The Community Land Model - Biogeophysics

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Thanks to Dave Lawrence (co-chair LMWG)

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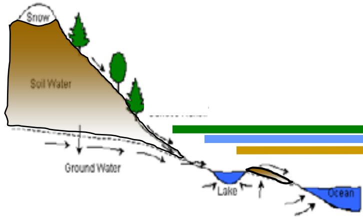


Outline

- Why is the land surface an important component of the climate system?
- Role of a land surface model in an Earth System Model
- Main features of CLM
  - Structural aspects (surface/input datasets)
  - Component submodels
    - Biogeophysics (SP)
    - Biogeochemistry (Carbon-Nitrogen(CN), Dynamic Vegetation (CNDV), Biogenic Volatile Organic Compounds (BVOCs), Dust)

How do we test, evaluate and improve CLM?

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

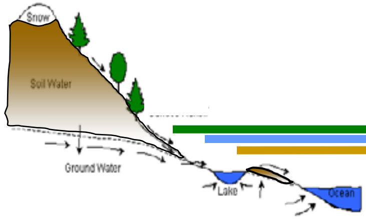
The land is a critical interface

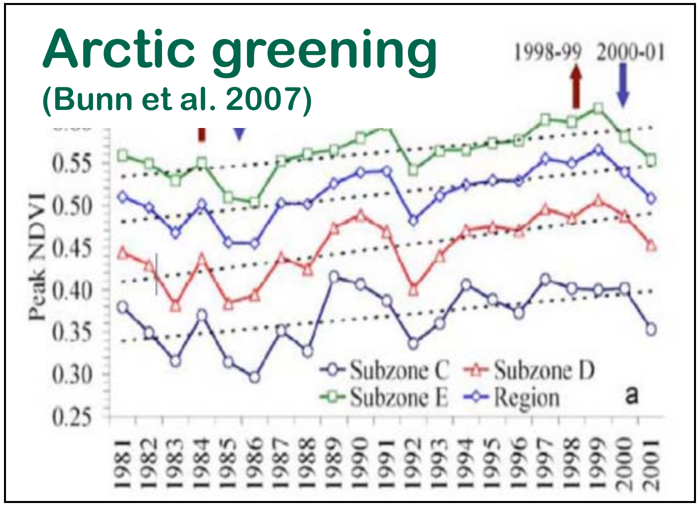
through which climate, and climate change impacts humans and ecosystems

and

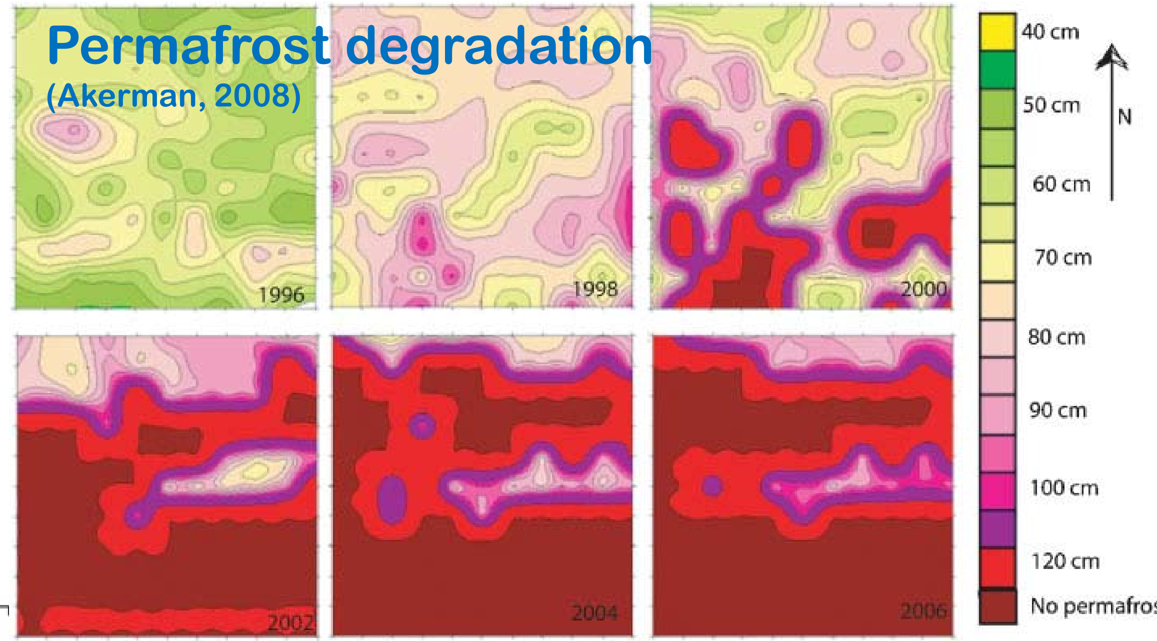
through which humans and ecosystems can effect global environmental and climate change

Observed terrestrial change

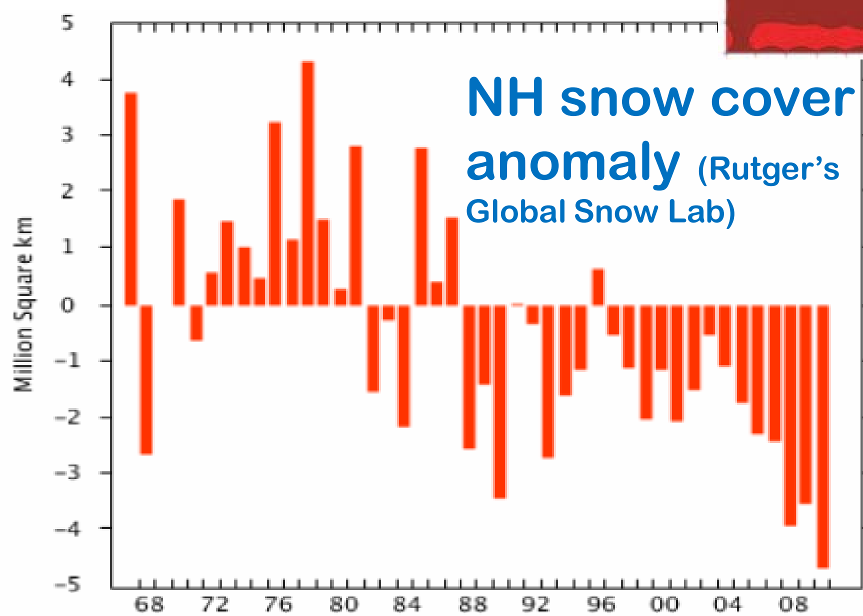




Arctic greening (Bunn et al. 2007)



Permafrost degradation (Akerman, 2008)

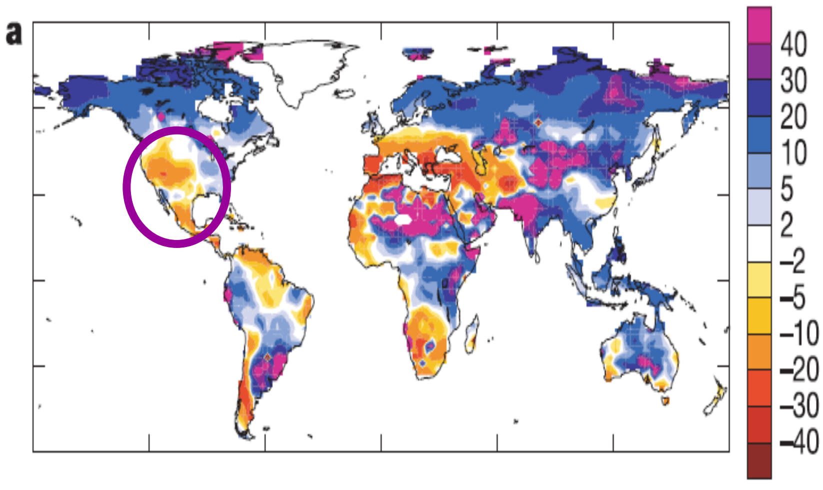


NH snow cover anomaly (Rutger's Global Snow Lab)

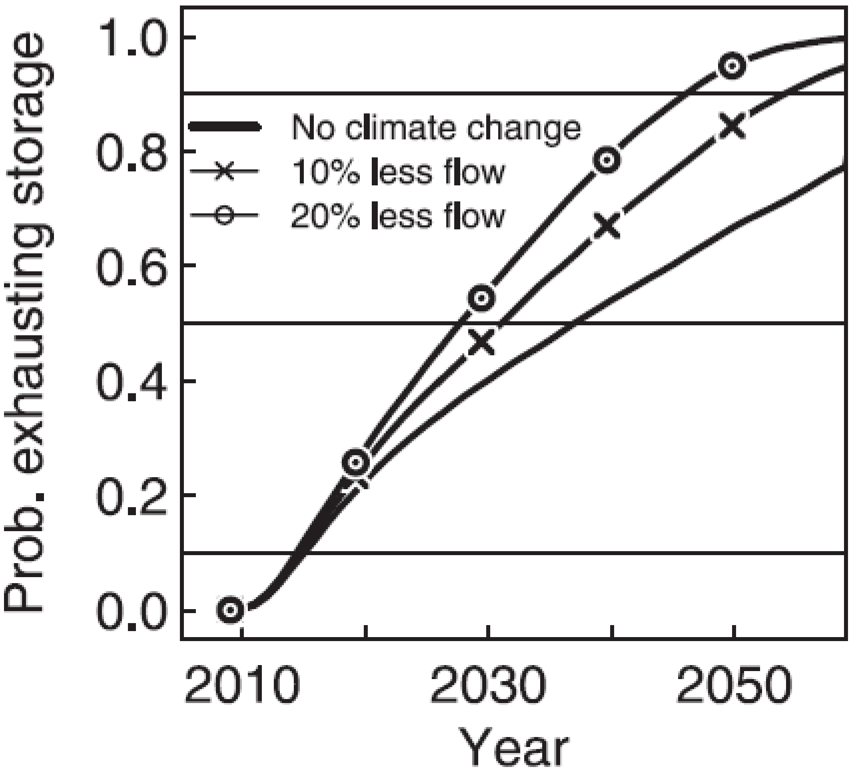
Deforestation

Water resources: When will Lake Mead go dry?

% Change in Runoff by 2050 (A1B)



Milly et al., 2005



Barnett and Pierce 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?

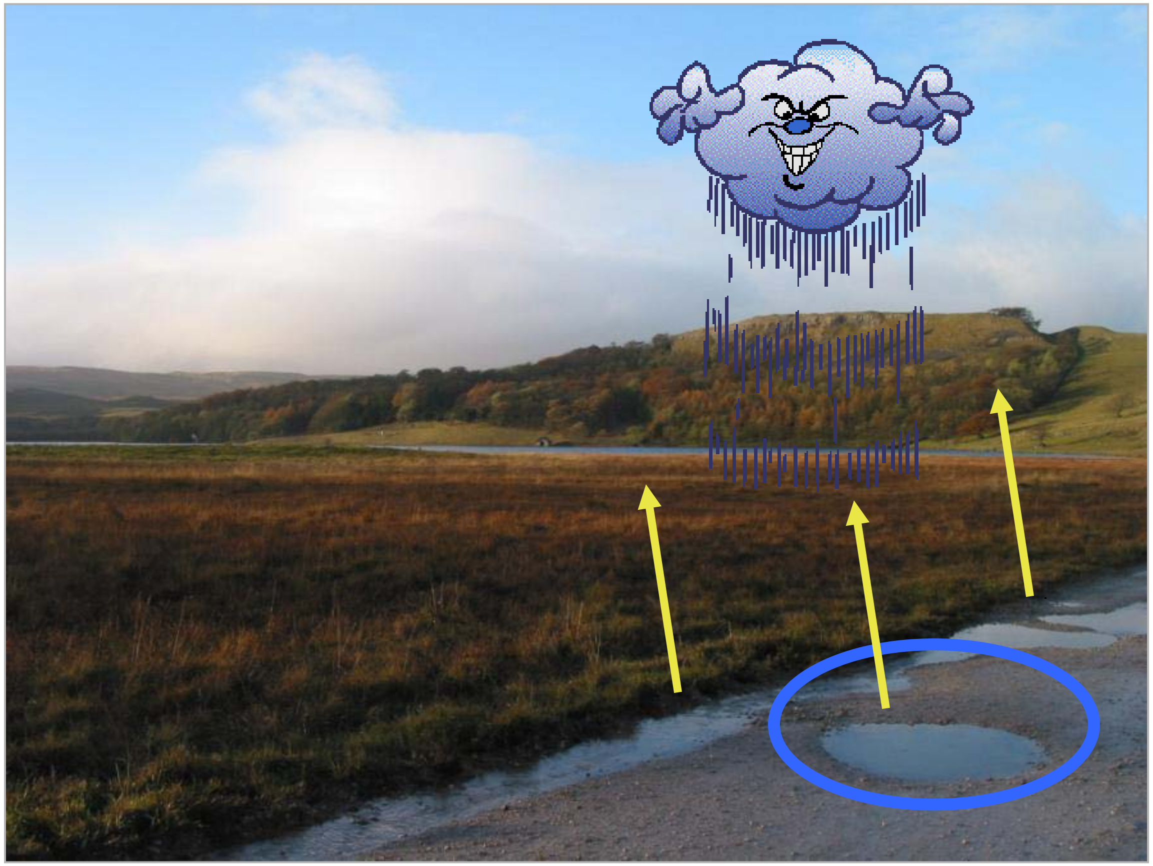
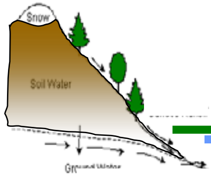
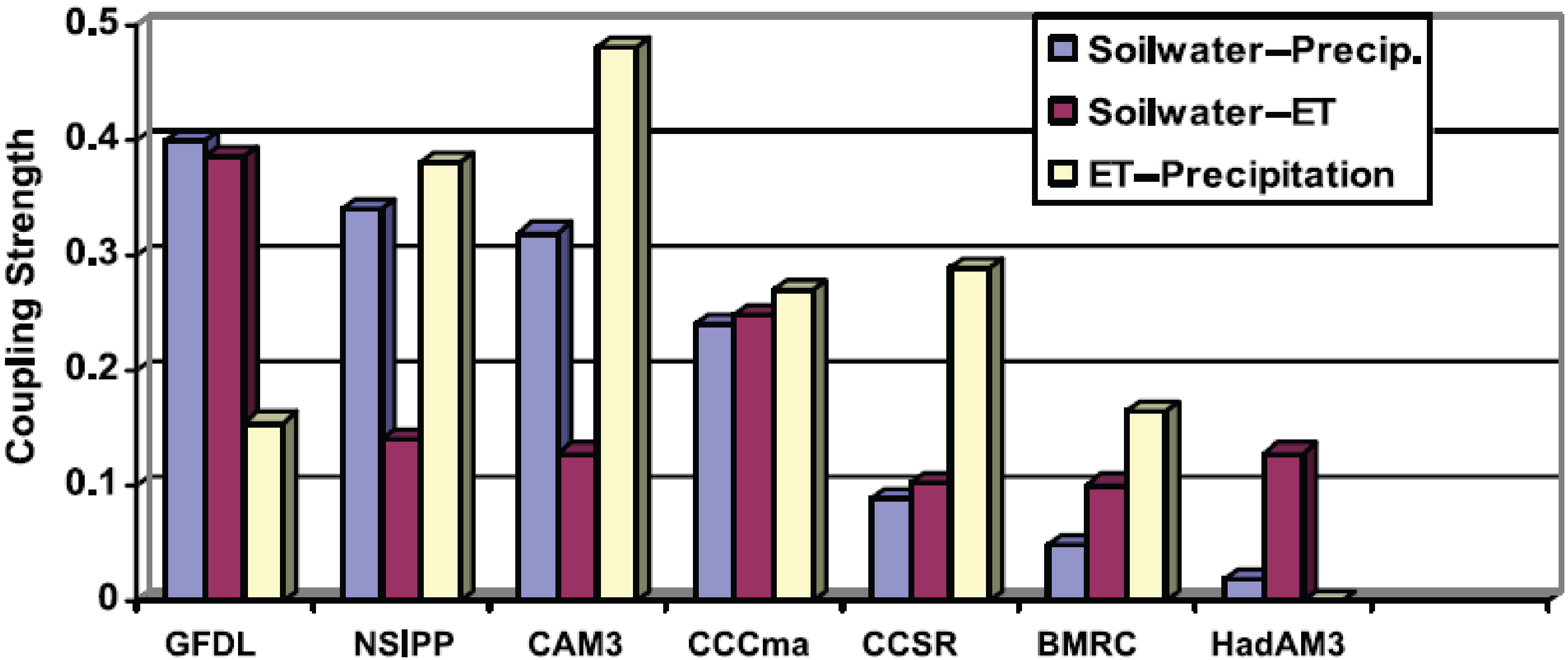


