The Community Land Model

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with input from lots of LMWGers

NCAR is sponsored by the National Science Foundation

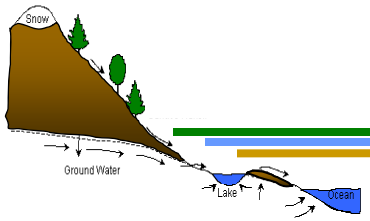
What distinguishes a land model within an Earth System Model that consists of so many important pieces?

The land is a critical interface

through which climate, and climate change impacts humans and ecosystems

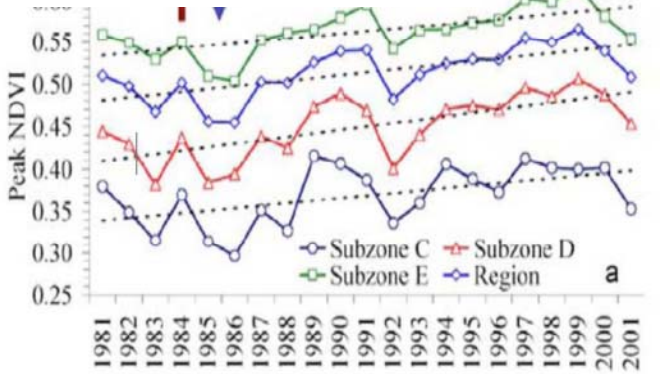
and

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

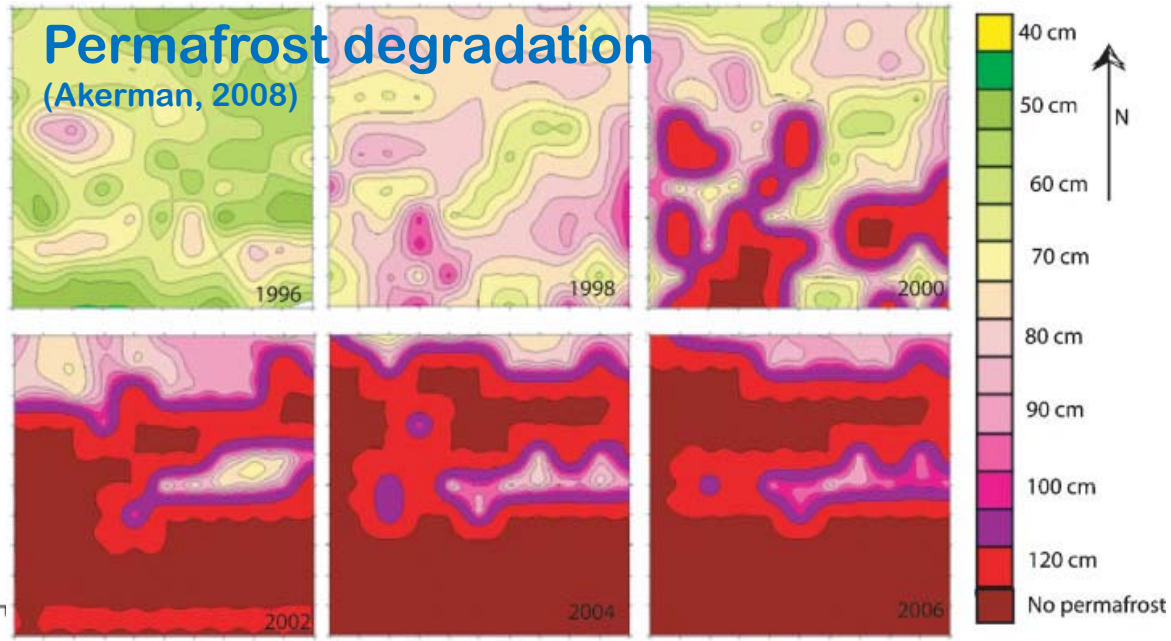


Observed terrestrial change

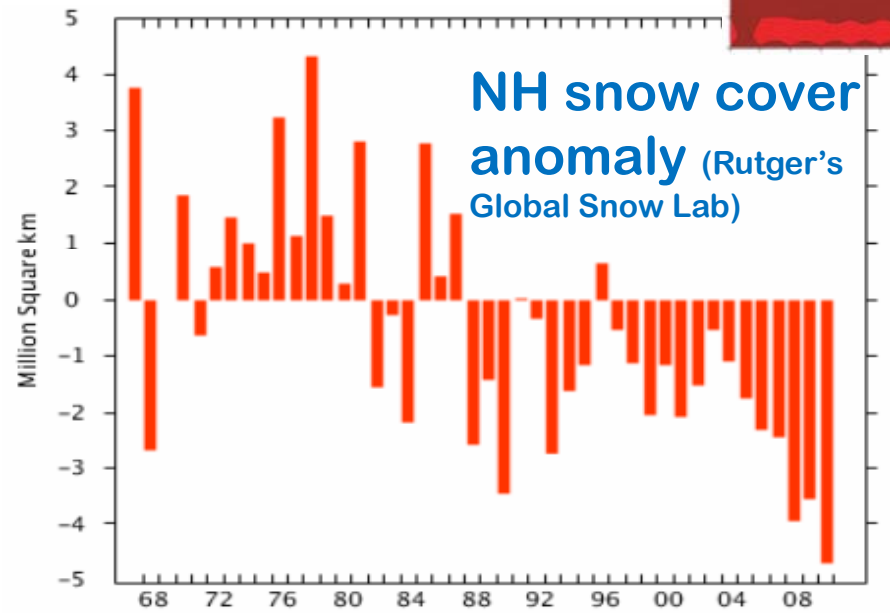
Arctic greening
(Bunn et al. 2007)



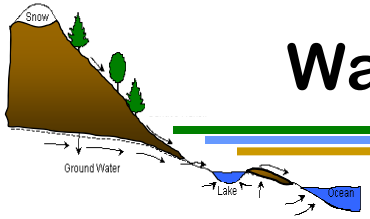
Permafrost degradation
(Akerman, 2008)



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

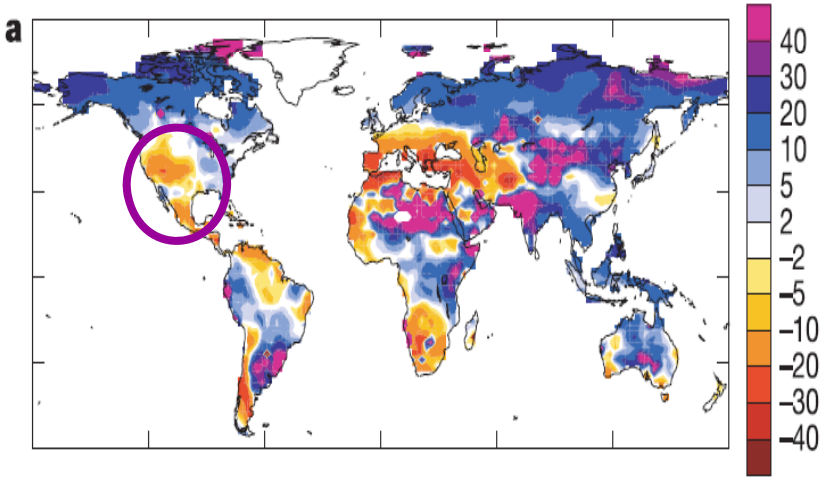


Deforestation

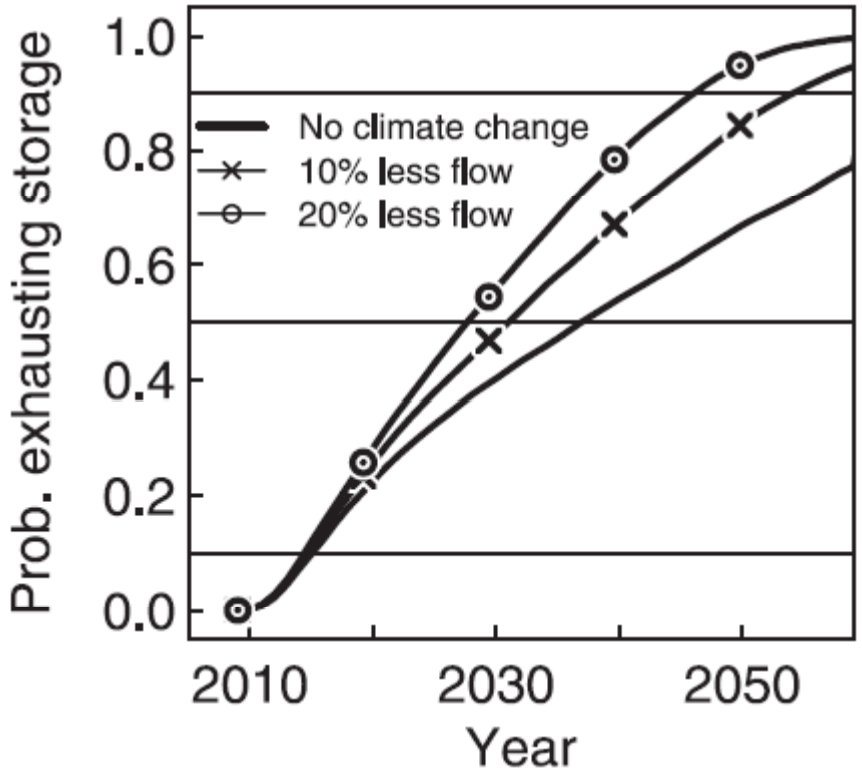


Water resources: When will Lake Mead go dry?

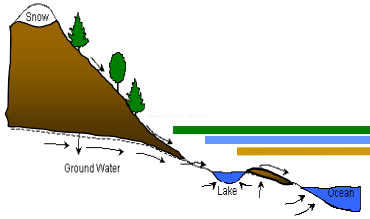
% Change in Runoff by 2050 (A1B)



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?

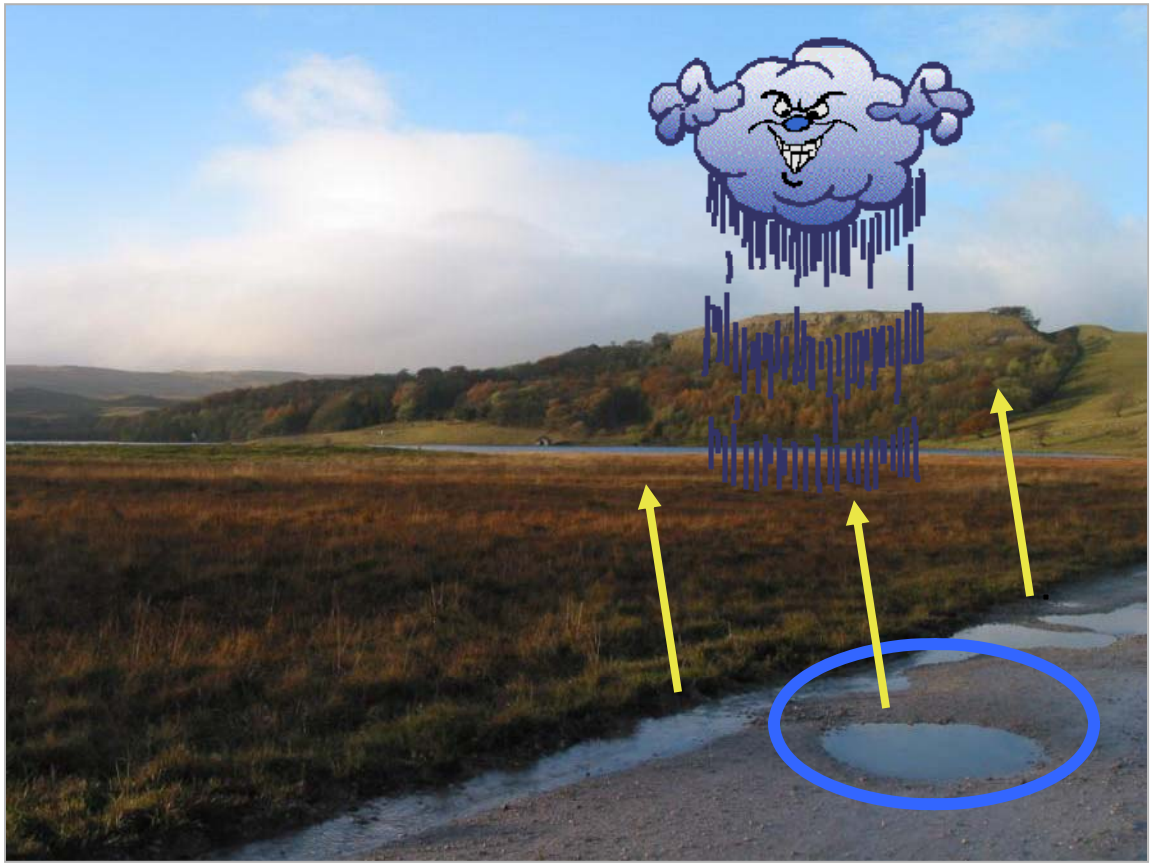
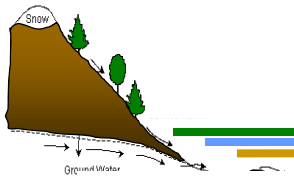
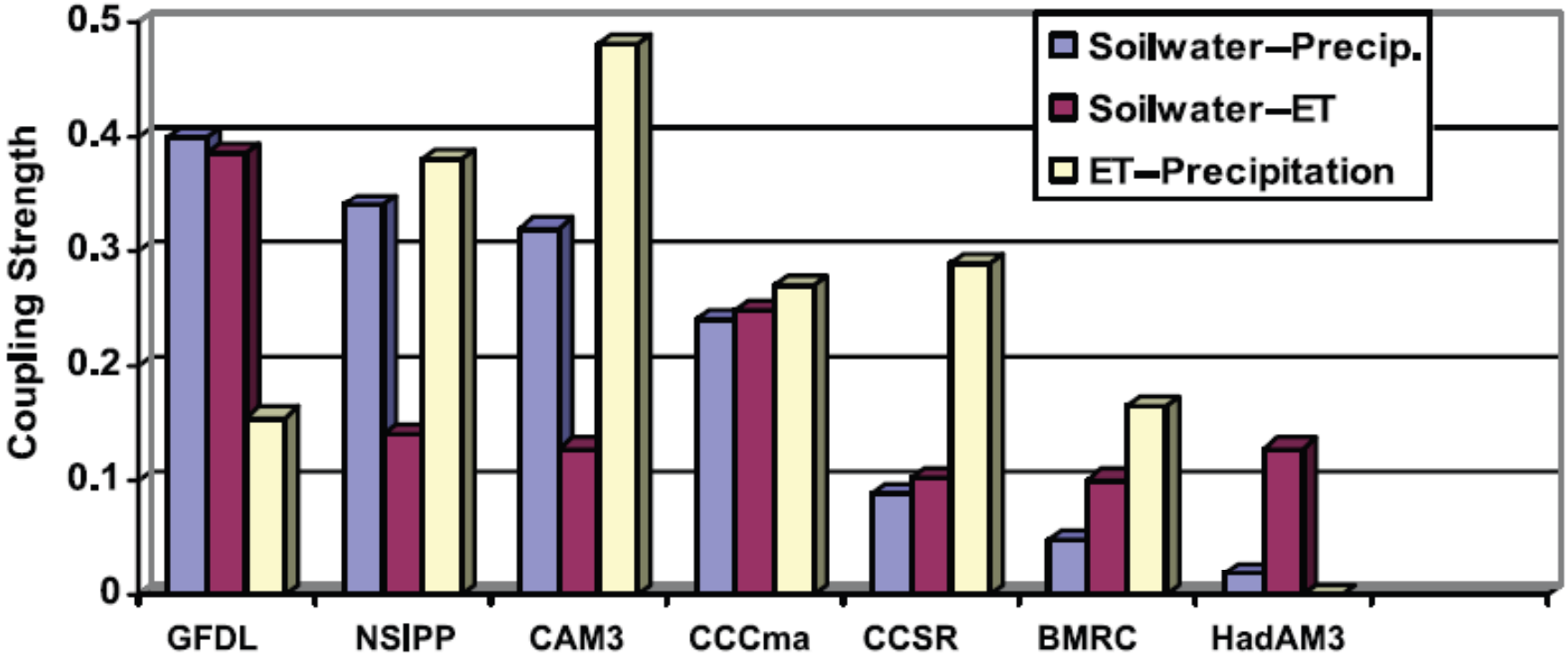


Photo by D. Fritz



Land-atmosphere interactions

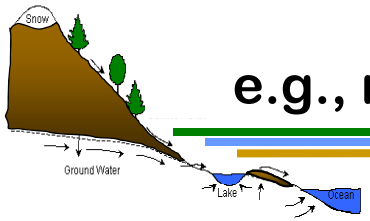
GLACE: To what extent does soil moisture influence the overlying atmosphere and the generation of precipitation?



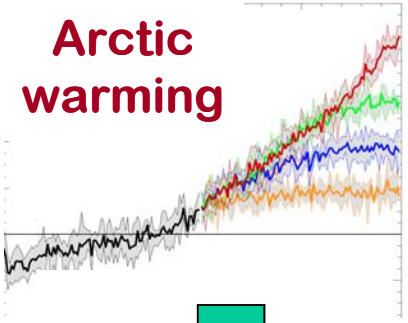
How does the representation of land-atmosphere interactions affect simulation of droughts, floods, extremes?

Koster et al., 2004; IPCC

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



Arctic warming



Carbon sequester

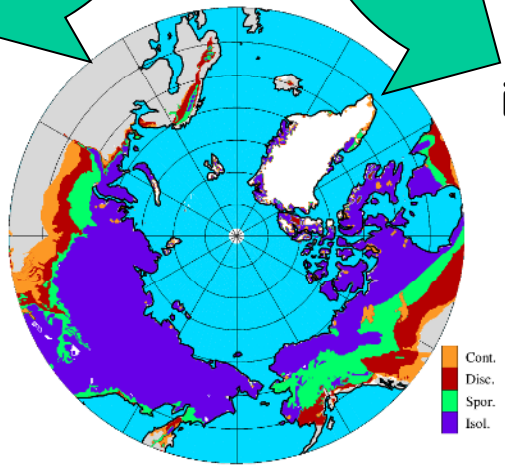
Shrub growth

Enhanced [nitrogen]

Microbial activity increases

Permafrost warms and thaws

Expanded wetlands



Lakes drain, soil dries

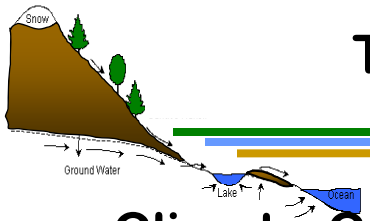
Arctic runoff increases

CO_2 efflux

CH_4 efflux

Global warming

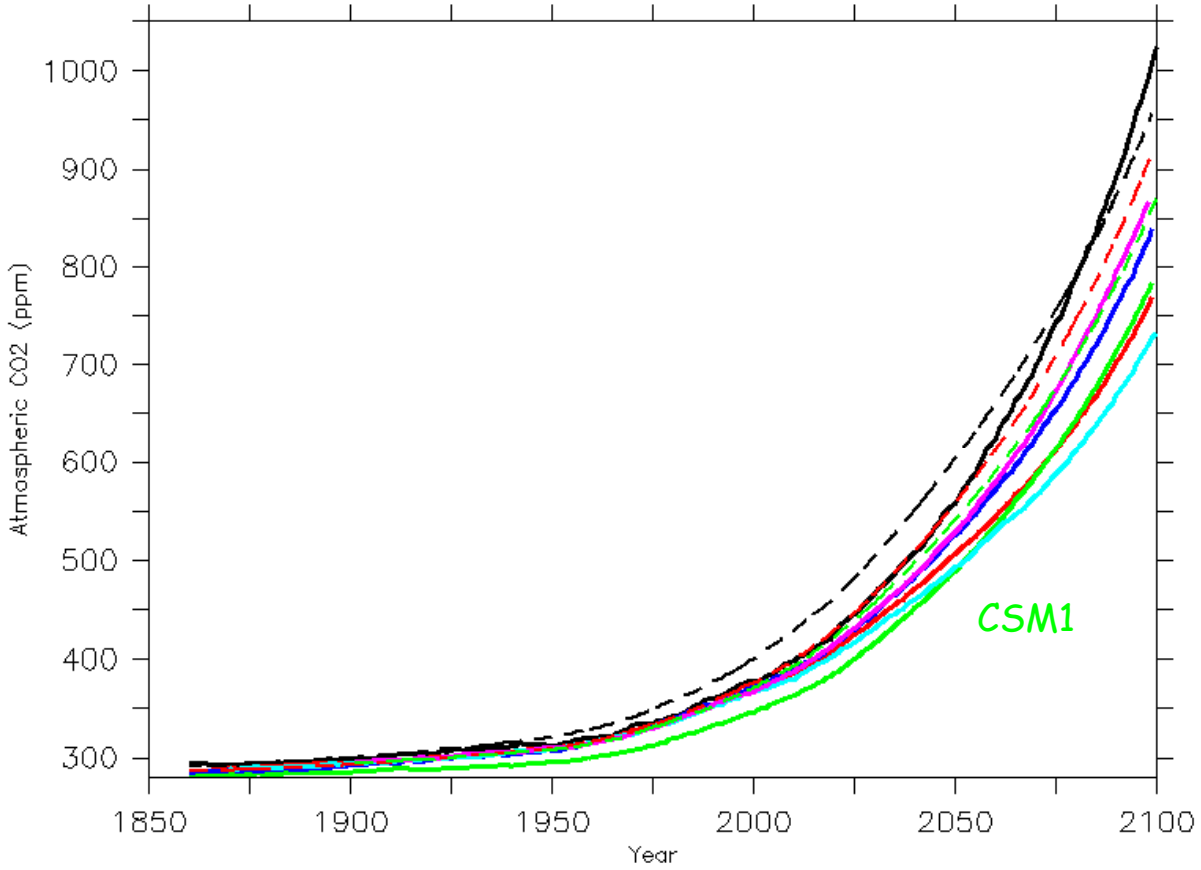
Adapted from McGuire et al., 2006



Terrestrial carbon cycle impact on atmospheric CO_2

Climate-Carbon model intercomparison (C_4MIP):

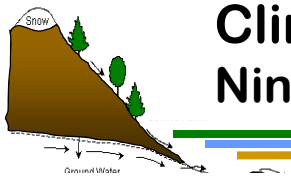
Nine climate models of varying complexity with active carbon cycle



Large range in simulated atmospheric CO_2 at 2100

max is > 1000 ppm
min is < 750 ppm

Courtesy of Pierre Friedlingstein



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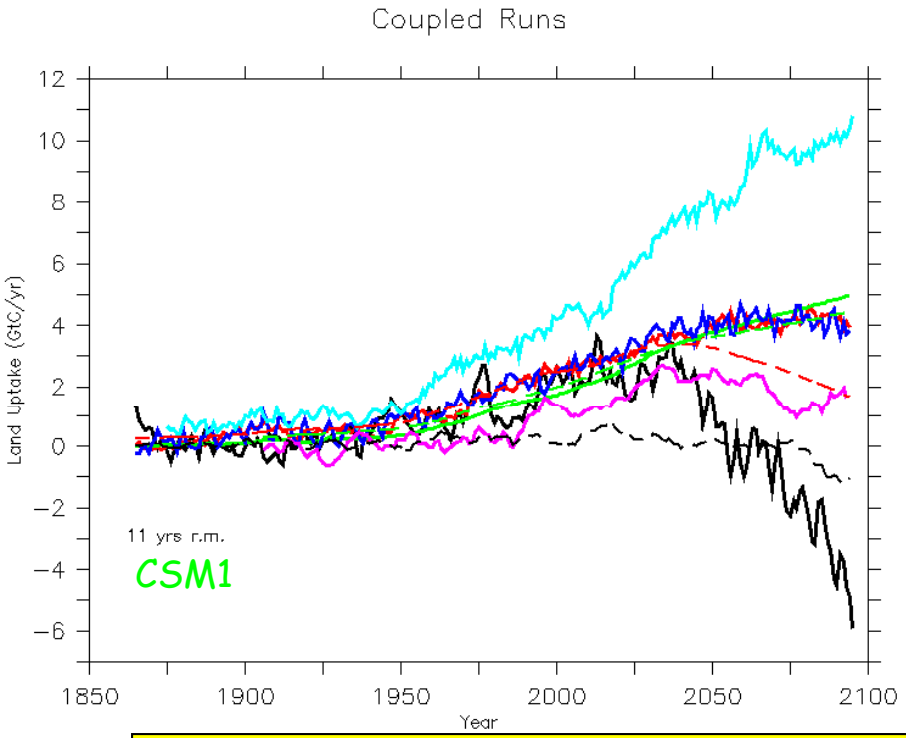

