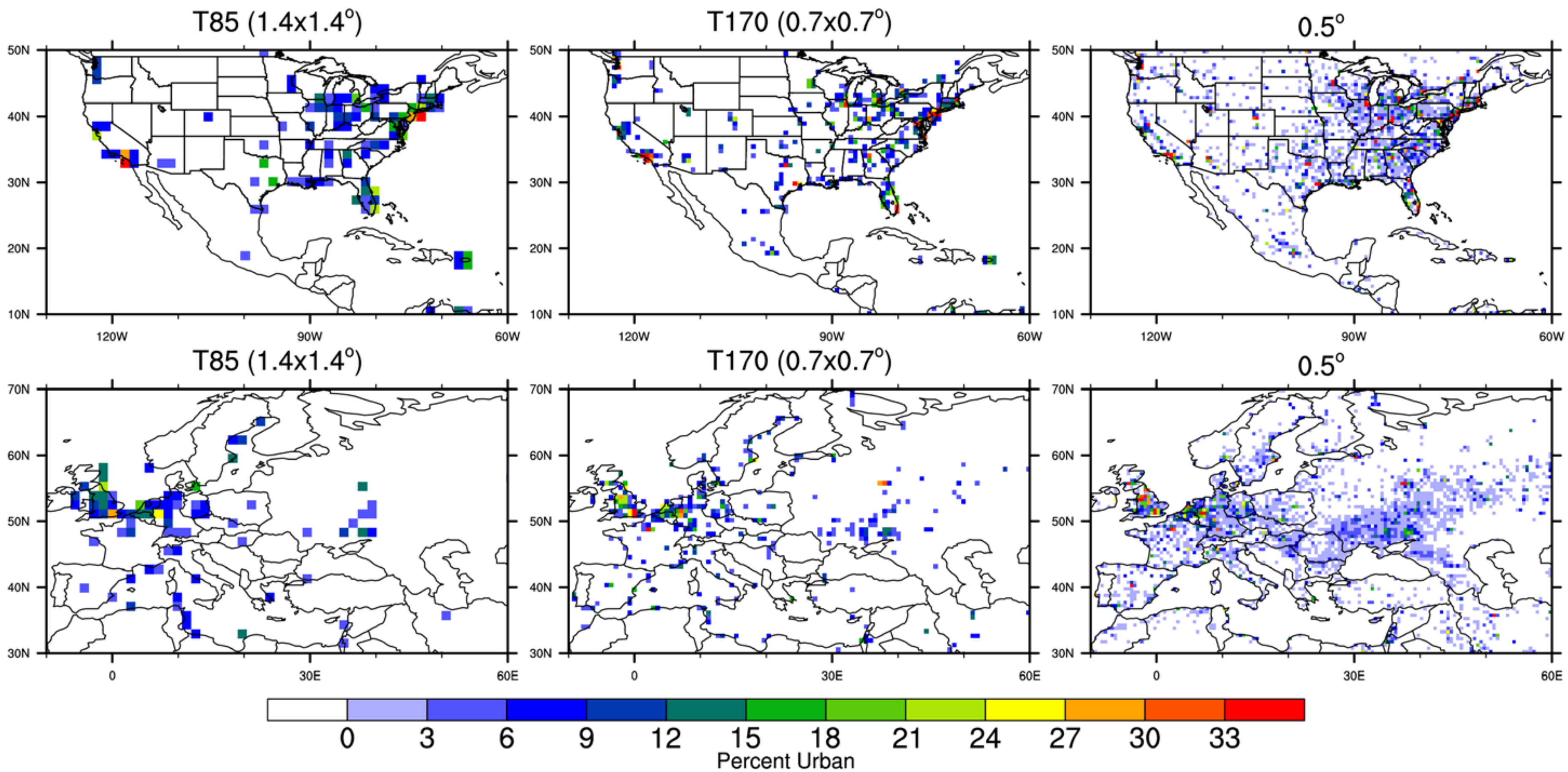
(Wang and Zender, 2010)

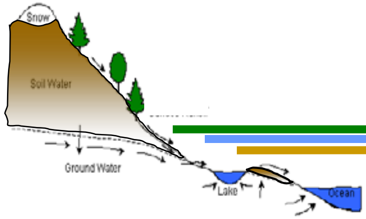
Urban Model



Atmospheric Forcing
u_{atm}
T_{atm}, q_{atm}
$P_{atm}, S_{atm}, L_{atm}$
$H, E, L\uparrow, S\uparrow, \tau$
Roof
R_{roof}
$T_{roof,s}$
$T_{roof,1}$
$T_{roof,10}$
H_{roof}
E_{roof}
H_{waste}
$T_{shdwl,10}$
$T_{shdwl,1}$
$T_{sunwl,1}$
$T_{sunwl,10}$
Canopy Air Space
T_s, q_s, u_s
$T_{sunwall,s}$
$H_{sunwall}$
$T_{shdwall,s}$
$H_{shdwall}$
H
$T_{min} < T_{i,build} < T_{max}$
Sunlit Wall
Shaded Wall
$H_{imprvrd}$
$E_{imprvrd}$
$H_{traffic}$
H_{prvrd}
E_{prvrd}
$R_{imprvrd}$
R_{prvrd}
$T_{imprvrd,1}$
$T_{imprvrd,s}$
$T_{imprvrd,10}$
$T_{prvrd,s}$
$T_{prvrd,1}$
$T_{prvrd,10}$
Impervious
Pervious
Canyon Floor
W

