NCAR Earth System Laboratory NESL

Lecture 5: Land Modeling I: Biogeophysics

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(With thanks to TSS group for their many contributions)

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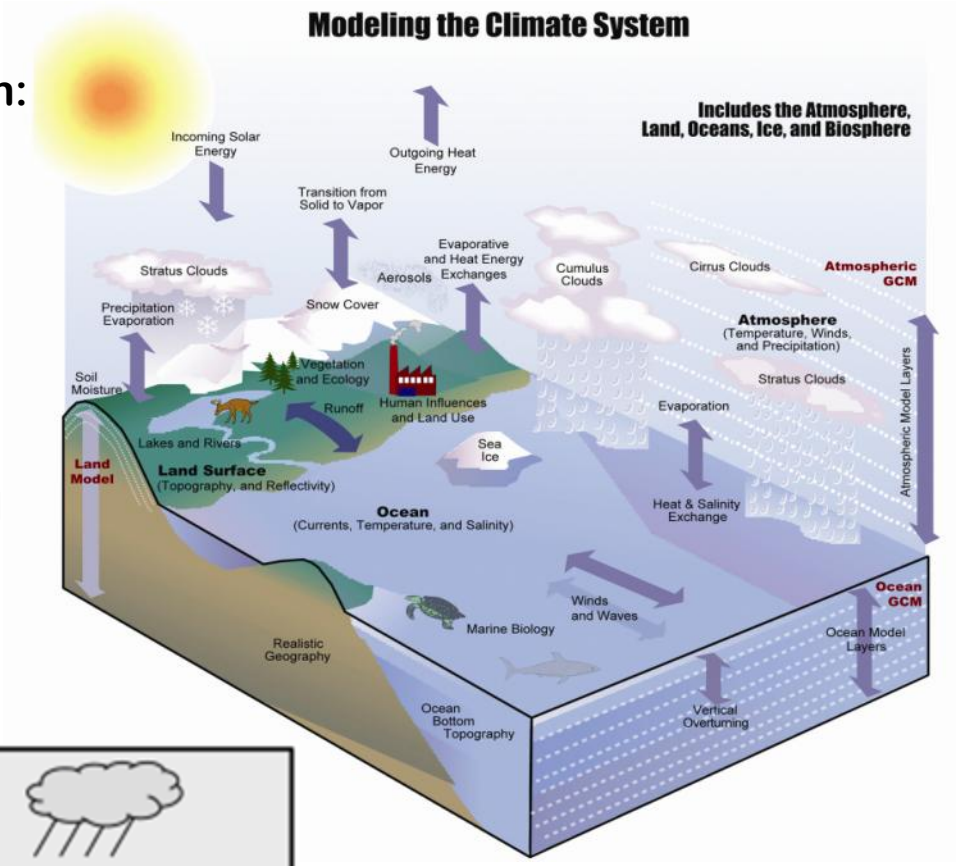
Understanding the Land Surface in the Climate System: Investigations with an Earth System Model (NCAR CESM)

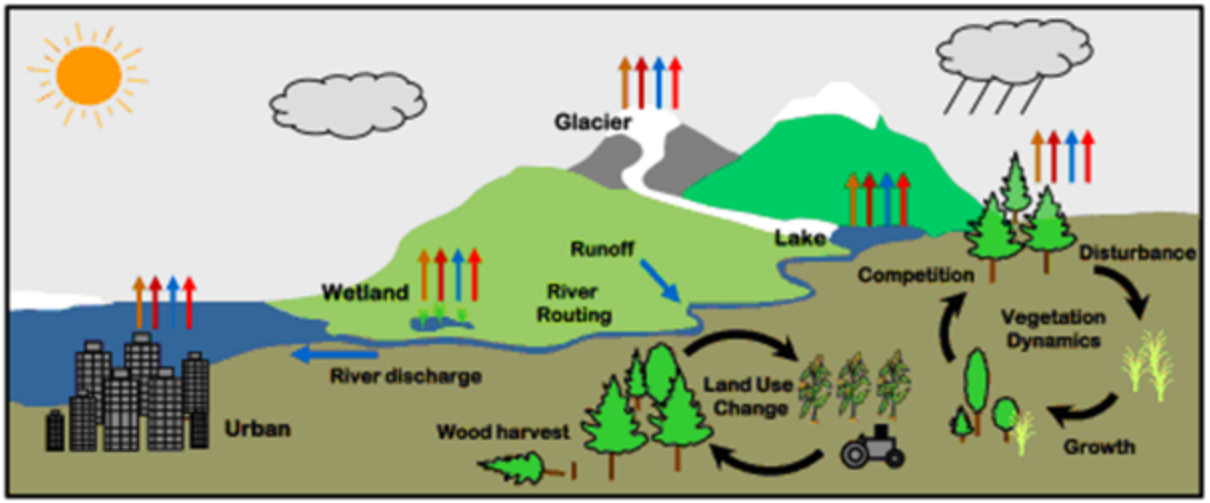
The land is a critical interface through which:

1. Climate and climate change impacts humans and ecosystems

and

2. Humans and ecosystems can force global environmental and climate change





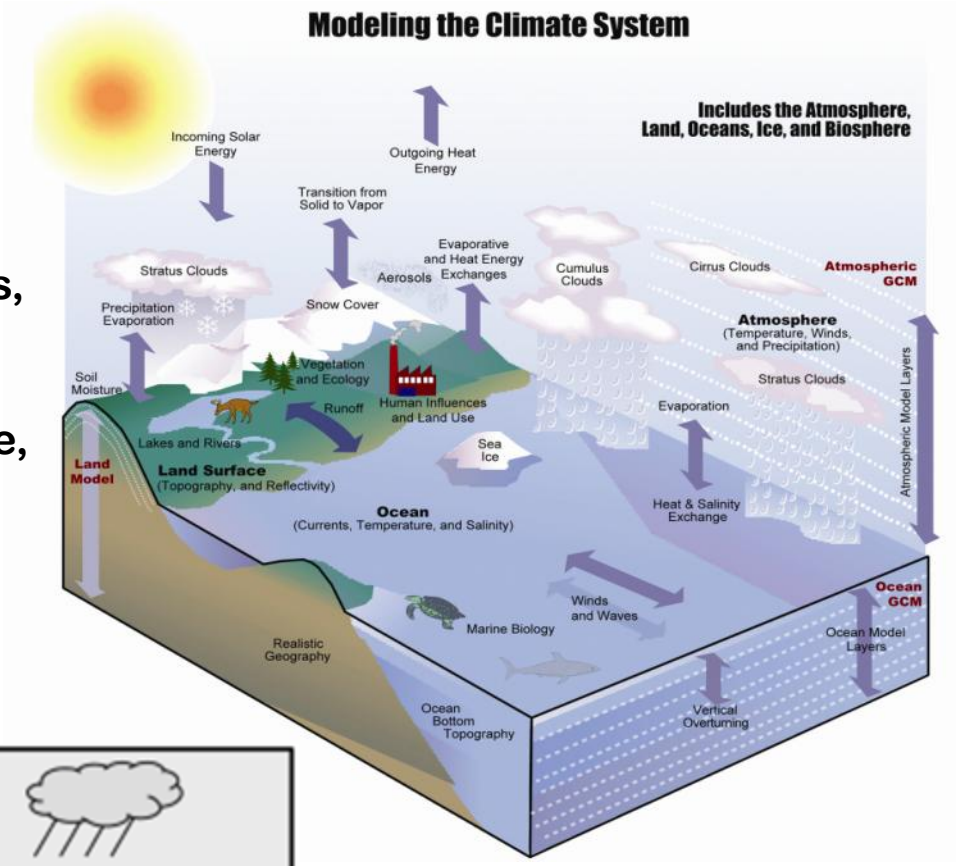
Understanding the Land Surface in the Climate System: Investigations with an Earth System Model (NCAR CESM)