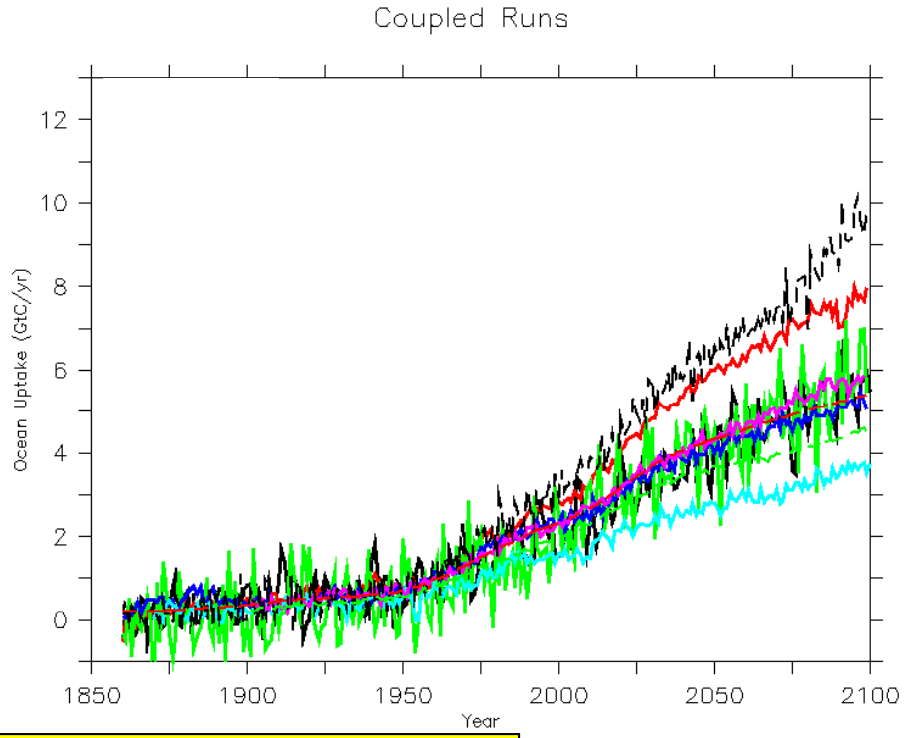

Uncertainty arises from differences in terrestrial fluxes

- **One model simulates a large source of carbon from the land**
- **Another simulates a large terrestrial carbon sink**
- **Most models simulate modest terrestrial carbon uptake**
- **Terrestrial carbon cycle can be a large climate feedback**
- **Considerable more work is needed to understand this feedback**

urtesy 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
  - Determine absorbed solar radiation, surface albedo
- Runoff to ocean

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

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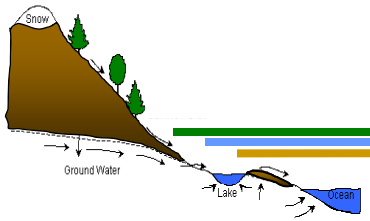
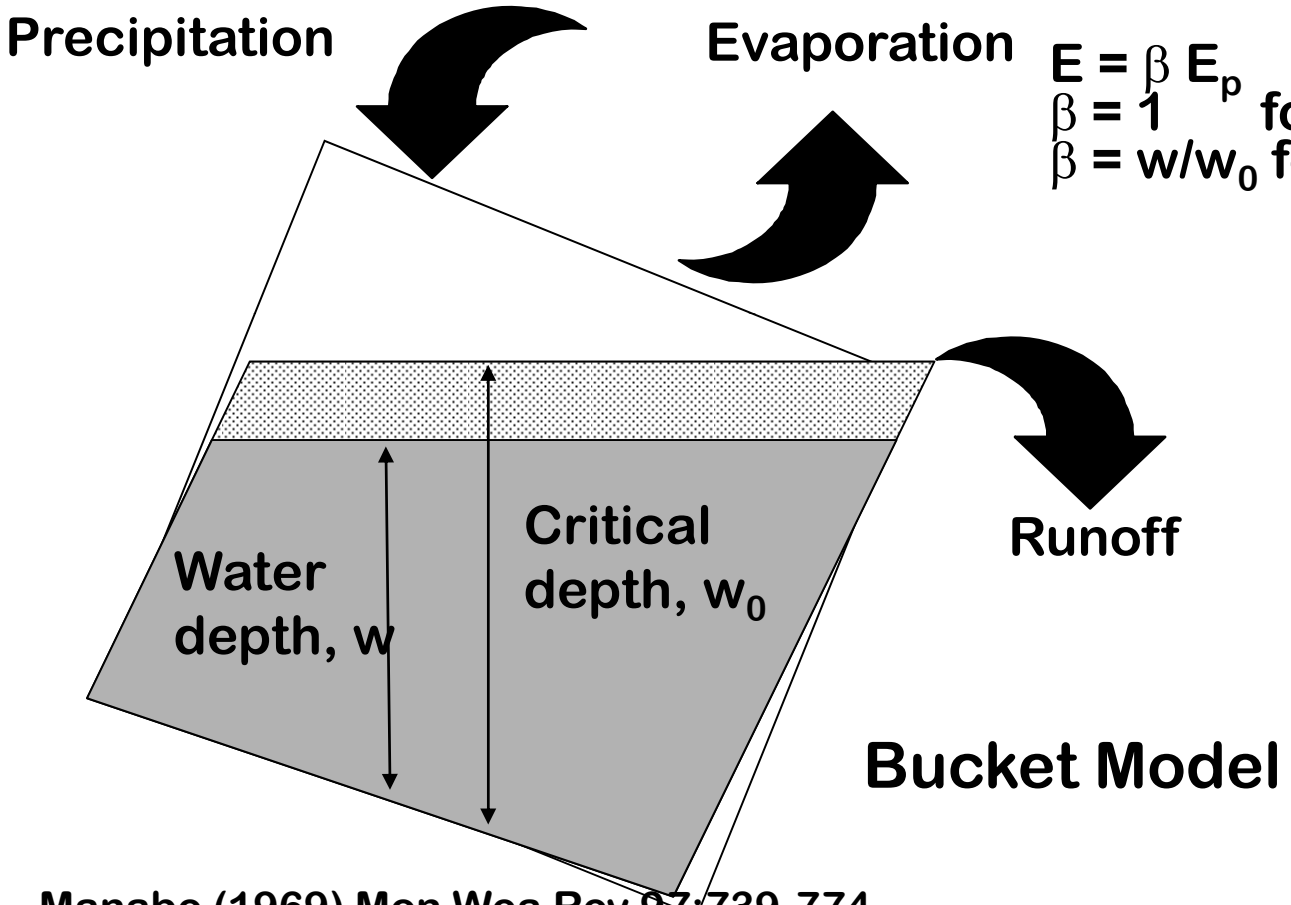
  - Dust emissions
  - Biogenic Volatile Organic Compound emissions
  - CH_4, N_2O

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)



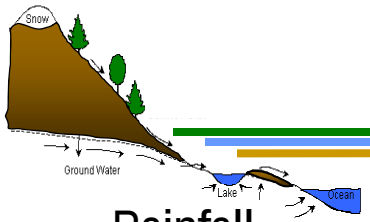
Land models have come a long way
1st Generation: Bucket Model



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

Figure courtesy G. Bonan

Land model processes



Rainfall

Canopy evaporation

Transpiration

Throughfall

Surface runoff

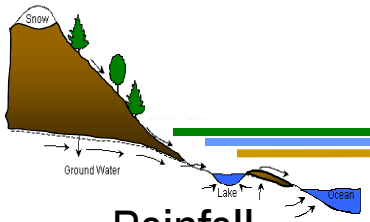
Soil evaporation

Sublimation

α, T_*, z_0

Sub-surface runoff

Land model processes



Rainfall

Canopy evaporation

Transpiration

Photosynthesis model

Stomatal conductance:
solar radiation, temp, humidity deficit, soil moisture, [CO_2] … Nitrogen fertilization

Bonan, 1995; Denning, 1995; Cox, 1999

Throughfall

Surface runoff

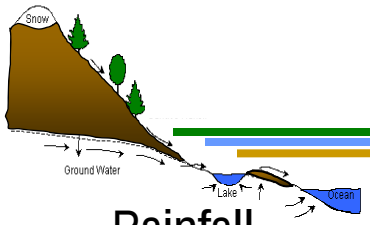
Soil evaporation

Sublimation

α, T_*, z_0

Sub-surface runoff

Land model processes



Rainfall

Canopy evaporation

Transpiration

Photosynthesis model

Throughfall

Surface runoff

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Sublimation

α, T_*, z_0

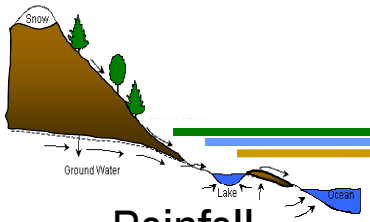
Soil hydrology model

T_1,
T_2,
T_3,
T_{10}

Runoff
Vertical water flow
Phase change

Sub-surface runoff

Land model processes



Rainfall

Canopy evaporation

Transpiration

accumulation
compaction
melt

Photosynthesis model

Snow model

Throughfall

Sublimation

Surface runoff

Soil evaporation

α, T_*, z_0

Soil hydrology model

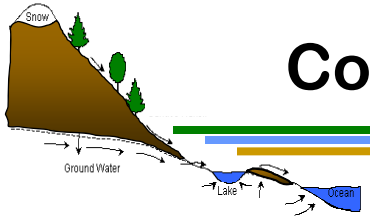
T_1,
T_2,
T_3,

T_{10}

Sub-surface runoff

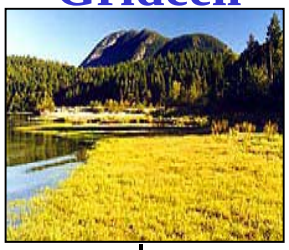
Main Features of the Community Land Model

- **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

Gridcell

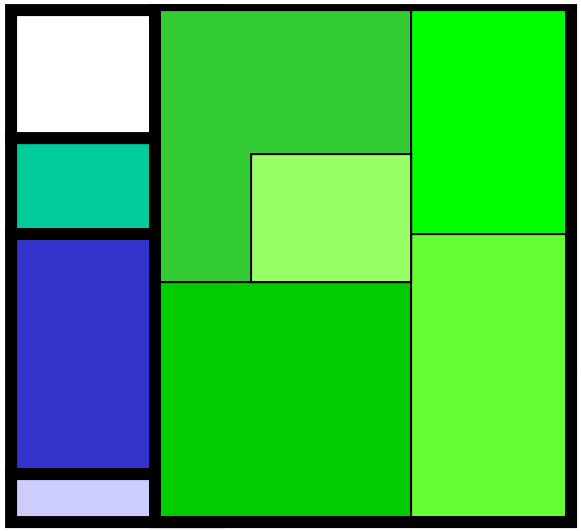


Landunit





Glacier **Wetland** **Vegetated** **Lake** **Urban**

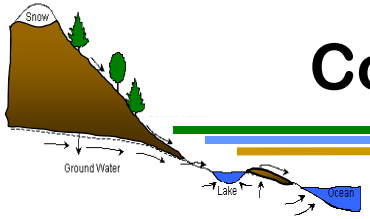


Columns

Soil Type 1

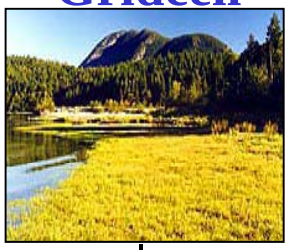
PFTs



Community Land Model subgrid tiling structure

Gridcell



Landunit





Glacier **Wetland** **Vegetated** **Lake** **Urban**

Columns

Soil Type 1

PFTs




Plant Functional Types:

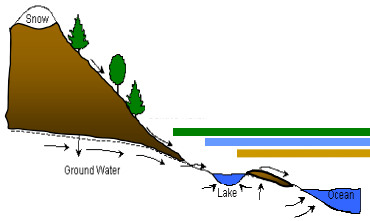
0. Bare

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

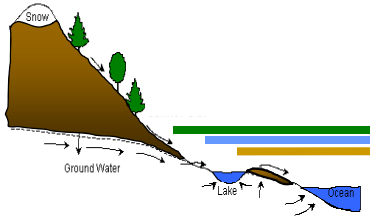


Plant Functional Type Parameters (CLM)

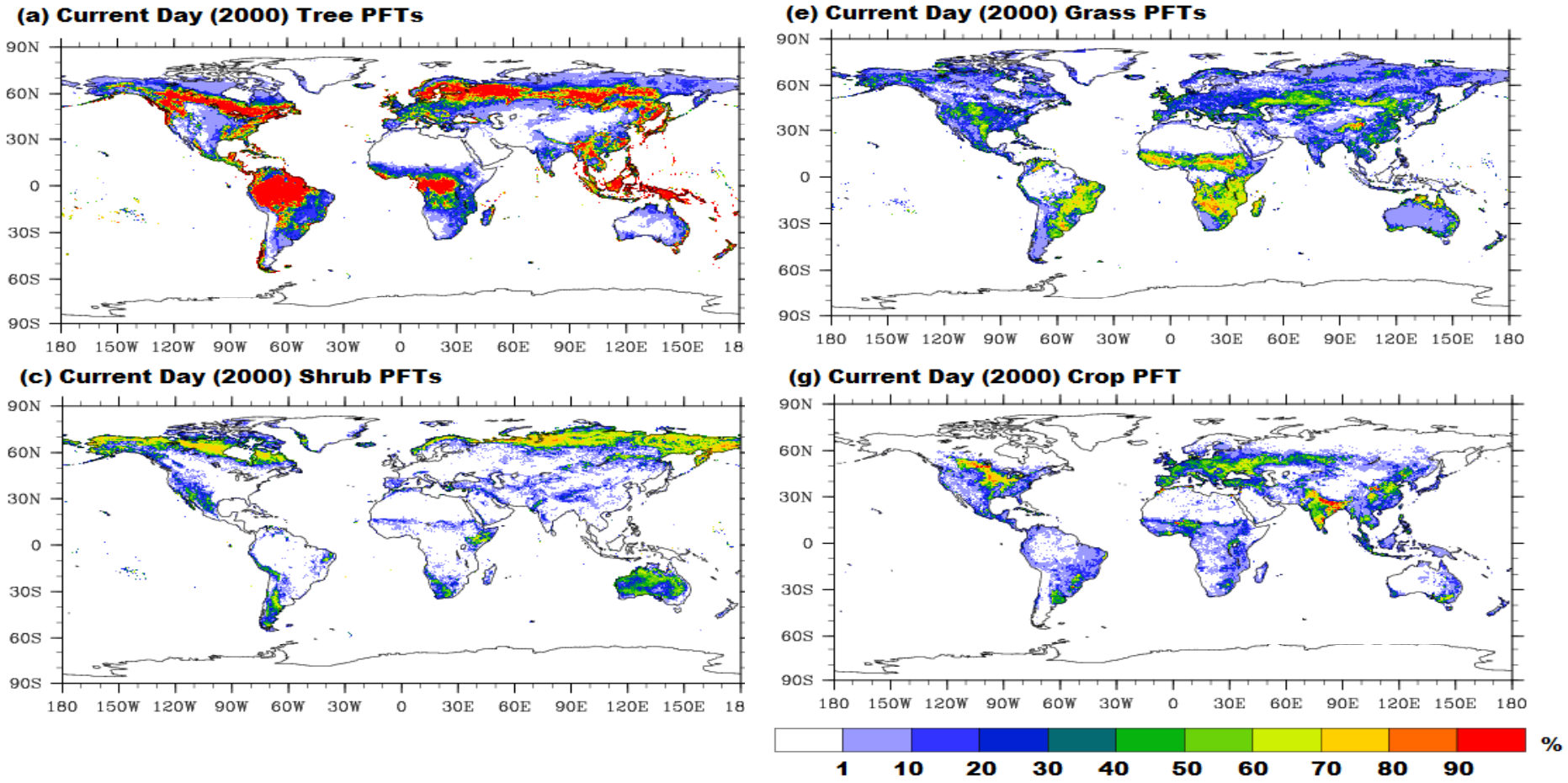
- Optical properties (visible and near-infrared):
  - Leaf angle
  - Leaf reflectance
  - Stem reflectance
  - Leaf transmittance
  - Stem transmittance

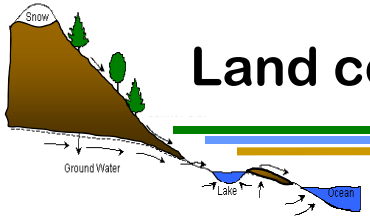
- **Land-surface models are parameter heavy!!!**

- 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)



Plant Function Type distribution in CLM4



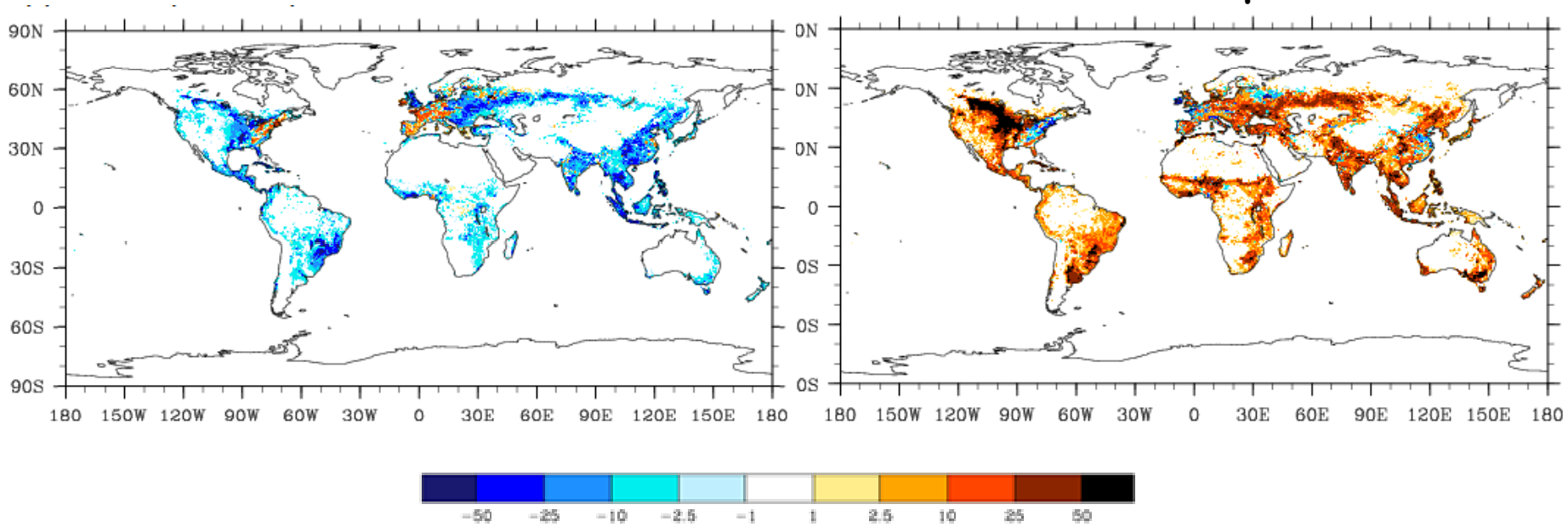


Land cover change (prescribed changes in distribution of PFTs)

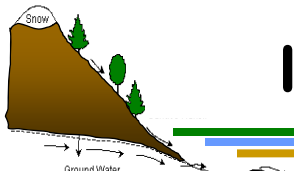
2005 – 1850

Trees

Crops

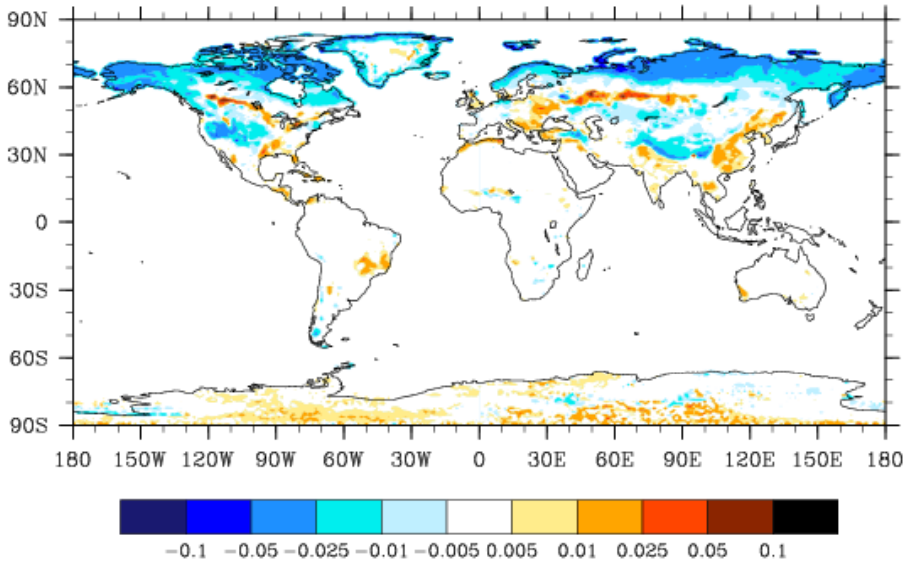


Deforestation across Eastern North America, Eastern Europe, India, China, Indonesia, SE South America for Crops

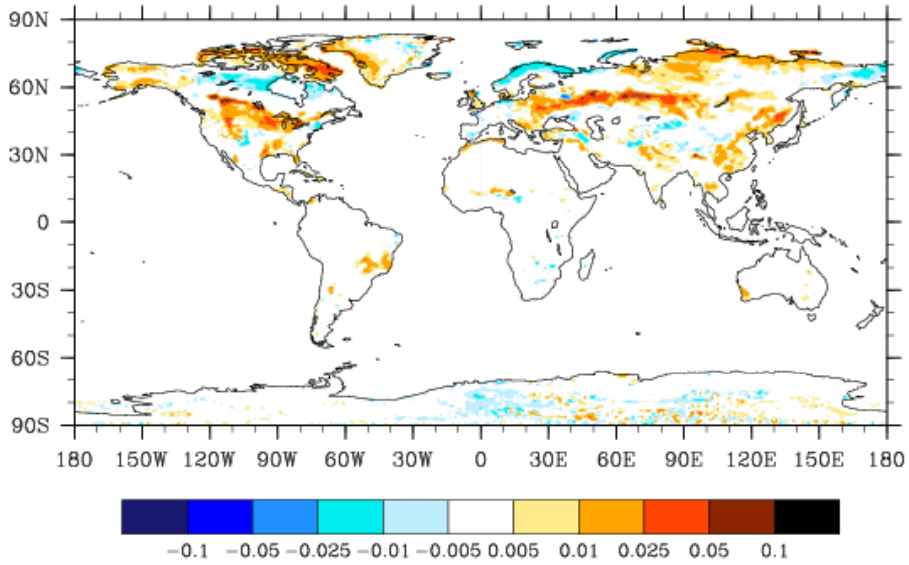


Impact of historic land cover change on climate

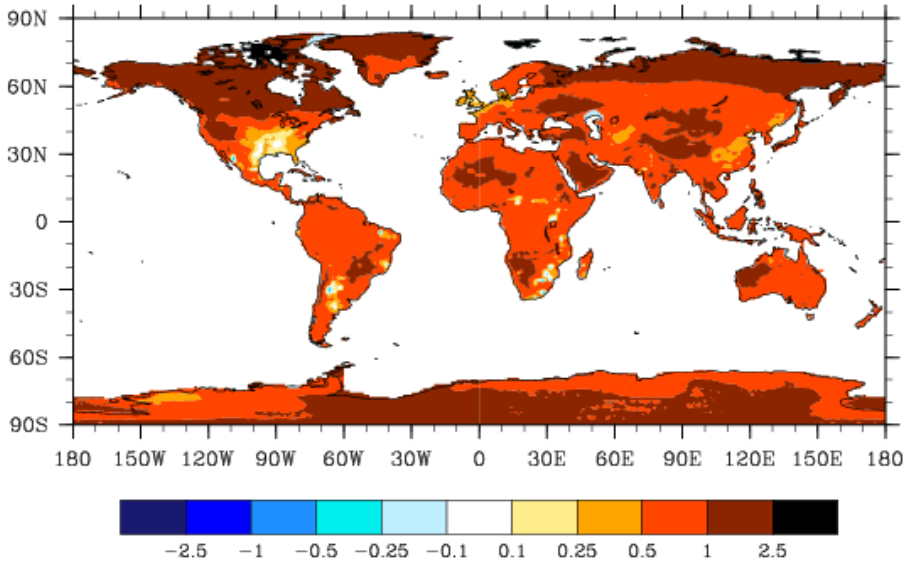
(a) Full Transient - Change in Albedo



(b) Land Cover Change Only - Change in Albedo



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



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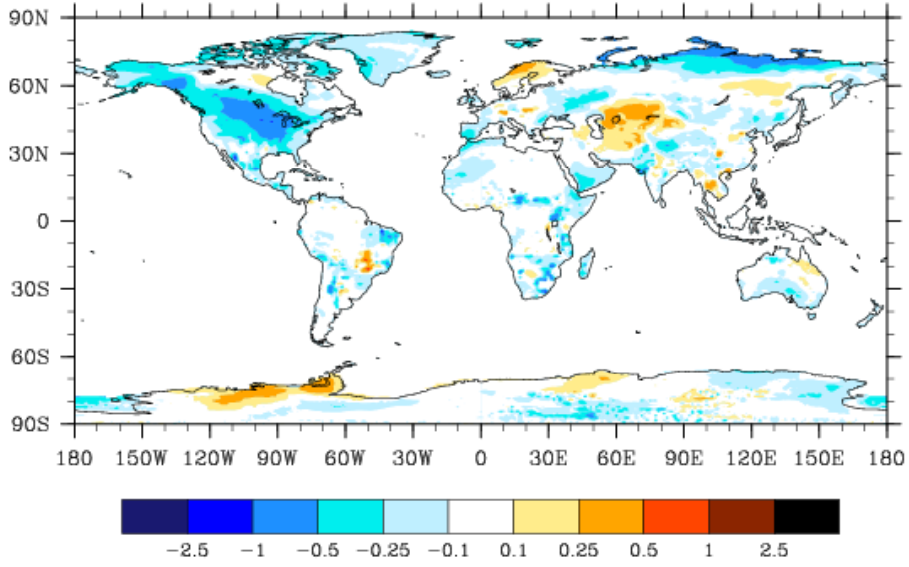
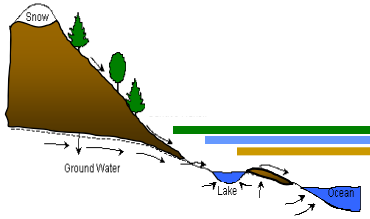