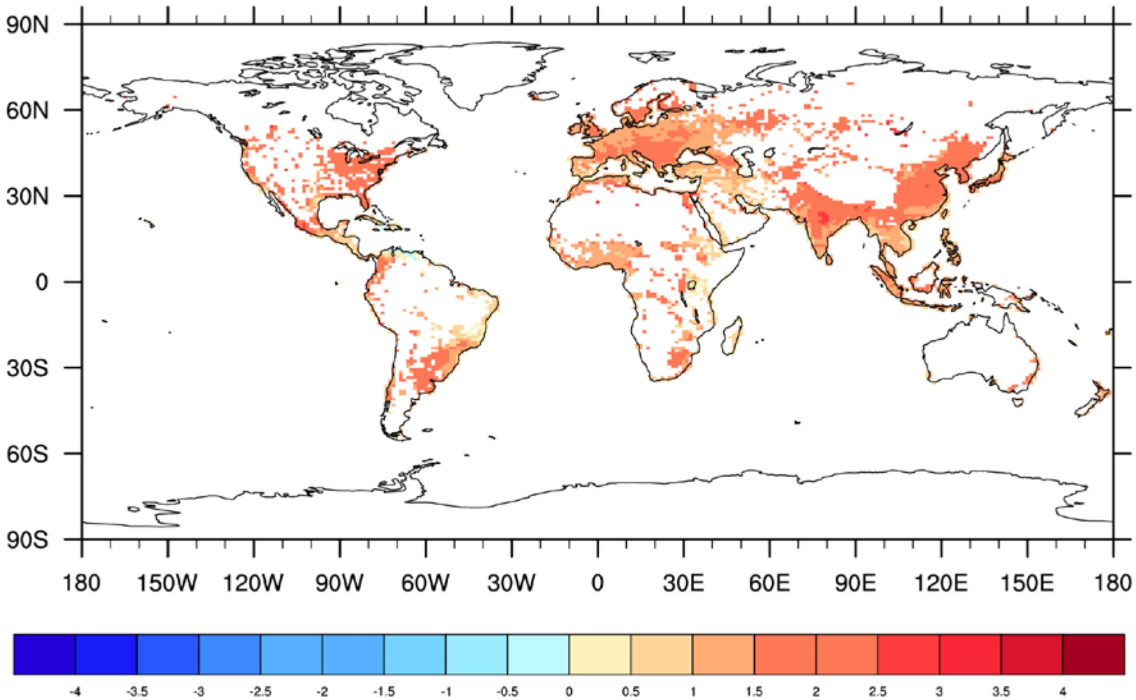
Percent Urban at Climate Model Resolutions





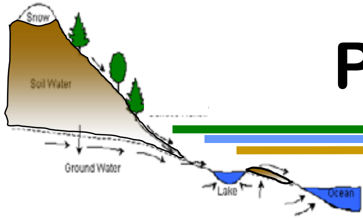
Urban Modeling in CCSM4

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.

Oleson, K.W., G.B. Bonan, J. Feddema, M. Vertenstein, C.S.B. Grimmond, 2008a, *J. Appl. Meteor. Climatol.*
Oleson, K.W., G.B. Bonan, J. Feddema, M. Vertenstein, 2008b, *J. Appl. Meteor. Climatol.*



Putting it all together: CLM on a single slide!