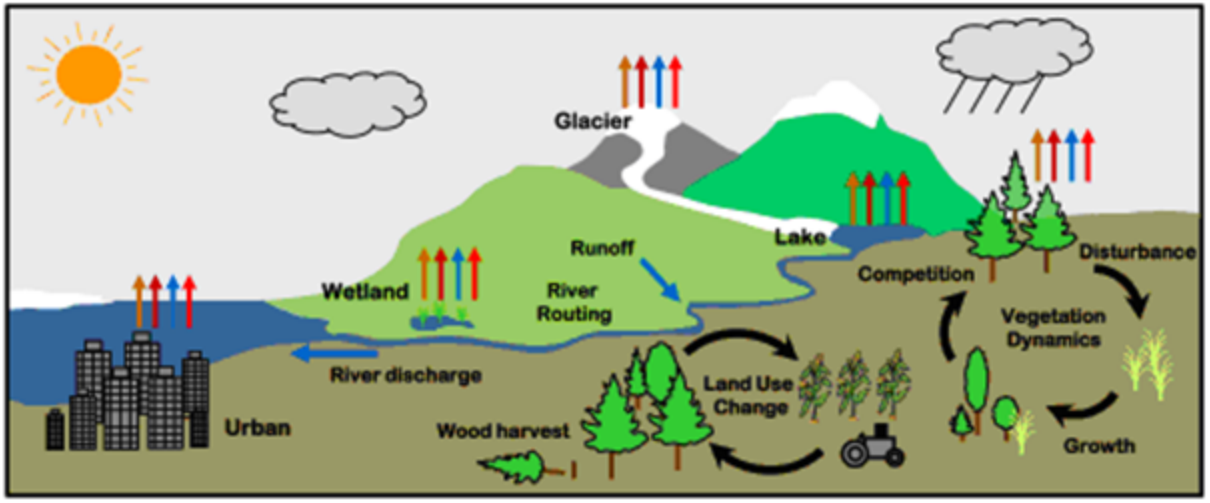
Land Surface Elements modeled in CESM:

- Glaciers, Lakes, Wetlands and Rivers

- Forests, Savannas, Shrublands, Grasslands, Tundras and Deserts

- Human Modified Landscapes of Agriculture, Forestry and Cities





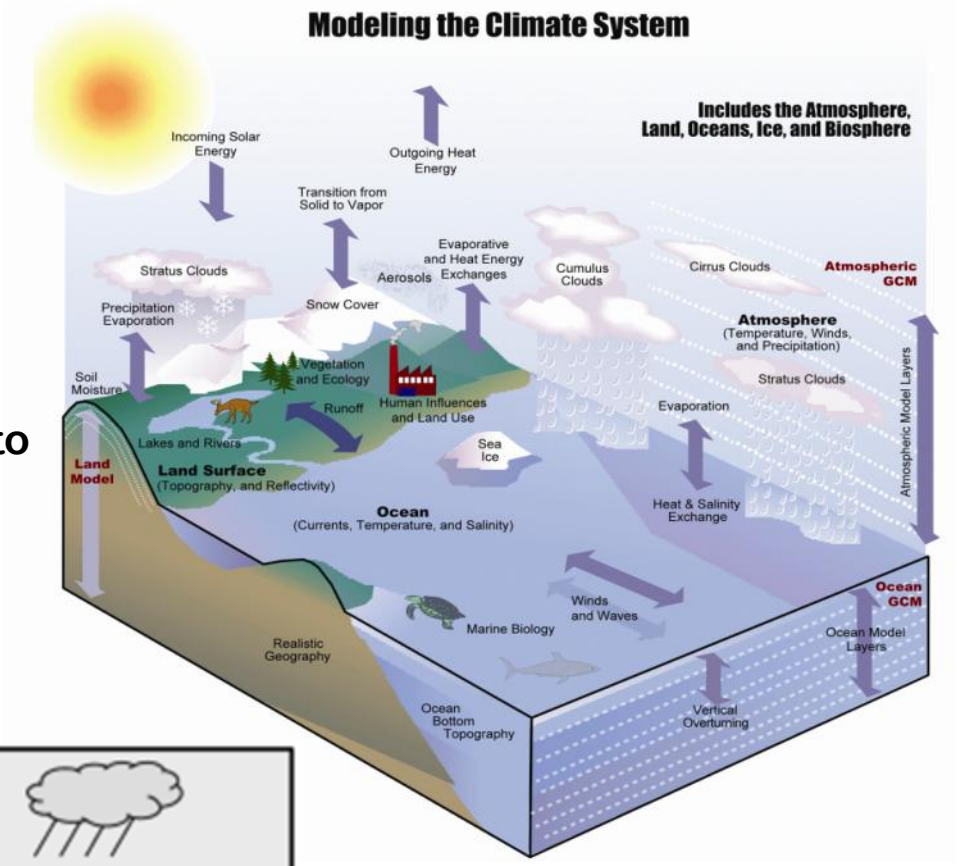
Understanding the Land Surface in the Climate System: Investigations with an Earth System Model (NCAR CESM)

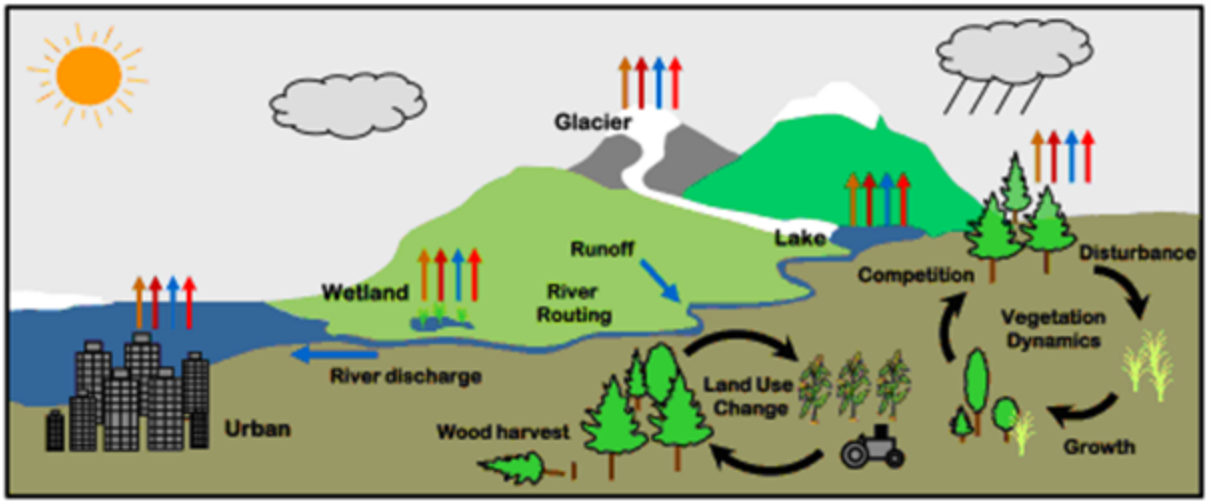
Global Environmental and Climate Change from the Land Surface in CESM:

- Solar Radiation heating the land surface through snow, ice, vegetation, soils and cities

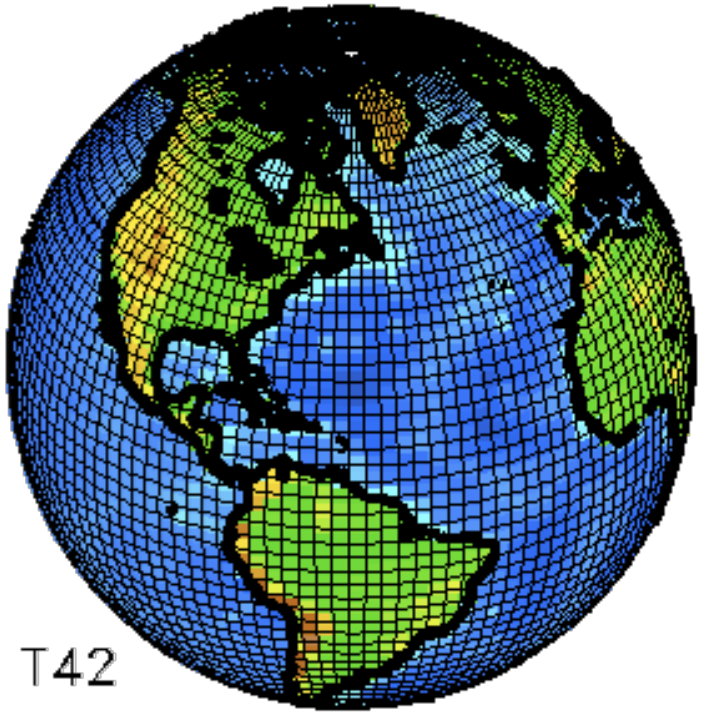
- Changes in the water stored and returned to the atmosphere and oceans

- Changes in the carbon and nutrient cycles between the land, the atmosphere, and the oceans





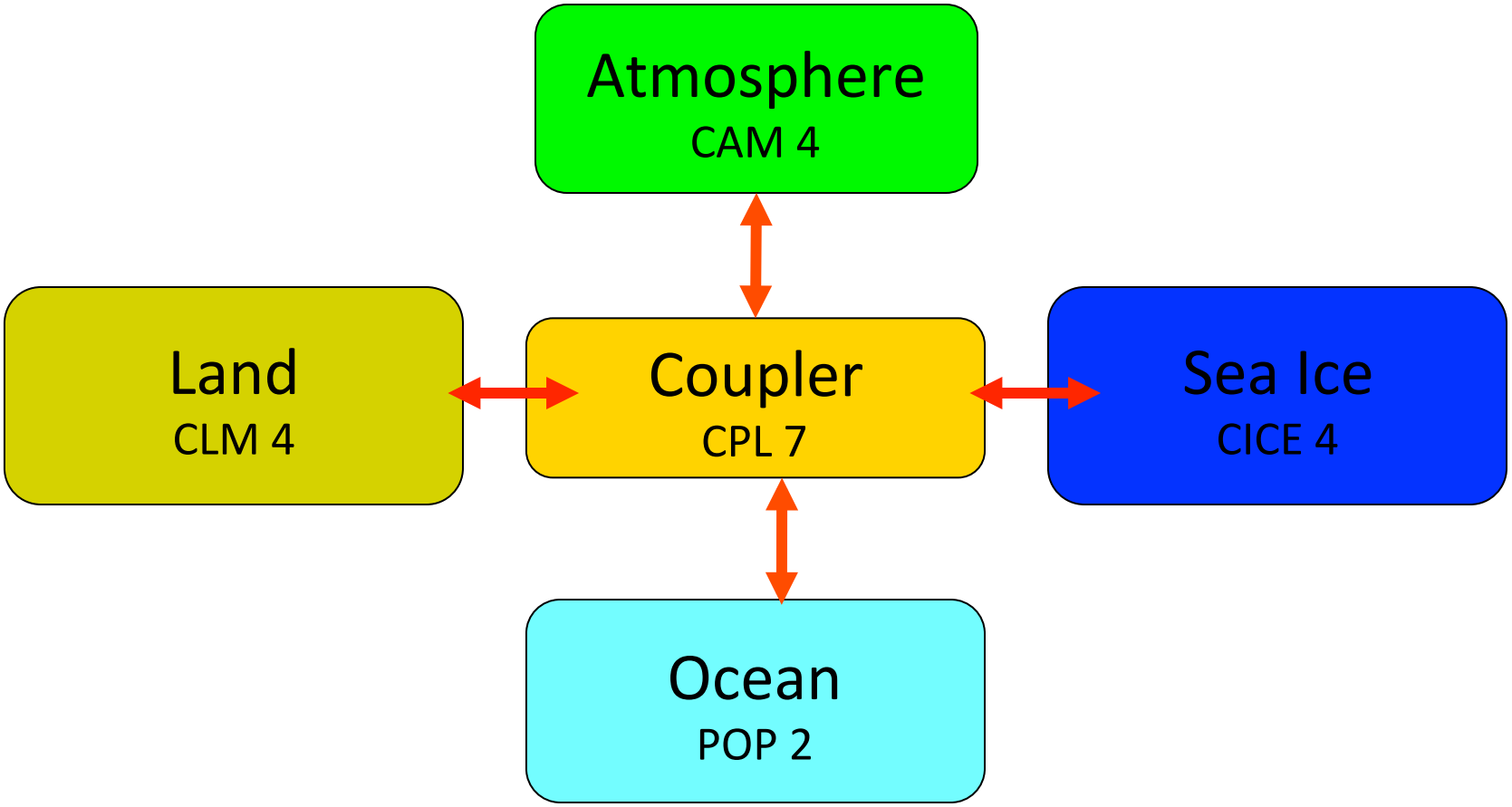
Community Earth System Model (CESM1)