Photo by D. Fritz



Land-atmosphere interactions

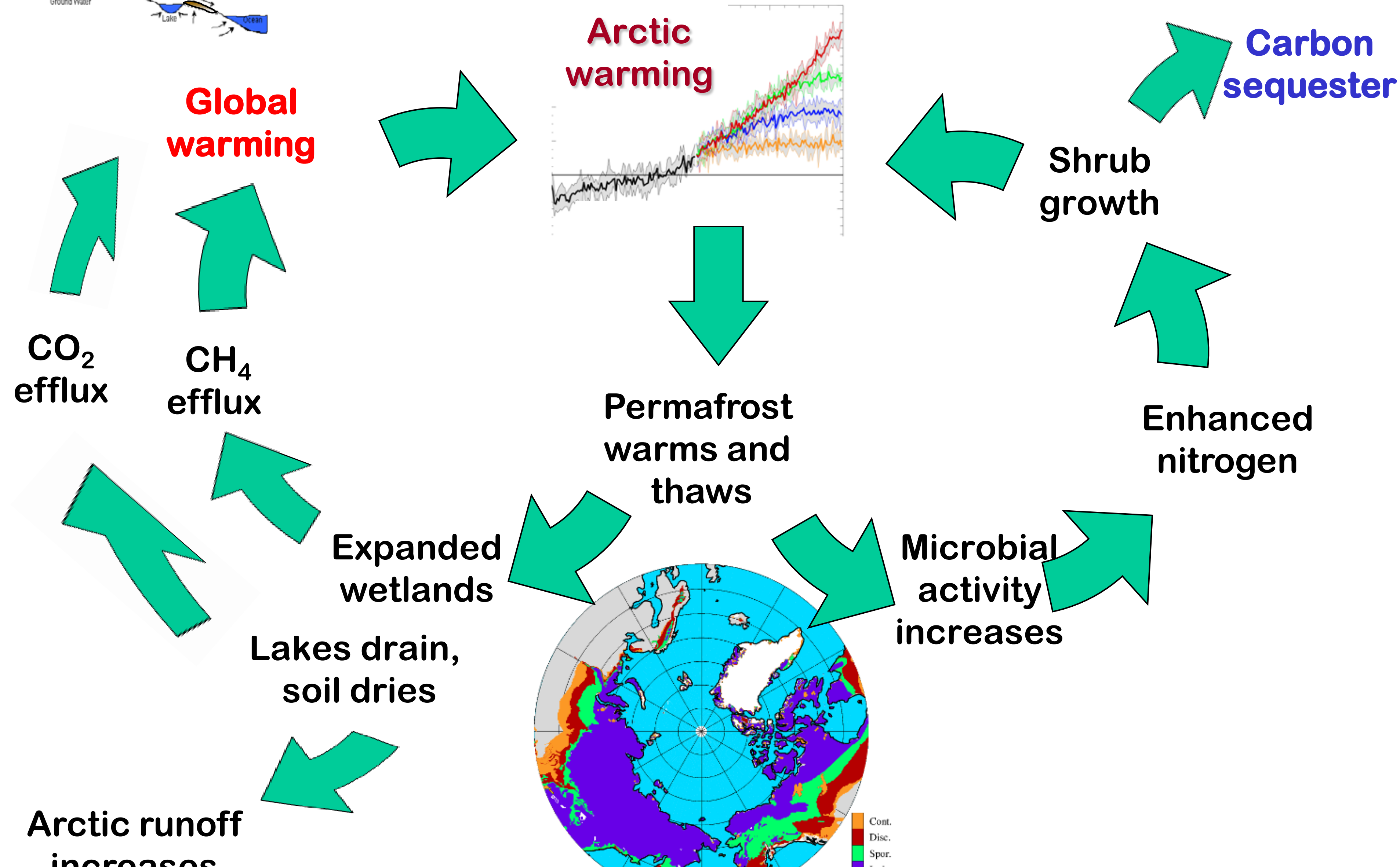
GLACE: To what extent does soil moisture influence the overlying atmosphere and the generation of precipitation?



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

Koster et al., 2004; IPCC

Arctic climate-change feedbacks



Adapted from McGuire et al., 2006

The role of the land model in an Earth System Model

- **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)
- **states** of land surface (e.g., soil moisture, soil temperature, canopy temperature, snow water equivalent, C and N stocks in veg and soil)
- **characteristics** of land surface (e.g., soil texture, surface roughness, albedo, emissivity, vegetation type, cover extent, leaf area index, and seasonality)

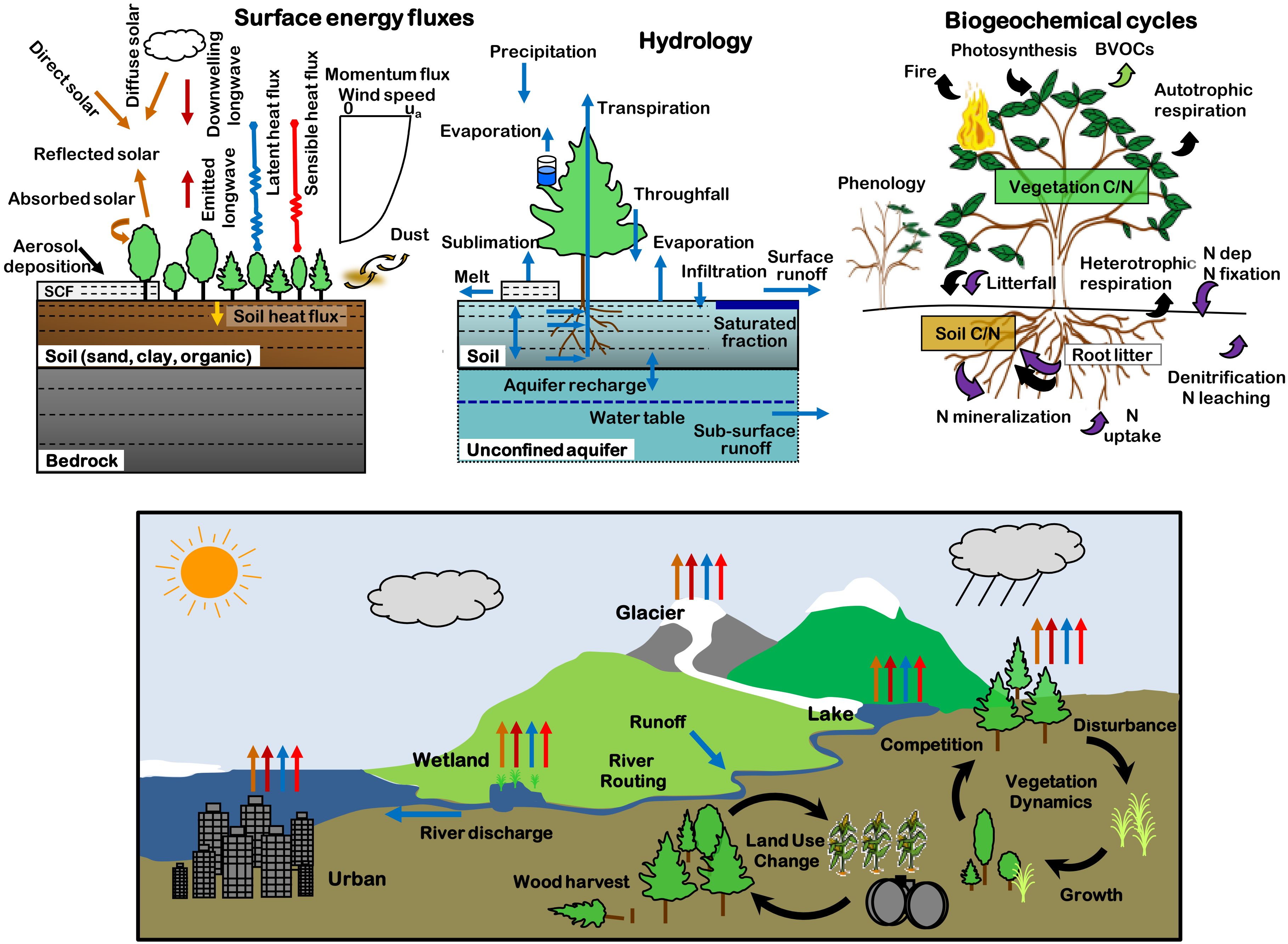
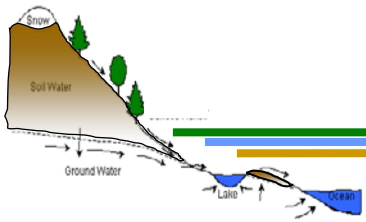
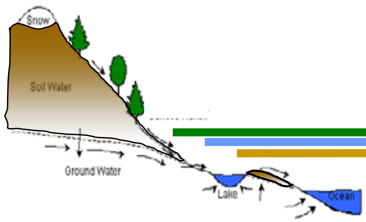


Figure 1: Lawrence et al., Journal Advances Modeling Earth Systems, 2011

The role of CLM in CESM: Land to Atmosphere

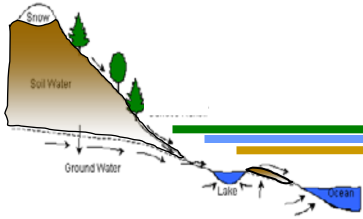


[1]Latent heat flux	$\lambda_{vap}E_v + \lambda E_g$	W m^{-2}
Sensible heat flux	$H_v + H_g$	W m^{-2}
Water vapor flux	$E_v + E_g$	mm s^{-1}
Zonal momentum flux	τ_x	kg m^{-1} s^{-2}
Meridional momentum flux	τ_y	kg m^{-1} s^{-2}
Emitted longwave radiation	$L\uparrow$	W m^{-2}
Direct beam visible albedo	$I\uparrow_{vis}^{\mu}$	-
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}



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**
  - $P = E_S + E_T + E_C + R_{surf} + R_{Sub\text{-}Surf} + (\Delta W_{soi} + \Delta W_{sno} + \Delta W_{can} + \Delta W_a) / \Delta t$

    P is rainfall/snowfall,

    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

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

Main Features of the Community Land Model

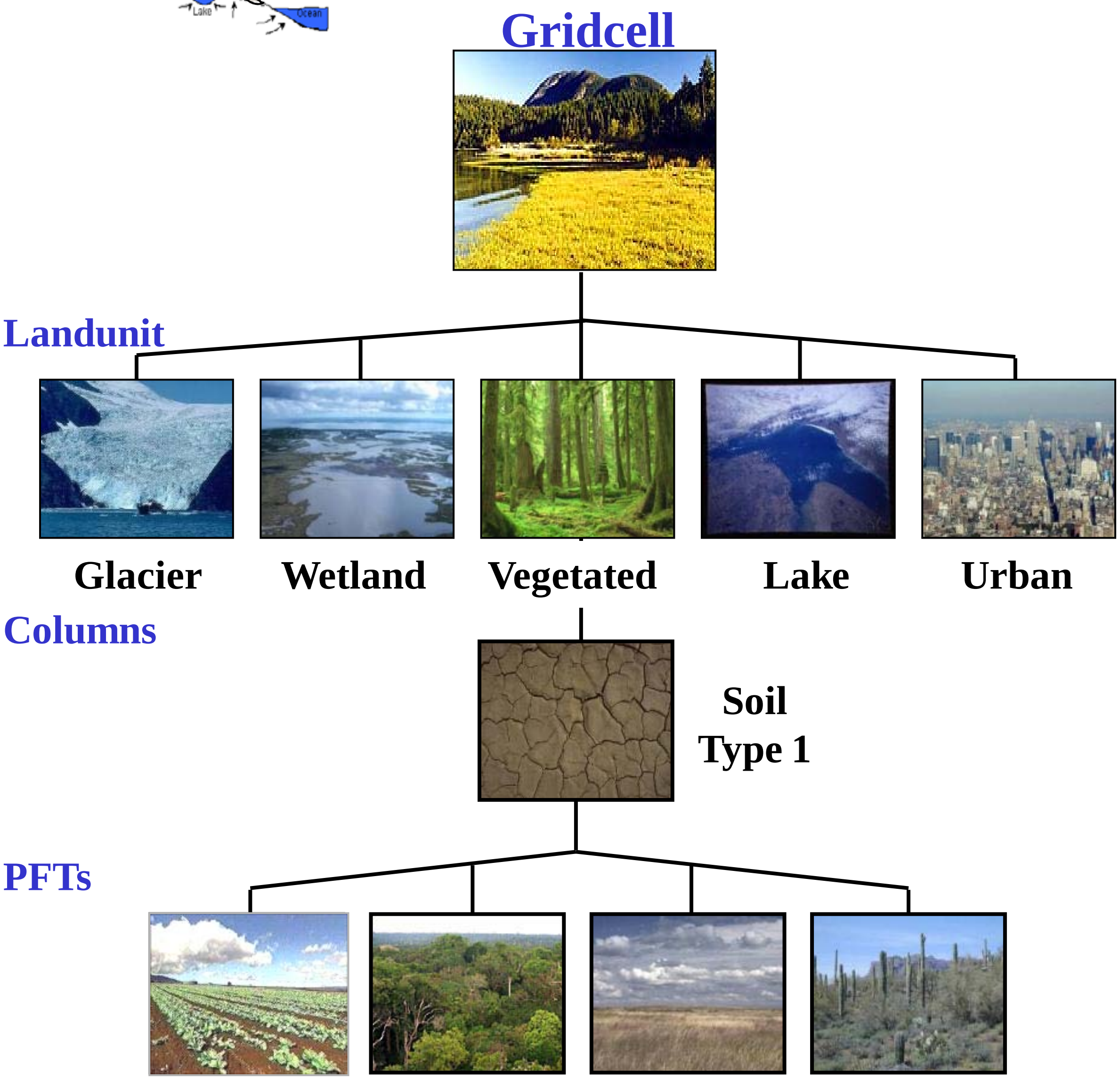
- **Structural aspects (surface and input datasets)**

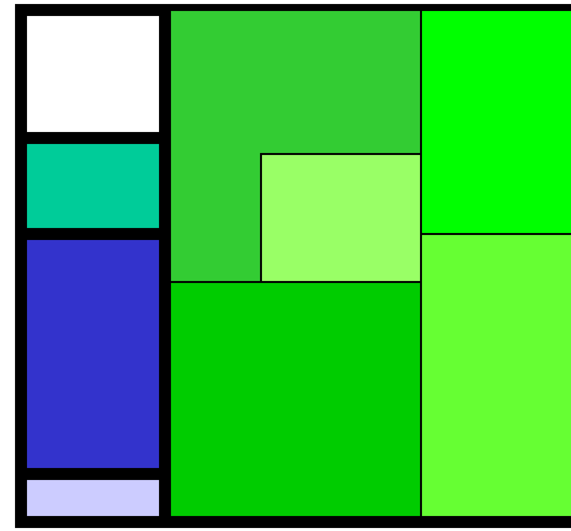
- **Component submodels**

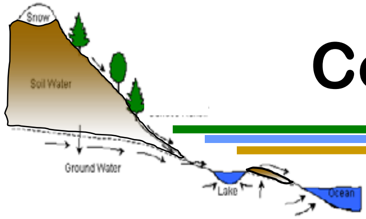
Main Features of the Community Land Model

- **Structural aspects (surface and input datasets)**
  - Heterogeneity of landscape, tiling (vegetated, urban, lake, wetland, glacier)
  - Plant Functional Types and associated properties (optical, morphological, photosynthetic)
  - Land cover change (changes in PFTs over time)
  - Soil texture (sand, silt, clay, organic matter) and color (albedo)
  - River routing
  - Aerosol (snow albedo) and nitrogen deposition (CN)

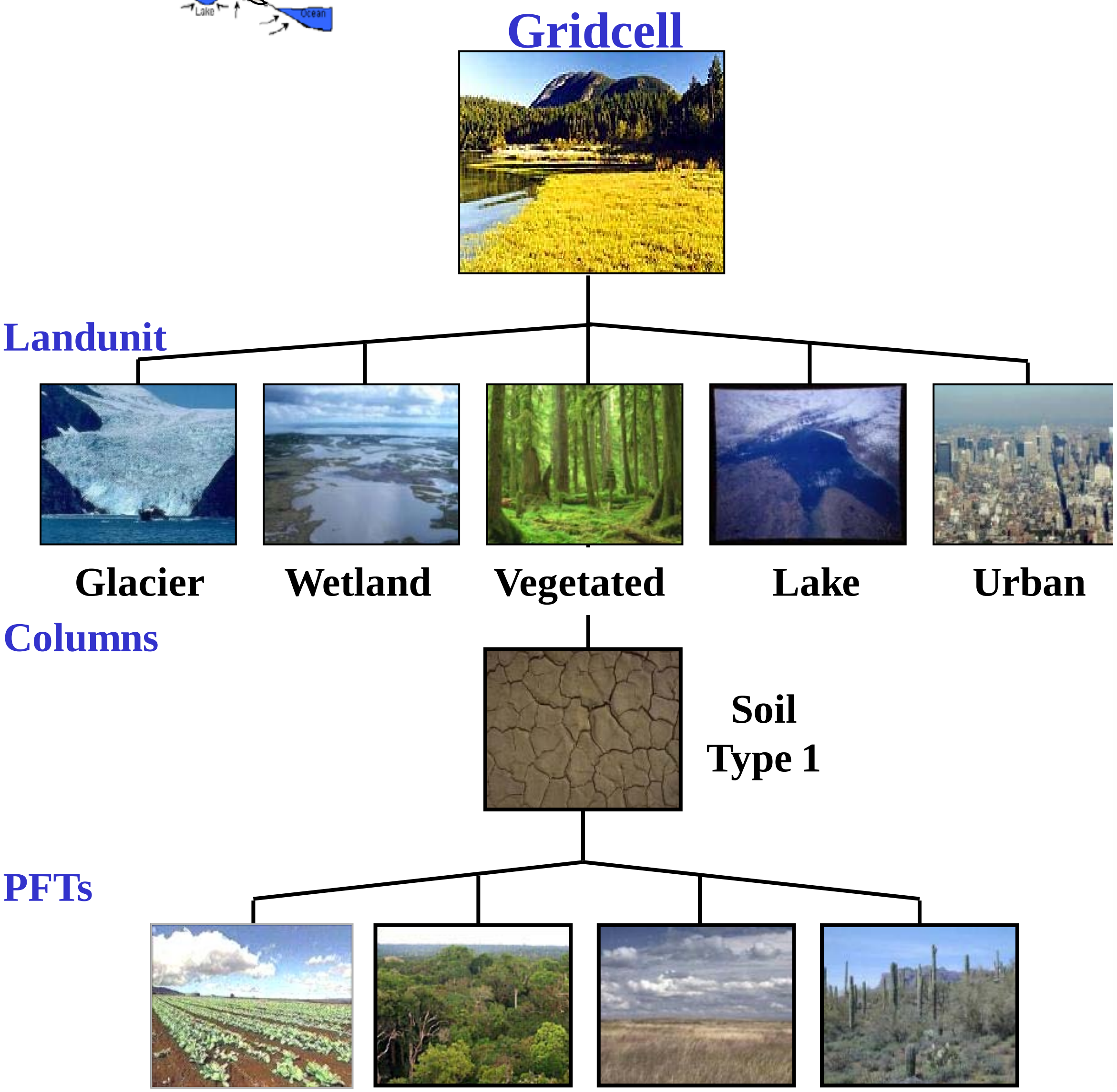
Community Land Model subgrid tiling structure