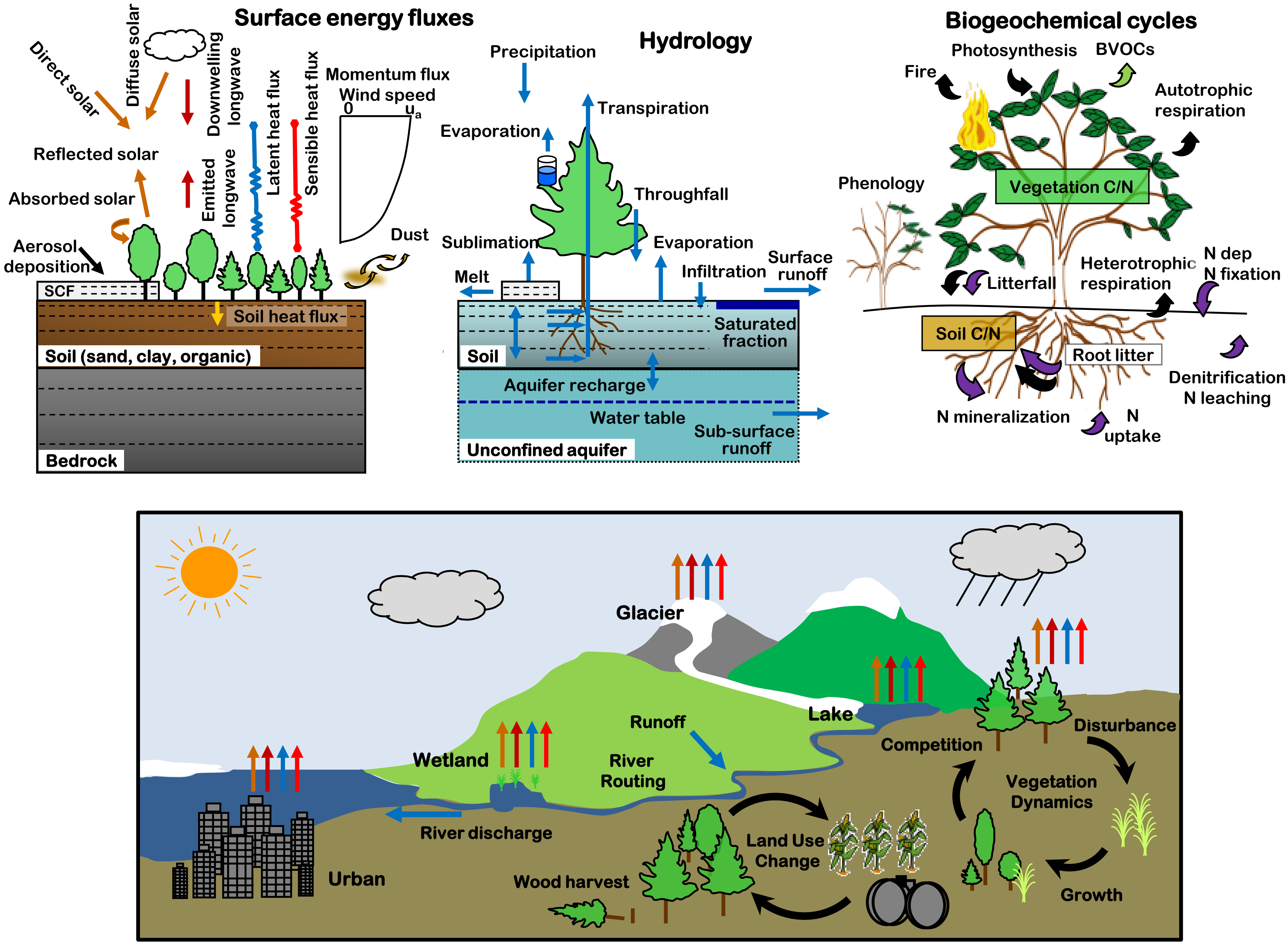
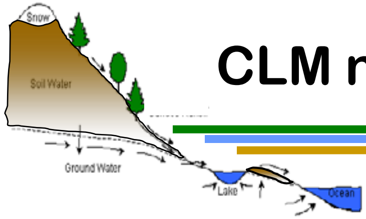


Figure 1: Lawrence et al., Journal Advances Modeling Earth Systems, 2011

Future and Ongoing Challenges

- With steadily increasing complexity, just keeping everything operating *and* working together well is a challenge
- Heterogeneity
- C, N, water interactions
- …



CLM near-term development activities, CLM4.5 (late next year?)

- Crops and irrigation
- Revised cold region hydrology
  - Prognostic wetland
  - 2-way RTM / grid cell interactions
- Revised canopy processes
- Methane emissions model
- Improved fire algorithm including human triggers and suppression
- Revised lake model
- Dynamic landunits
  - Transitions glacier to vegetated, lake area change

Community Earth System Model

CESM1.0: CLM DOCUMENTATION

Introduction

The Community Land Model version 4.0 (CLM4.0) is the land model used in the CESM1.0. CLM4.0 is the latest in a series of land models developed through the CESM project. More information on the CLM project and access to previous CLM model versions and documentation can be found via the CLM Web Page.

Documentation

- CLM4.0 User's Guide [html] [pdf] (Last update: Jun/17/2010)
- What's new in the CESM1.0 release of CLM4? [pdf]
- What's new in CLM4.0 relative to CLM3.5? [pdf]
- CLM4.0 Technical Note [pdf] (Last update: Jun/17/2010)
- CLM4.0 Urban Model Technical Note [pdf] (Last update: Jun/17/2010)
- CLM4.0 Carbon-Nitrogen (CN) Model Technical Note (in preparation)
- CLM4.0 Code Reference Guide [html]