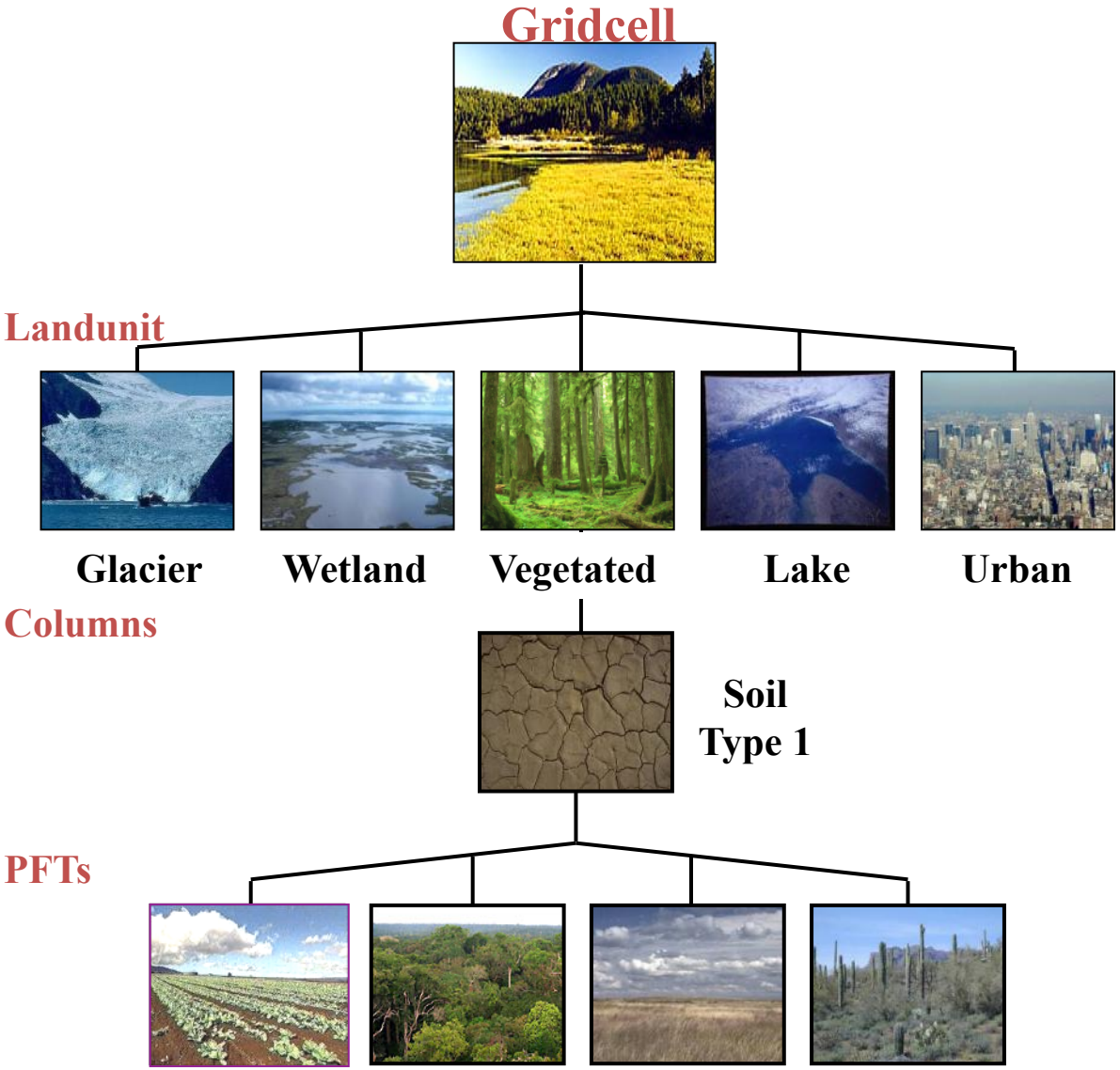
Core is a Coupled Ocean-Atmosphere-Land- Sea Ice model (CCSM4)

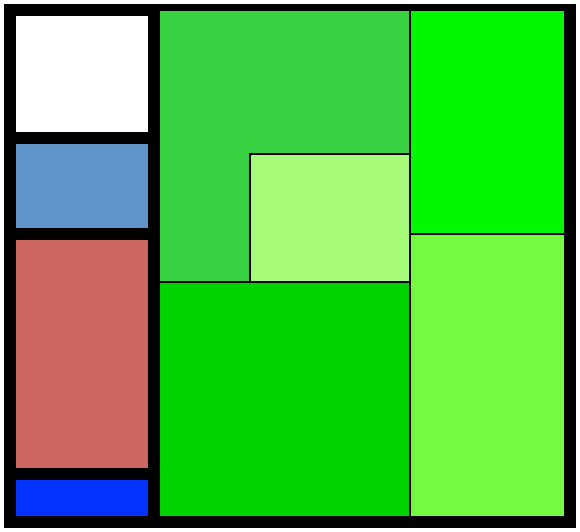
- 0.25°, 0.5°, 1° , 2°, T31 resolutions
- 30 minute time step
- 26 atmosphere levels
- 60 ocean levels
- 15 ground layers
- ~5 million grid boxes at 1°
- ~1.5 million lines of computer code
- Archive data (monthly, daily, hourly) for hundreds of geophysical fields (over 250 in land model alone)

Configuration of CCSM4



Community Land Model (CLM) subgrid tiling structure





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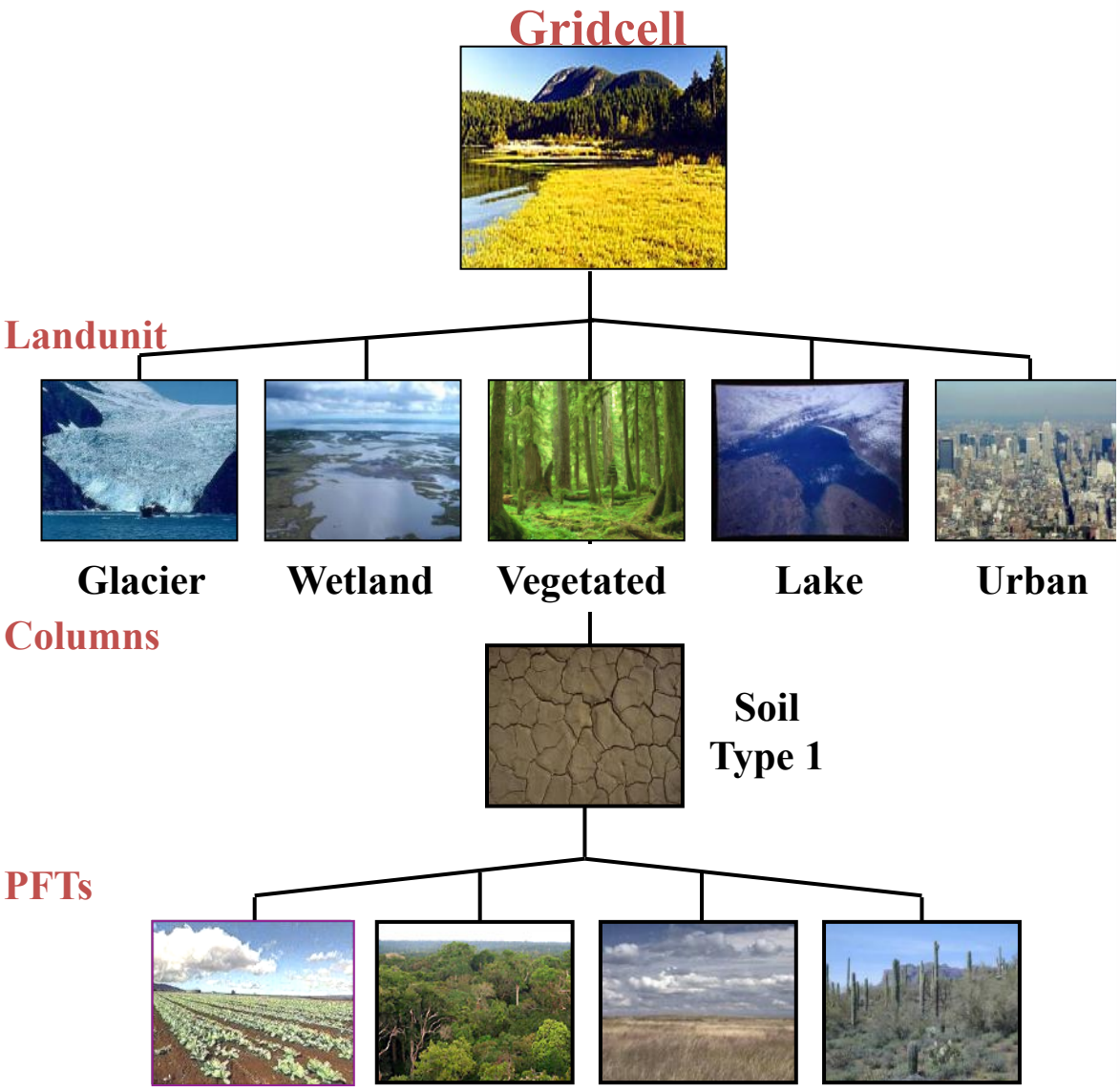