Main Features of the Community Land Model

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

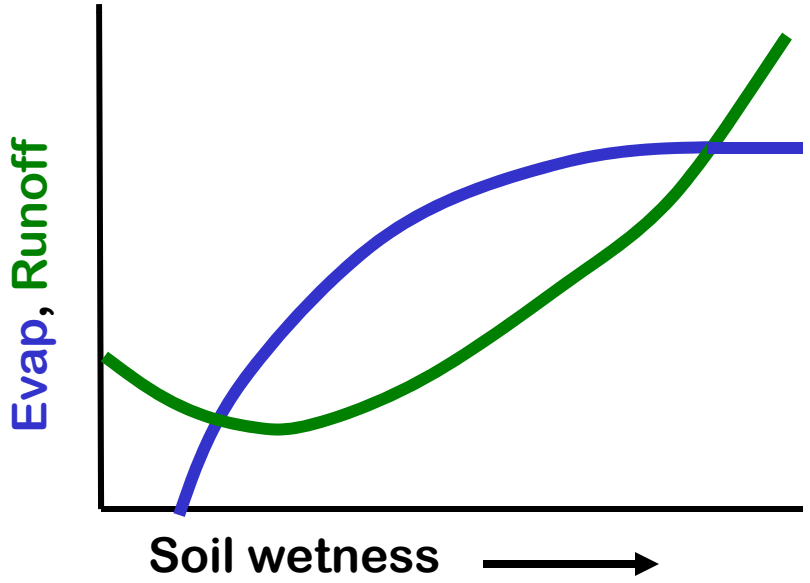


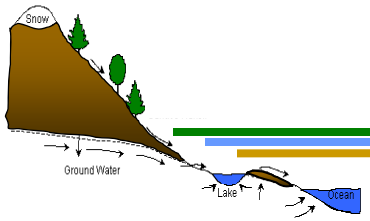
Modeling evaporation and runoff

"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).

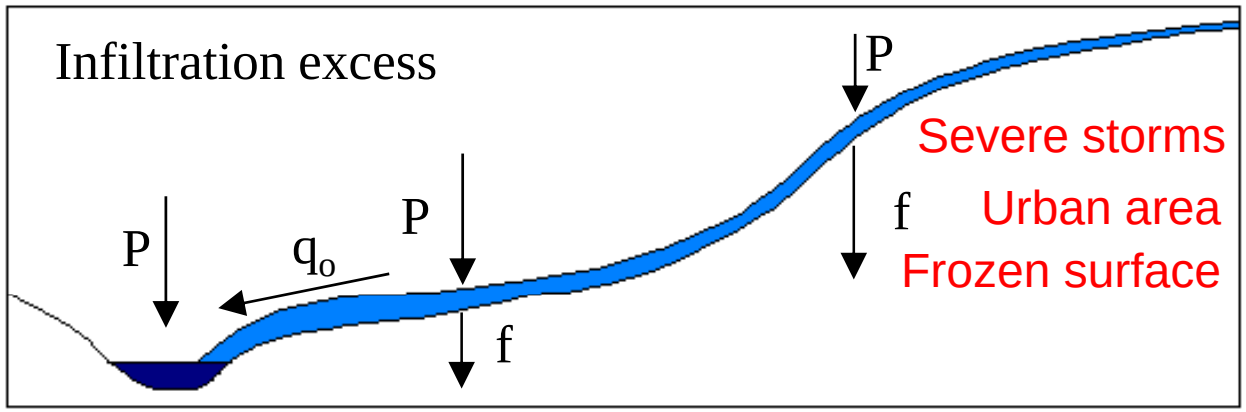
Runoff and evaporation vary non-linearly with soil moisture

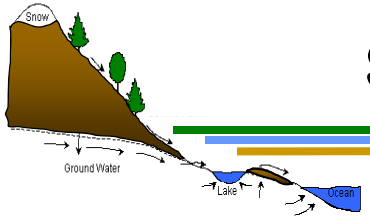




Runoff processes

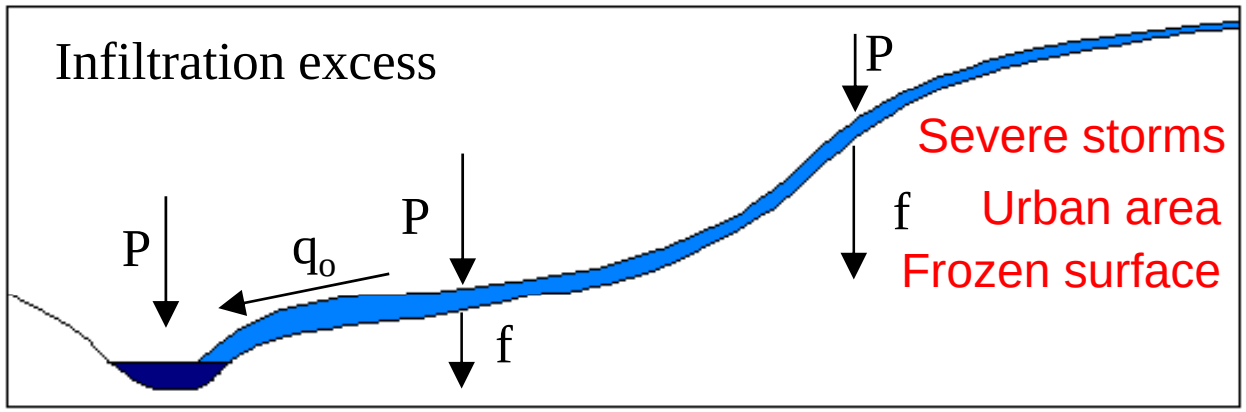
SIMTOP: TOPMODEL-based runoff

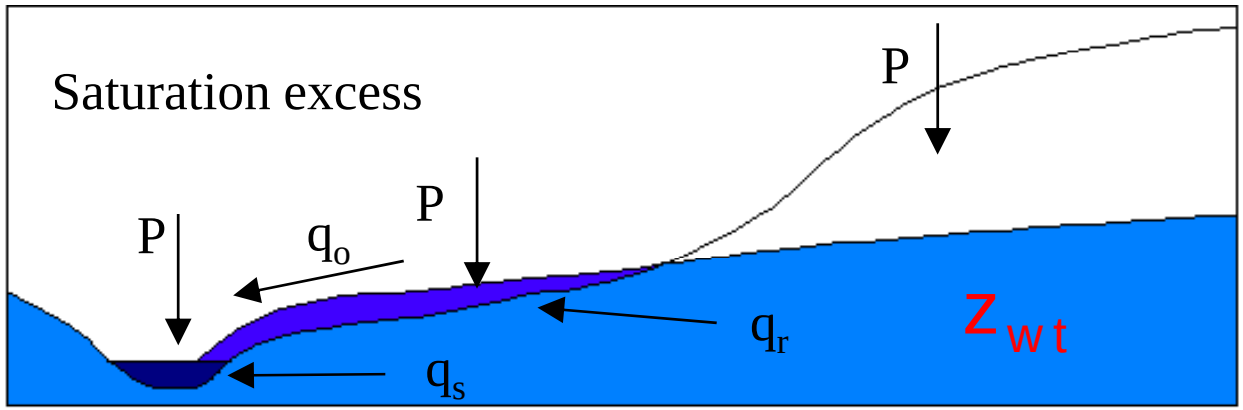


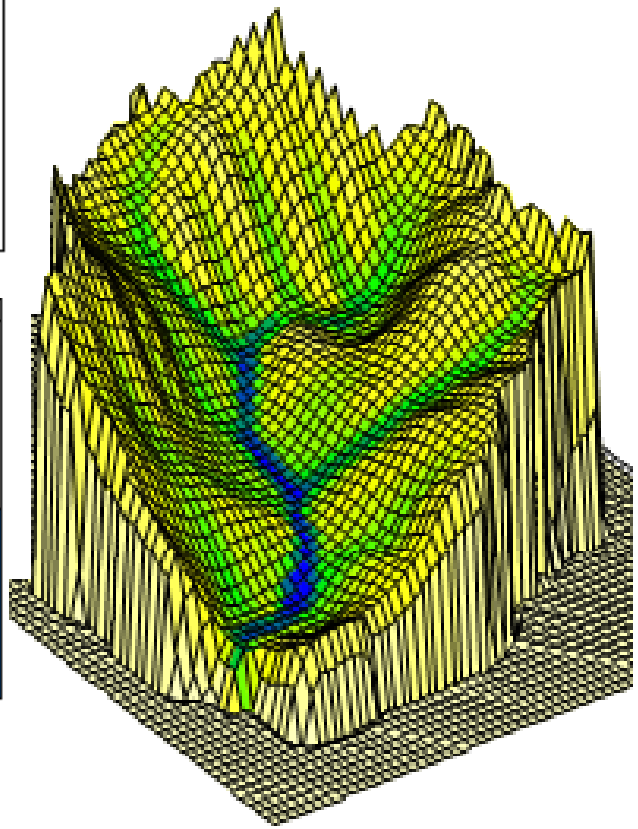


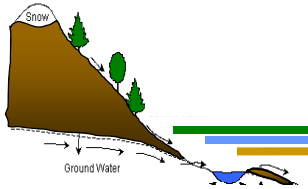
Subgrid-scale soil moisture heterogeneity

SIMTOP: TOPMODEL-based runoff





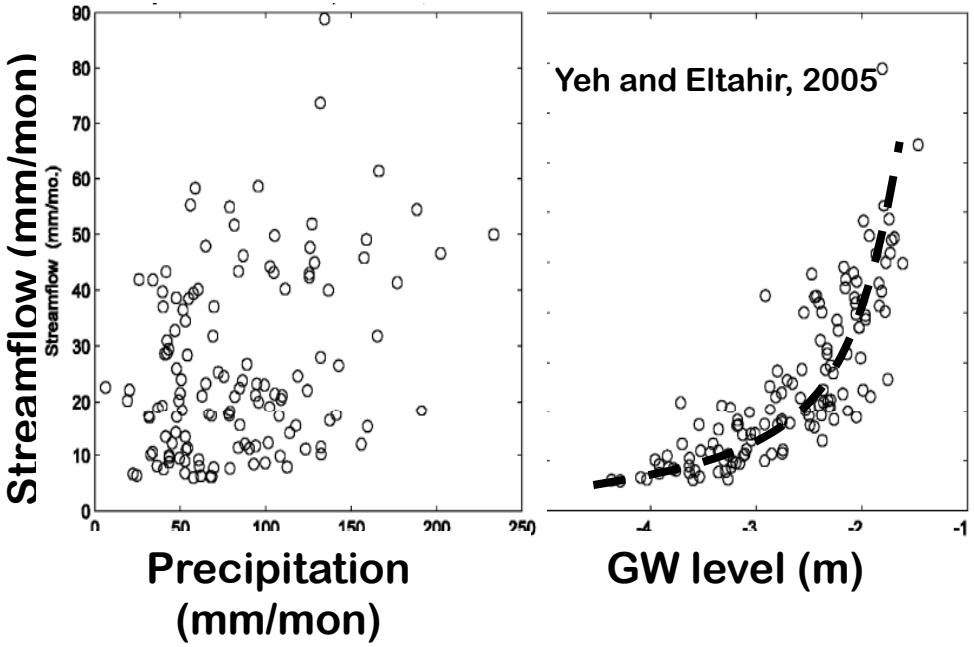


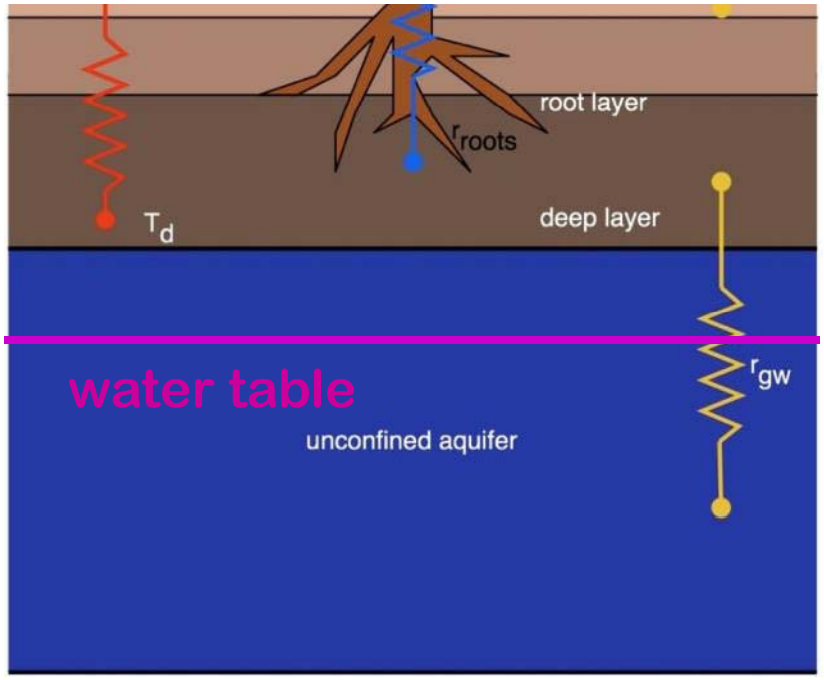


Groundwater in CLM

Groundwater exerts greater control on runoff than precip
(Yeh and Eltahir, 2005)

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

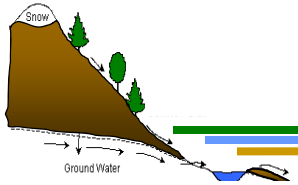




Groundwater model (SIMGM) determines water table depth

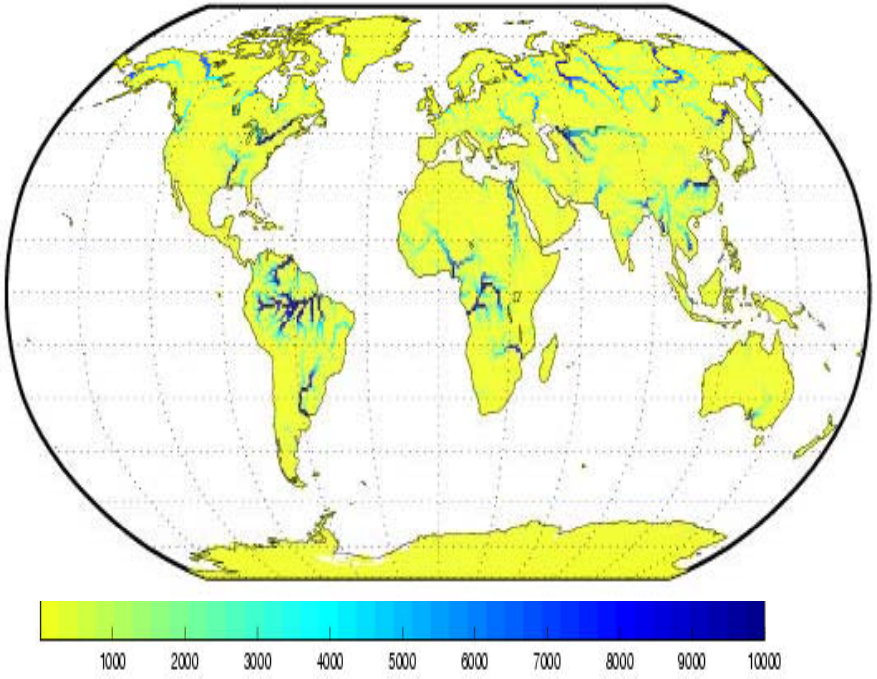
Subsurface runoff is exponential function of water table depth

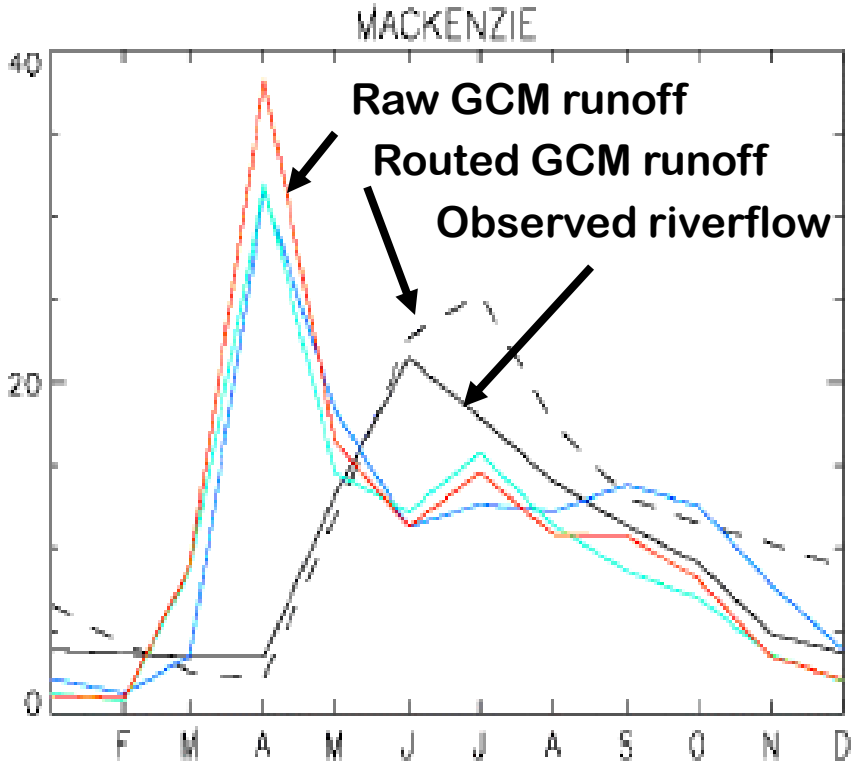
Niu and Yang, 2005

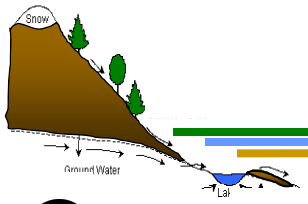


River Transport Model

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

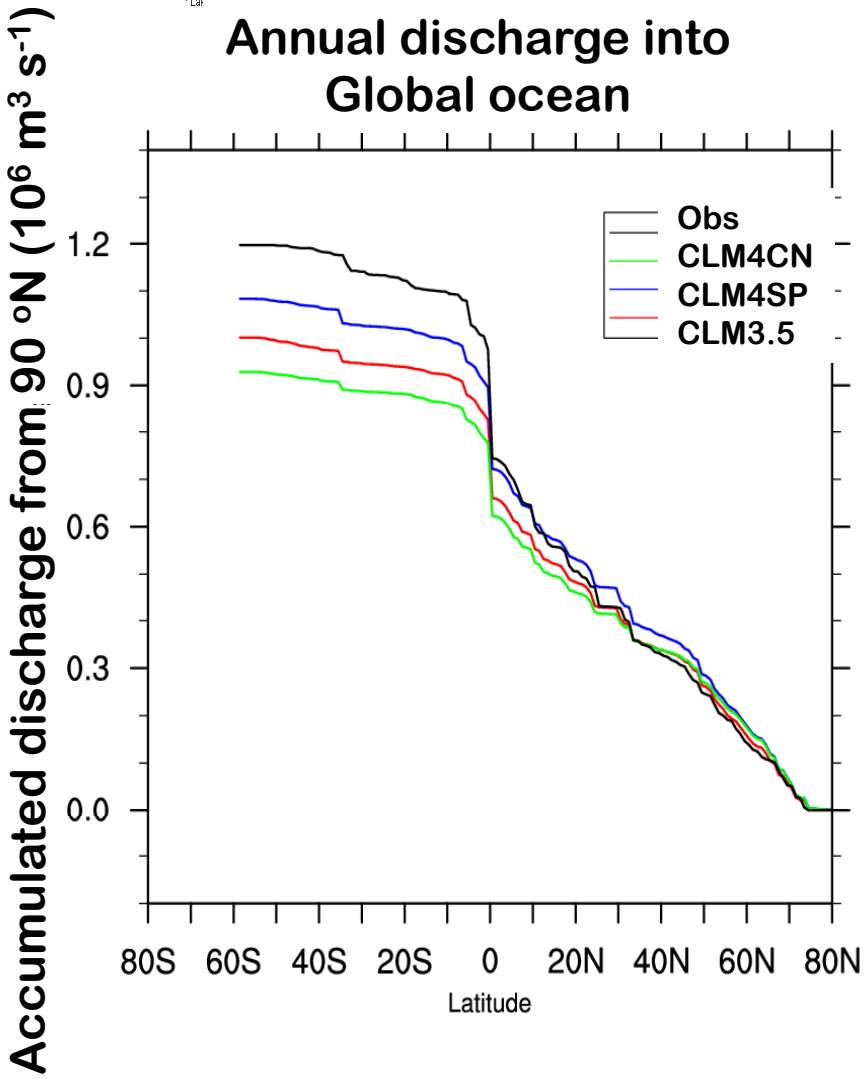




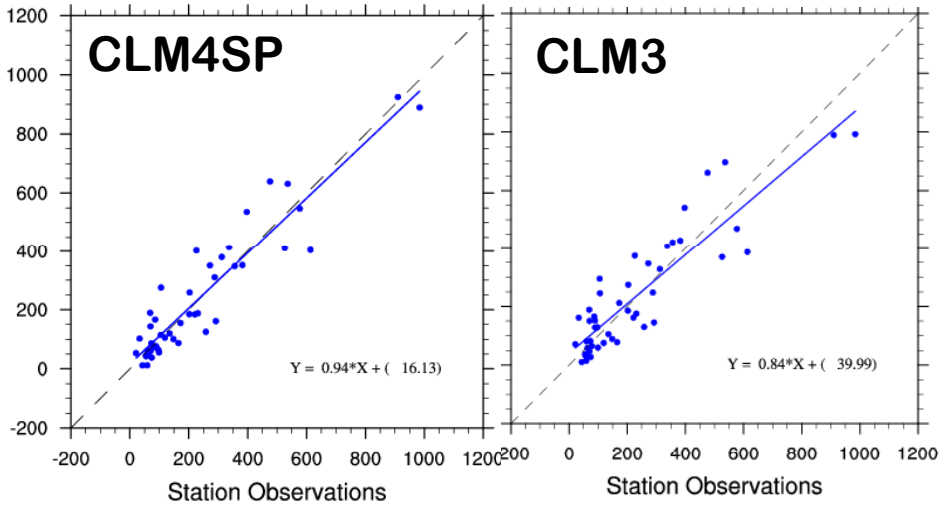


River Discharge

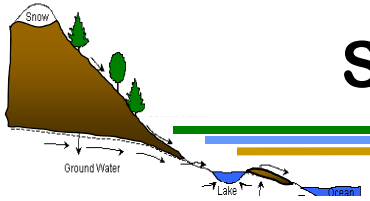
Annual discharge into Global ocean



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

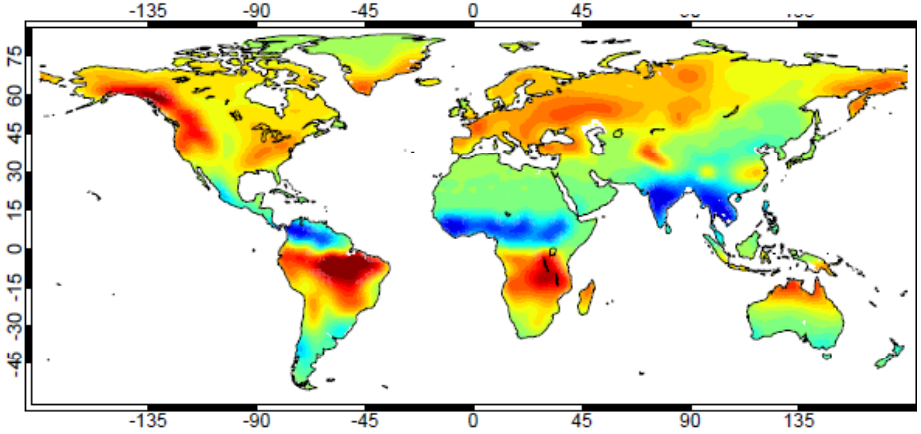


CLM3: r = 0.86
CLM3.5: r = 0.87
CLM4SP: r = 0.94
CLM4CN: r = 0.77

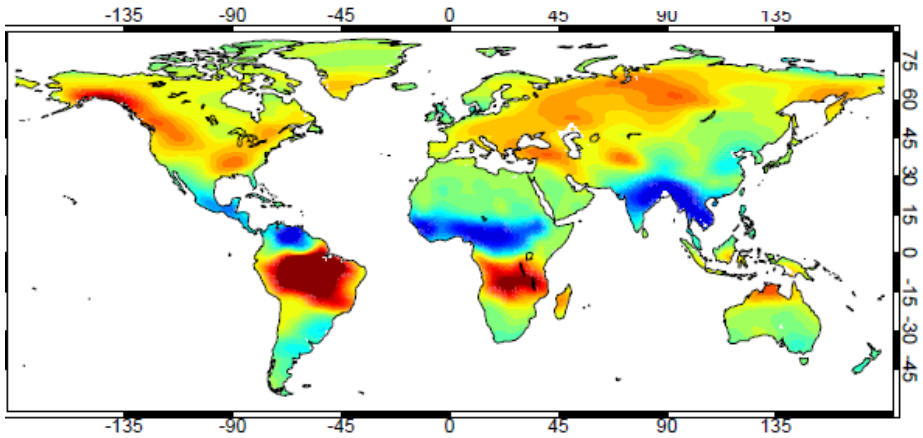


Soil (and snow) water storage (MAM – SON)