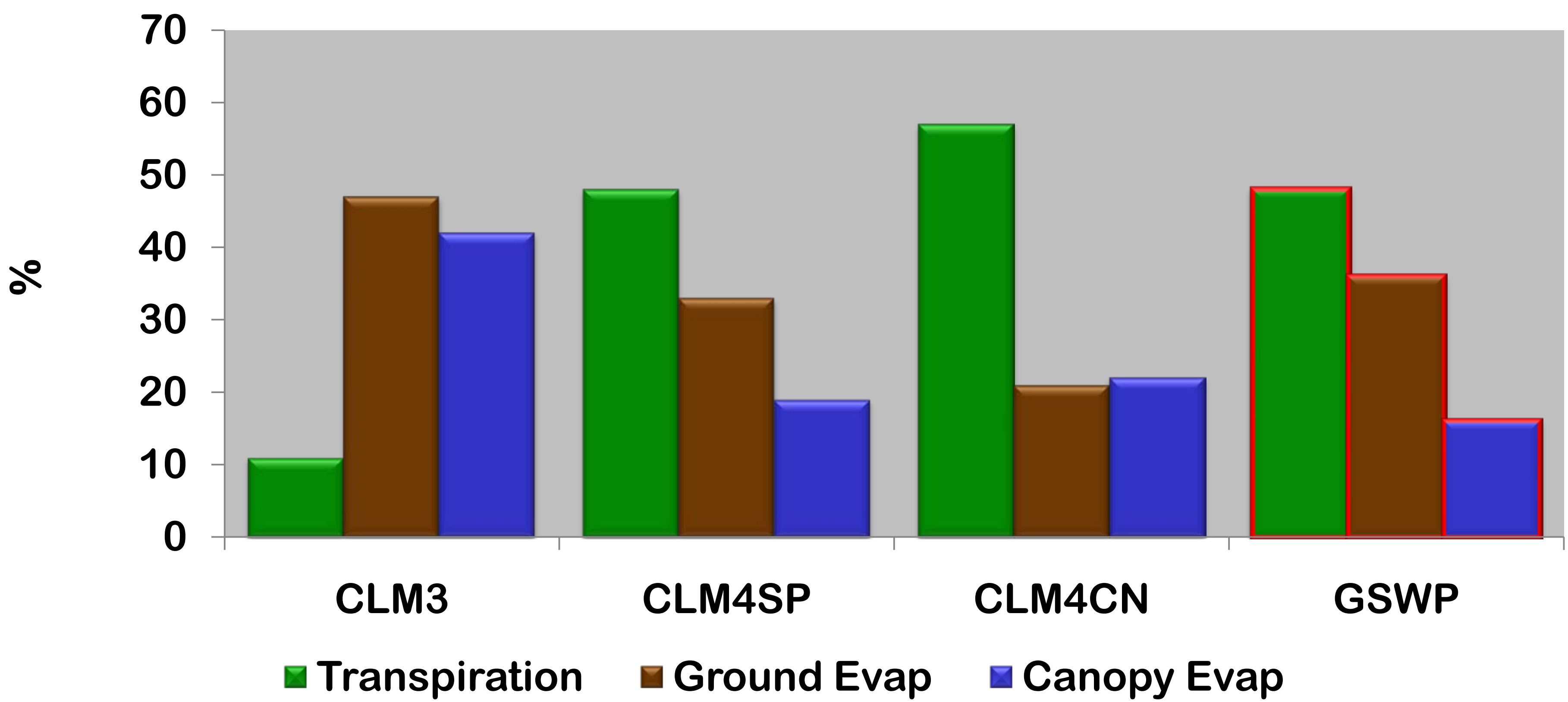
Model output and offline forcing data and diagnostic plots

- CLM4.0 offline control simulations: Diagnostic plots
- CLM4.0 offline control simulations: Model output data
- CLM4.0 offline control simulations: Model forcing data

CLM Post-Processing Utilities

- CLM Diagnostic Package: Code (via svn repository, registration required)
- CLM Diagnostic Package: User's Guide

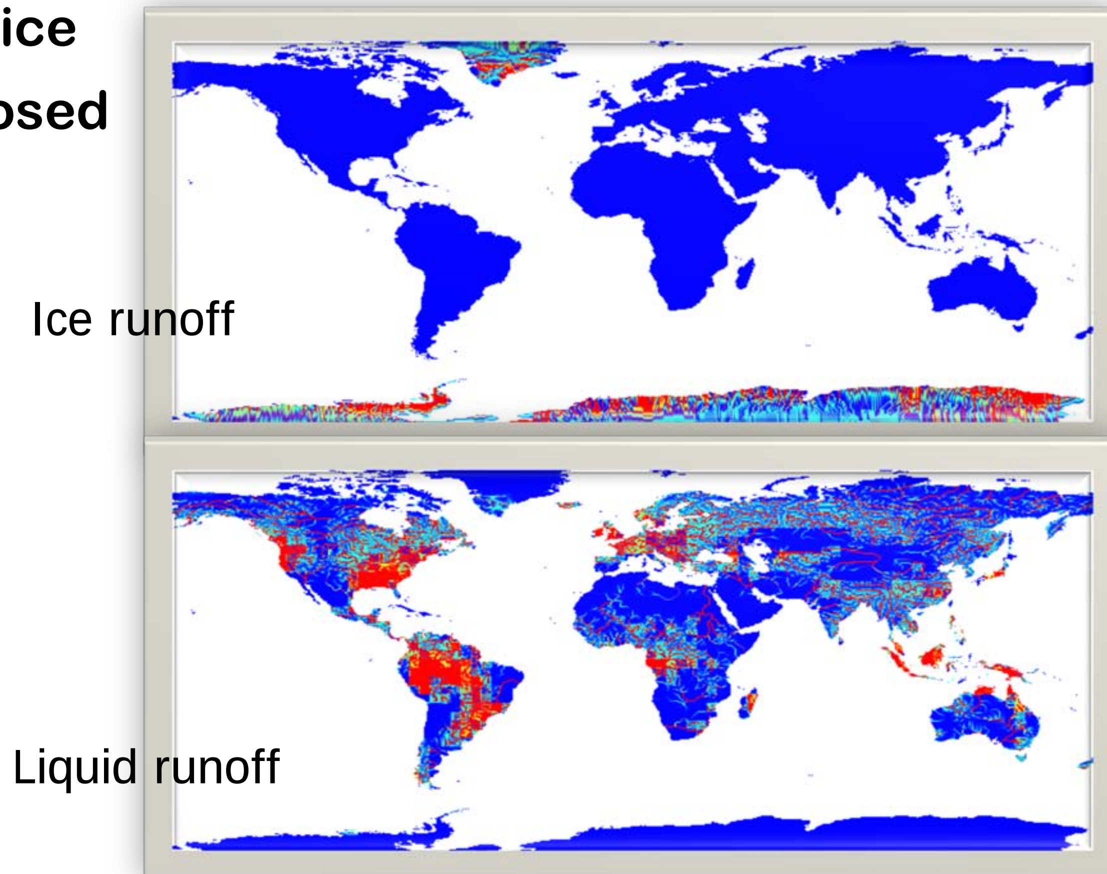
Global Partitioning of Evapotranspiration