Plant Functional Types:

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

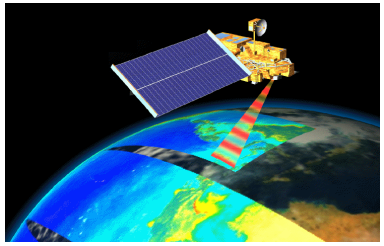
Plant Functional Type Parameters

- 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)

Current Day MODIS PFTs 0.05 degrees



MODIS Vegetation Continuous Fields
(tree%,herbaceous%, bare%)

MODIS Land Cover
(IGBP Classes for Shrub% and Grass%)

Ramankutty (2008) Cropping 2000
(Crop %)

Plant Functional Type Mapping

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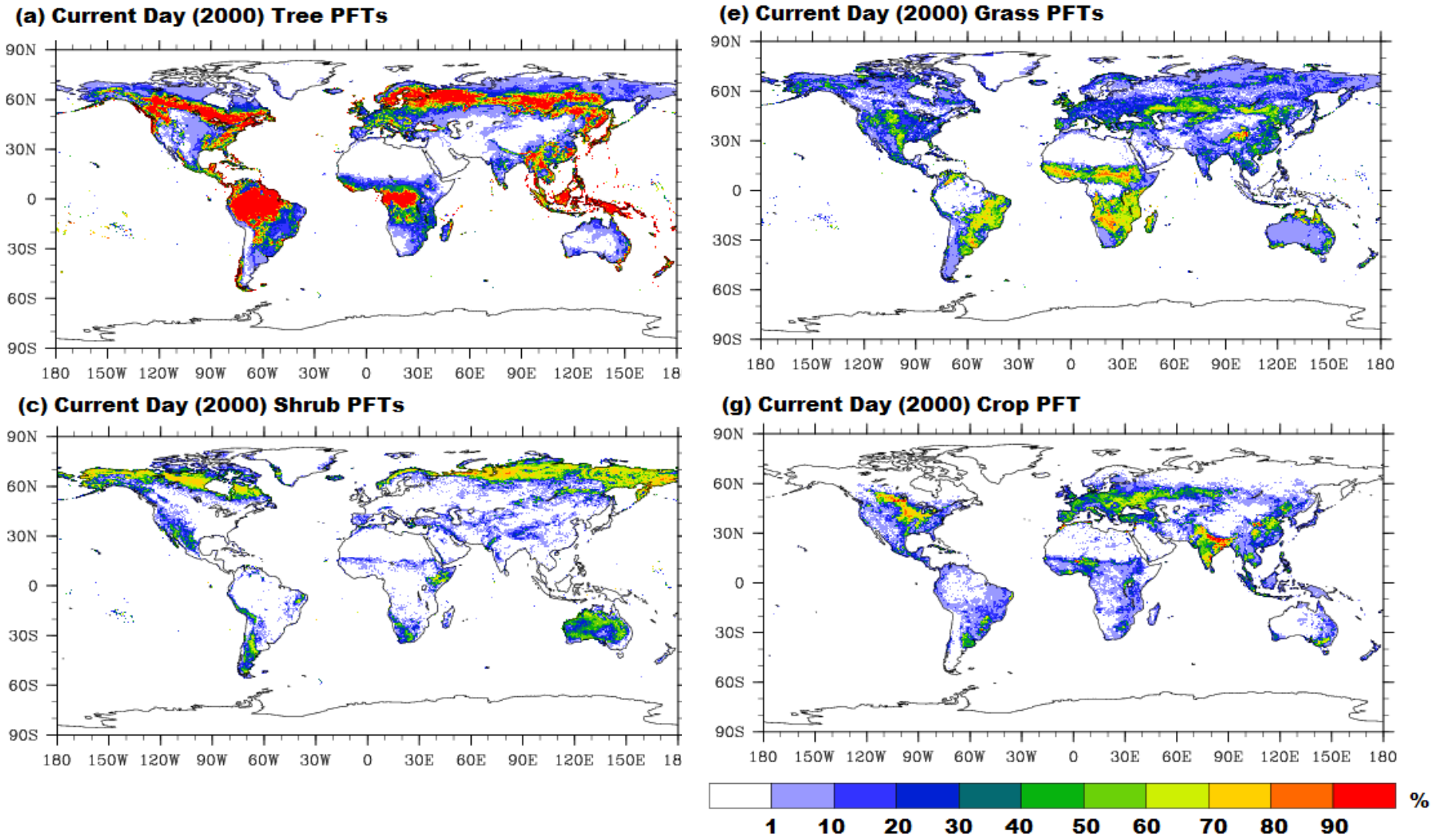
AVHRR Continuous Fields Tree Cover
(Needle%, Broad%, Evergreen%, Decid%)

Willmott and Matsuura Climate
(Air Temperature, Precipitation)

MODIS Monthly LAI
(Monthly LAI for C3/C4 Grass Growing Months)

Lawrence and Chase (2007)

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



Lawrence and Chase, 2007

Land Surface in the Climate System

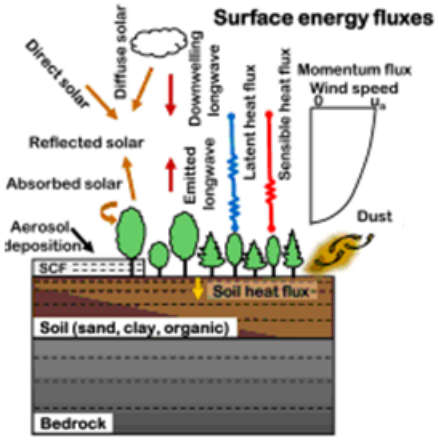
1. Surface Energy Fluxes:
- Solar Energy Fluxes (Albedo – Vegetation, Snow, Soils)
- Long Wave Energy Fluxes (Surface Temp & Emissivity)
- Latent Heat Fluxes (Transpiration, Evaporation)
- Sensible Heat Fluxes (Surface Temp & Roughness)

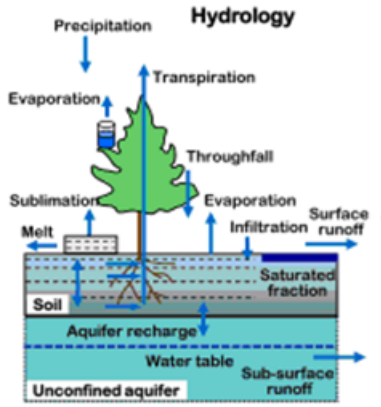
2. Surface Hydrology:
- Rain and Snow (Vegetation, Snow Pack, Runoff)
- Transpiration, Evaporation, Snow melt, Sublimation
- Soil Hydrology 10 Soil Layers in CLM (Richards Eqns)
- Deep Aquifer recharge and drainage (Top Model)