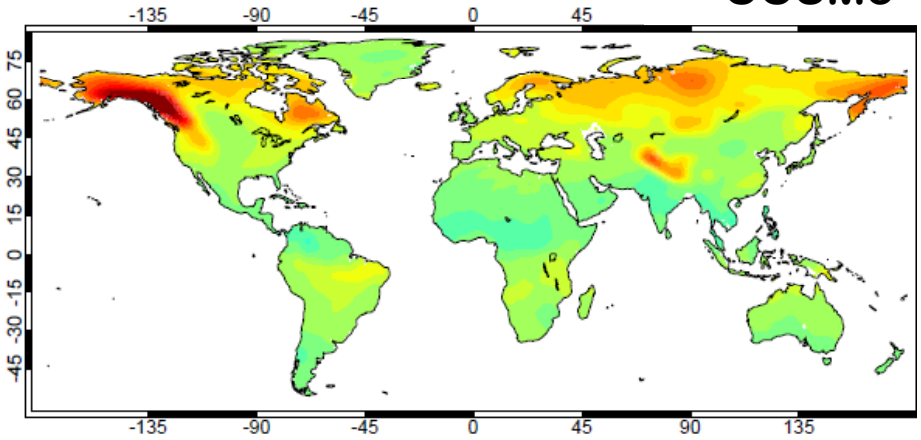
CCSM4



GRACE (obs)



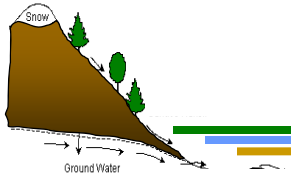
CCSM3



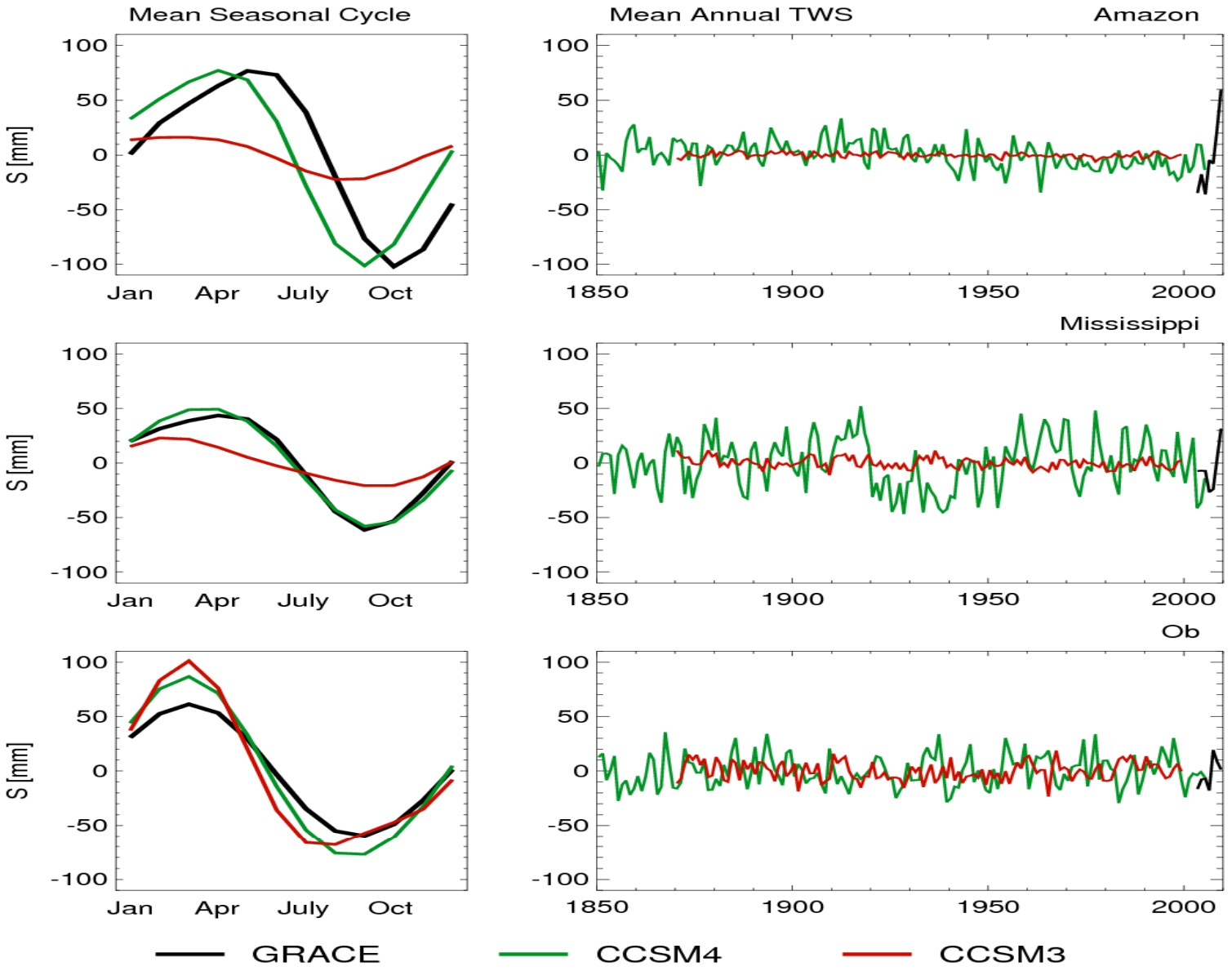
300 200 100 0 -100 -200 -300 (mm)

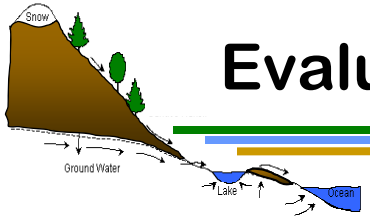
GRACE satellite measures small changes in gravity which on seasonal timescales are due to variations in water storage

CCSM3 and CCSM4 data from 1870 and 1850 control

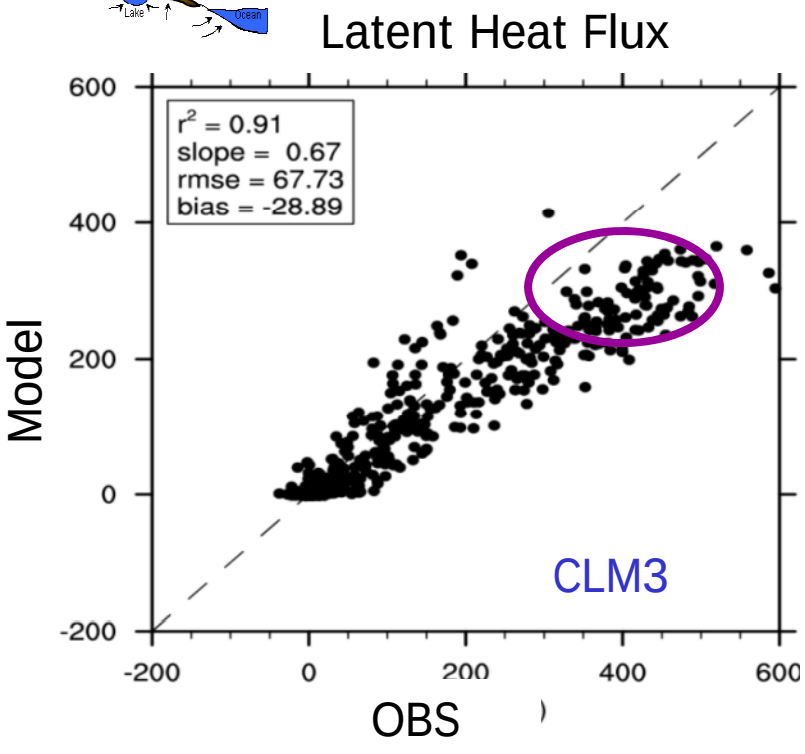


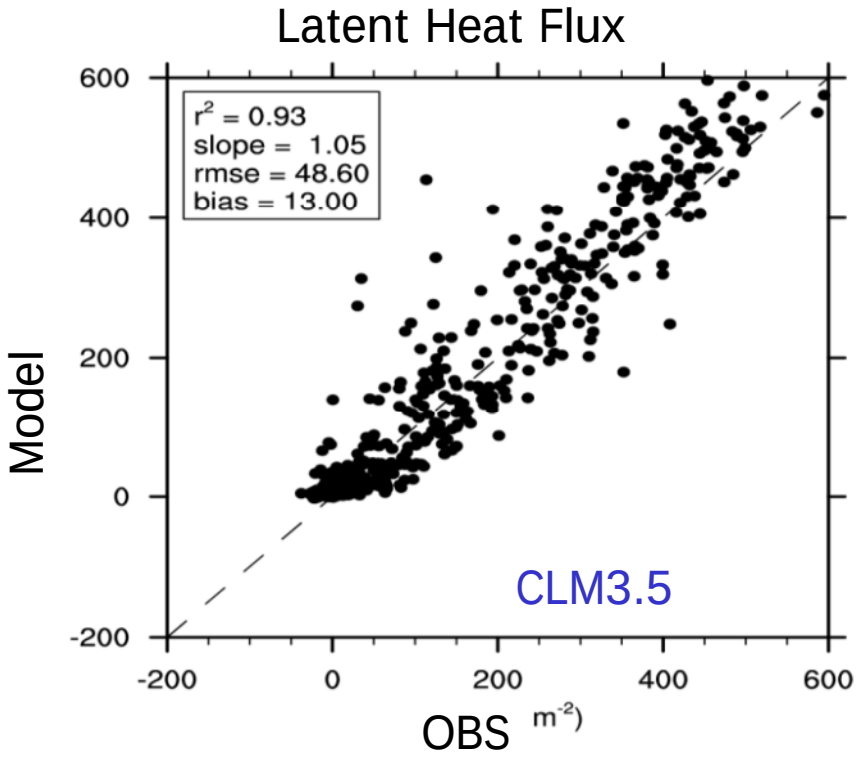
Total Land Water Storage (CCSM vs GRACE)

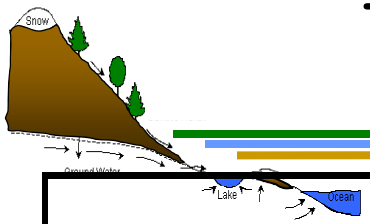




Evaluating the model: Abracos tower site (Amazon)

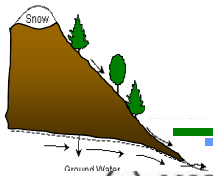




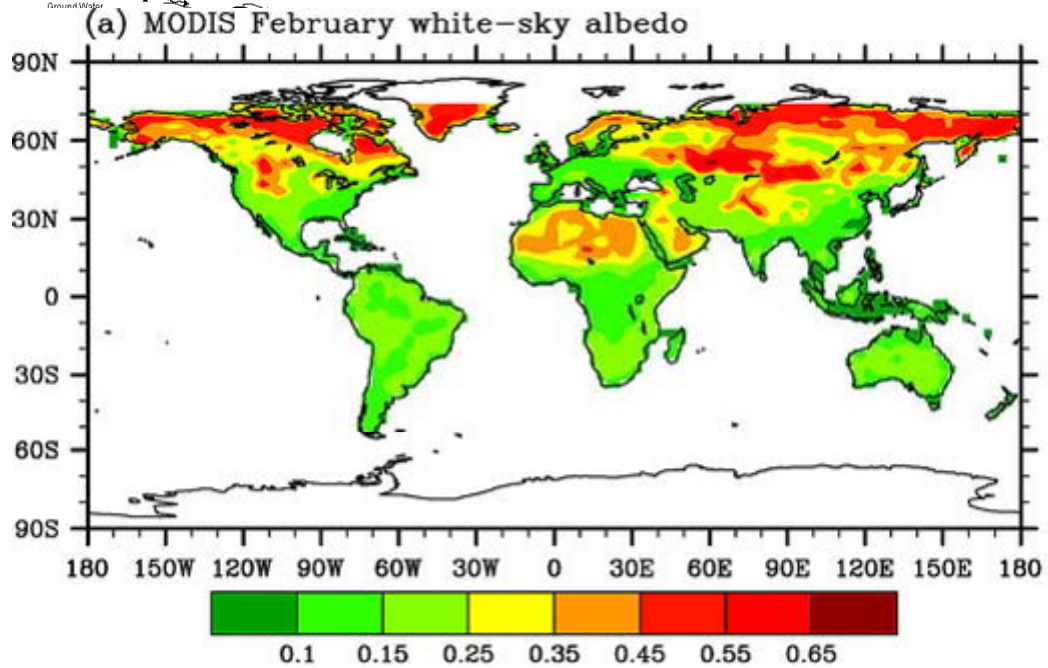


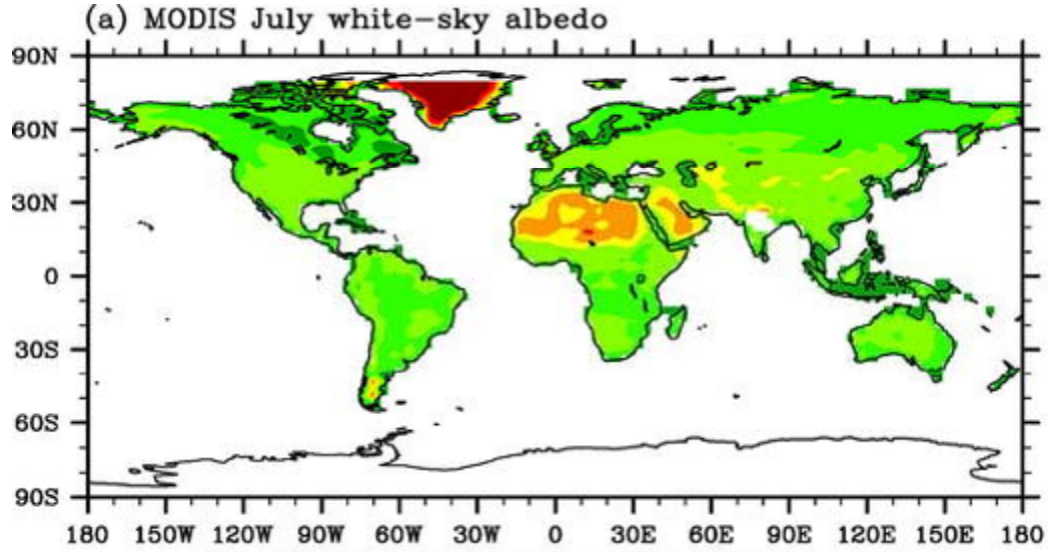
Tower flux statistics (15 sites incl. tropical, boreal, mediteranean, alpine, temperate; hourly)

	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



Modeling surface albedo



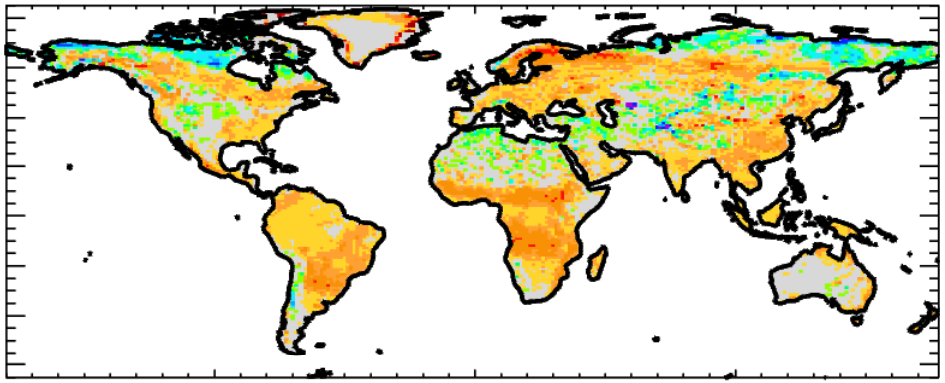


Surface albedo a function of

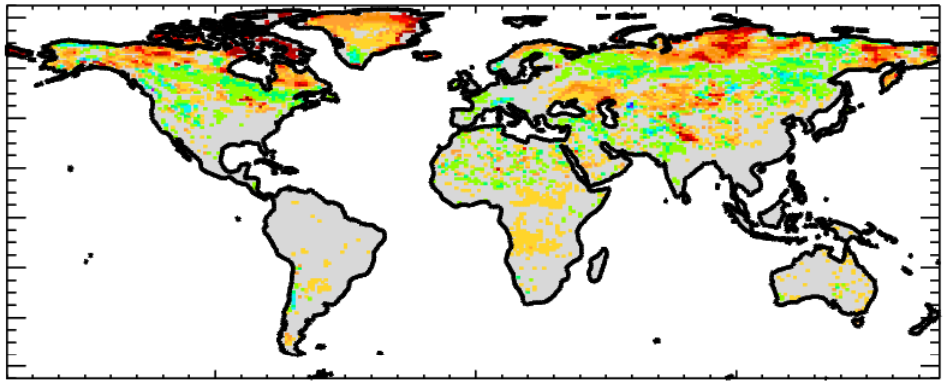
- Vegetation cover and type
- Snow cover
- Snow age
- Solar zenith angle
- Soil moisture
- Amount of direct vs diffuse solar radiation
- Amount of visible vs IR solar radiation

Surface albedo (CLM offline compared to MODIS)

CLM3.5 – Obs

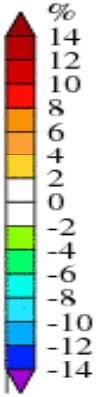


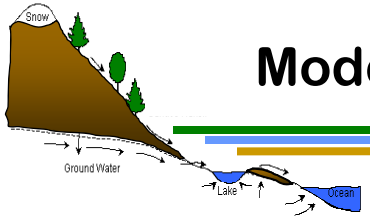
CLM4SP – Obs



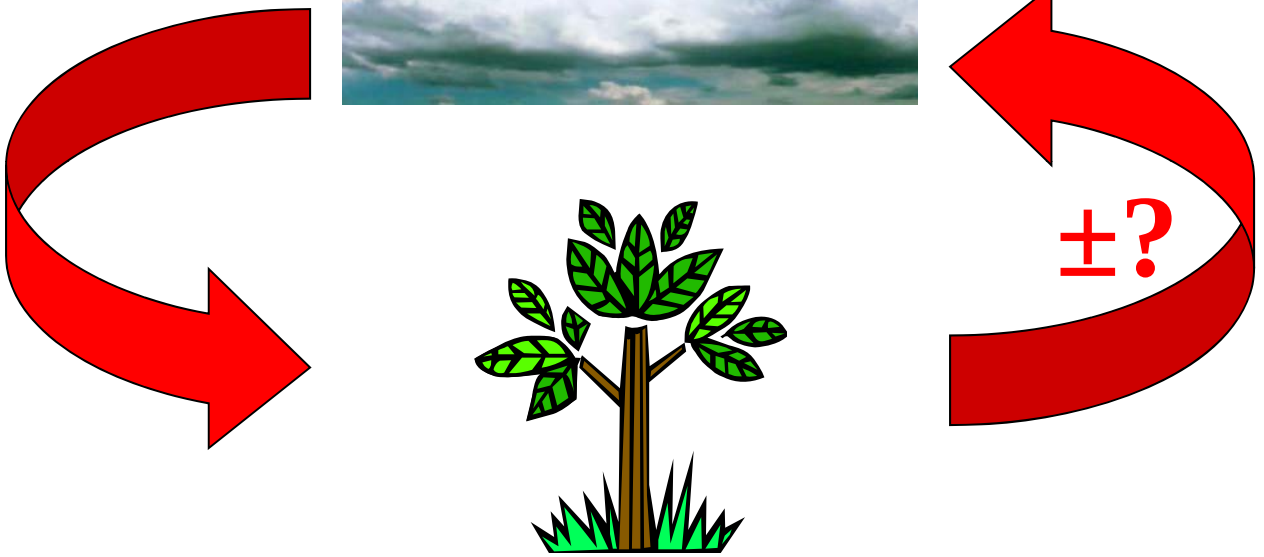
	Bias (%)		RMSE (%)	
Model	**Snow-free**	**Snow depth> 0.2m**	**Snow-free**	**Snow depth > 0.2m**
CLM3.5	**2.7**	**-5.0**	**4.1**	**11.9**
CLM4SP	**0.4**	**2.9**	**2.0**	**13.2**

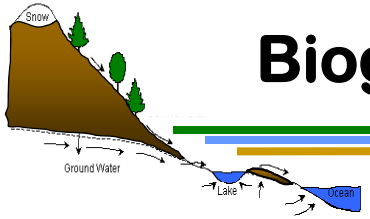
Note: MODIS albedo biased high for snow at high zenith angle
(Wang and Zender, 2010)