CLM3.5 → CLM4

– Ice stream in River Transport Model

- **For snow capped regions send excess water to ice stream (poor man's ice sheet calving)**
- **Reduces CCSM energy imbalance by ~0.15-0.2 W/m^2**
- **Unrealistic high sea-ice thickness in semi-closed bays**

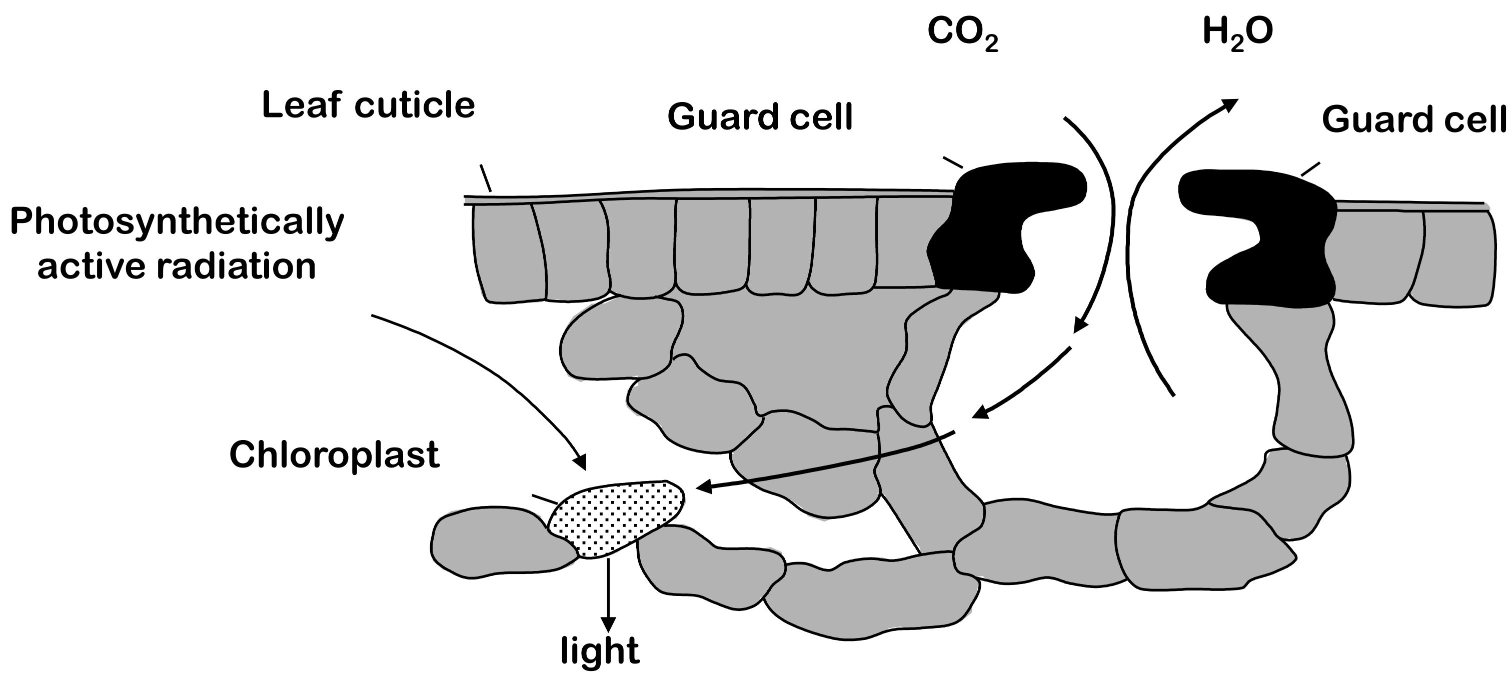


Photosynthesis model

Plant physiological controls on evapotranspiration