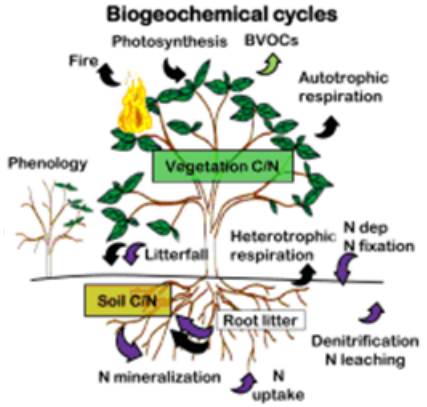
3. Biogeochemistry (Carbon and Nitrogen Cycles):
- Plant Photosynthesis and Respiration

$$6\,CO_2 + 6\,H_2O + \text{light} \rightarrow C_6H_{12}O_6 + 6\,O_2$$

- Carbohydrates are allocated to Leaves, Roots, Wood
- Leaves, roots and wood become litter, debris, soil C
- Organic decomposition and fire remove carbon
- Nitrogen is cycled impacting growth and decay







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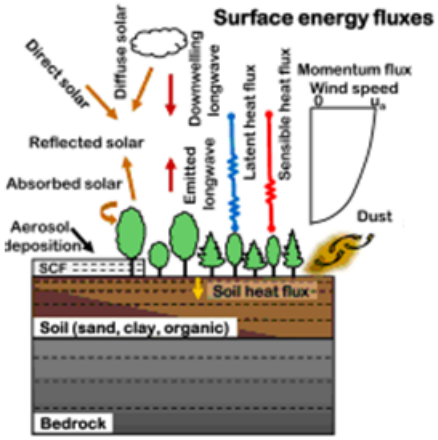

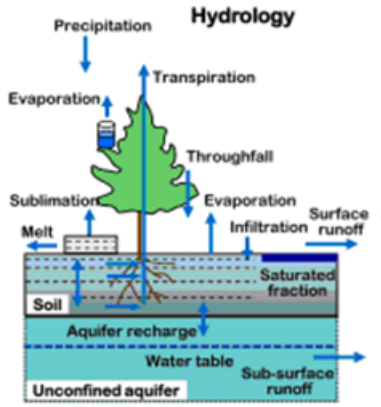

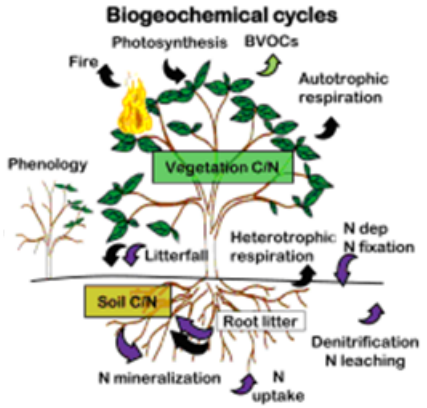

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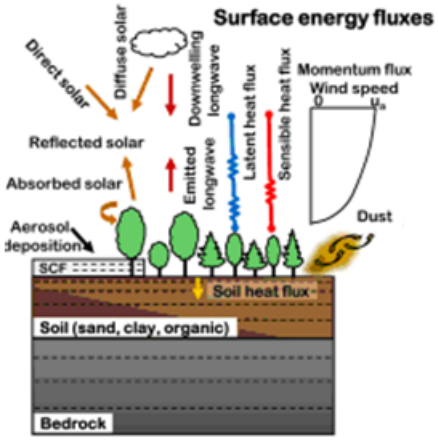
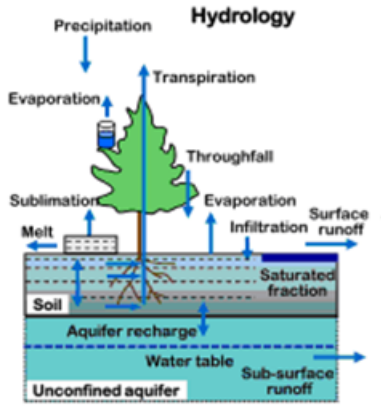
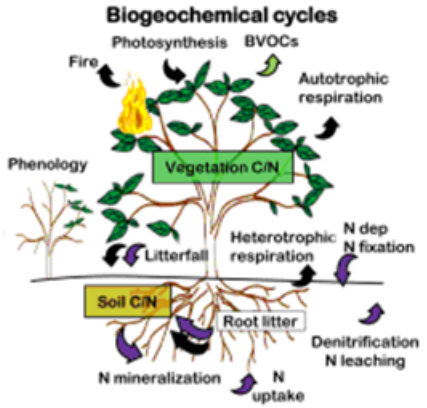






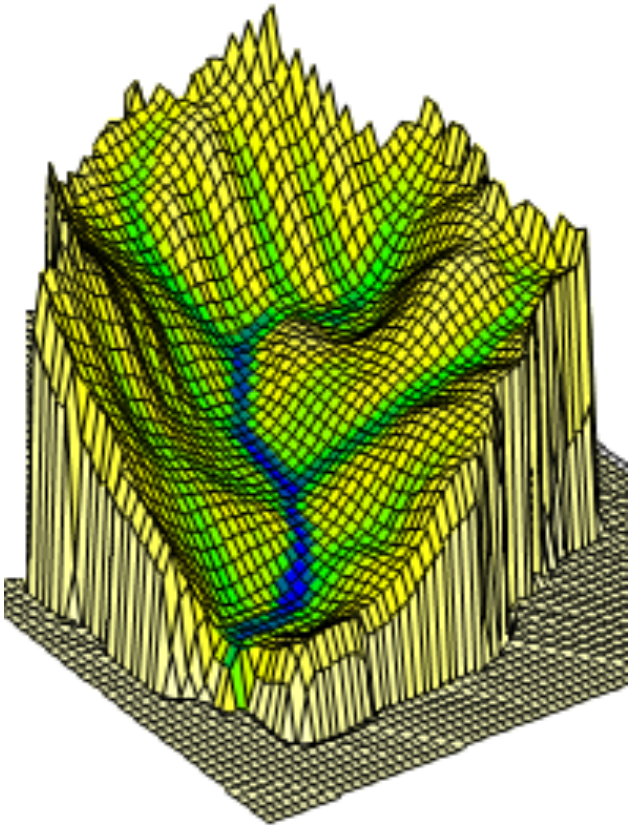
At each timestep the CLM land scheme solves …

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

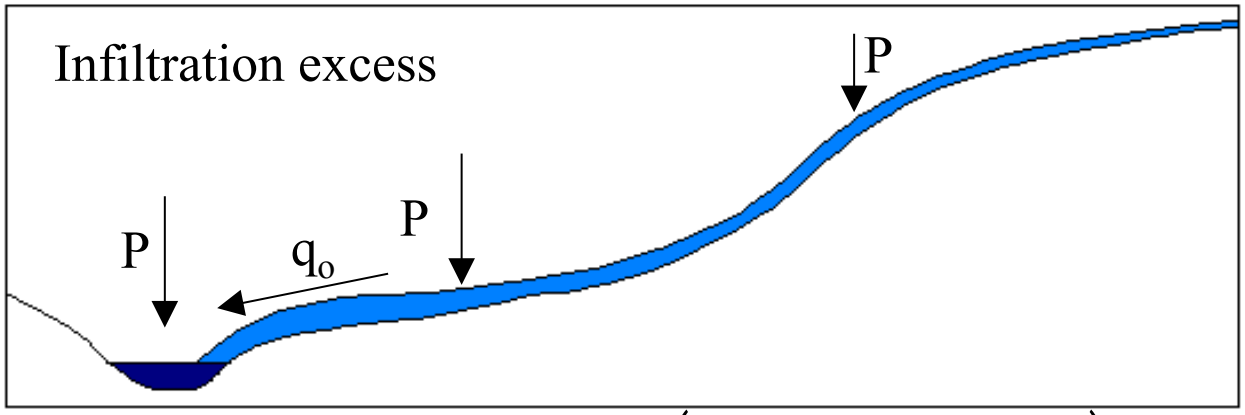
Subgrid-scale soil moisture heterogeneity

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.