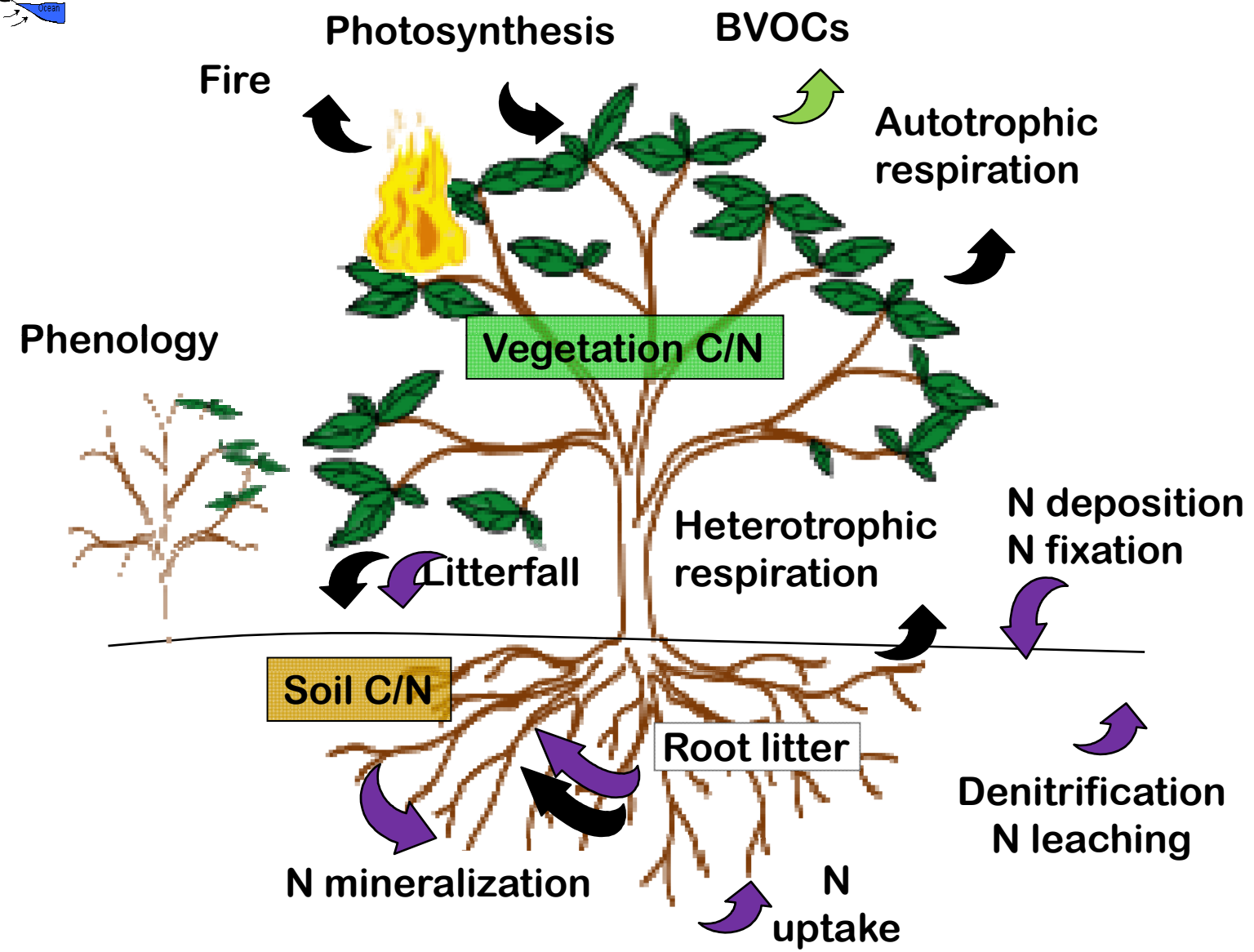


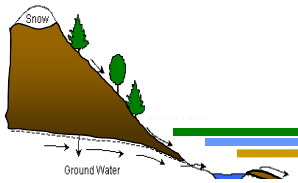
Modeling the Ecosystem and Ecosystem-Climate Interactions





Biogeochemical cycles (Carbon, Nitrogen) in CLM4





Carbon and Nitrogen cycling (CLM-CN)

Carbon cycle

Nitrogen cycle

Internal (fast)

External (slow)

Atm CO_2

photosynthesis

Plant

respiration

litterfall & mortality

3 C and 3 N litter pools

Litter / CWD

decomposition

4 C and 4 N soil pools

Soil Organic Matter

denitrification

N deposition

assimilation

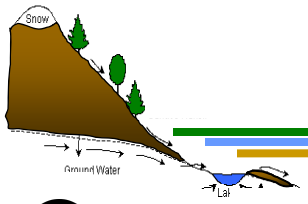
Soil Mineral N

N fixation

mineralization

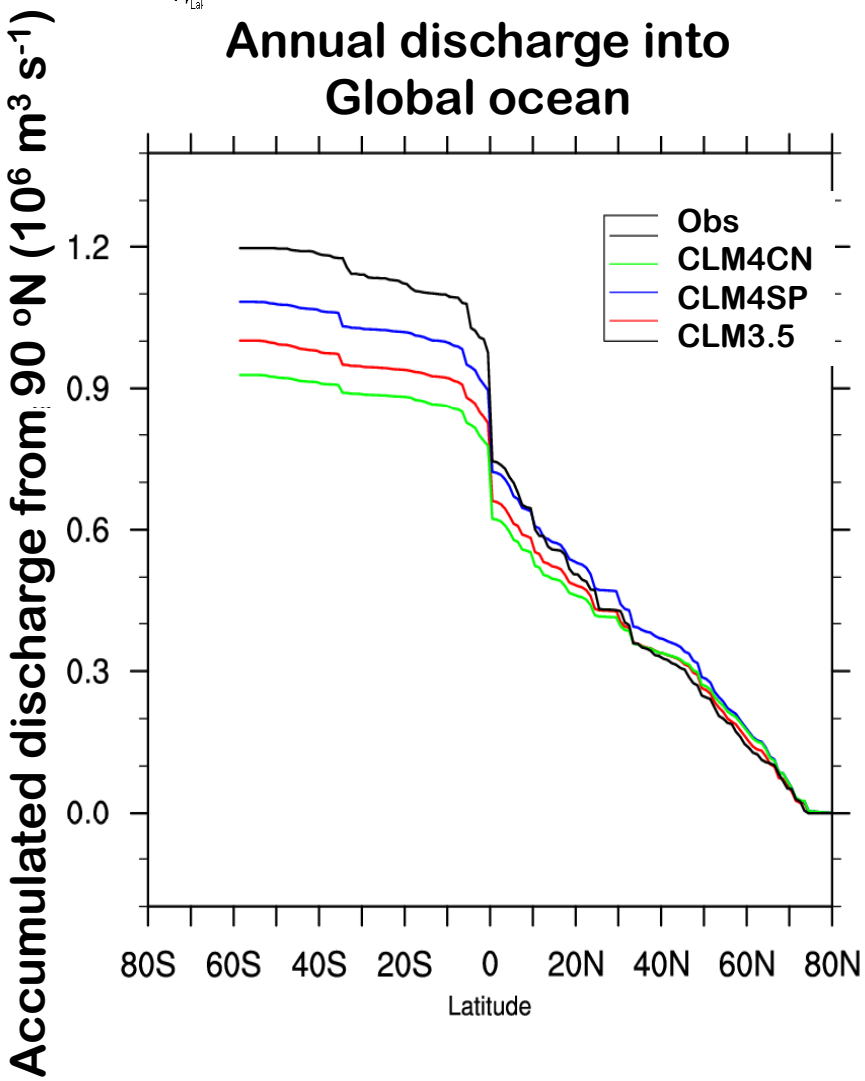
N leaching

Based on Biome-BGC, Thornton et al., 2009



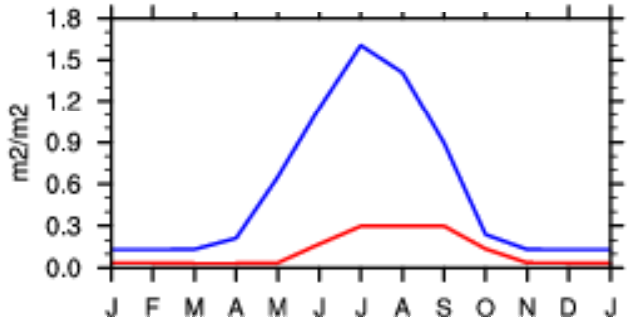
Prognostic vegetation state with CN active

Annual discharge into Global ocean

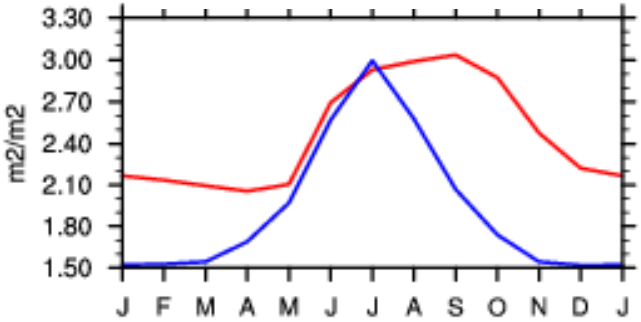


LAI

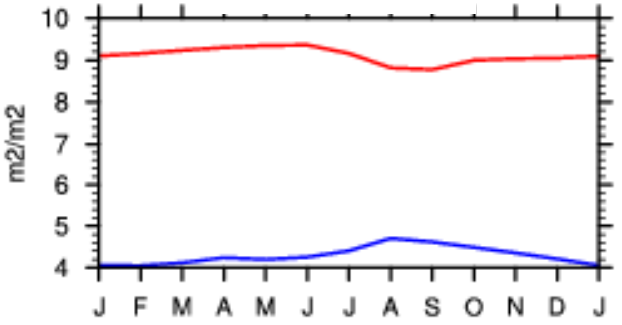
Alaskan Arctic

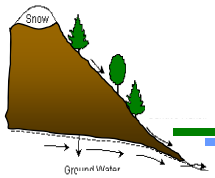


Northwest Europe

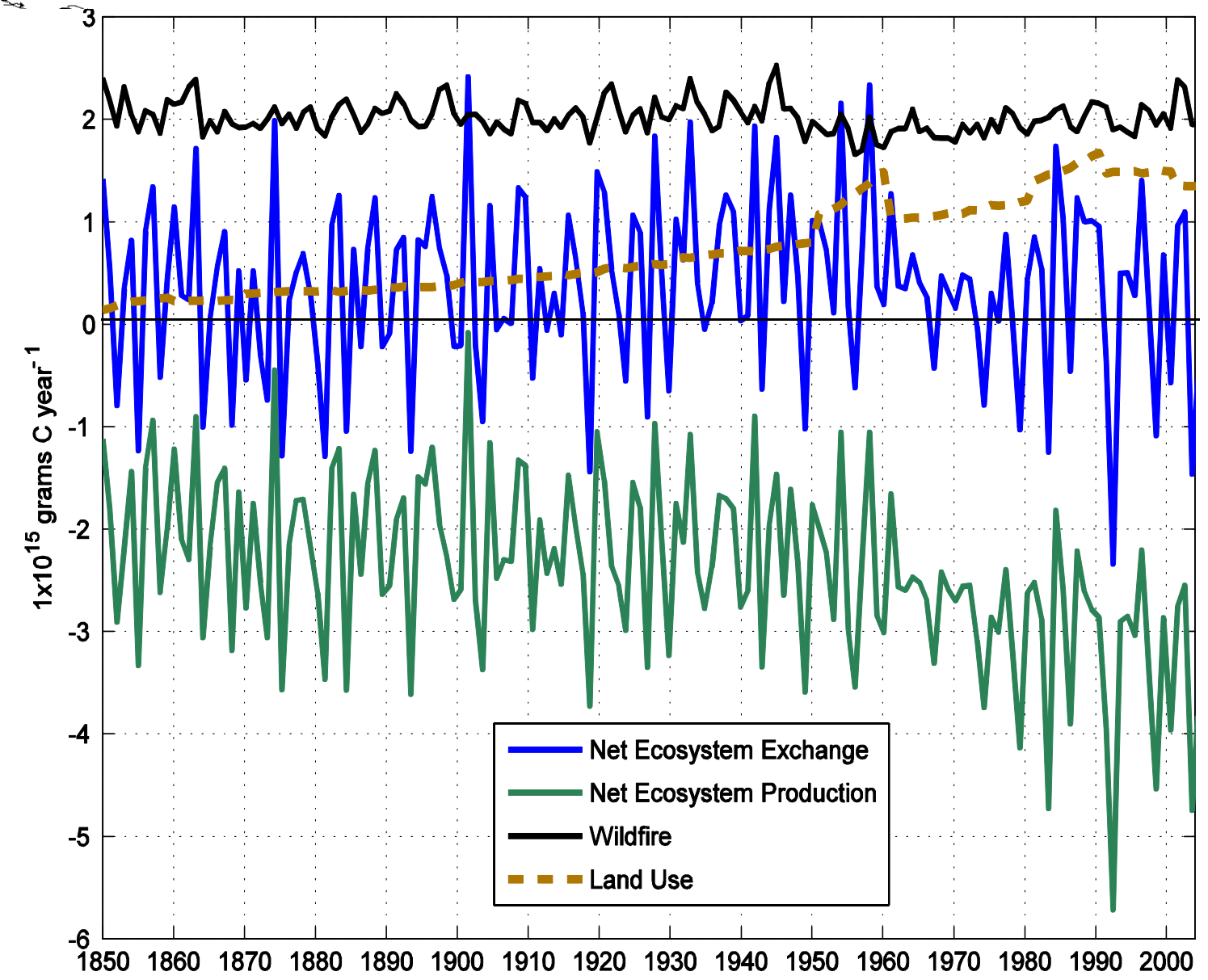


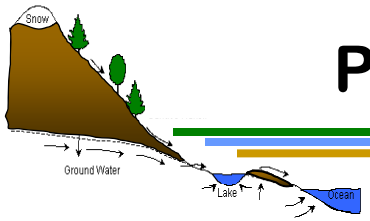
Amazonia





Land Carbon Fluxes
+ is flux to atm, CESM1 (BGC) 20th C





Putting it all together: CLM on a single slide!

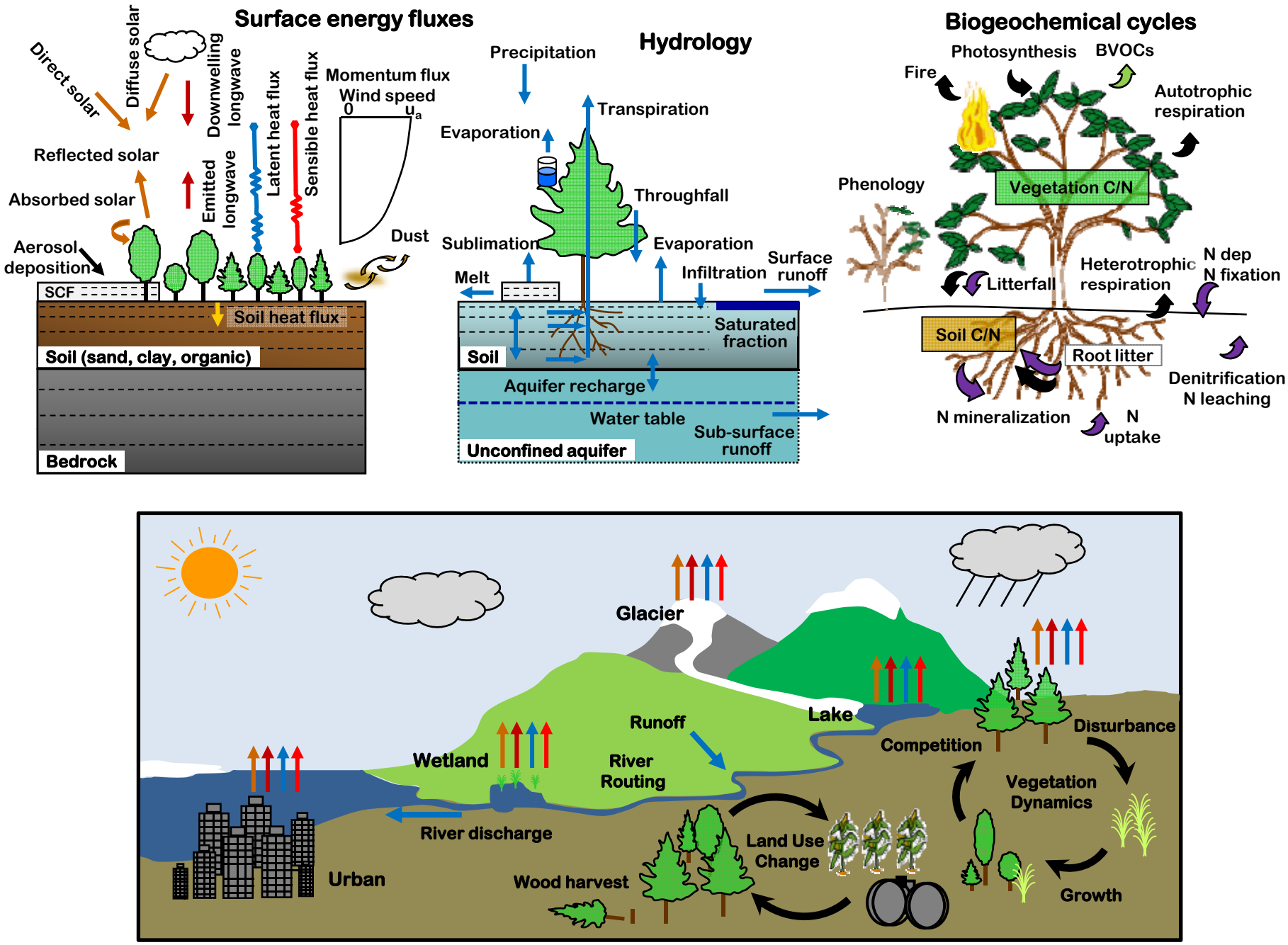
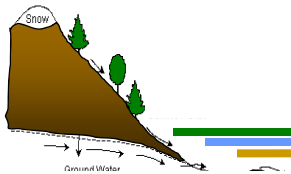
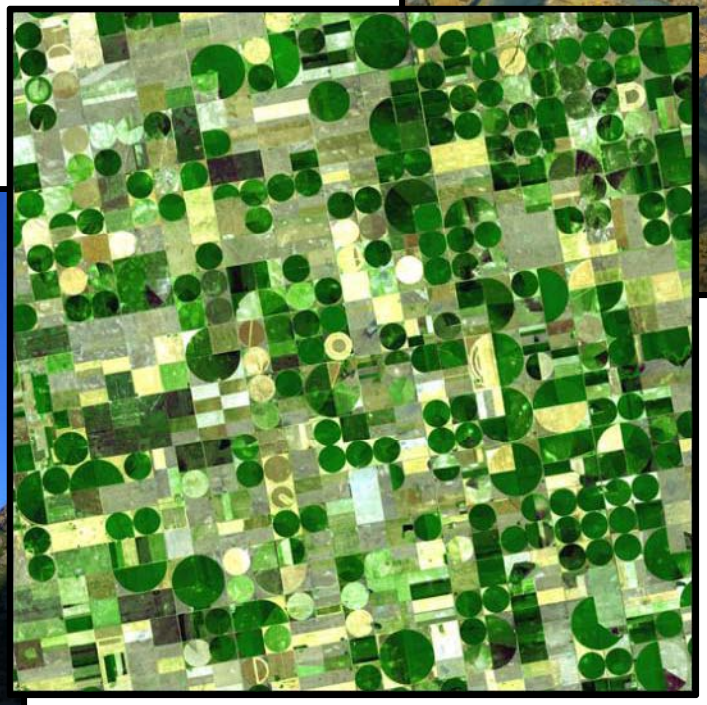


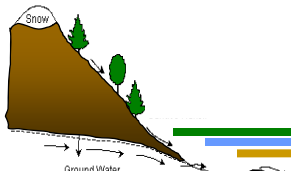
Figure 1: Lawrence et al., Journal Advances Modeling Earth Systems, 2011



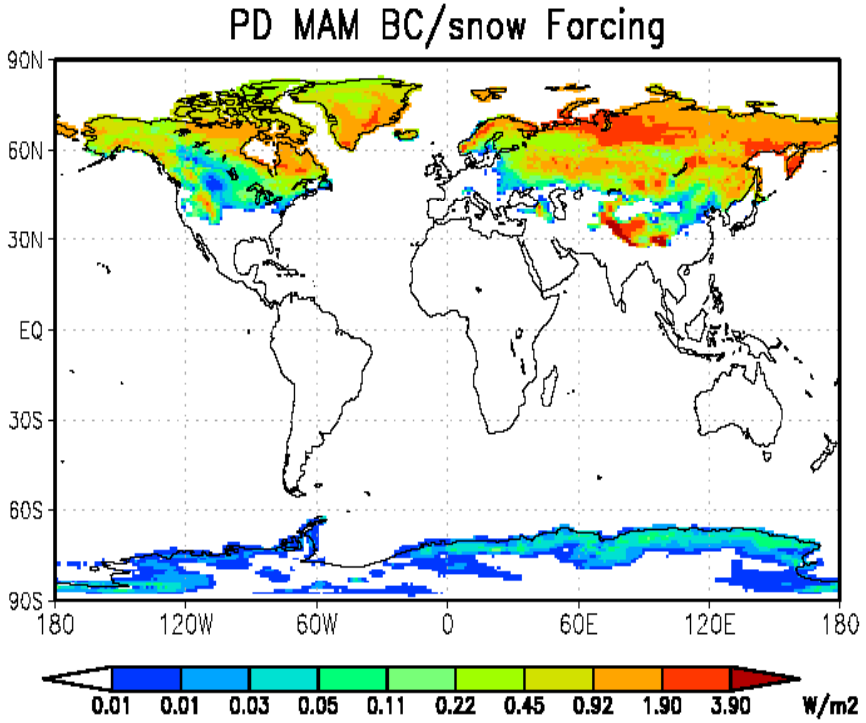
Future and Ongoing Challenges

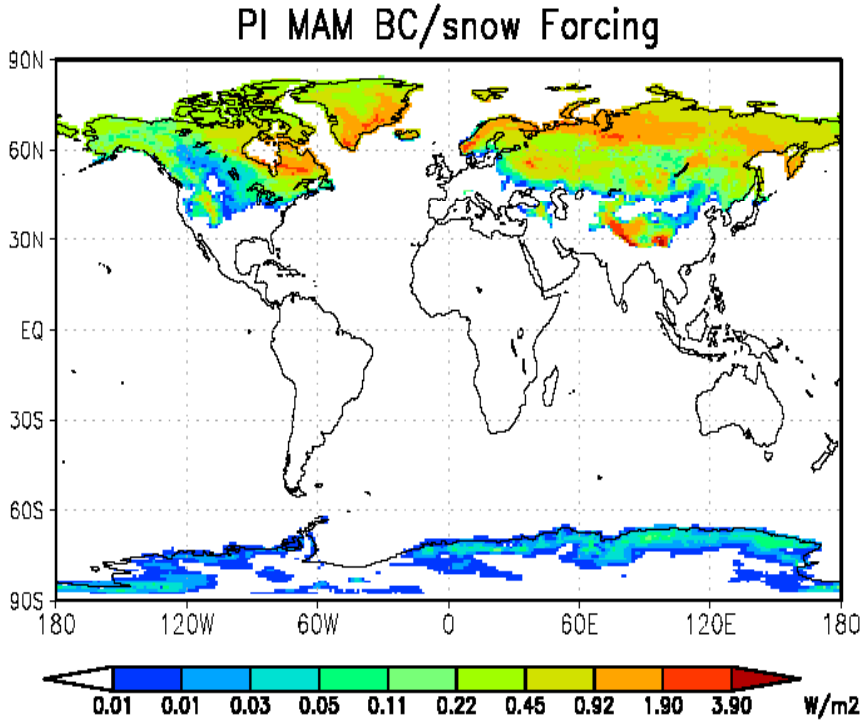
- **With steadily increasing complexity, just keeping everything operating *and* working together well is a challenge**
- **Heterogeneity**
- **C, N, water interactions**
- **…**