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

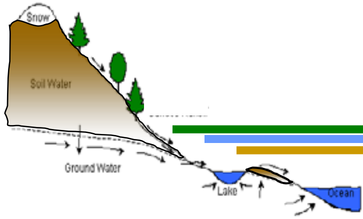
Stomatal Gas Exchange



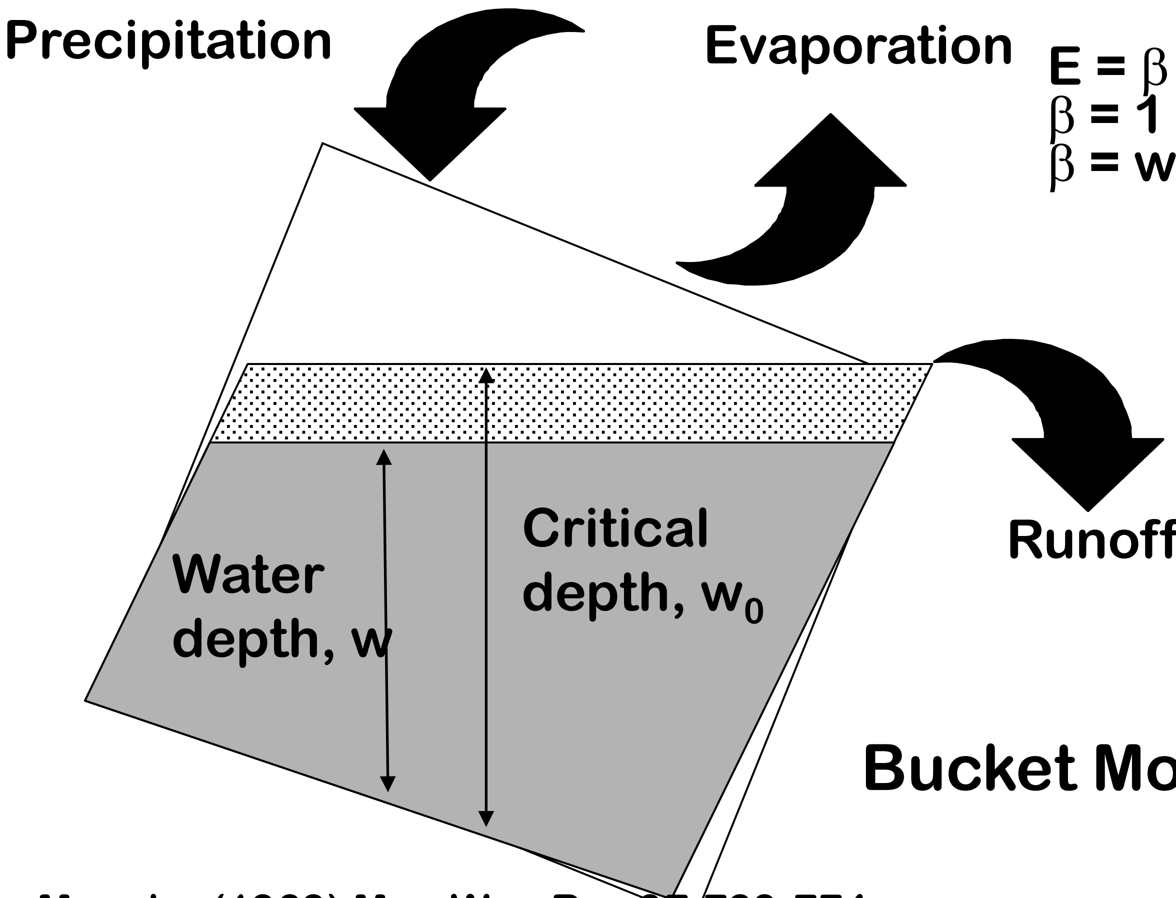
$$CO_2 + 2\,H_2O \rightarrow CH_2O + O_2 + H_2O$$

Bonan (1995) JGR 100:2817-2831
Denning et al. (1995) Nature 376:240-242
Denning et al. (1996) Tellus 48B:521-542, 543-567
Cox (1999)