Community Land Model subgrid tiling structure



Plant Functional Types:

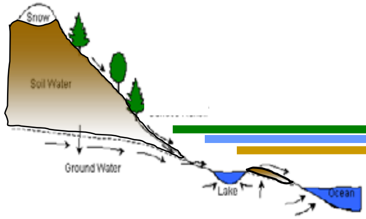
0. Bare

Tree:

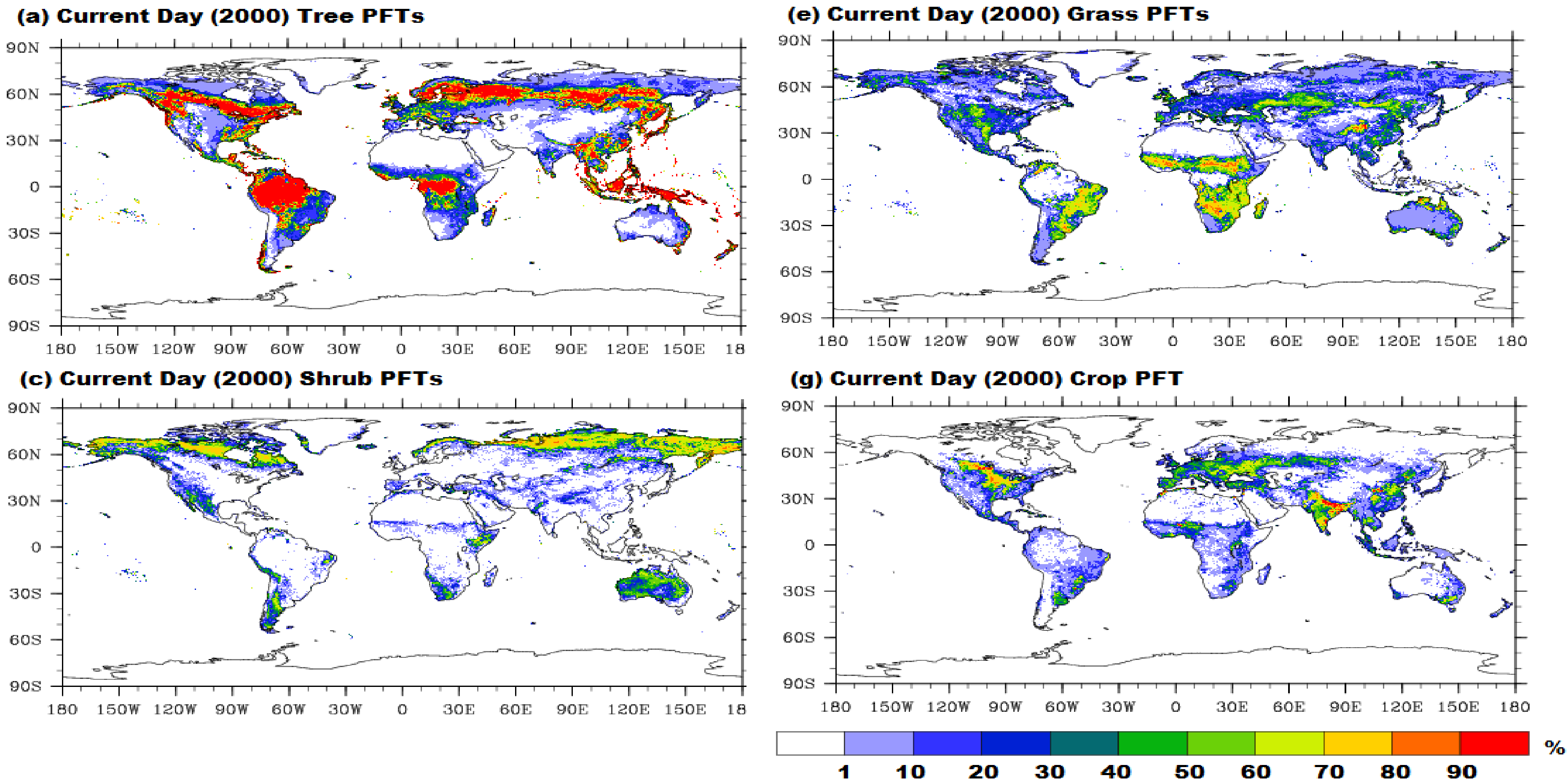
1. Needleleaf Evergreen, Temperate
2. Needleleaf Evergreen, Boreal
3. Needleleaf Deciduous, Boreal
4. Broadleaf Evergreen, Tropical
5. Broadleaf Evergreen, Temperate
6. Broadleaf Deciduous, Tropical
7. Broadleaf Deciduous, Temperate
8. Broadleaf Deciduous, Boreal

Herbaceous / Understorey:

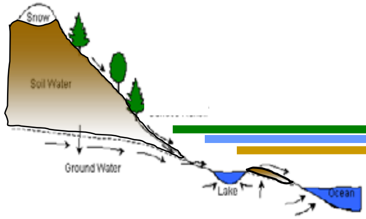
9. Broadleaf Evergreen Shrub, Temperate
10. Broadleaf Deciduous Shrub, Temperate
11. Broadleaf Deciduous Shrub, Boreal
12. C3 Arctic Grass
13. C3 non-Arctic Grass
14. C4 Grass
15. Crop



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



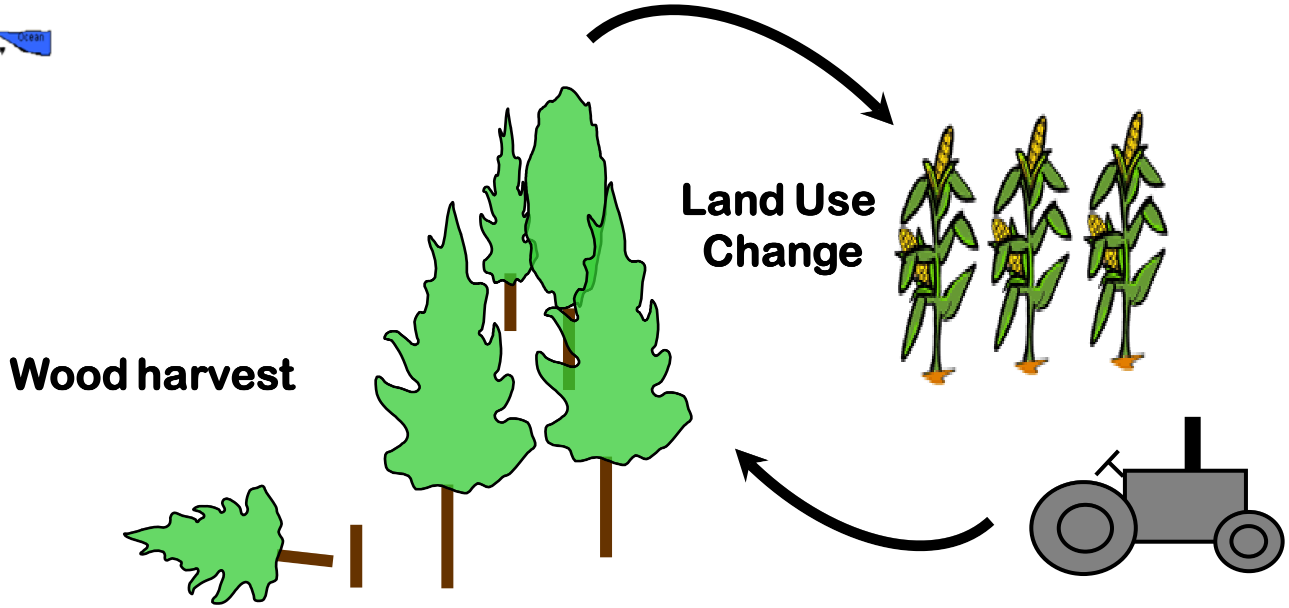
Lawrence and Chase, 2007

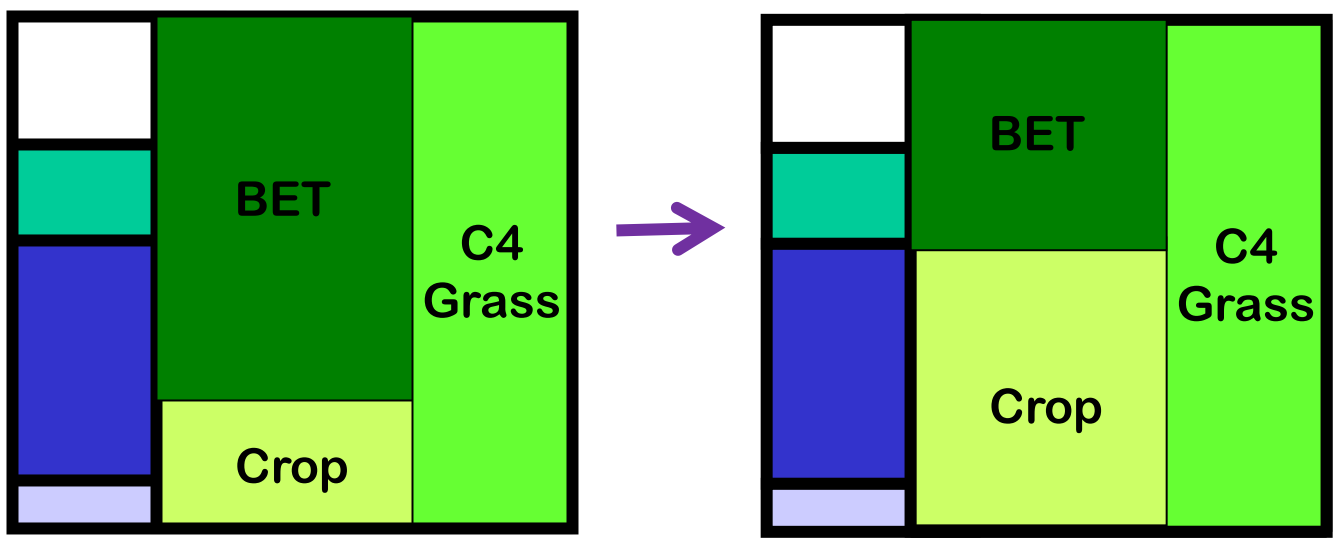


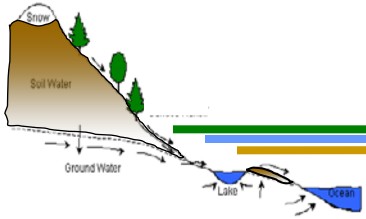
Plant Functional Type Parameters

- 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
  - Roughness length/displacement height
  - Canopy height
  - Root distribution
- Photosynthetic parameters:
  - specific leaf area (m^2 leaf area g^{-1} C)
  - m (slope of conductance-photosynthesis relationship)

Land cover / land use change (prescribed)



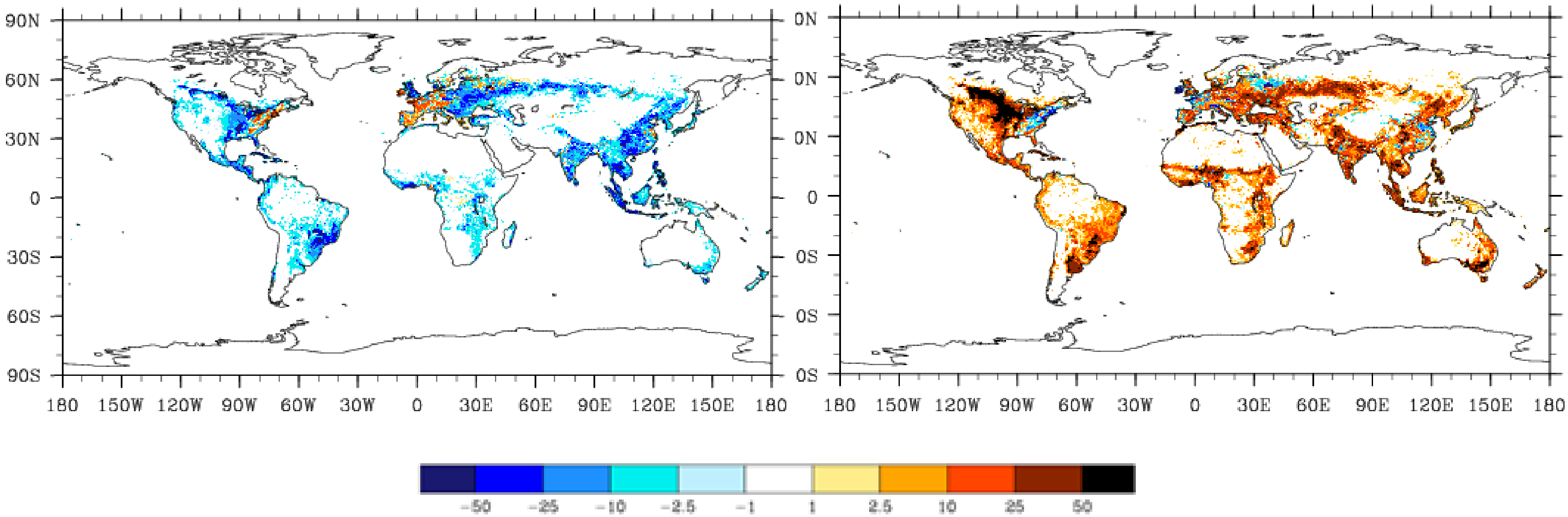




Land cover change (prescribed)

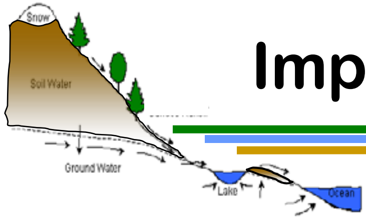
2005 – 1850

Trees | **Crops**



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

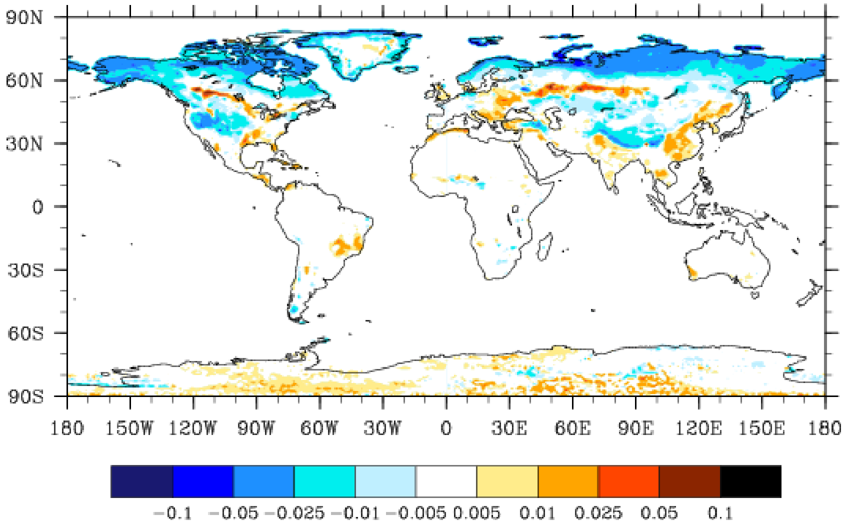
Lawrence, P et al. J. Climate, 2012



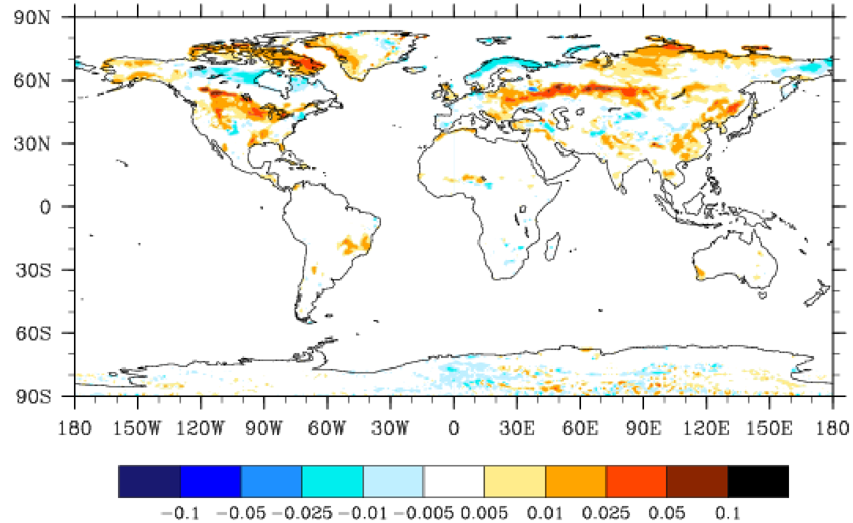
Impact of historical land cover change on climate