Black carbon snow forcing in CCSM4

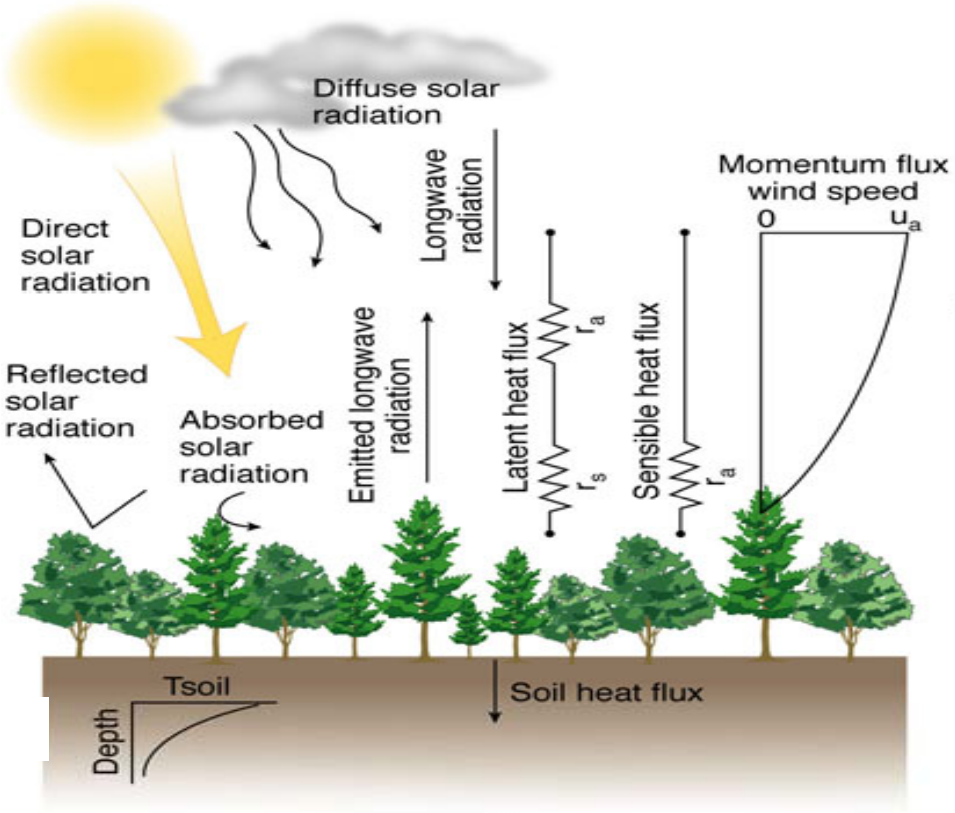




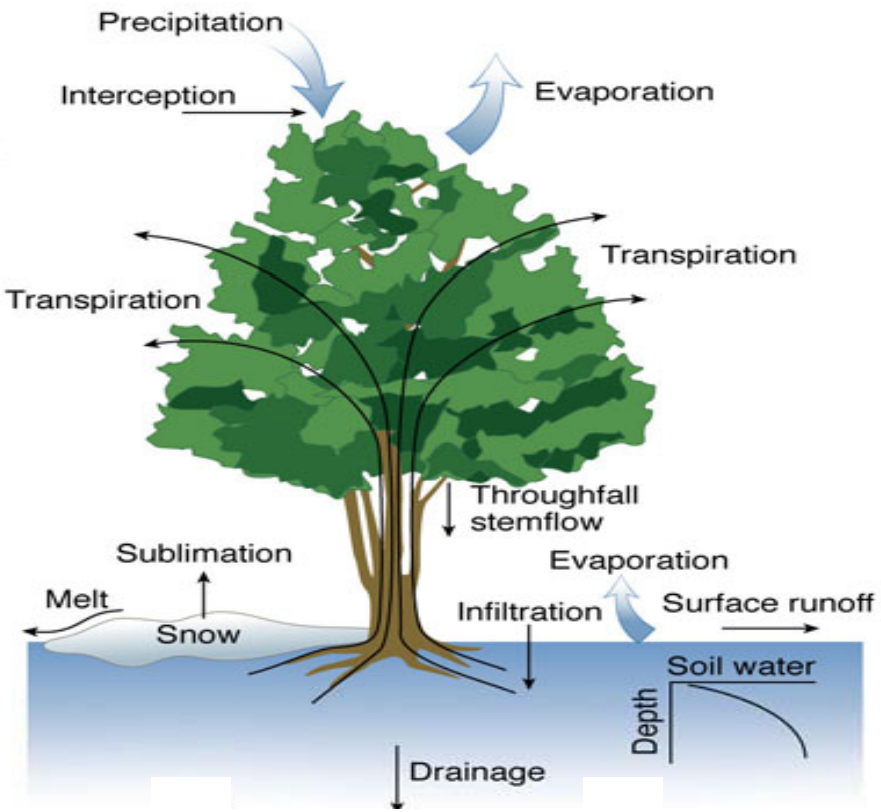
Species	Pre-Industrial (1850-1869) (W m^{-2})	Present (1986-2005) (W m^{-2})
Black carbon	0.023	0.037
Mineral dust	0.046	0.036
Combined effect	0.075	0.083

CLM3

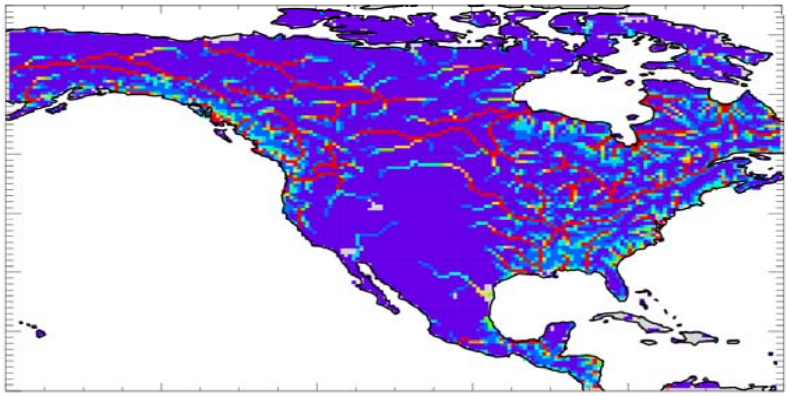
Surface energy fluxes



Hydrology



River transport model

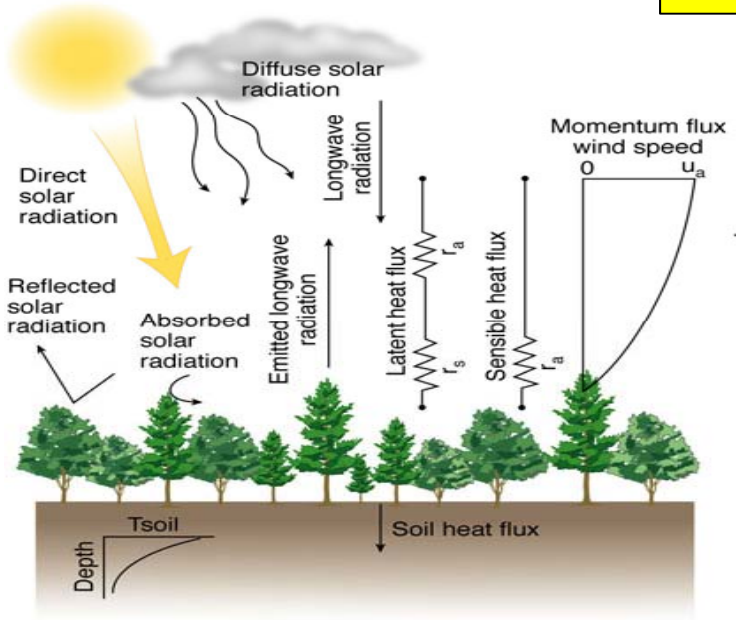


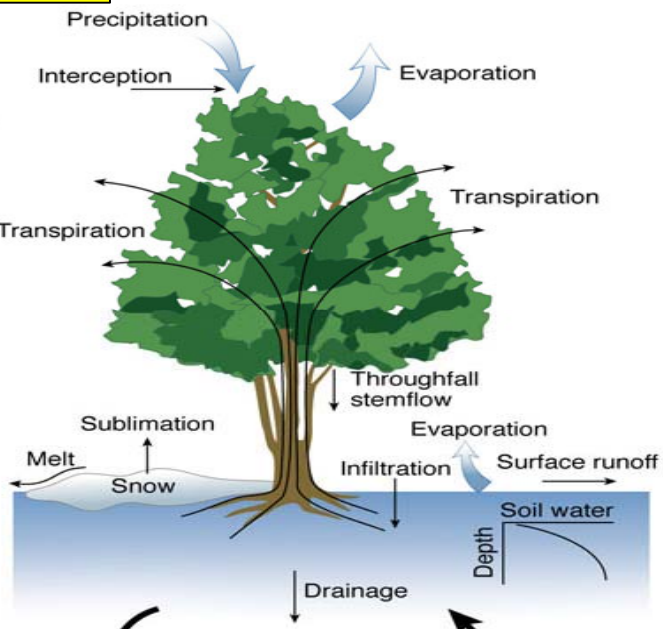
Surface Energy Fluxes

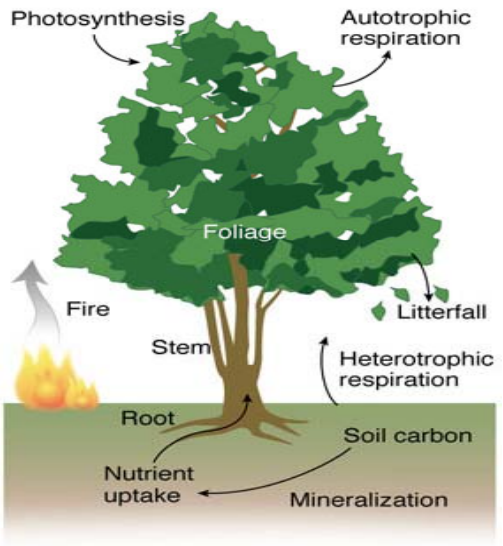
CLM4

Hydrology

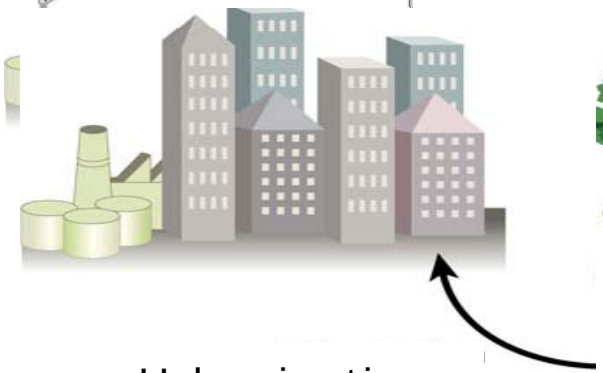
Carbon and Nitrogen Cycling



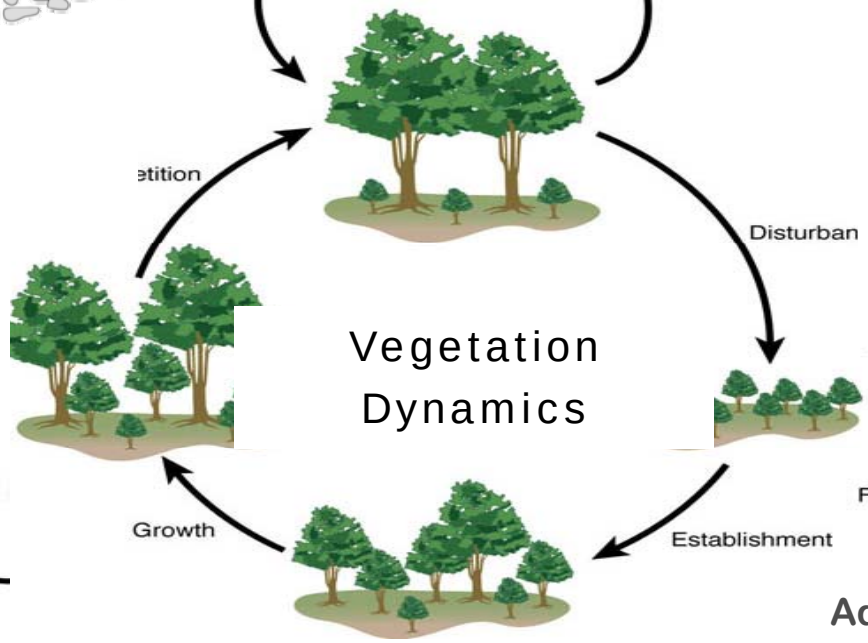




Permafrost

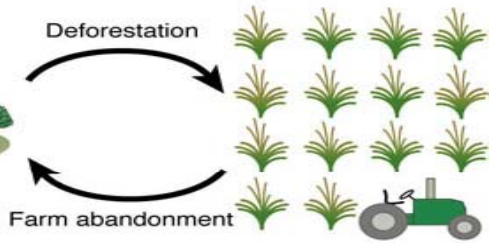


Urbanization

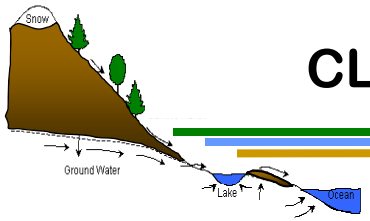


Vegetation Dynamics

Land cover / use



Adapted from Bonan, 2008



CLM near-term development activities, CLM4.x (~ 1 year)

- **Crops and irrigation (by end of summer) – still CLM4.0**
  - Unified PFT physiology file in netCDF
  - Connections not perfect
- **Revised cold region hydrology**
  - Impedance factor, root depth for Arctic veg, perched water table
- **Gross Primary Productivity**
  - Canopy radiation, update photosynthesis model (co-limitation)
- **Improved fire algorithm including human triggers and suppression**
  - Kloster et al., *Biogeosciences*, 2010
- **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

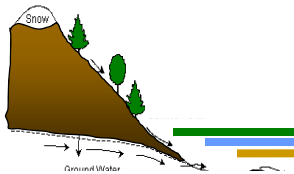
- CLM4.0 User's Guide [html] [pdf] (Last update: Jun/17/2010)
- What's new in the CESM1.0 release of CLM4? [pdf]
- What's new in CLM4.0 relative to CLM3.5? [pdf]
- CLM4.0 Technical Note [pdf] (Last update: Jun/17/2010)
- CLM4.0 Urban Model Technical Note [pdf] (Last update: Jun/17/2010)
- CLM4.0 Carbon-Nitrogen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

Model output and offline forcing data and diagnostic plots

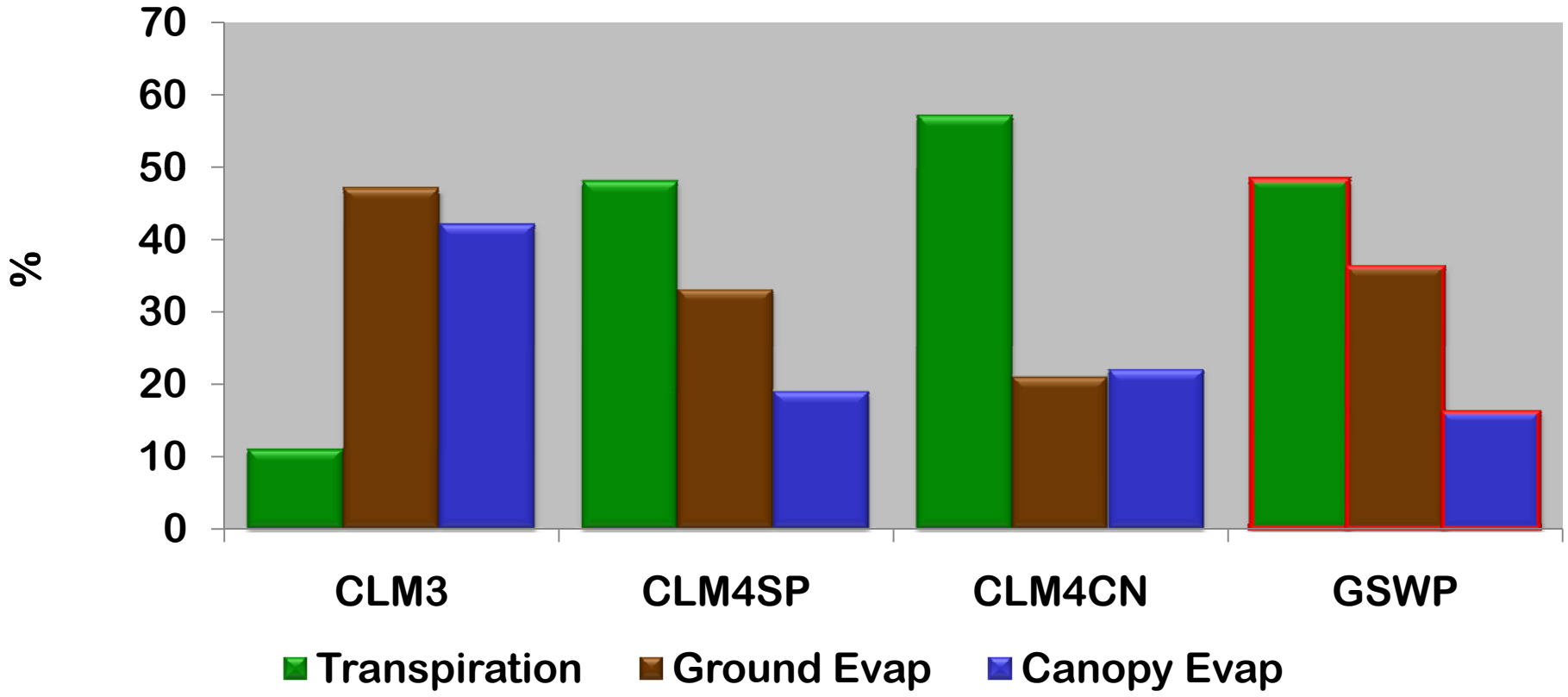
- CLM4.0 offline control simulations: Diagnostic plots
- CLM4.0 offline control simulations: Model output data
- CLM4.0 offline control simulations: Model forcing data

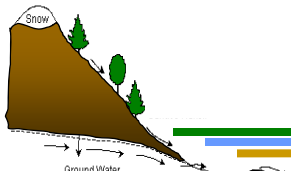
CLM Post-Processing Utilities

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



Global Partitioning of Evapotranspiration



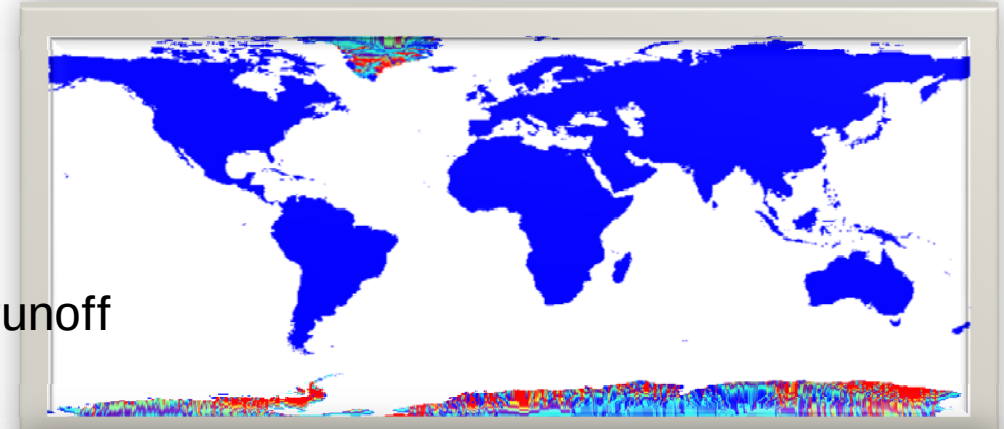


CLM3.5 → CLM4

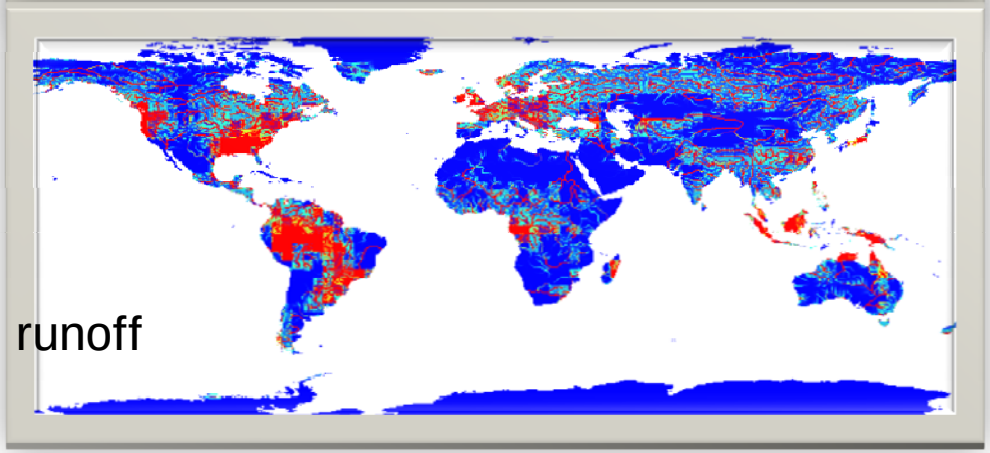
– Ice stream in River Transport Model

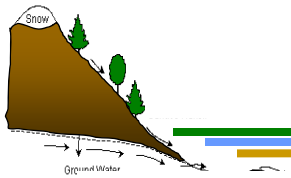
- For snow capped regions send excess water to ice stream (poor man's ice sheet calving)
- Reduces CCSM energy imbalance by ~0.15-0.2 W/m^2
- Unrealistic high sea-ice thickness in semi-closed bays

Ice runoff



Liquid runoff



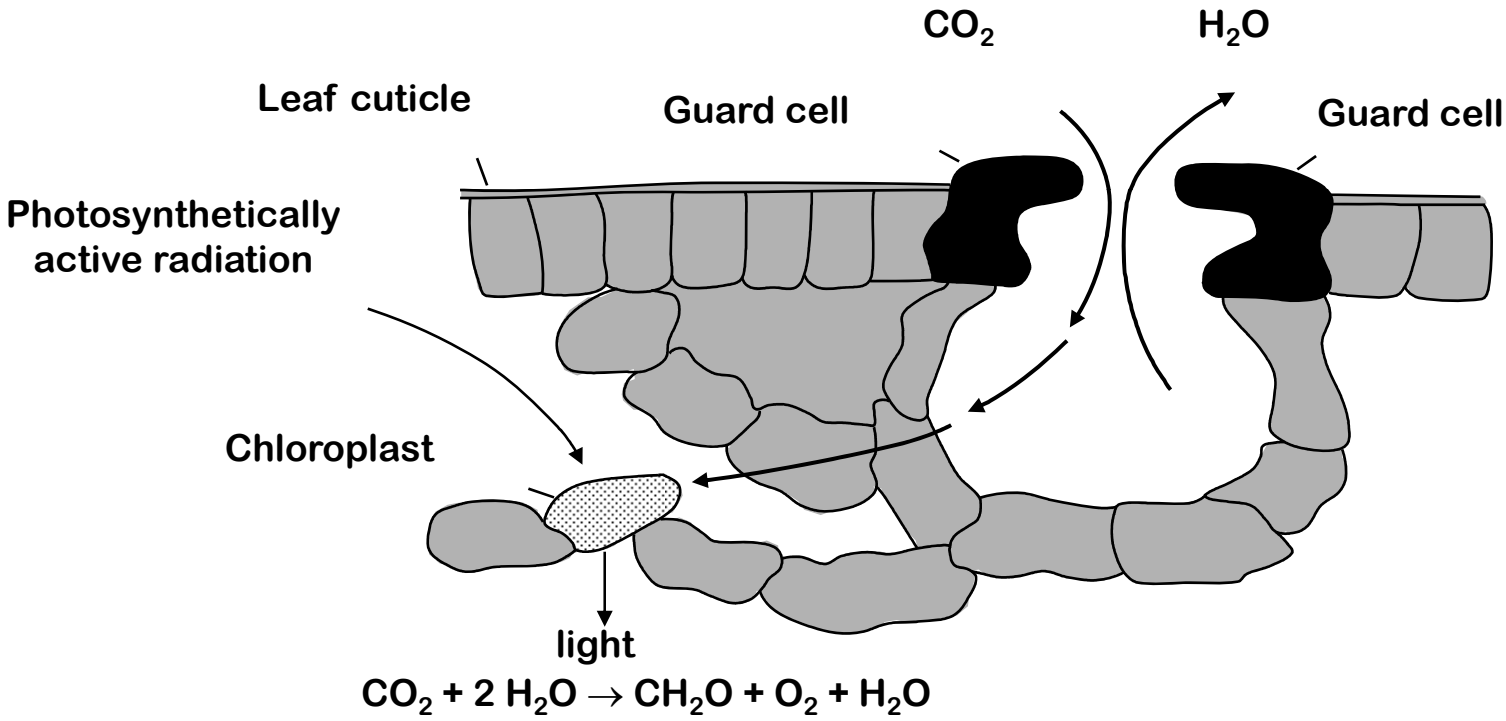


Photosynthesis model

Plant physiological controls on evapotranspiration

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

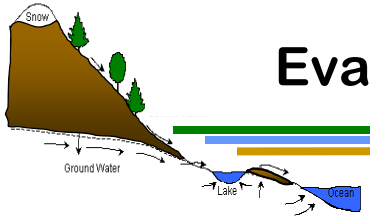
Stomatal Gas Exchange



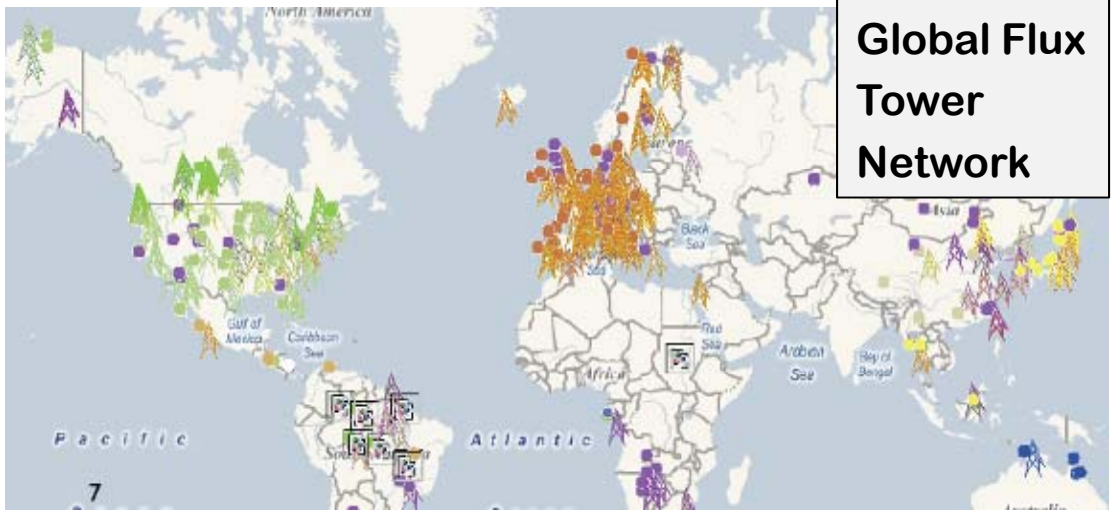
$$CO_2 + 2\,H_2O \rightarrow CH_2O + O_2 + H_2O$$