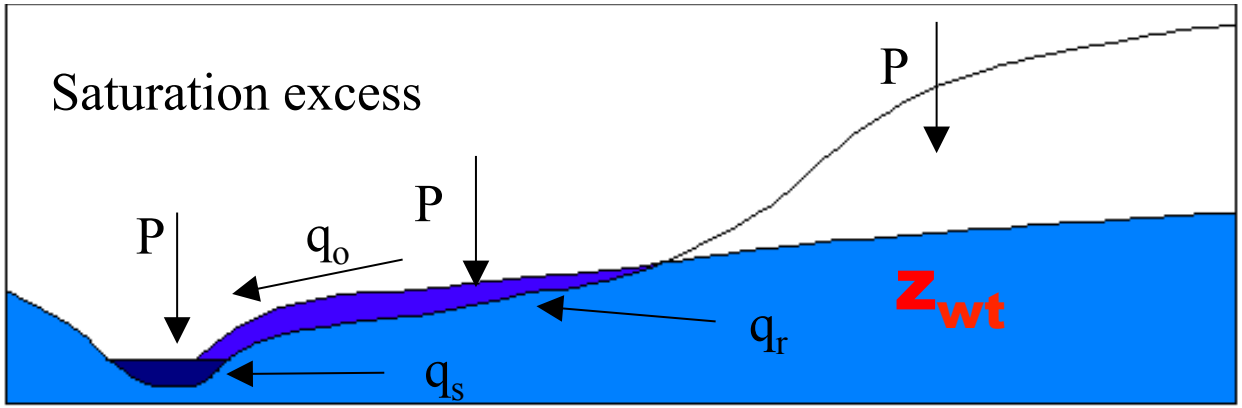
Three main sources of runoff:
- **Infiltration excess occurs over the unsaturated fraction**
- **Saturation excess occurs over the saturated fraction**
- **Baseflow (drainage)**

SIMTOP: Simple TOPMODEL-based runoff model



$$q_{over} = (1 - f_{sat})(q_{liq,0} - q_{infl,\max})$$

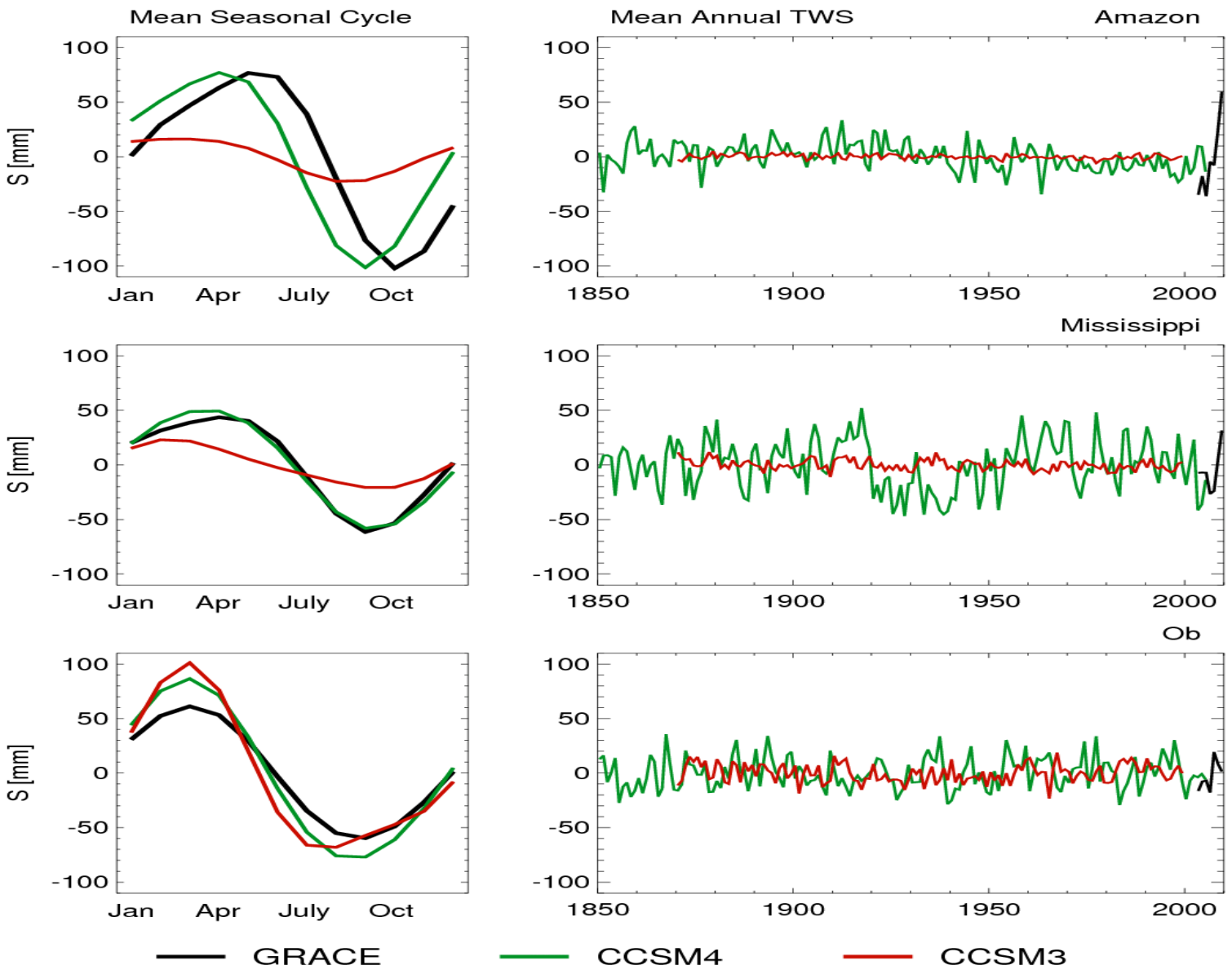
$$f_{sat} = (1 - f_{frz,1}) \times f_{\max} \exp(-0.5 f_{over} z_{wt}) + f_{frz,1}$$