1976 to 2005 – 1850 to 1879

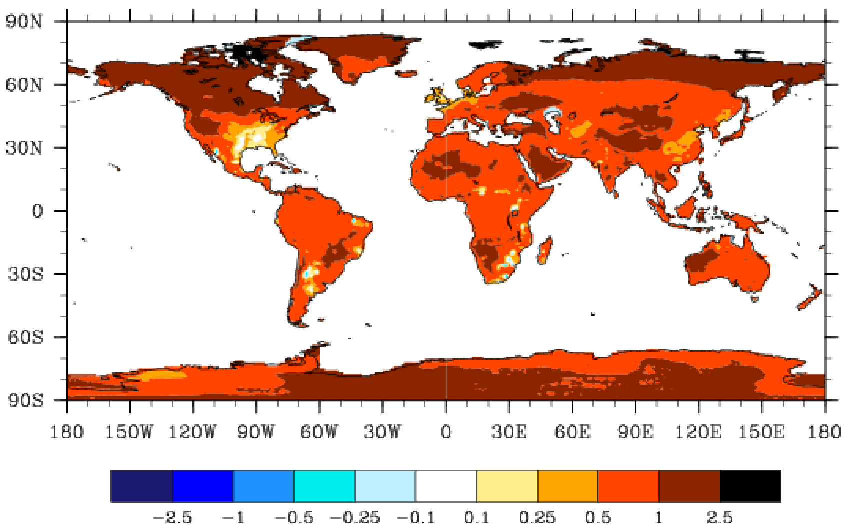
(a) Full Transient - Change in Albedo



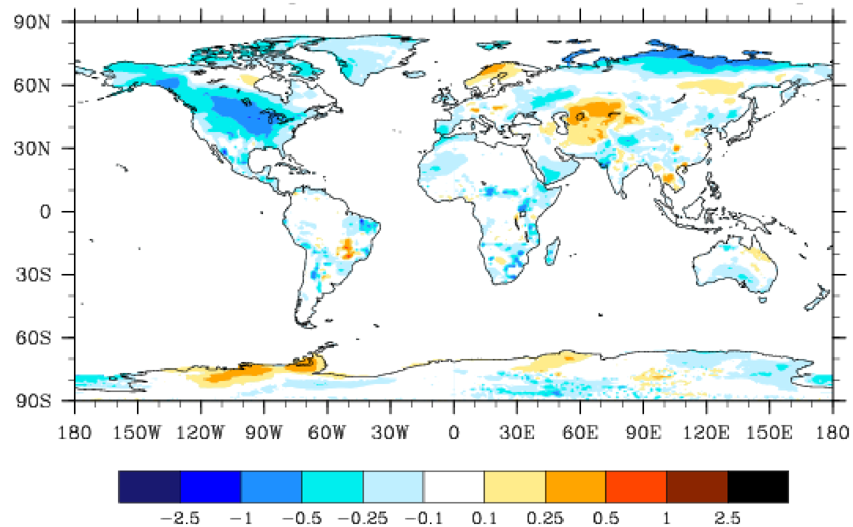
(b) Land Cover Change Only - Change in Albedo

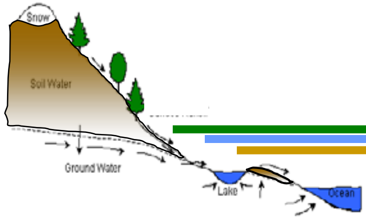


(c) Full Transient - Change in 2m Temperature Deg C



(d) Land Cover Change Only - Change in 2m Temp Deg C

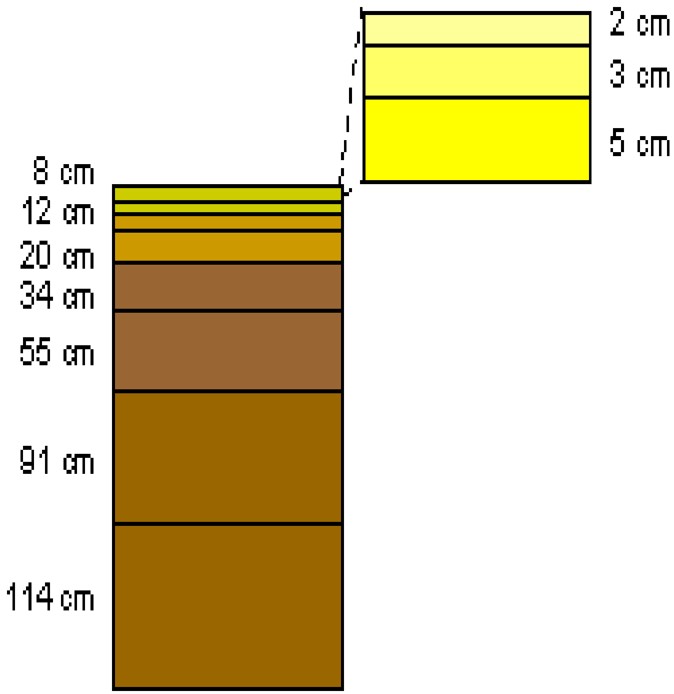




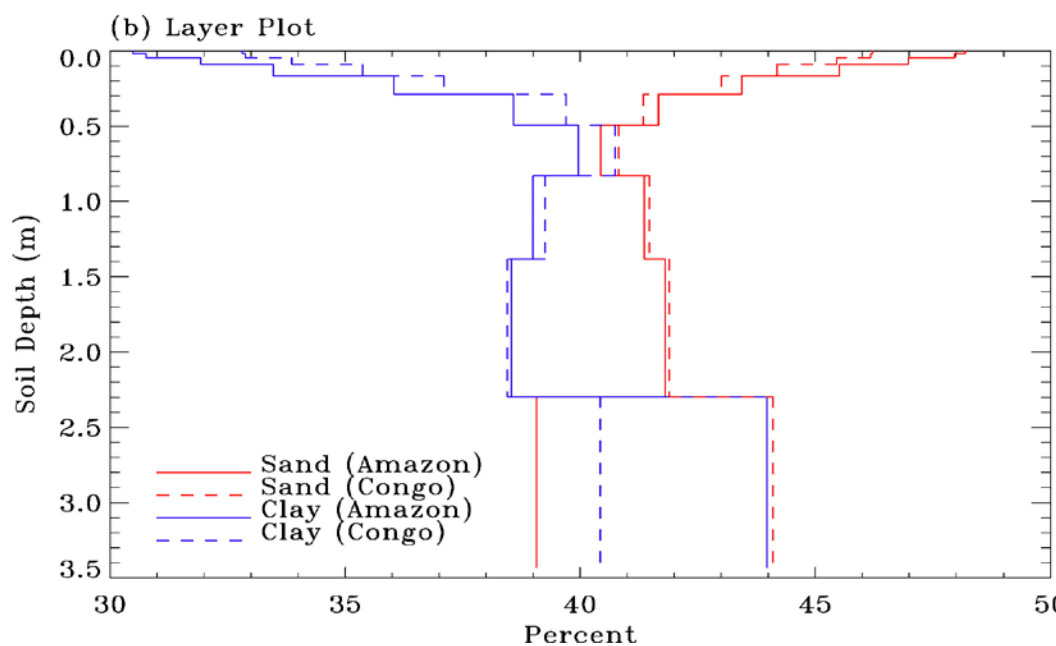
Soil Texture

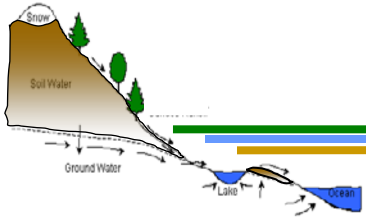
Soil parameters are derived from sand / clay percentage and soil organic matter content which is specified geographically and by soil level

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



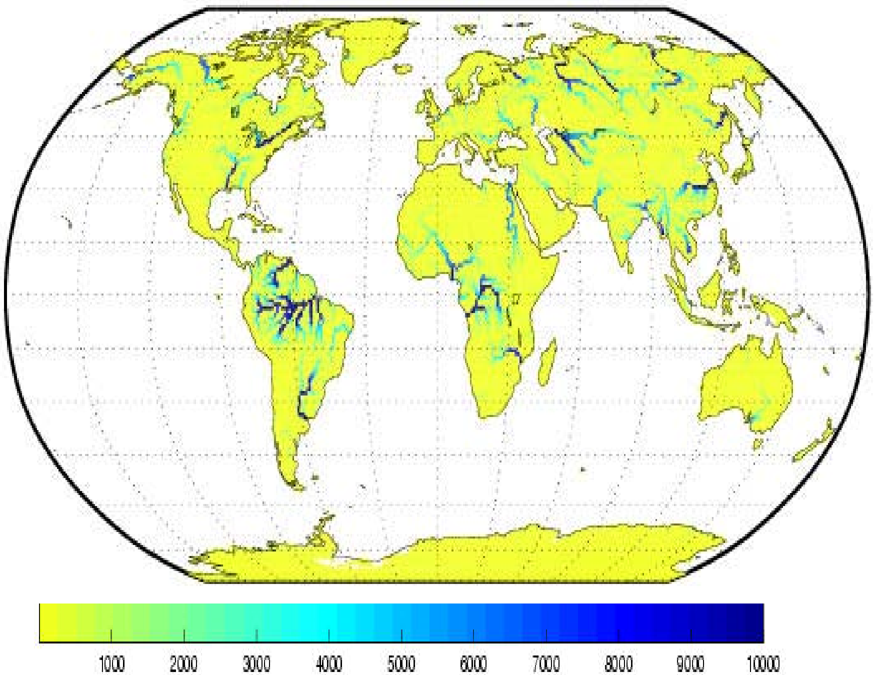
Soil profile
10 soil levels (~3.5m)
5 bedrock levels (~50m)

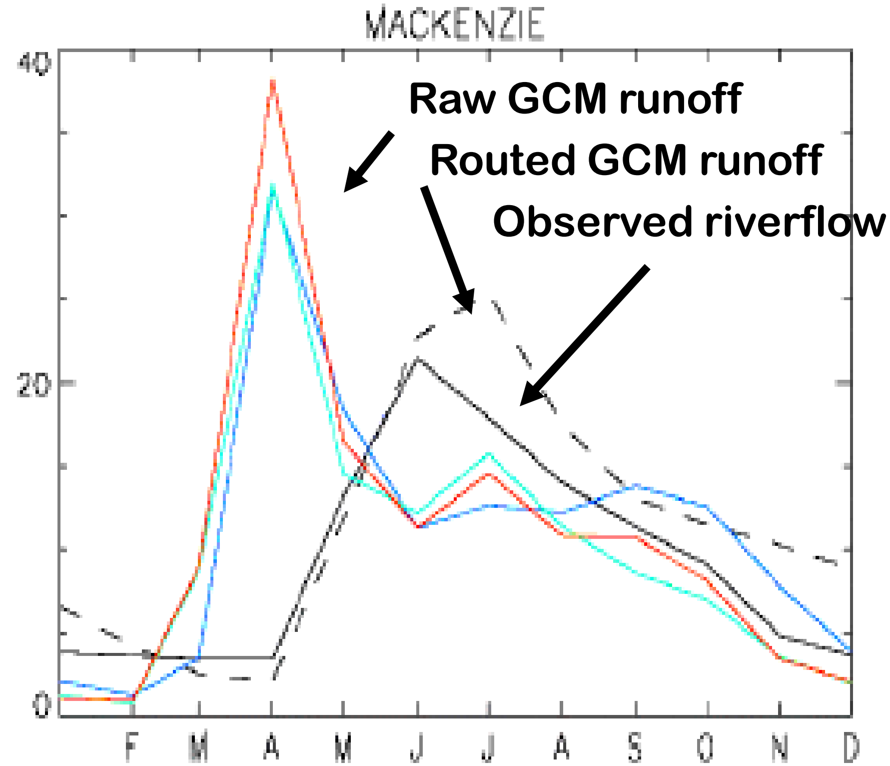




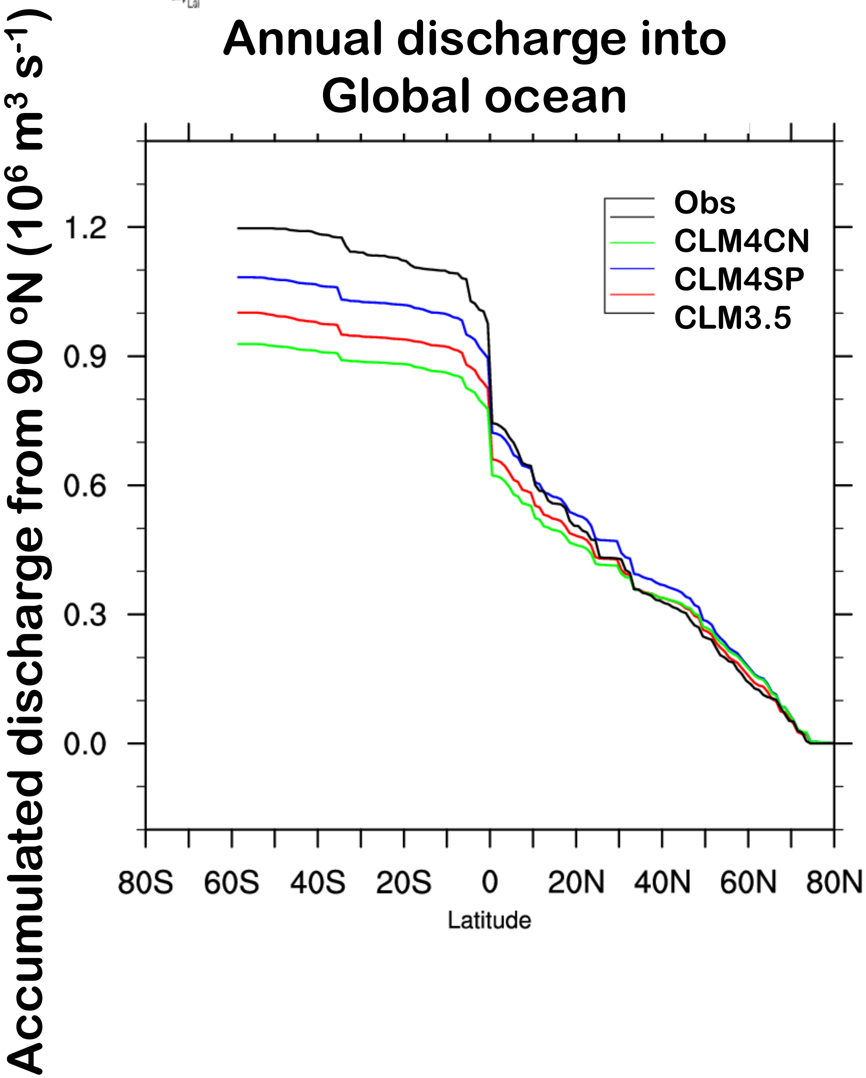
River Transport Model

20-yr average river flow ($m^3\ s^{-1}$)