Figure courtesy G. Bonan



Land models have come a long way
1st Generation: Bucket Model

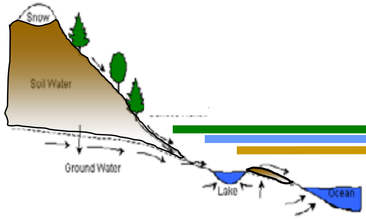


$E = \beta E_p$
$\beta = 1 \quad$ for $w \geq w_0$
$\beta = w/w_0$ for $w < w_0$

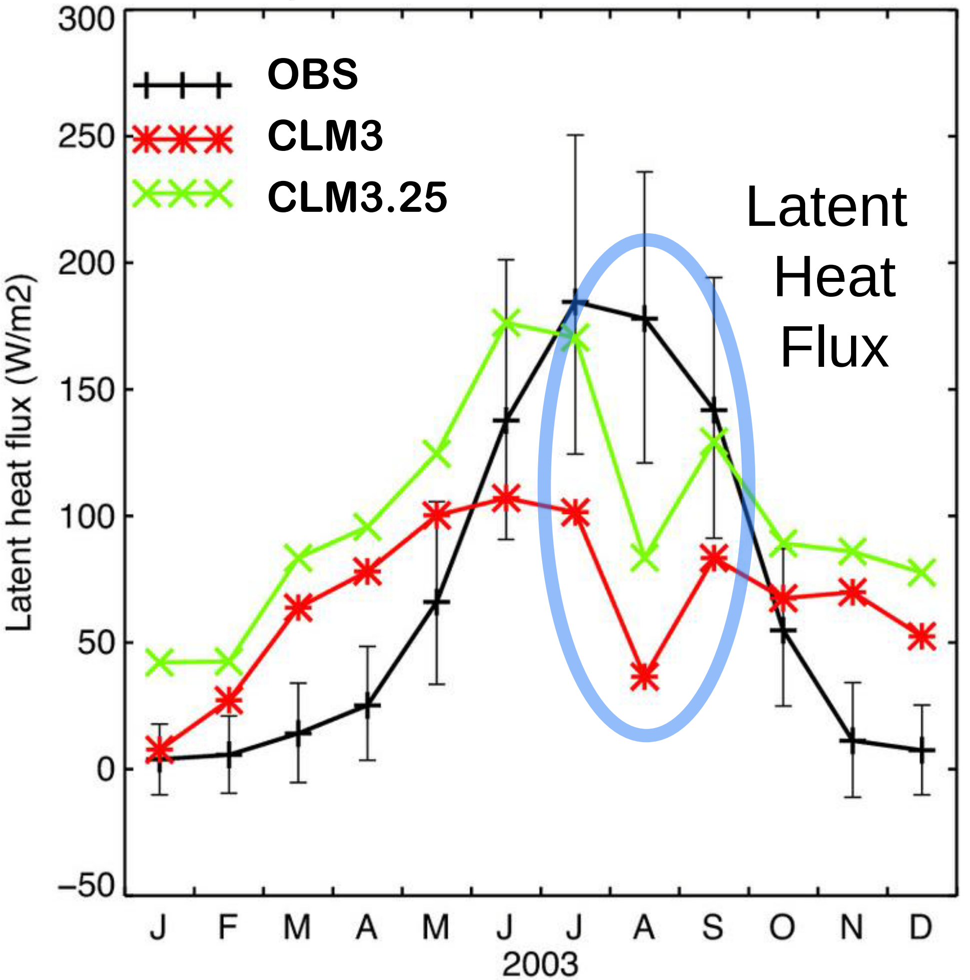
Bucket Model

Manabe (1969) Mon Wea Rev 97:739-774
Williamson et al. (1987) NCAR/TN-285+STR

Figure courtesy G. Bonan



Morgan Monroe State Forest tower site



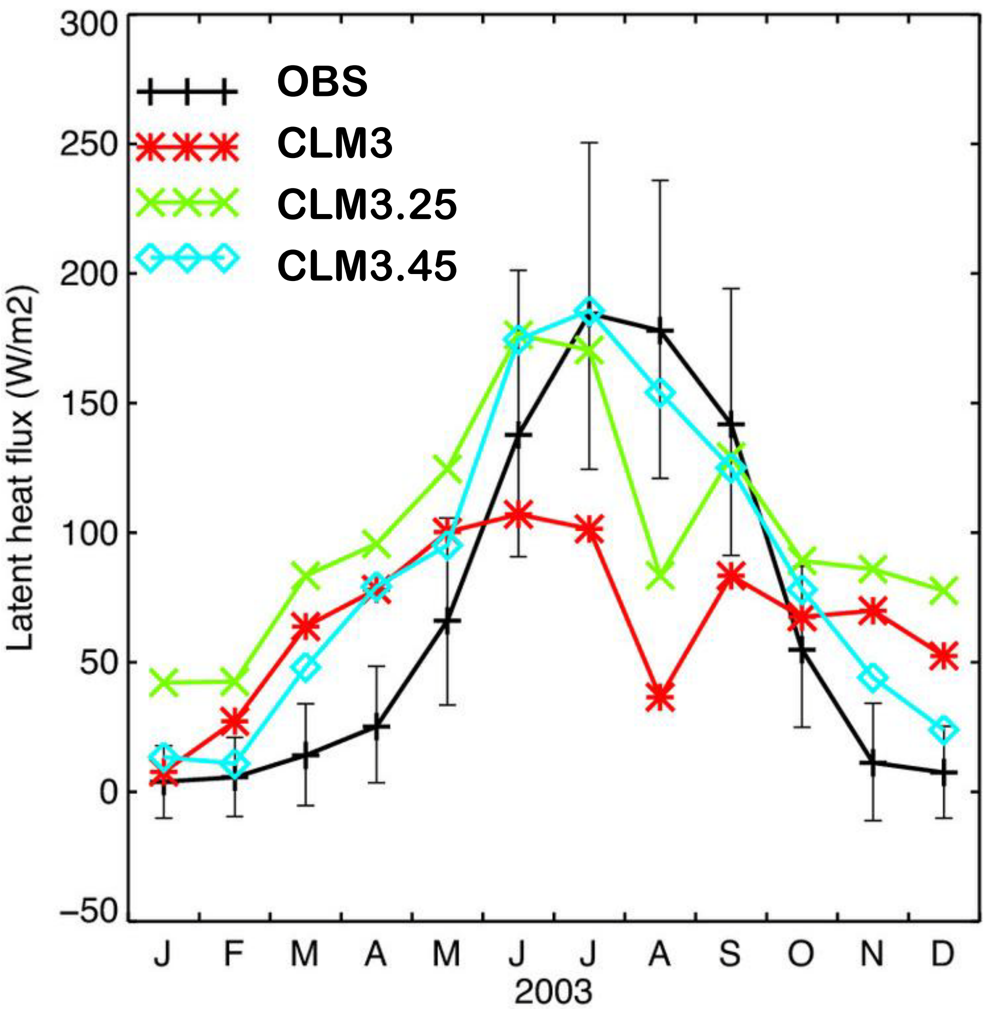
<u>Reduced canopy interception</u>

Permits more water to enter soil

<u>Groundwater/aquifer model</u>

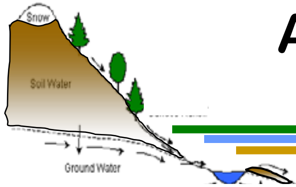
Stores/releases moisture on seasonal-decadal timescales

Morgan Monroe State Forest tower site



Soil evaporation resistance decreases LH in spring, more water available in summer for transpiration

Stöckli et al. , JGR-BGC (2008)



Another way of putting it is that at each timestep the land scheme solves …

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

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