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)

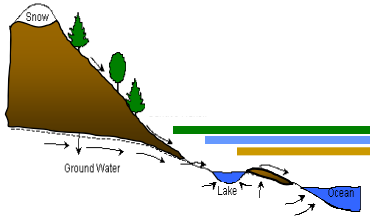
Figure courtesy G. Bonan



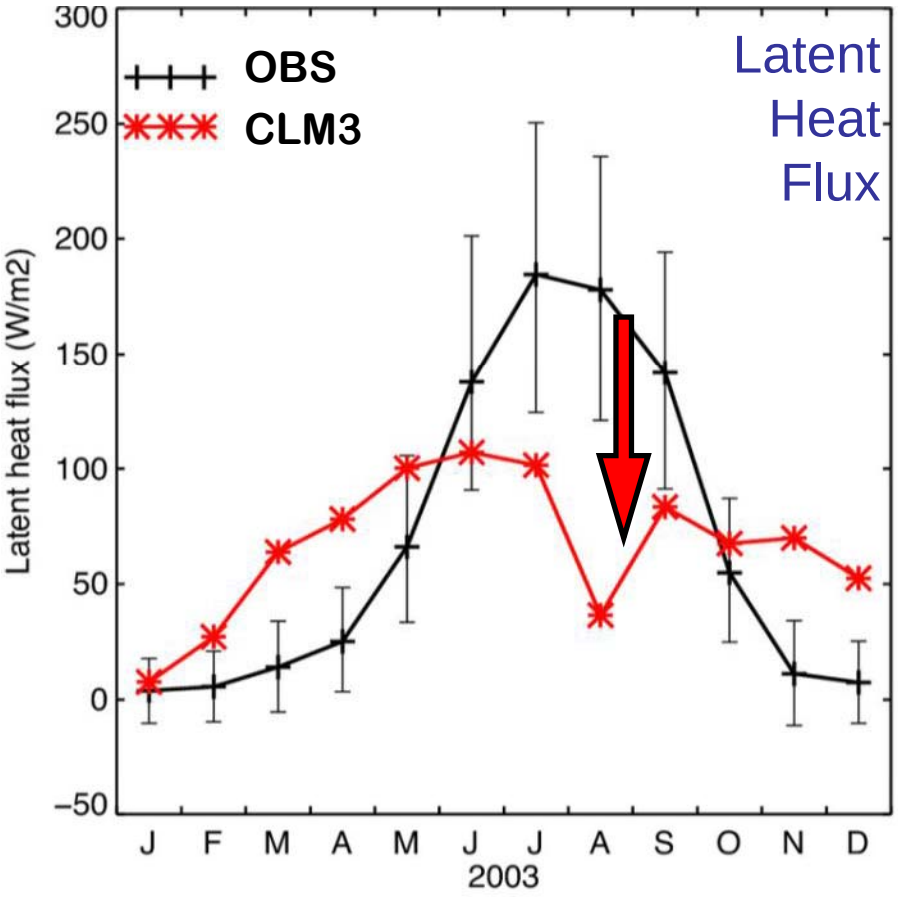
Evaluating and Improving the model with Tower Flux data

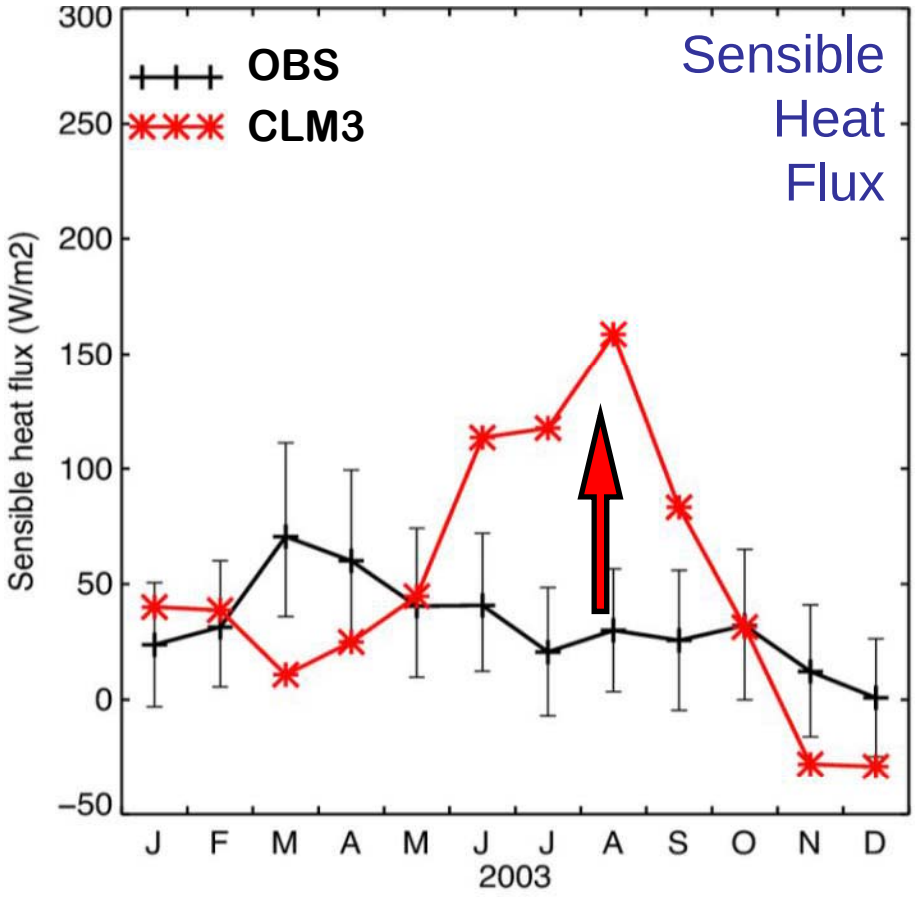


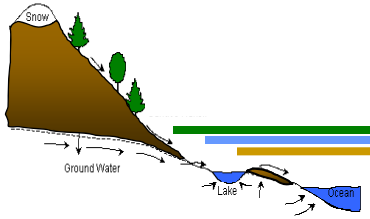
Global Flux Tower Network



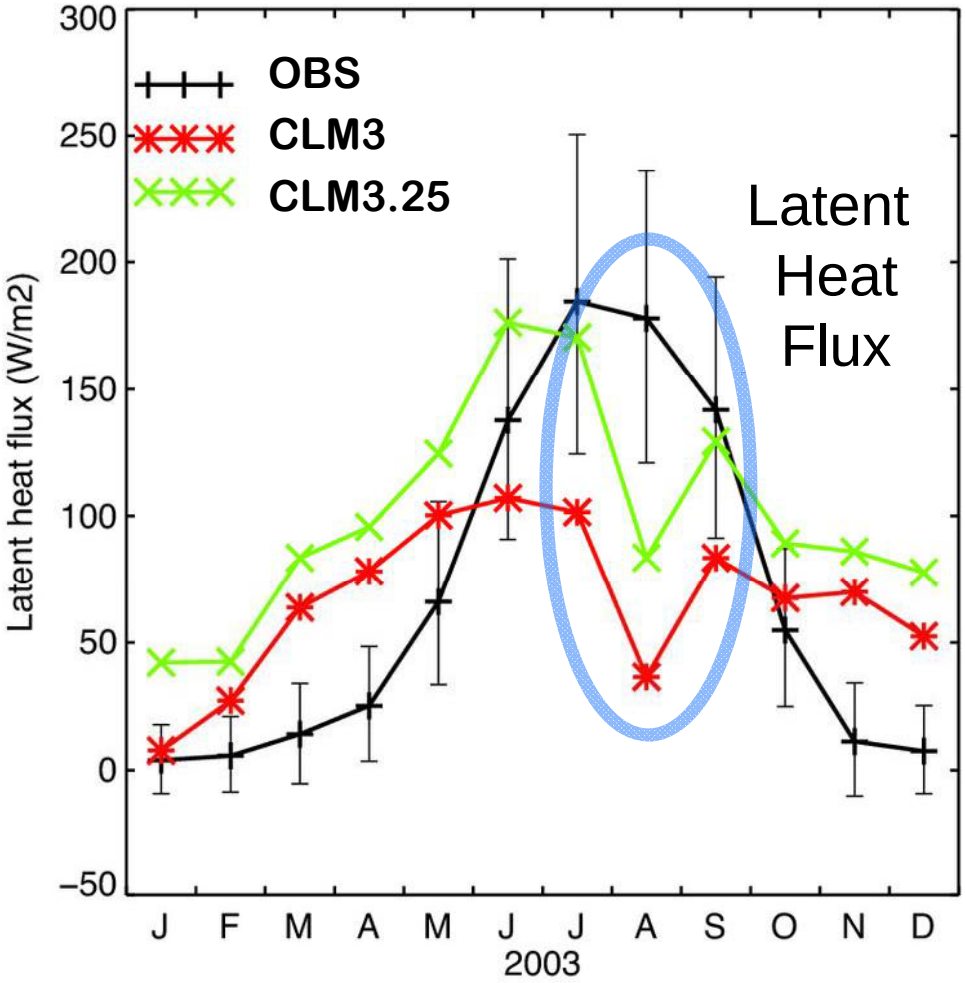
Morgan Monroe State Forest tower site







Morgan Monroe State Forest tower site

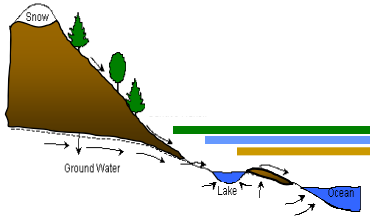


Reduced canopy interception

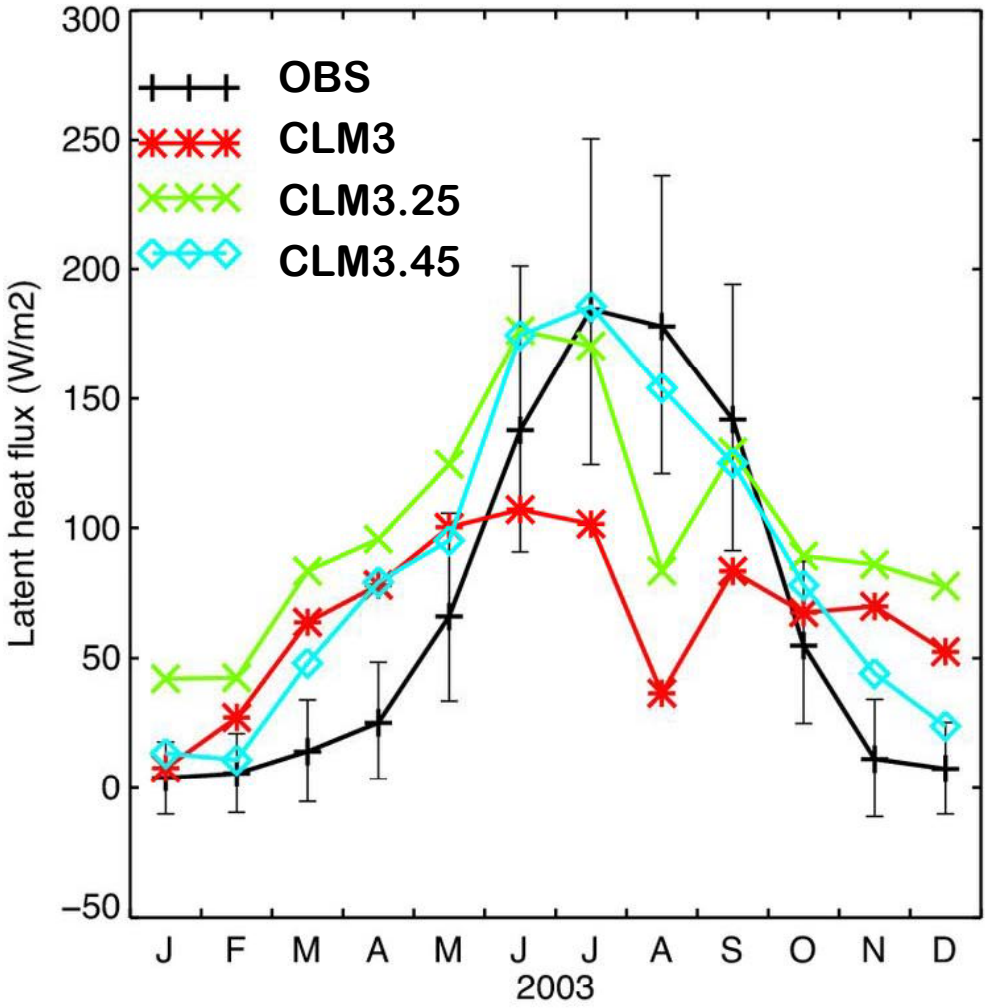
Permits more water to enter soil

Groundwater/aquifer model

Stores/releases moisture on seasonal-decadal timescales



Morgan Monroe State Forest tower site

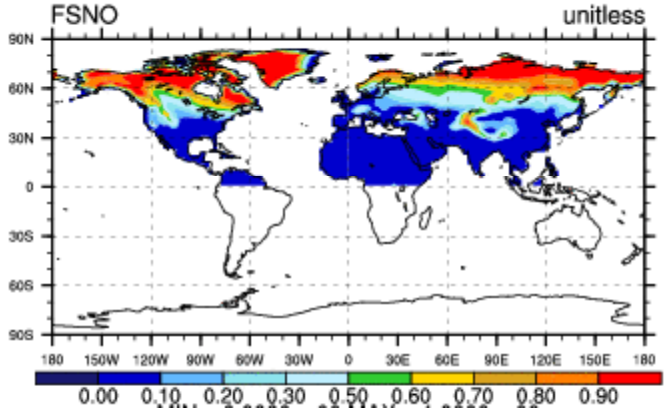


Soil evaporation resistance decreases LH in spring, more water available in summer for transpiration

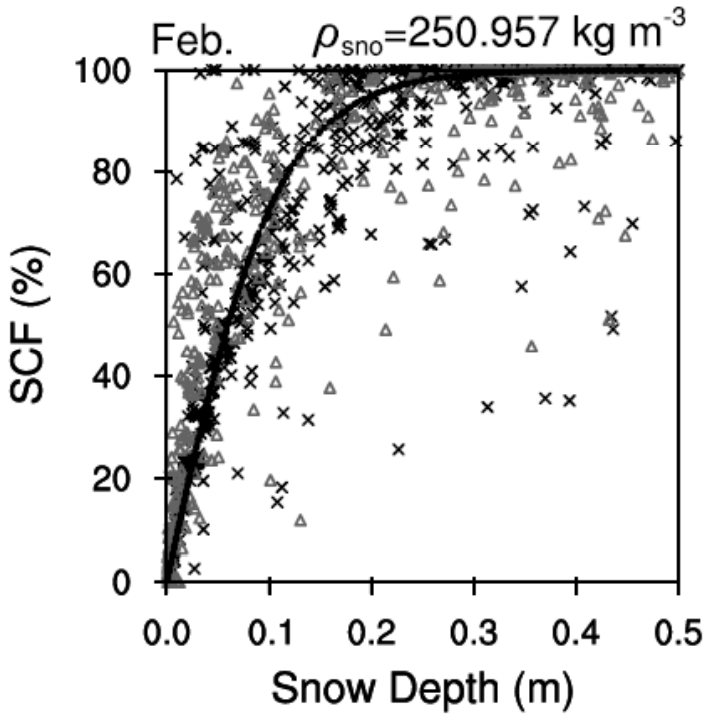
Stöckli et al. , JGR-BGC (2008)

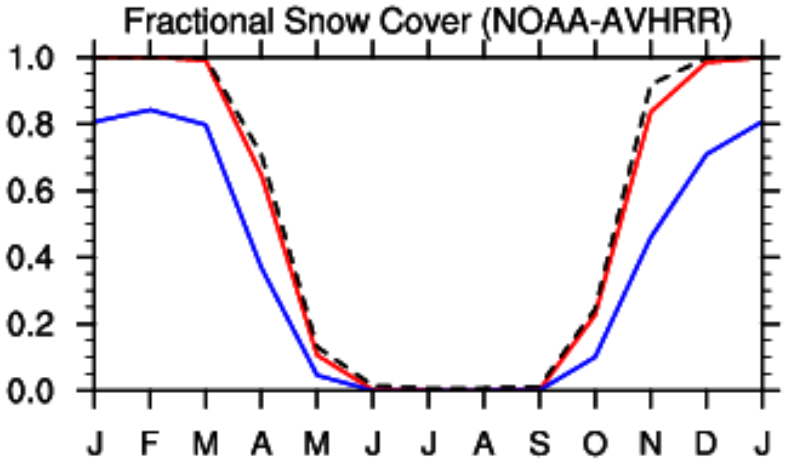
Snow cover fraction

NOAA AVHRR (1967-2003)

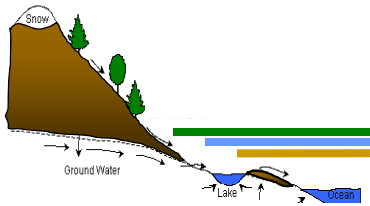


How much of a grid cell is covered with snow for a given snow depth?

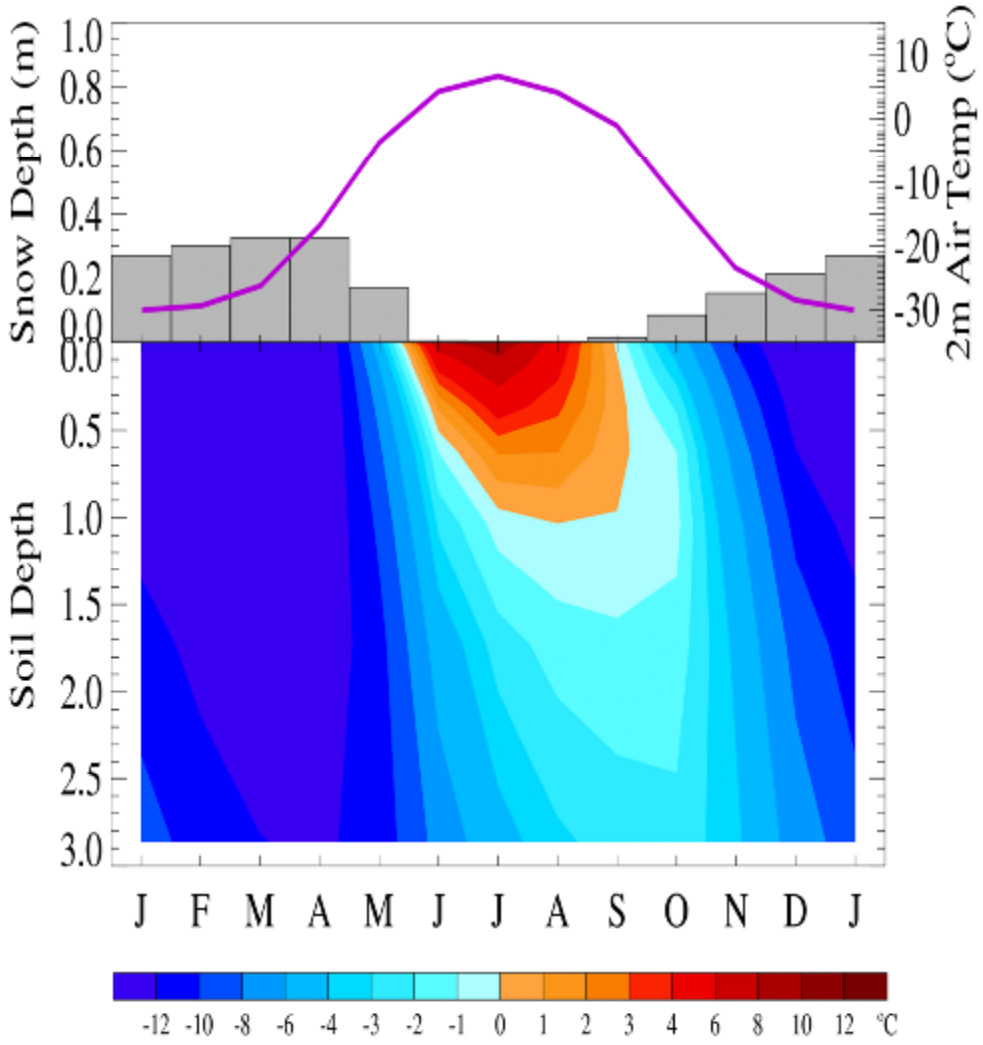




Niu and Yang, JGR, 2006



Soil thermodynamics

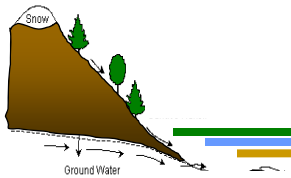


Solve the heat diffusion equation for multi-layer soil and snow model

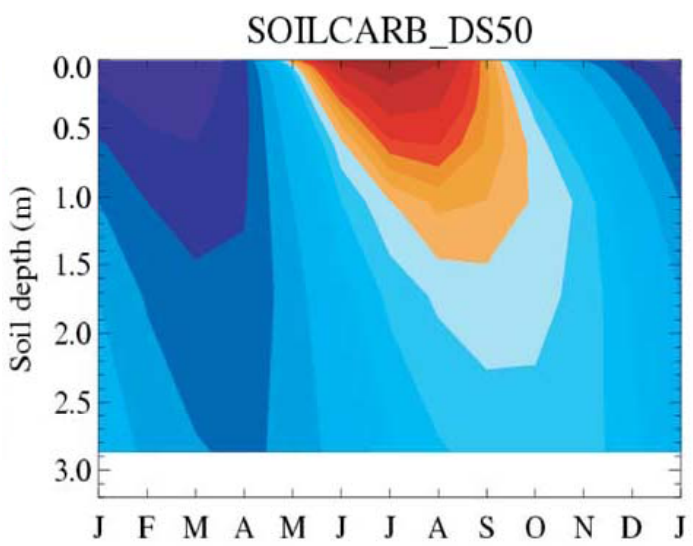
$$C_p \frac{\partial T}{\partial t} = \frac{\partial}{\partial z}\left(K \frac{\partial T}{\partial z} \right)$$