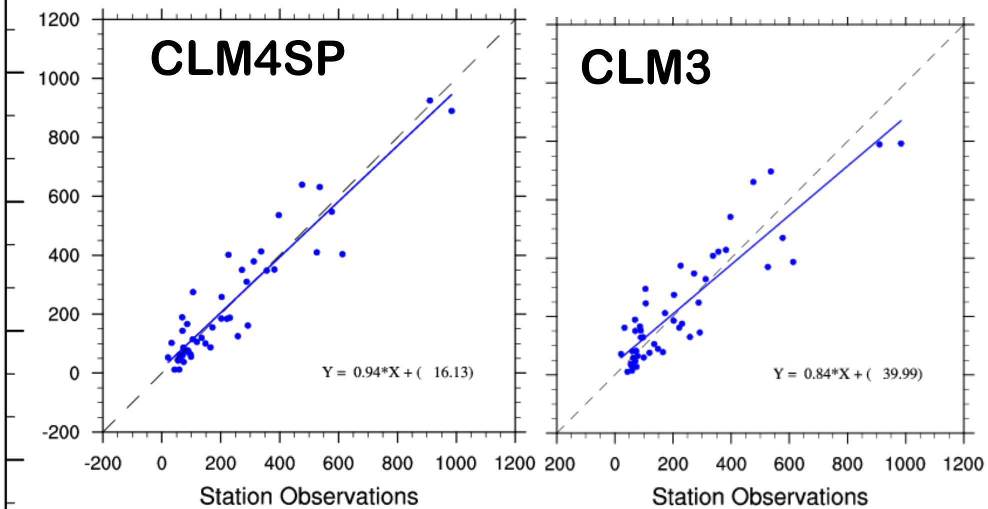




River Discharge



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

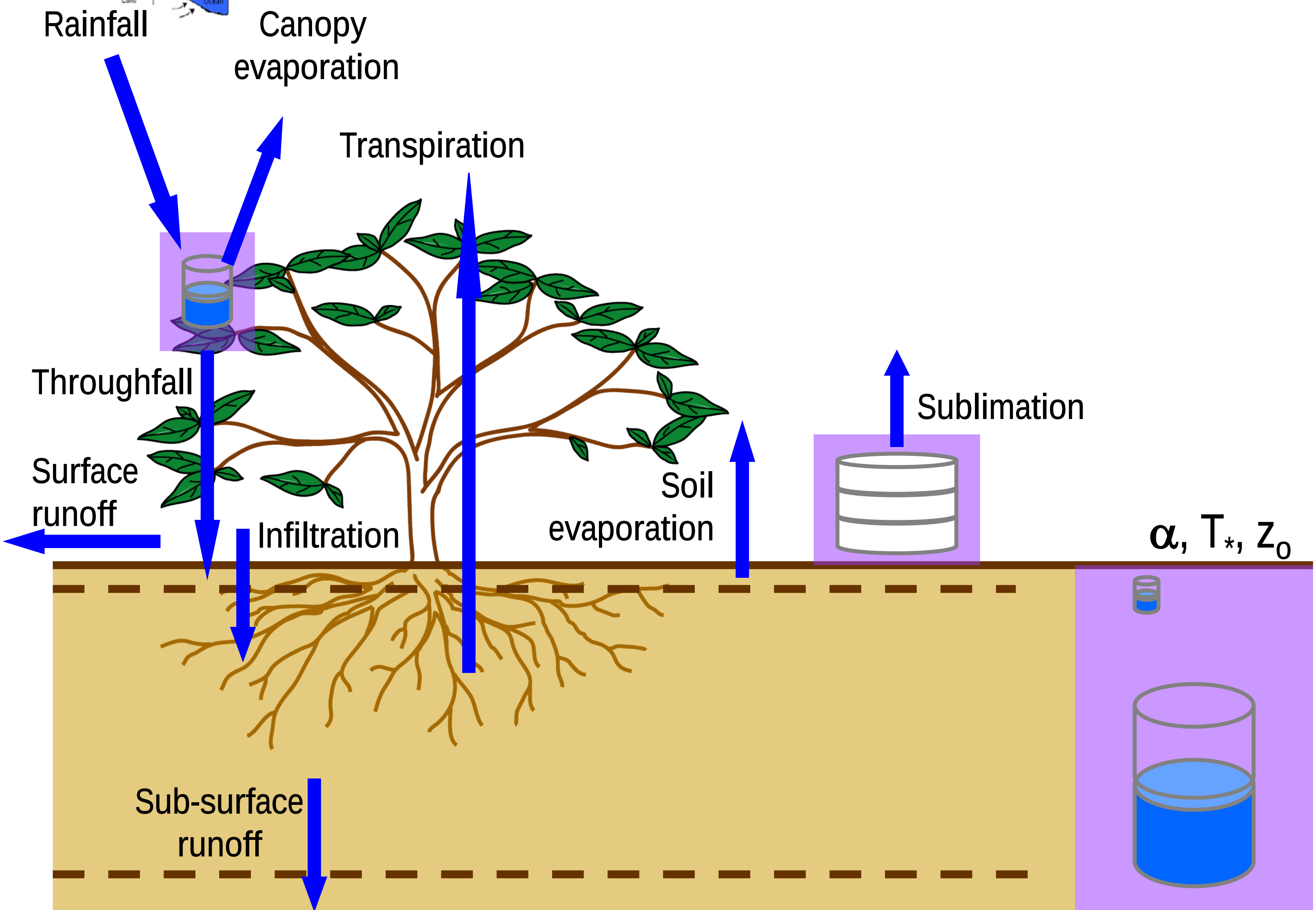


CLM3: r = 0.86
CLM3.5: r = 0.87
CLM4SP: r = 0.94
CLM4CN: r = 0.77

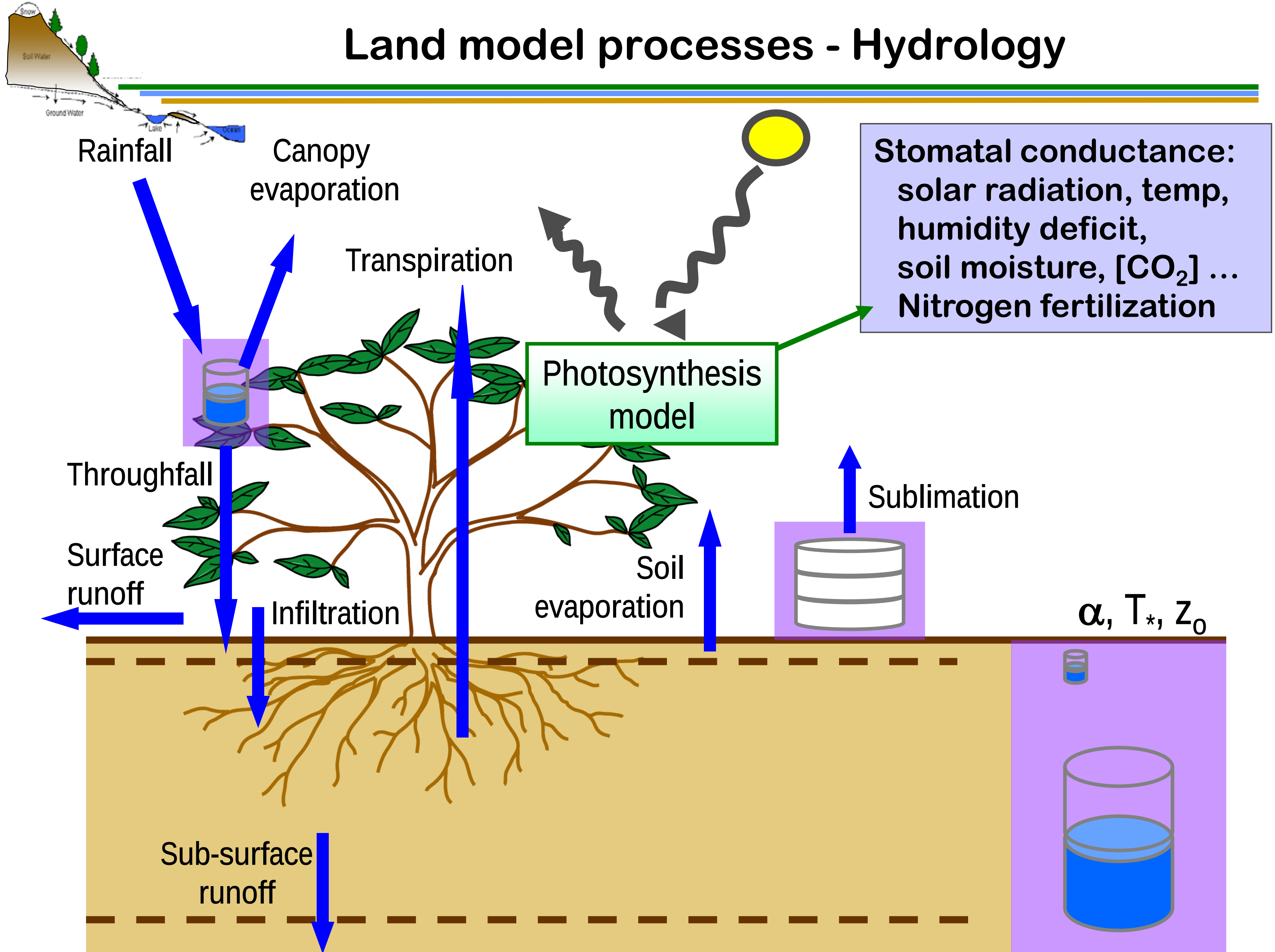
Main Features of the Community Land Model

- Component submodels
  - Vegetation/Soil
    - Hydrology (evapotranspiration, runoff, soil moisture, groundwater, river transport)
    - Snow
    - Soil thermodynamics
    - Surface albedo and radiative fluxes
  - Urban, Lake, Wetland, and Glacier
  - Biogeochemistry
    - Dust
    - Biogenic Volatile Organic Compounds
    - Carbon-Nitrogen
    - Dynamic Vegetation

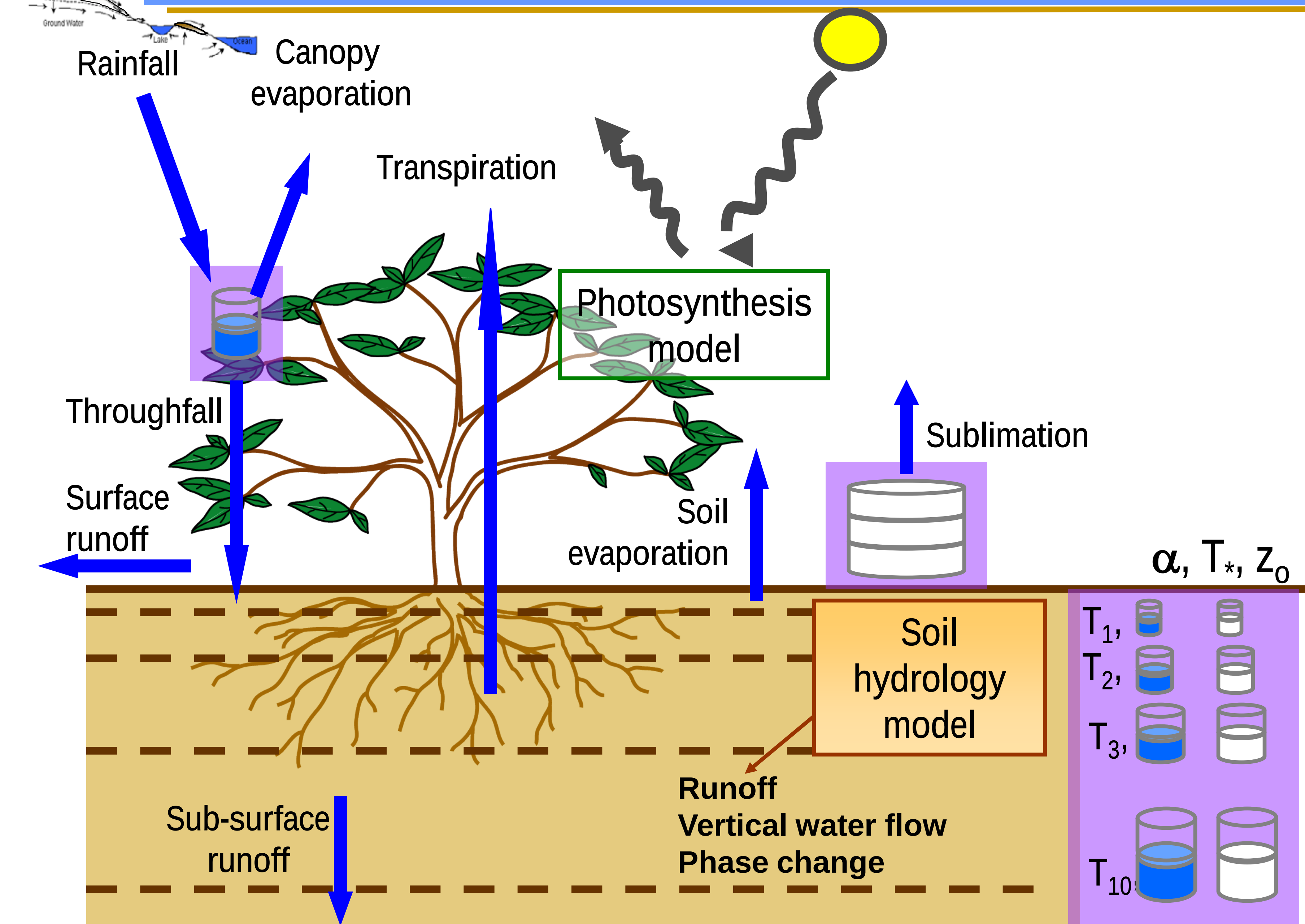
Land model processes - Hydrology



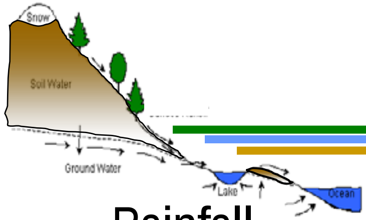
Land model processes - Hydrology

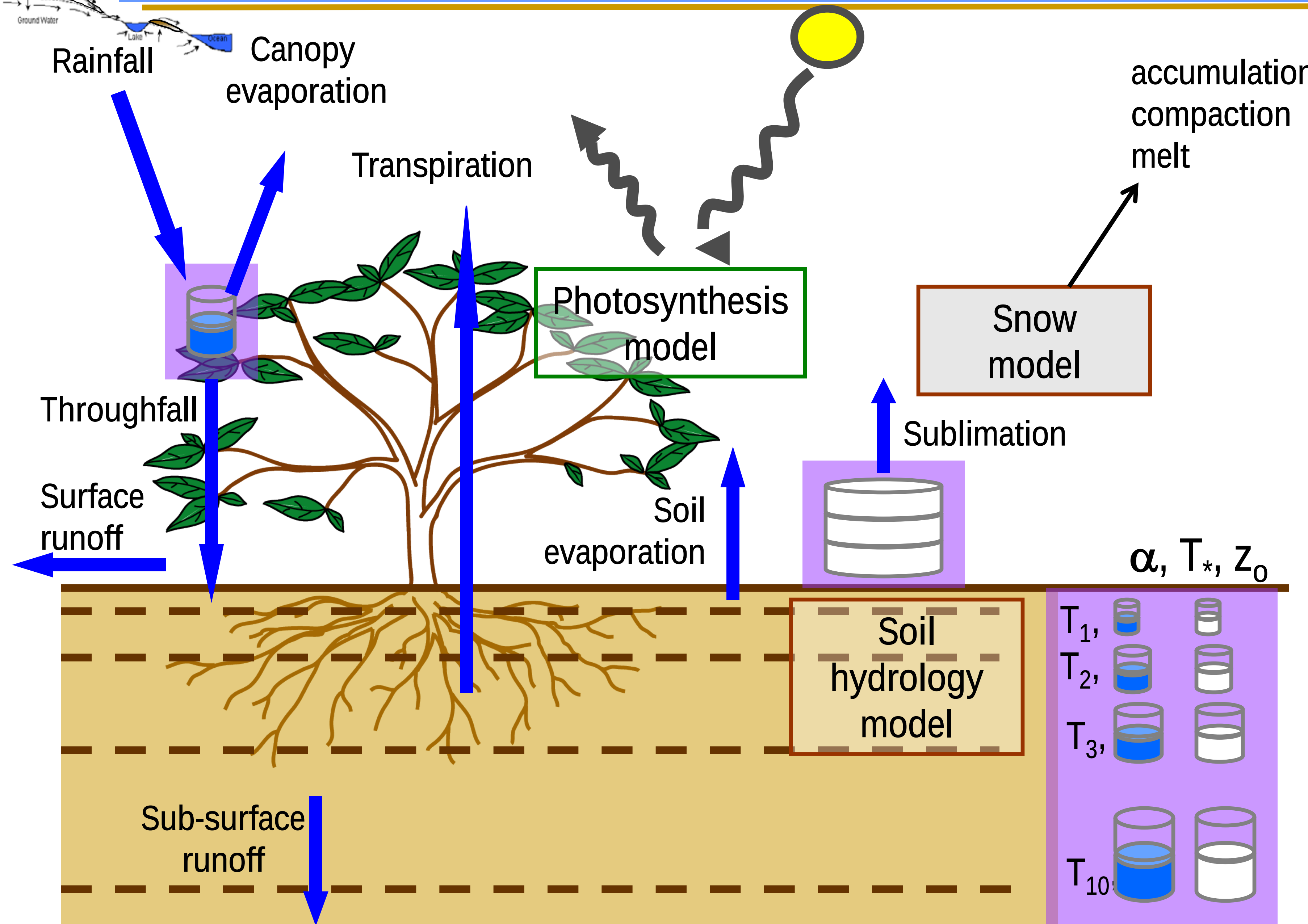


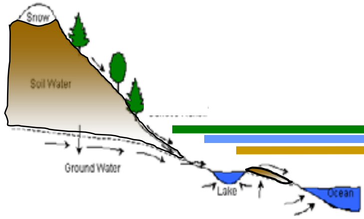
Land model processes - Hydrology



Land model processes - Hydrology





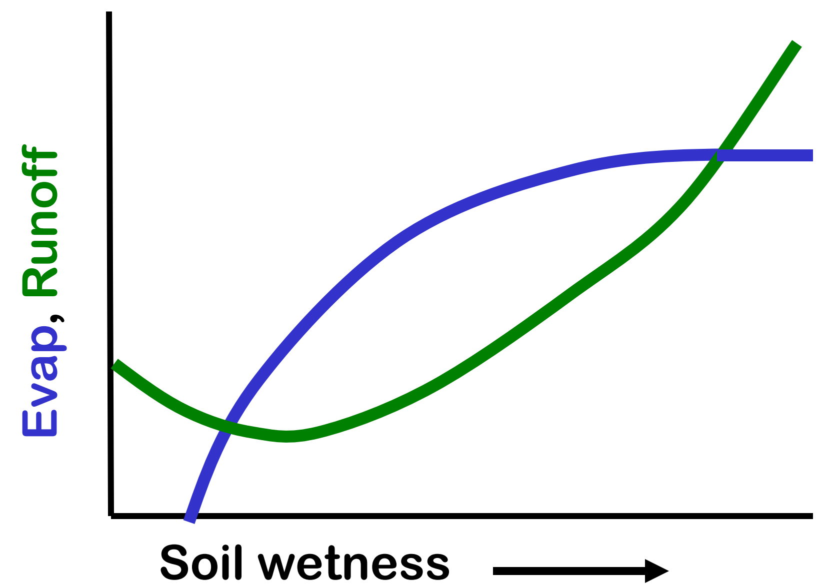


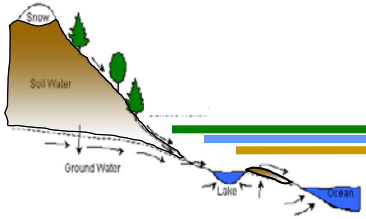
Modeling evaporation and runoff

"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).