    $L^{\uparrow}$, $L^{\downarrow}$ are up(down)welling longwave radiation,

    λ is latent heat of vaporization, E is evaporation,

    H is sensible heat flux, and G is ground heat flux

- Surface water balance
  - $P = E_S + E_T + E_C + R_{Surf} + R_{Sub\text{-}Surf} + \Delta SM / \Delta t$

    P is rainfall,

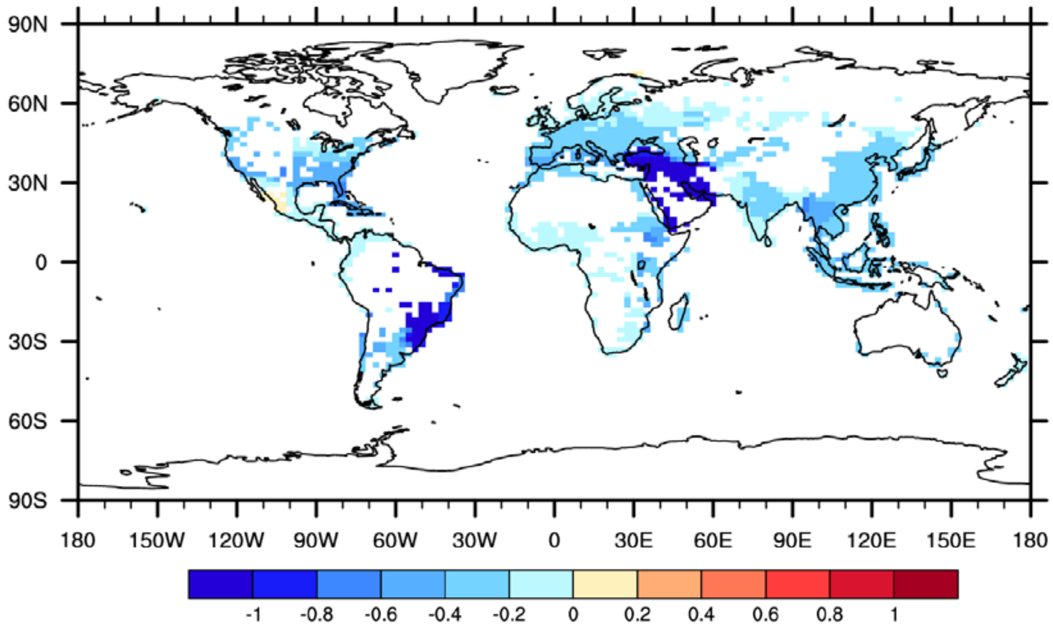
    E_S is soil evaporation, E_T is transpiration, E_C is canopy evaporation,

    R_{Surf} is surface runoff, $R_{Sub\text{-}Surf}$ is sub-surface runoff, and

    $\Delta SM / \Delta t$ is the change in soil moisture over a timestep

Mitigating the Urban Heat Island (UHI) with White Roofs

Reduction in the UHI simulated by Community Land Model Urban (CLMU) (°C)



- **Increasing global roof albedo to 0.9 in CLMU reduces annual UHI by 1/3 on average.**
- **Effectiveness of white roofs as a UHI mitigation technique varies according to urban design properties, climate, and interactions with space heating.**

Oleson, K.W., G.B. Bonan, and J. Feddema, 2010, *Geophys. Res. Lett.*