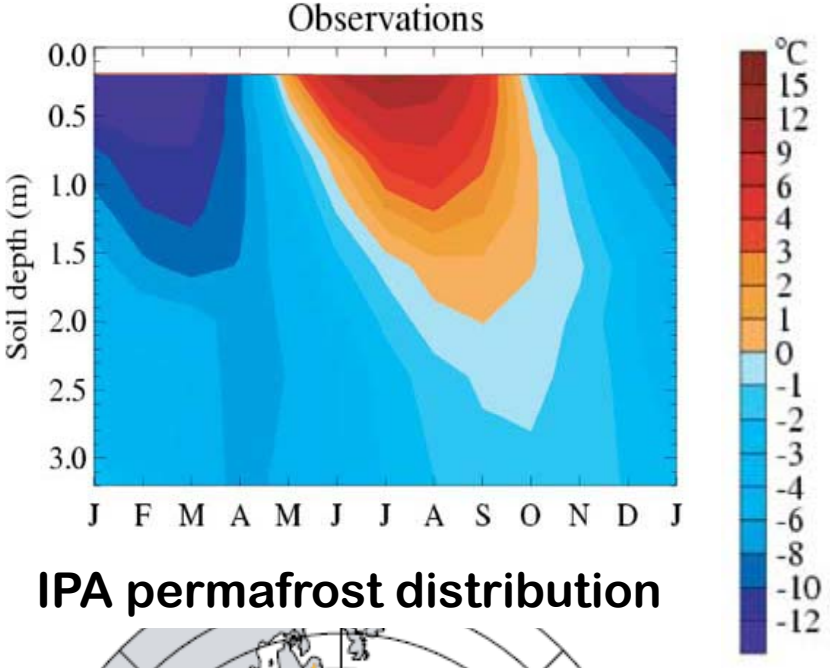
where C_p (heat capacity) and K (thermal conductivity) are functions of:

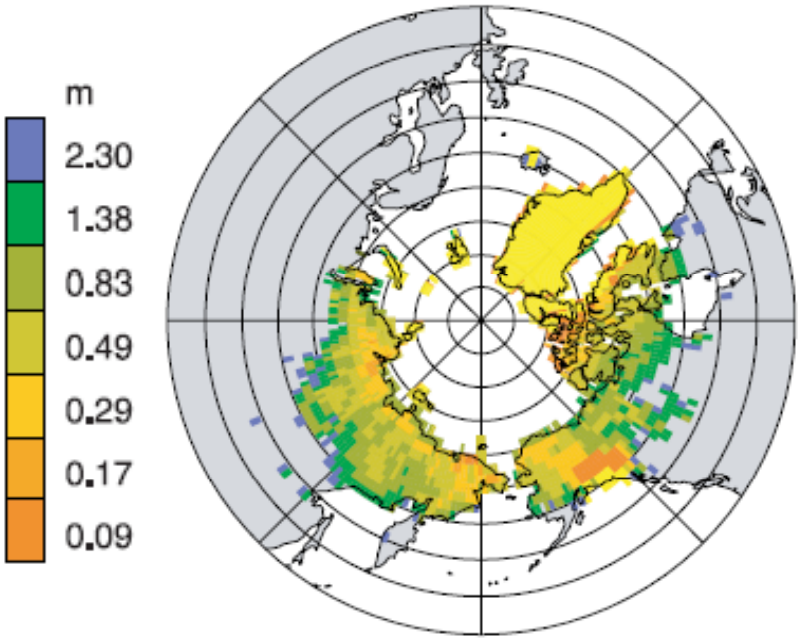
- temperature
- total soil moisture
- soil texture
- ice/liquid content



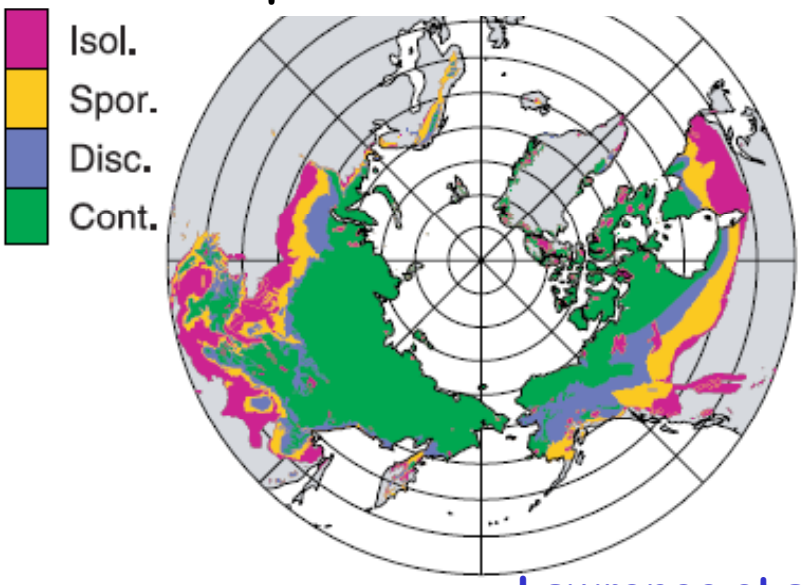
Modeling Permafrost in CLM



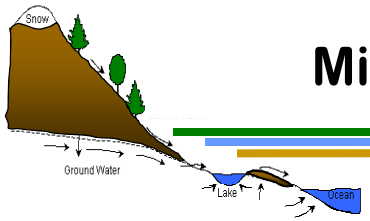




IPA permafrost distribution

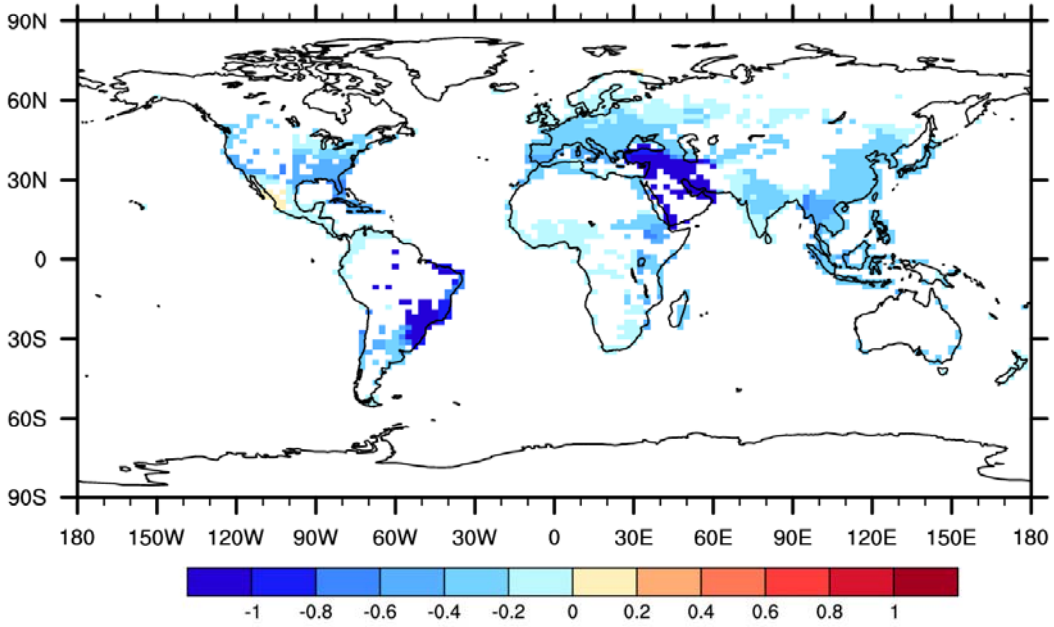


Lawrence et al., 2008a



Mitigating the Urban Heat Island (UHI) with White Roofs

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

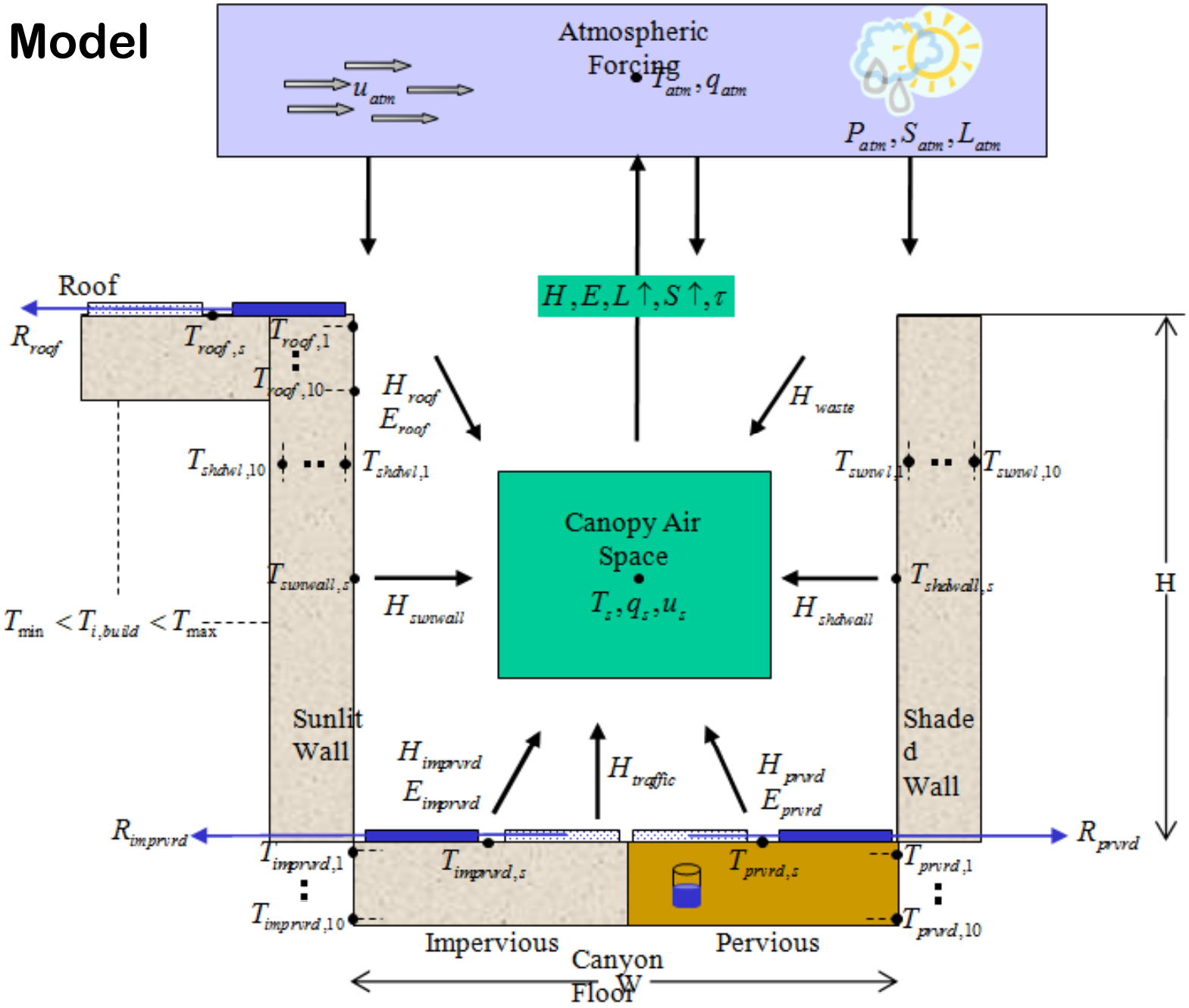


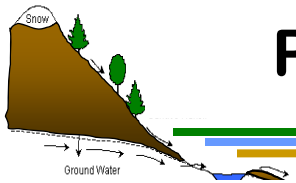
- **Increasing global roof albedo to 0.9 in CLMU reduces annual UHI by 1/3 on average.**

- **Effectiveness of white roofs as a UHI mitigation technique varies according to urban design properties, climate, and interactions with space heating.**

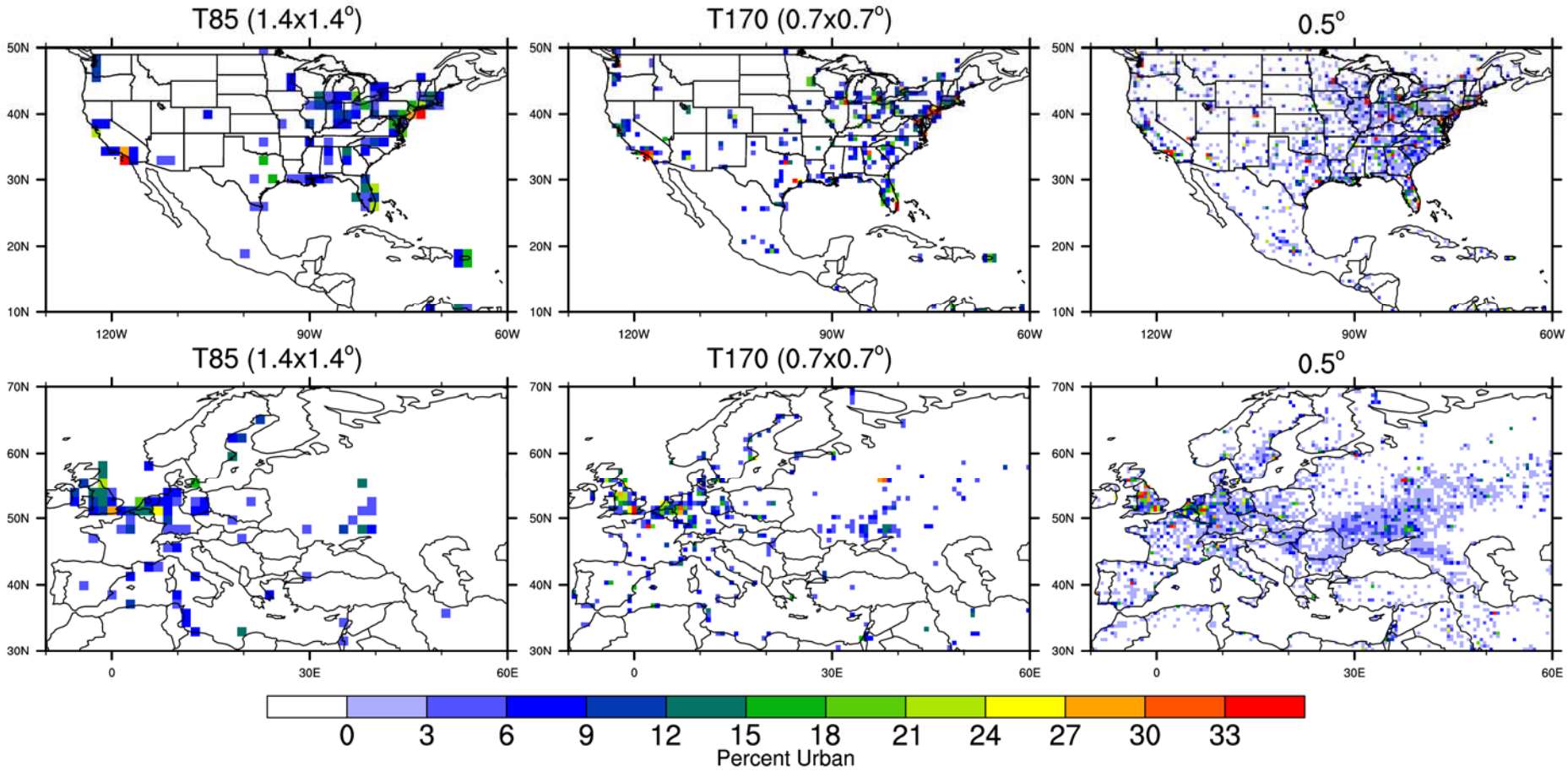
Oleson, K.W., G.B. Bonan, and J. Feddema, 2010, *Geophys. Res. Lett.*

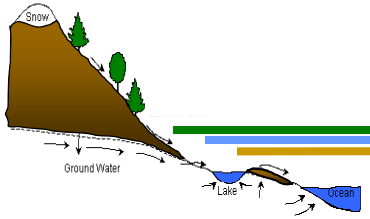
Urban Model


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
$T_{sunwall,s}$
$H_{sunwall}$
$H_{shdwall}$
$T_{shdwall,s}$
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



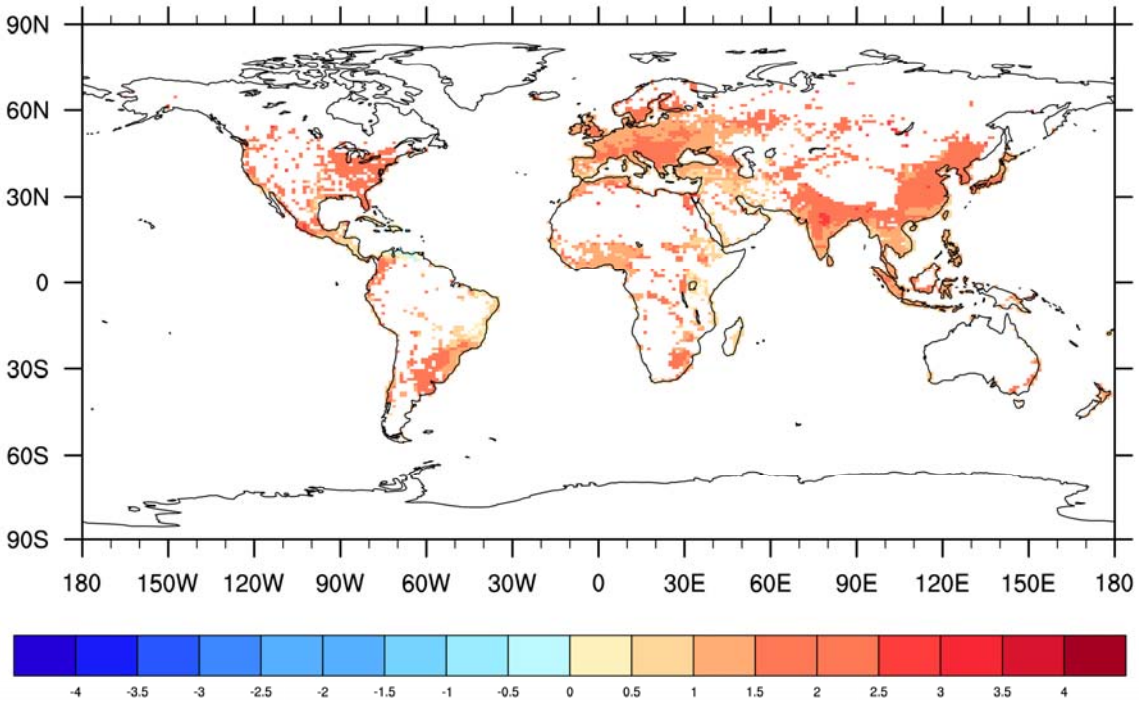
Percent Urban at Climate Model Resolutions





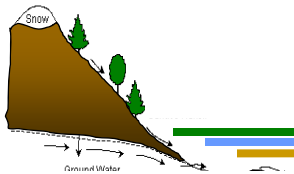
Urban Modeling in CCSM4

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



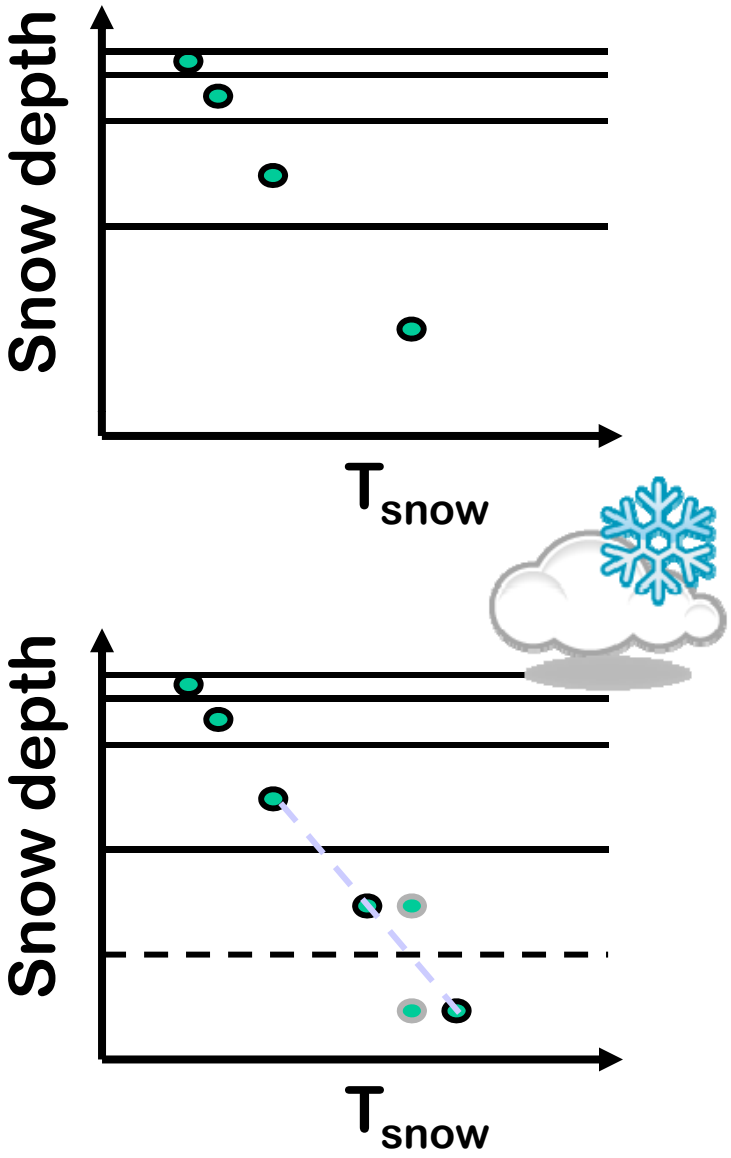
Modeled UHI ranges from near-zero up to 4°C with spatial and seasonal variability controlled by urban to rural contrasts in energy balance.

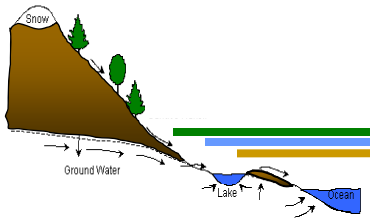
Oleson, K.W., G.B. Bonan, J. Feddema, M. Vertenstein, C.S.B. Grimmond, 2008a, *J. Appl. Meteor. Climatol.*
Oleson, K.W., G.B. Bonan, J. Feddema, M. Vertenstein, 2008b, *J. Appl. Meteor. Climatol.*



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 (SNICAR)

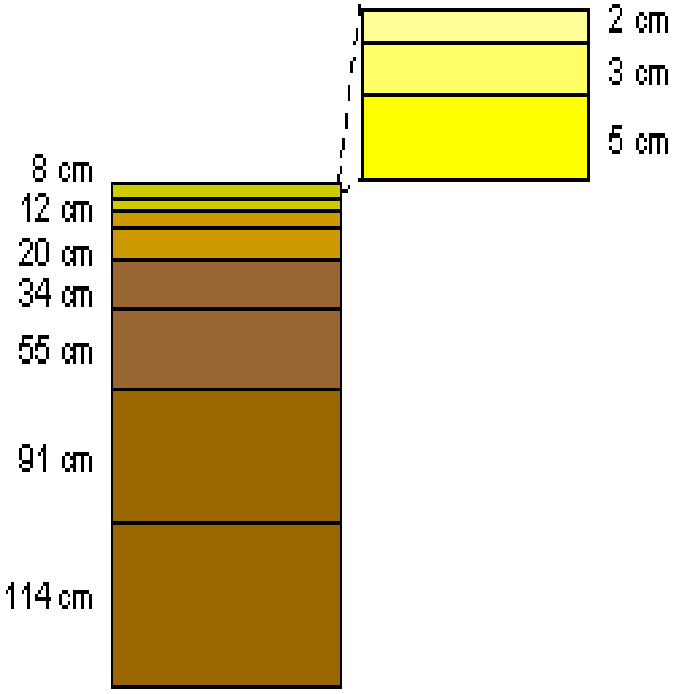




Soil Properties

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)