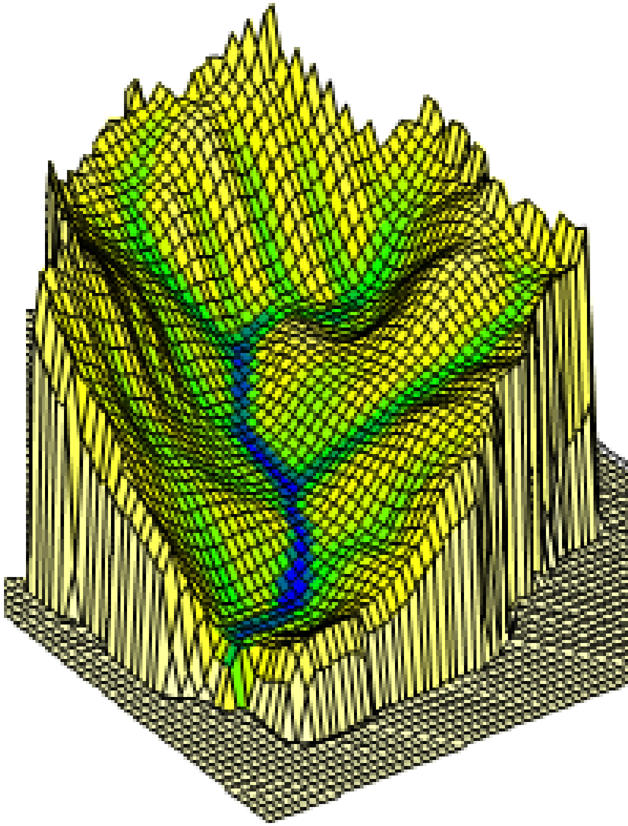
Runoff and evaporation vary non-linearly with soil moisture





Subgrid-scale soil moisture heterogeneity

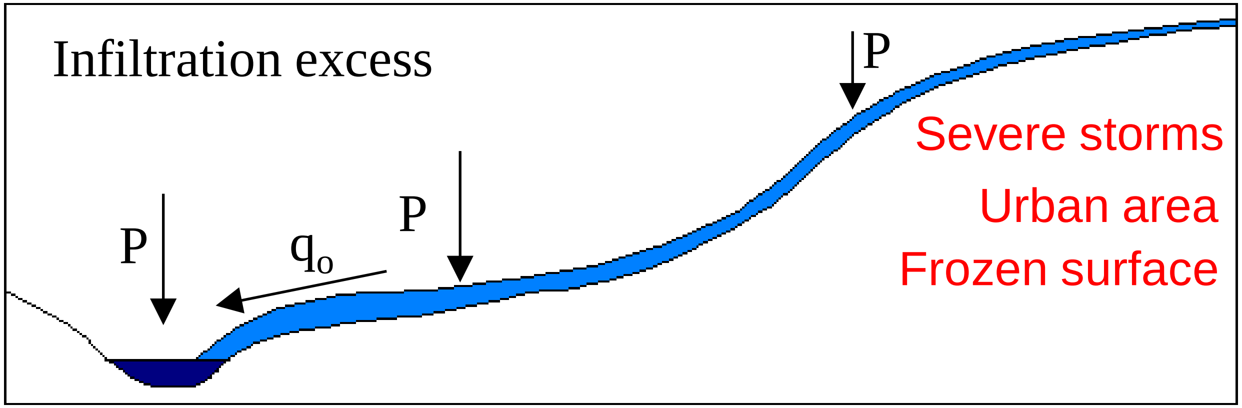
A major control on soil moisture heterogeneity and thus runoff is topography.
Lowland soils tend to be zones of high soil moisture content, while upland soils tend to be progressively drier.

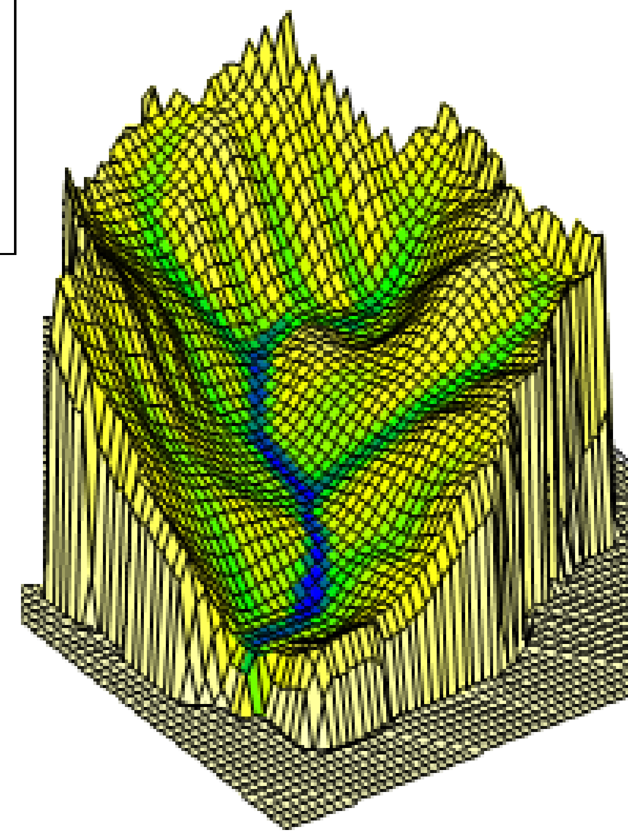


Three main sources of runoff:
- Infiltration excess occurs over the unsaturated fraction
- Saturation excess occurs over the saturated fraction
- Baseflow (drainage)

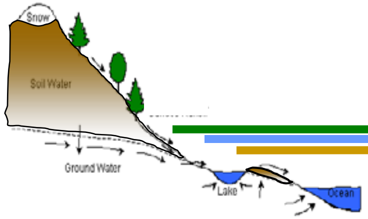
Runoff processes

SIMTOP: Simple TOPMODEL-based runoff model



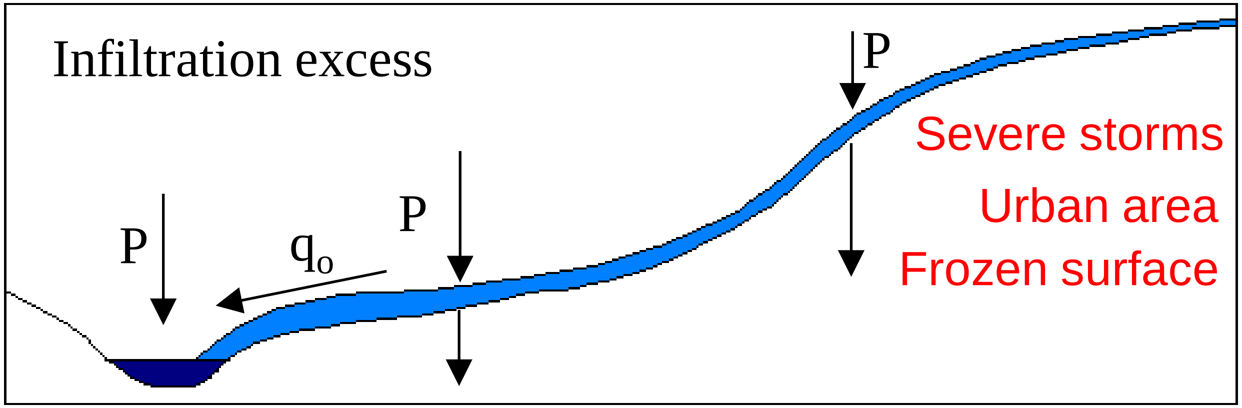


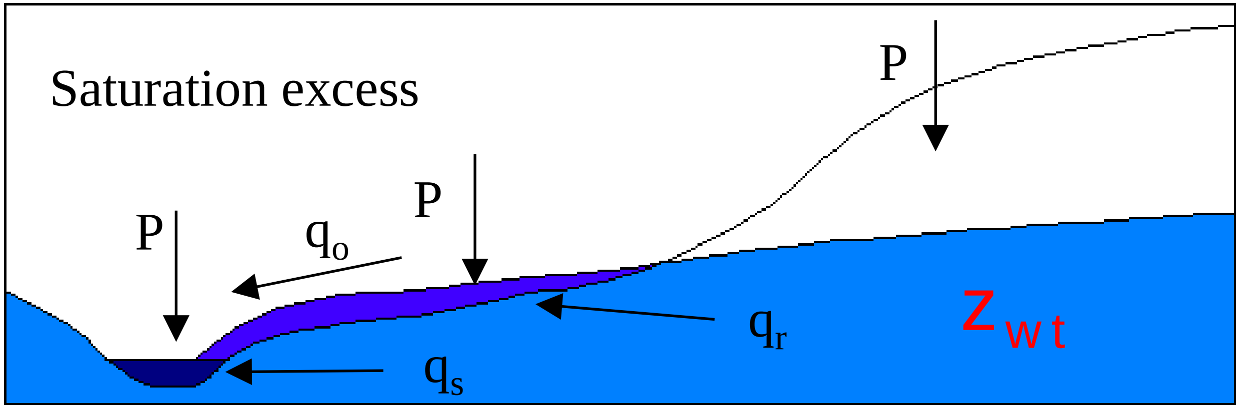
Niu et al. 2005

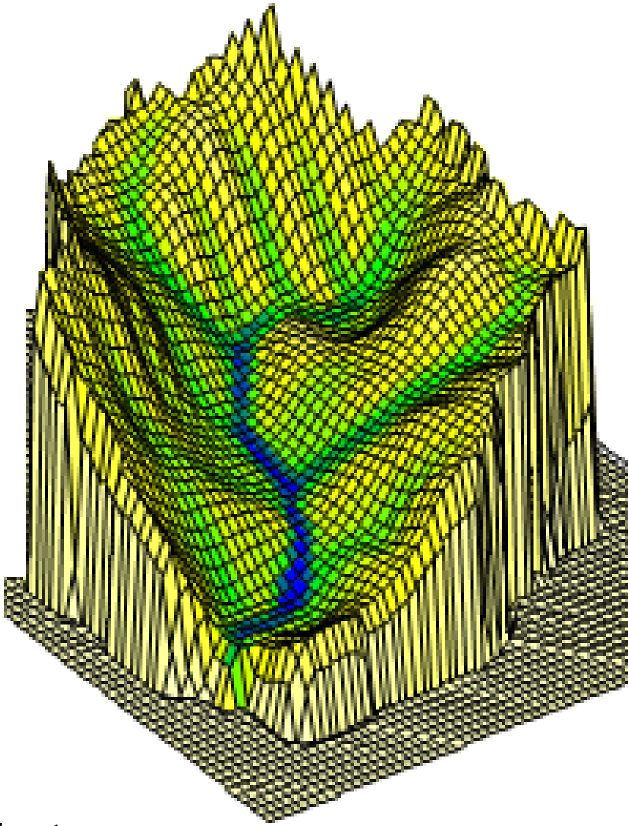


Subgrid-scale soil moisture heterogeneity

SIMTOP: Simple TOPMODEL-based runoff model







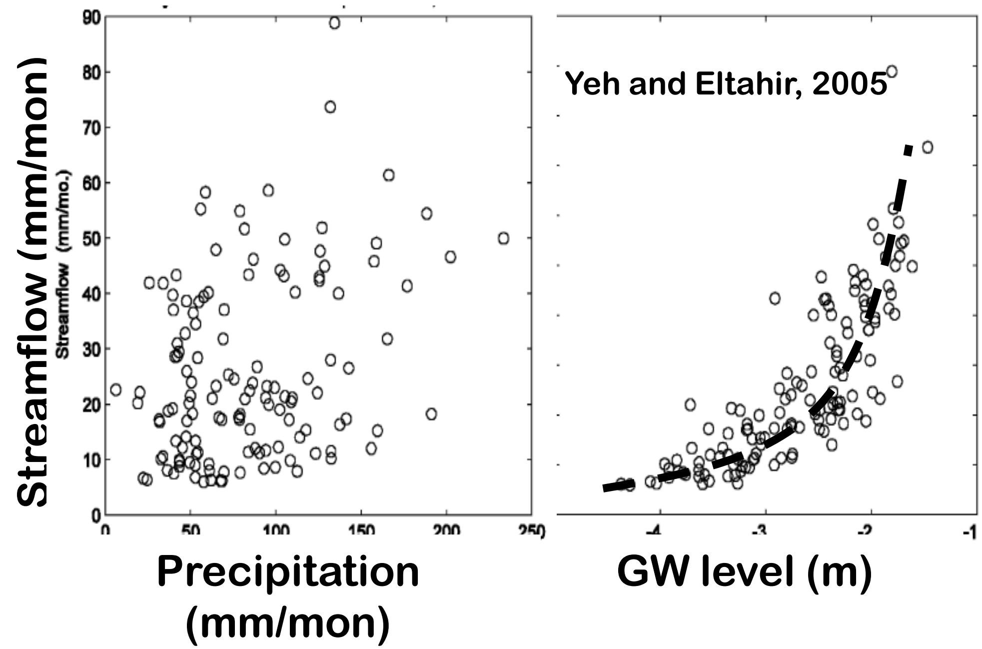
$$f_{sat} = \left(1 - f_{frz,1}\right) f_{\max} \exp\left(-0.5 f_{over} z_{wt}\right) + f_{frz,1}$$

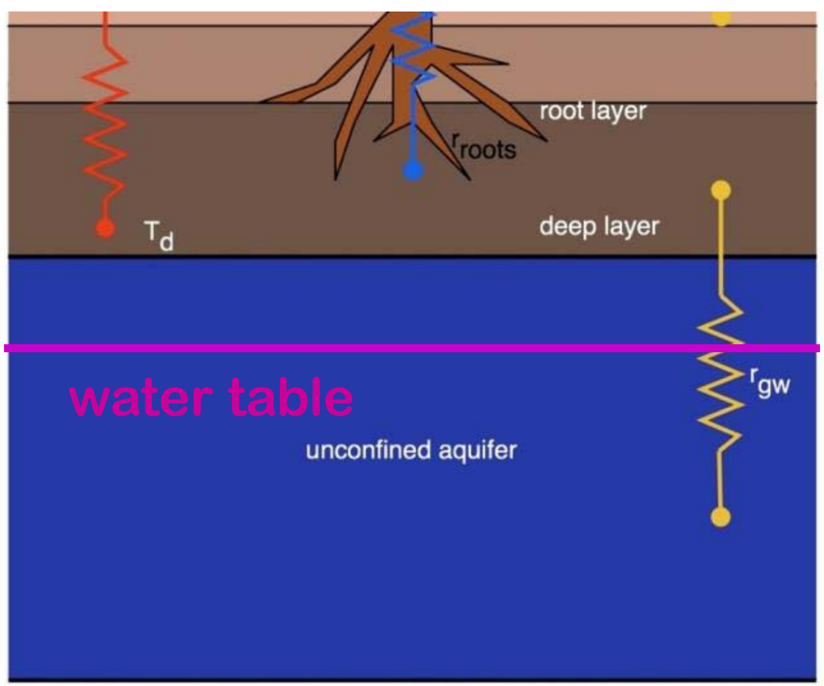
Niu et al. 2005

Groundwater in CLM

Groundwater controls runoff
(Yeh and Eltahir, 2005)

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

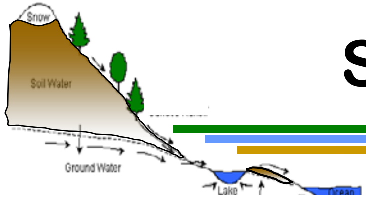




Groundwater model (SIMGM) determines water table depth

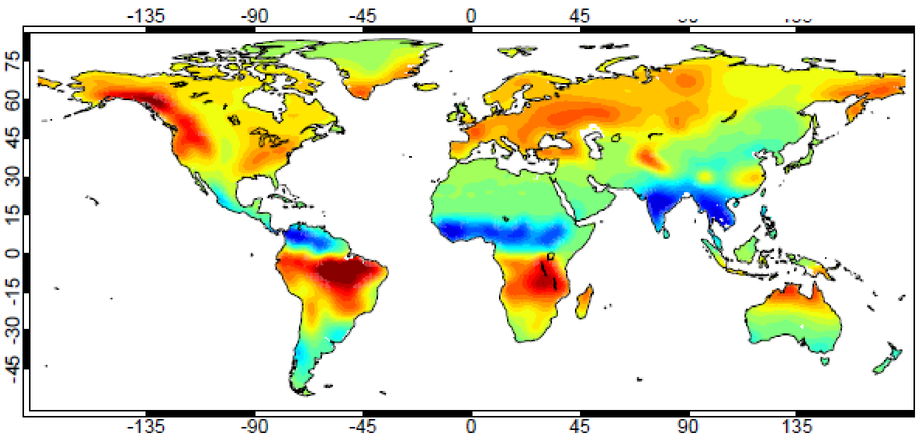
Subsurface runoff is exponential function of water table depth

Niu et al. 2007

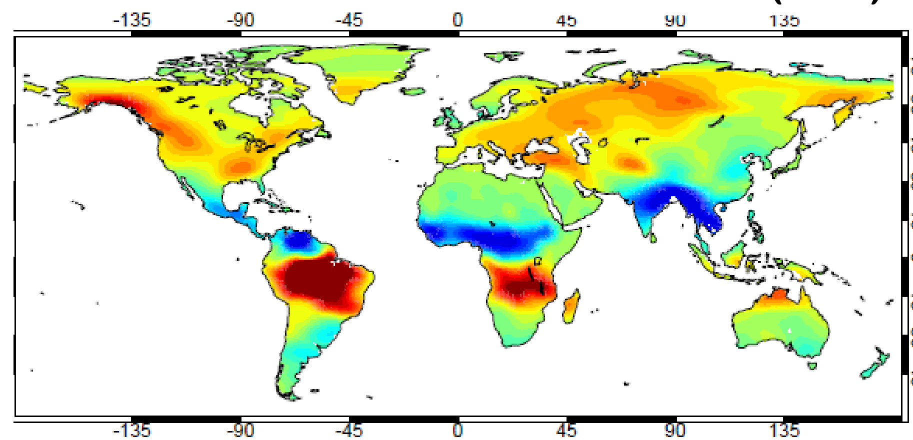


Soil (and snow) water storage (MAM – SON)

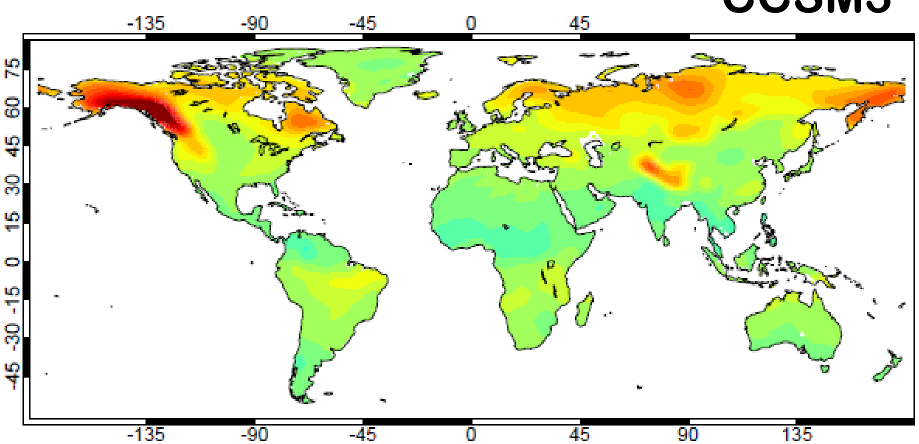
CCSM4

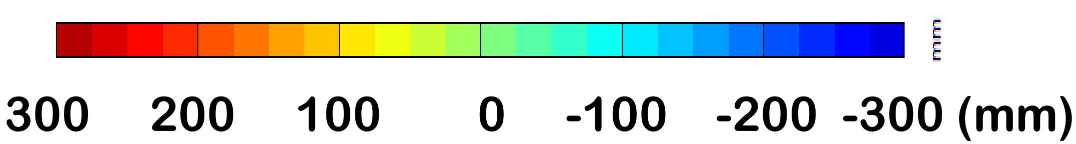


GRACE (obs)



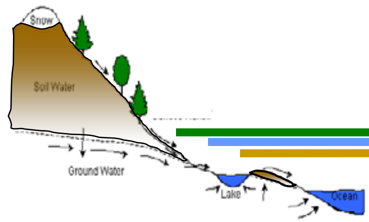
CCSM3



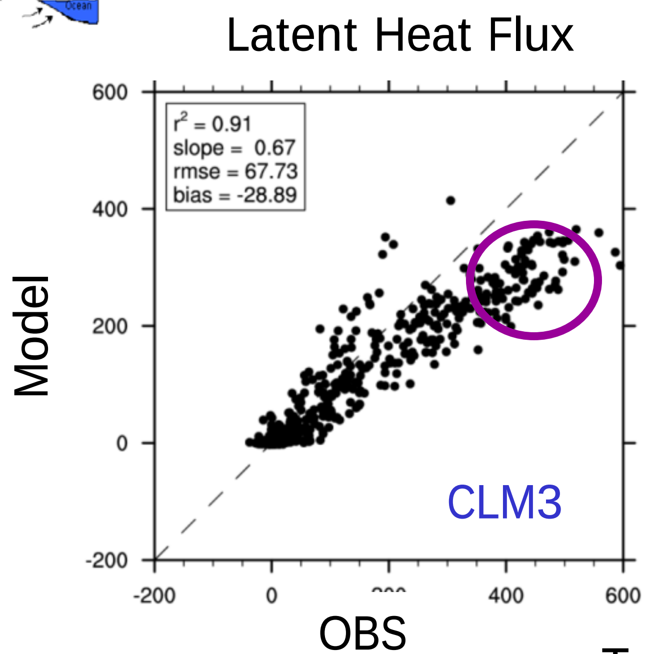


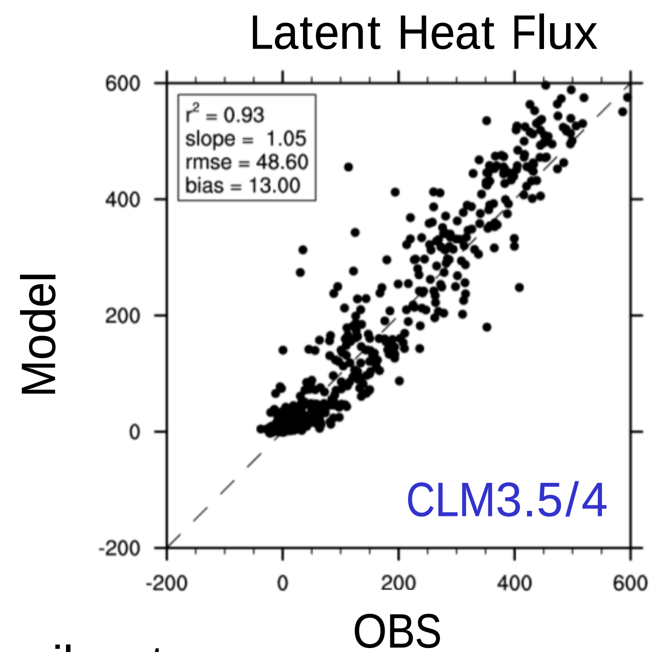
GRACE satellite measures small changes in gravity which on seasonal timescales are due to variations in water storage

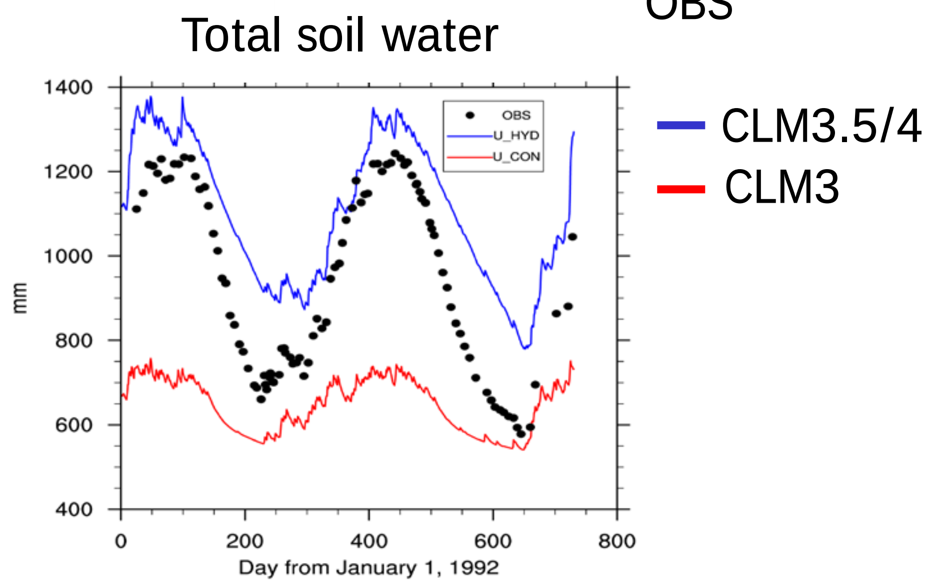
CCSM3 and CCSM4 data from 1870 and 1850 control

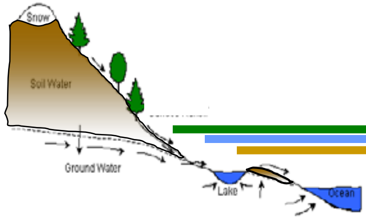


Abracos tower site (Amazon)



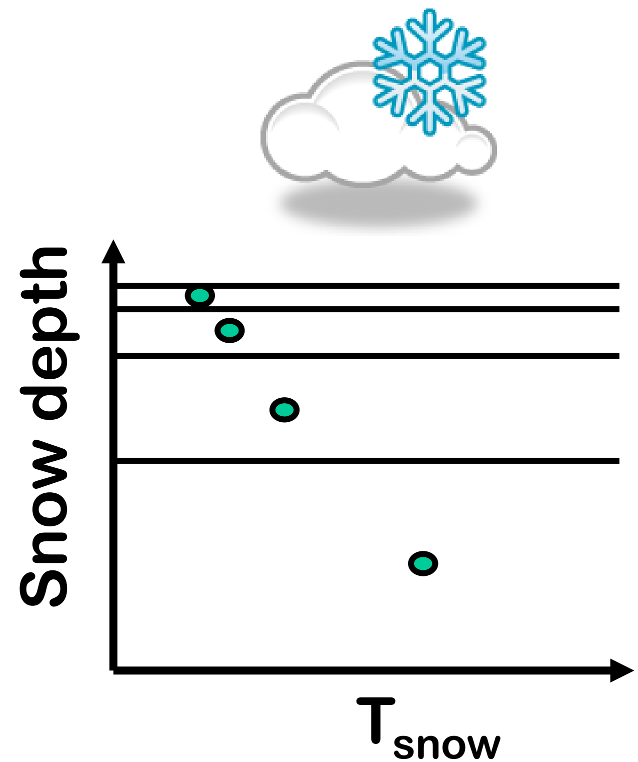






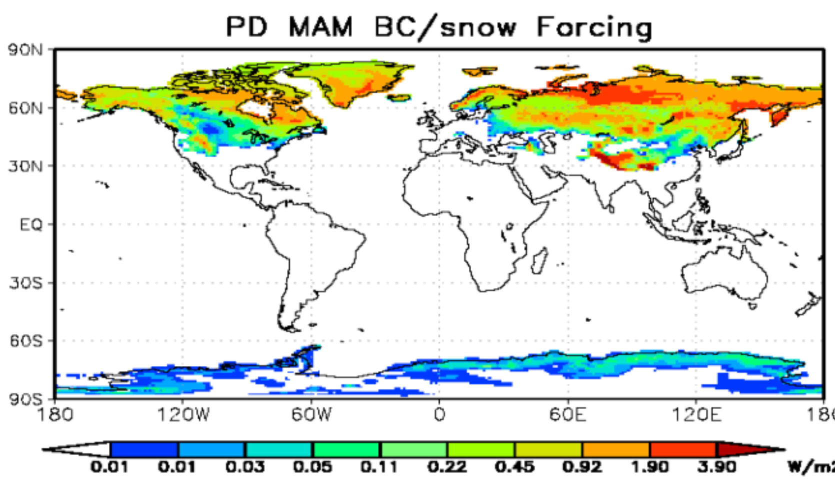
Model components: Snow Model

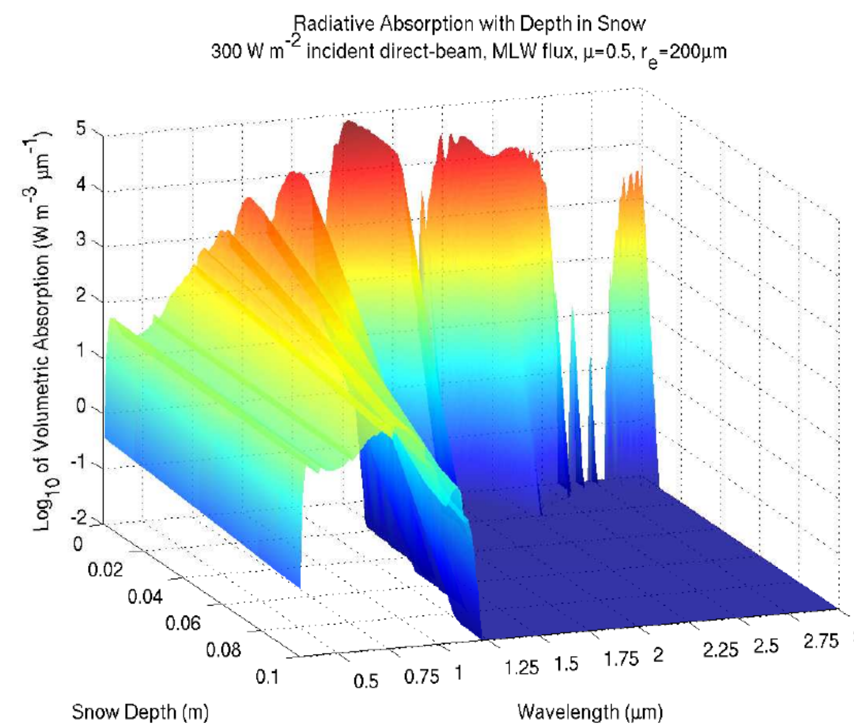
- Up to 5-layers of varying thickness
- Treats processes such as
  - Accumulation
  - Snow melt and refreezing
  - Snow aging
  - Water transfer across layers
  - Snow compaction
    - destructive metamorphism due to wind
    - overburden
    - melt-freeze cycles
  - Sublimation
  - Aerosol deposition



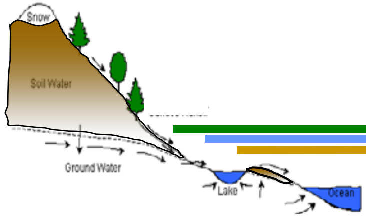
Snow, Ice, and Aerosol Radiative Model (SNICAR)

- 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

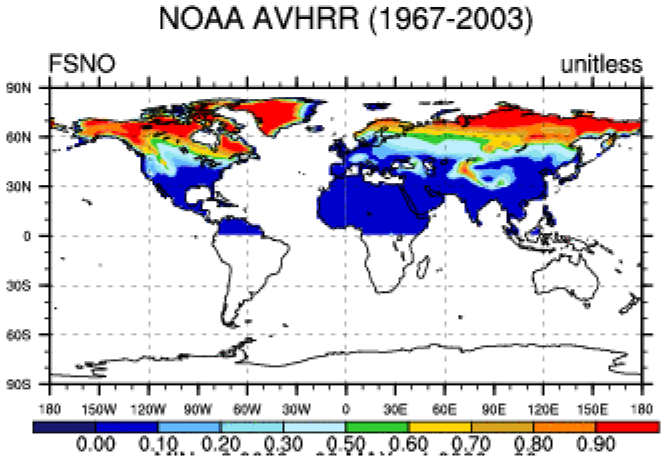




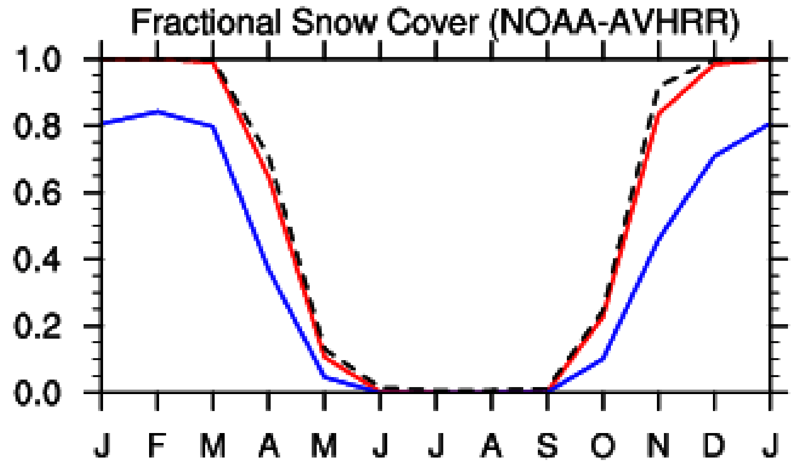
Flanner et al (2007), *JGR*
Flanner and Zender (2006), *JGR*
Flanner and Zender (2005), *GRL*

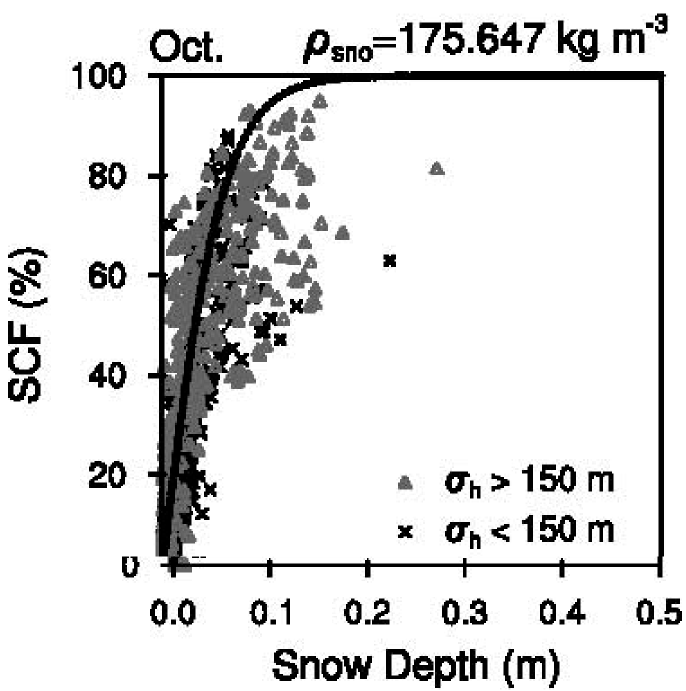


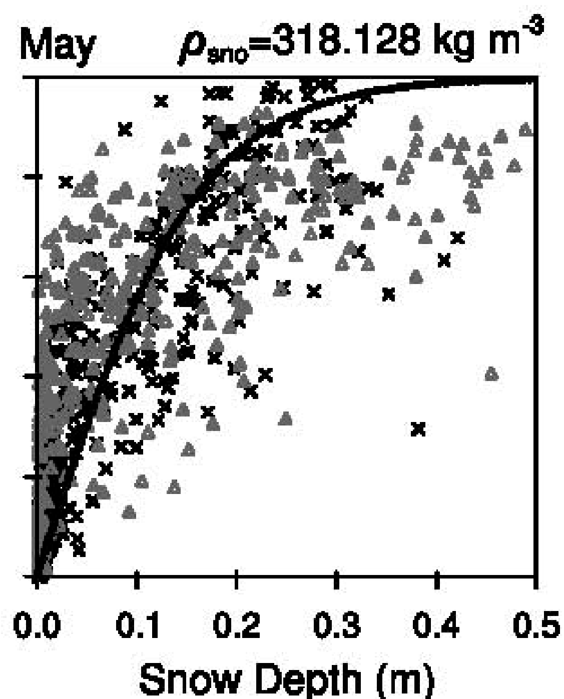
Snow cover fraction



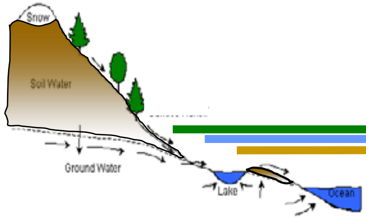
How much of a grid cell is covered with snow for a given snow depth?







Niu and Yang 2007



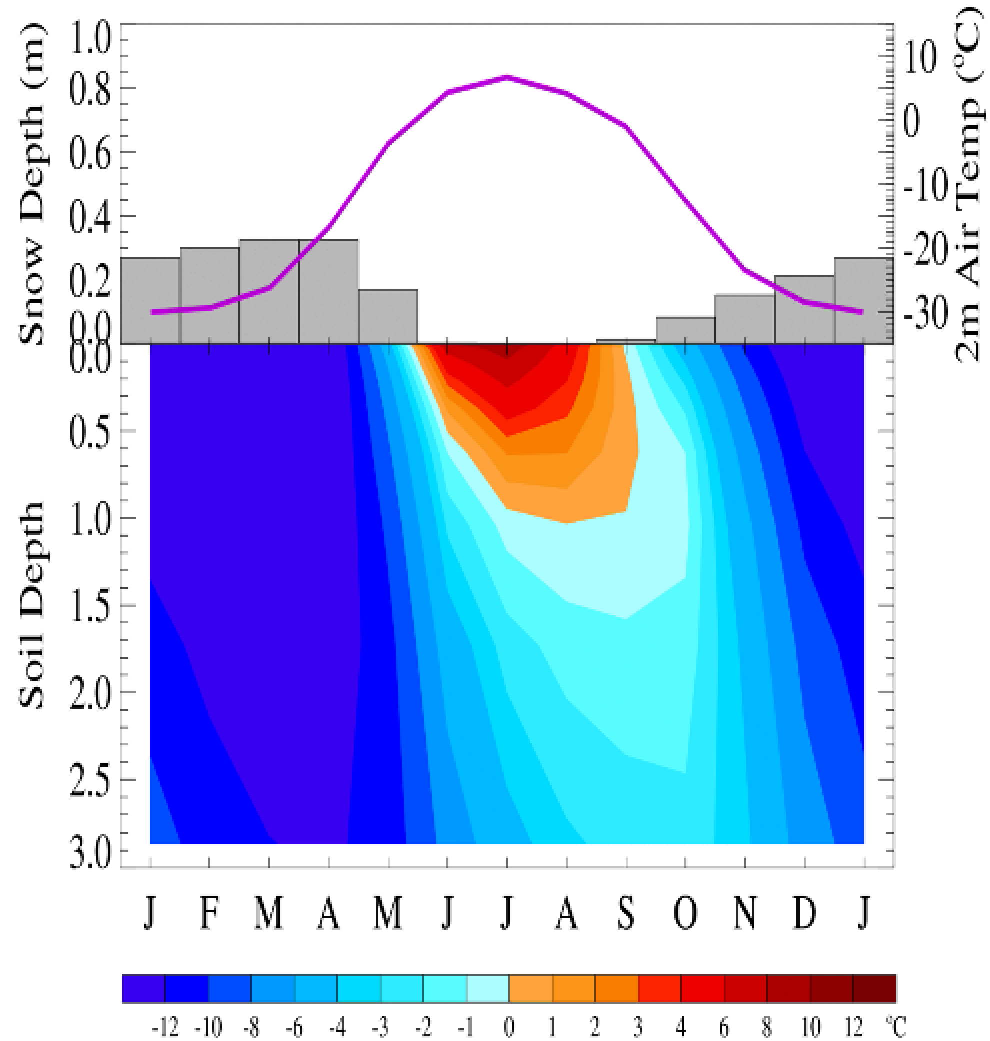
Snow/Soil thermodynamics

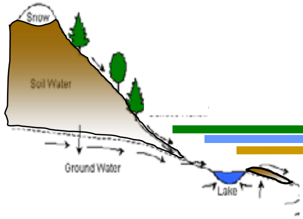
Solve the heat diffusion equation for multi-layer snow and soil model

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

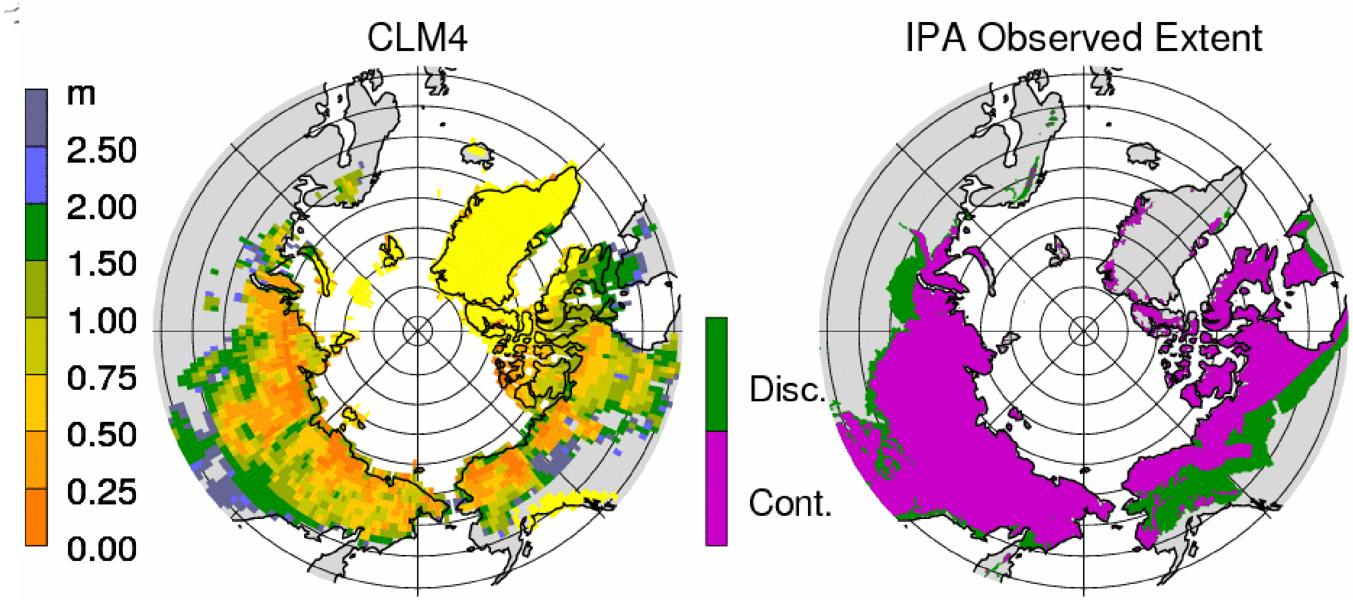
where C_p (heat capacity) and K (thermal conductivity) are functions of:

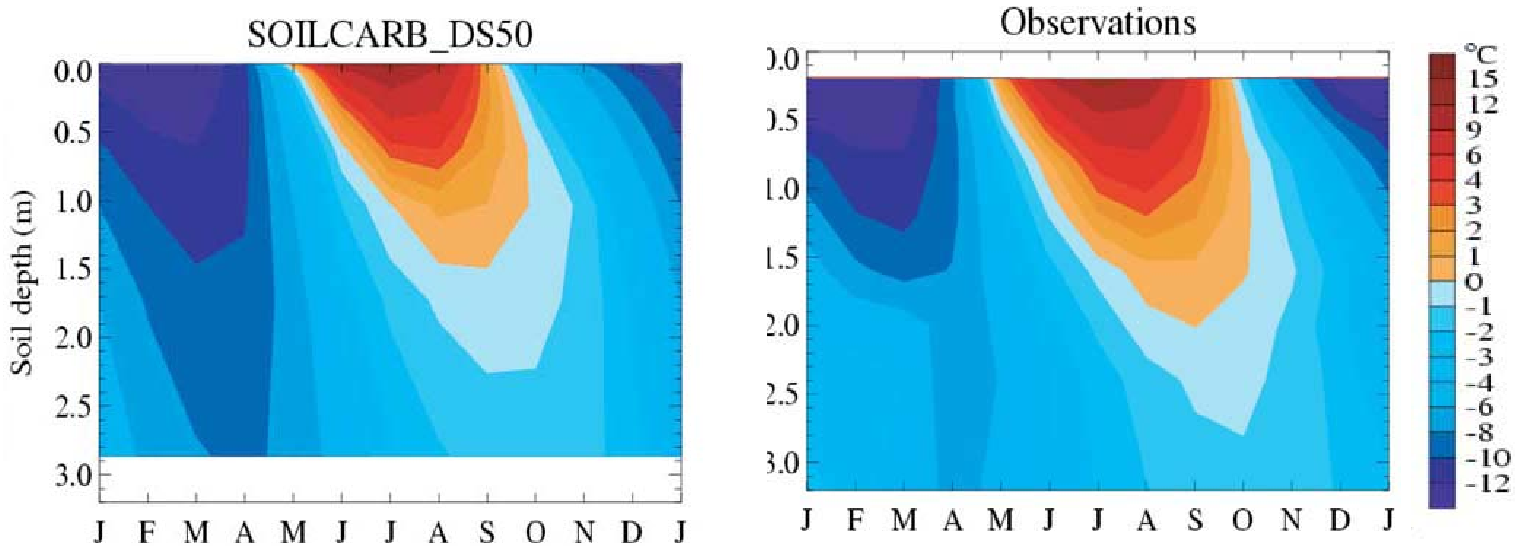
- **temperature**
- **total soil moisture**
- **soil texture**
- **ice/liquid content**





Modeling Permafrost in CLM

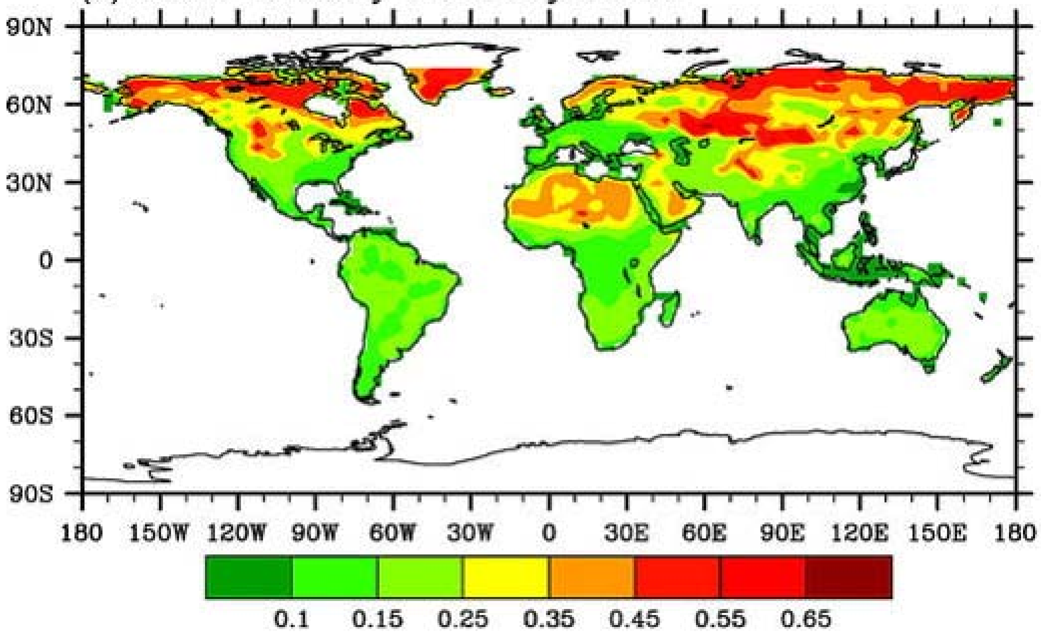




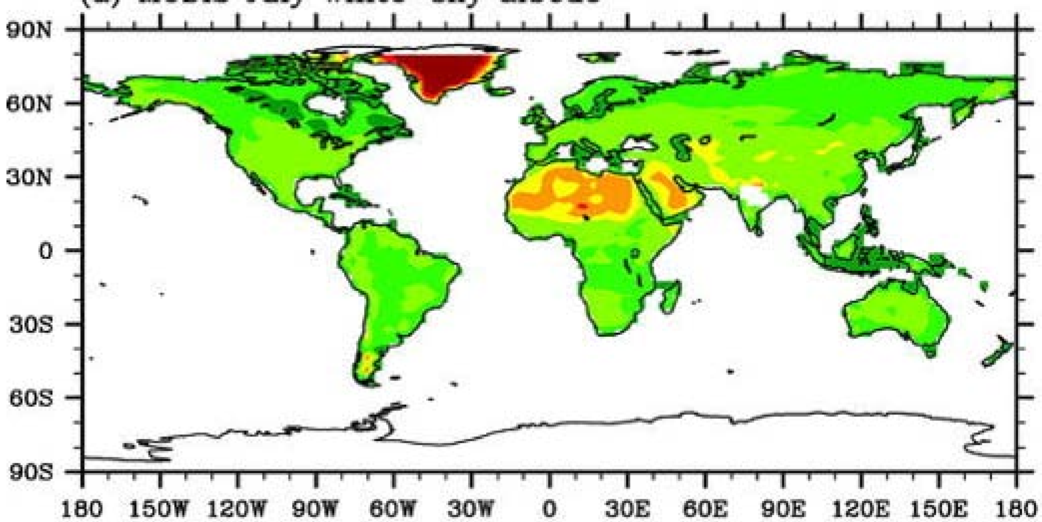
Lawrence et al., J. Climate, 2011

Modeling surface albedo

(a) MODIS February white-sky albedo



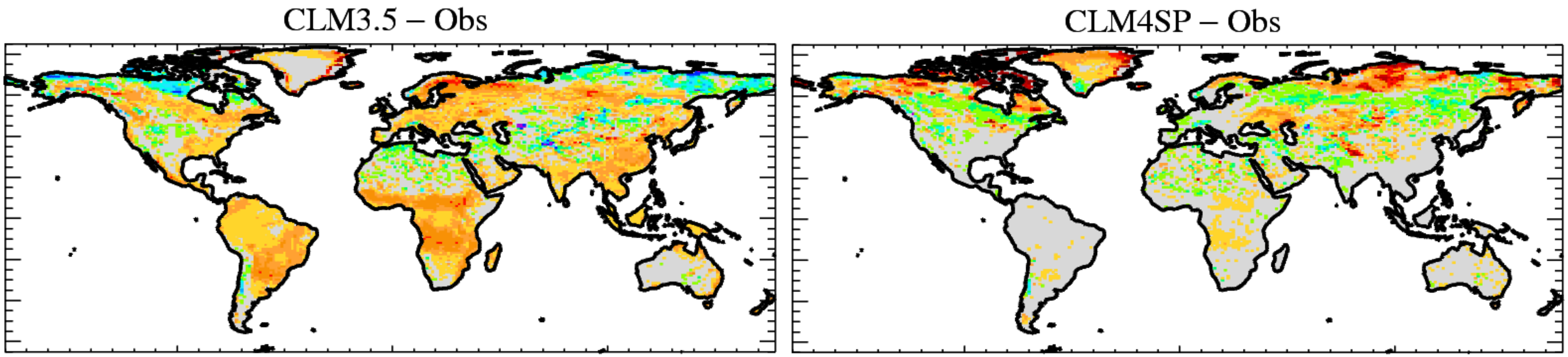
(a) MODIS July white-sky albedo



Surface albedo a function of

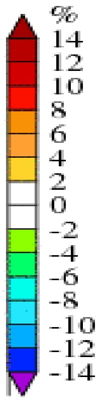
- Vegetation cover and type
- Snow cover
- Snow age
- Solar zenith angle
- Soil moisture
- Amount of direct vs diffuse solar radiation
- Amount of visible vs IR solar radiation

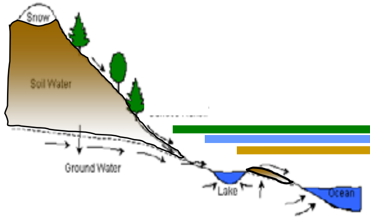
Surface albedo (CLM offline compared to MODIS)



	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)





CLM near-term development activities

- Crops and irrigation
- Revised cold region hydrology
- Revised canopy processes (radiation and photosynthesis)
- Methane emissions model
- Improved fire algorithm including human triggers and suppression
- Revised lake model
- High spatial resolution input datasets
- Multiple urban density types, improved anthropogenic fluxes

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

Thank You

The NESL Mission is:
To advance understanding of weather, climate, atmospheric composition and processes;
To provide facility support to the wider community; and,
To apply the results to benefit society.

NCAR is sponsored by the National Science Foundation