$$q_{over} = f_{sat} q_{liq,0}$$

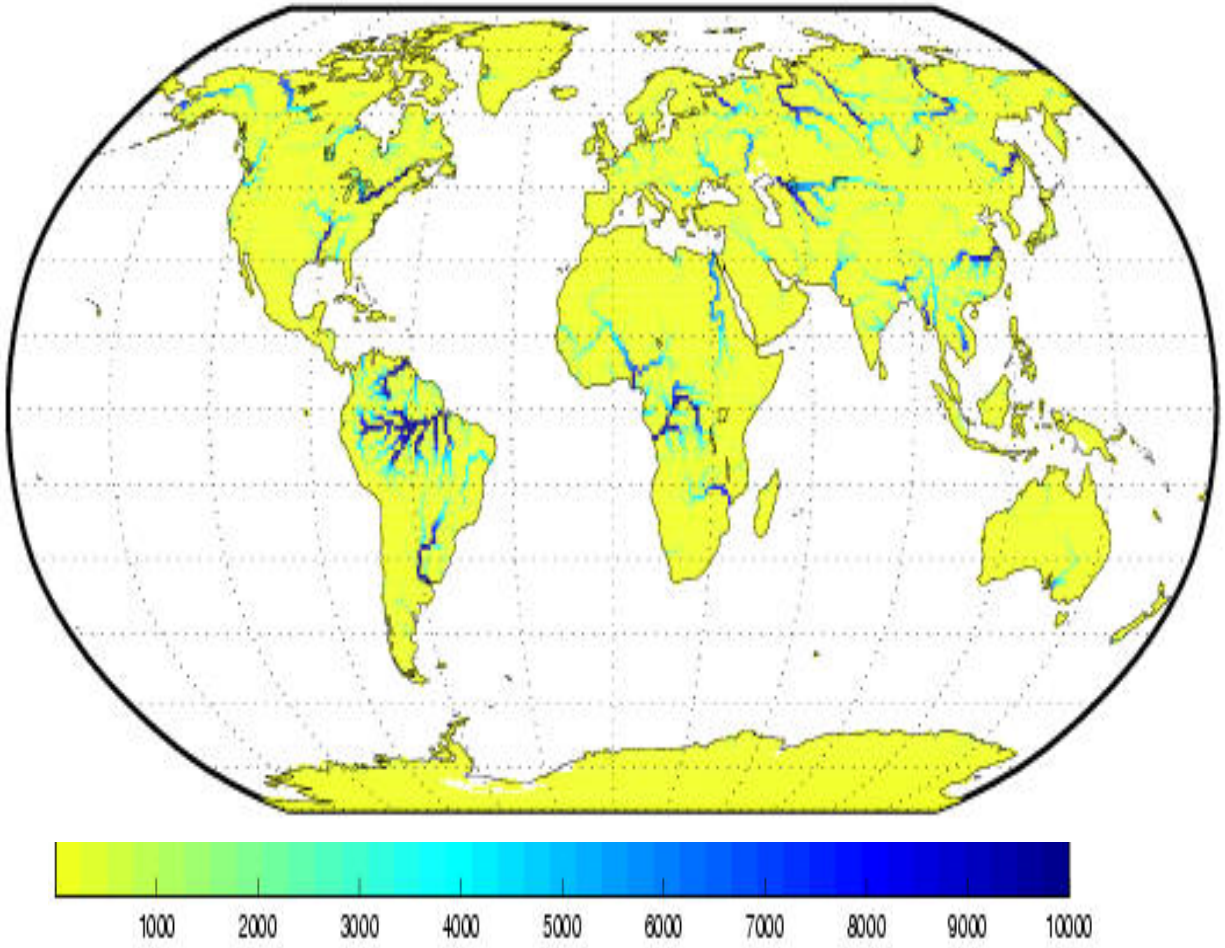
Niu et al. 2005

Total Land Water Storage (CCSM vs GRACE)

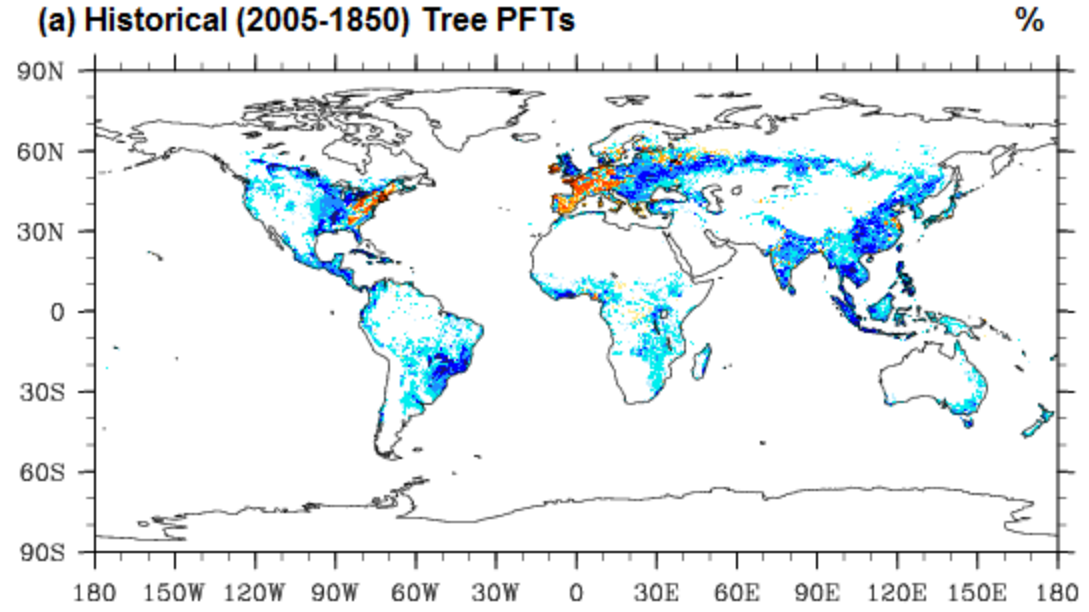


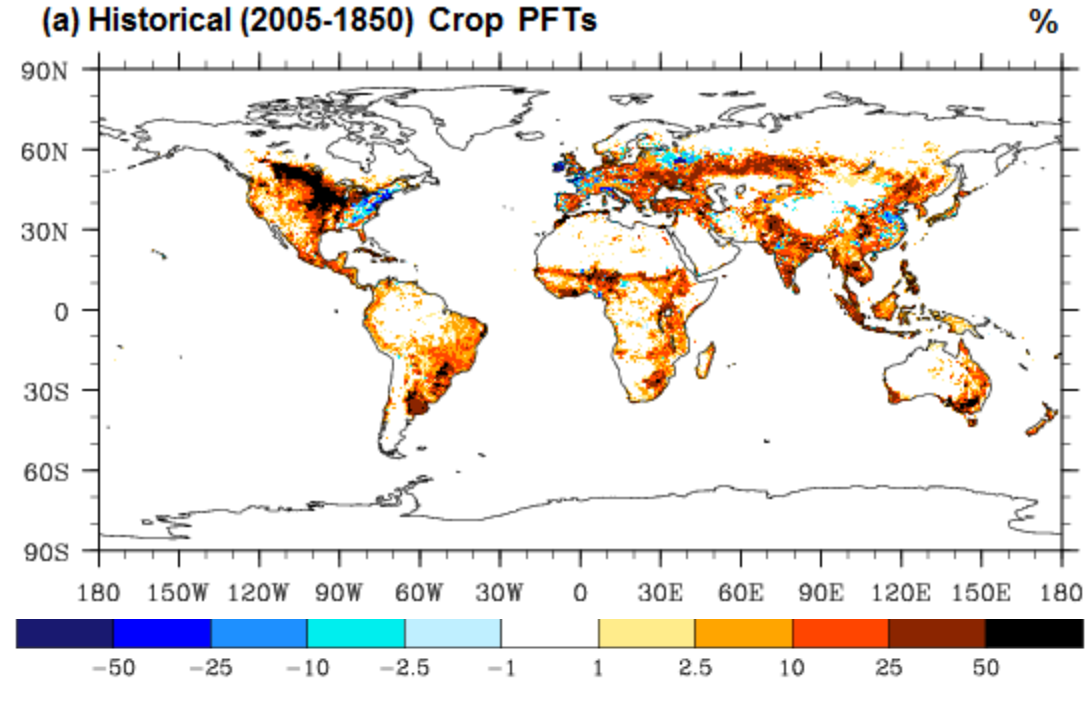
River Transport Model (RTM)

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



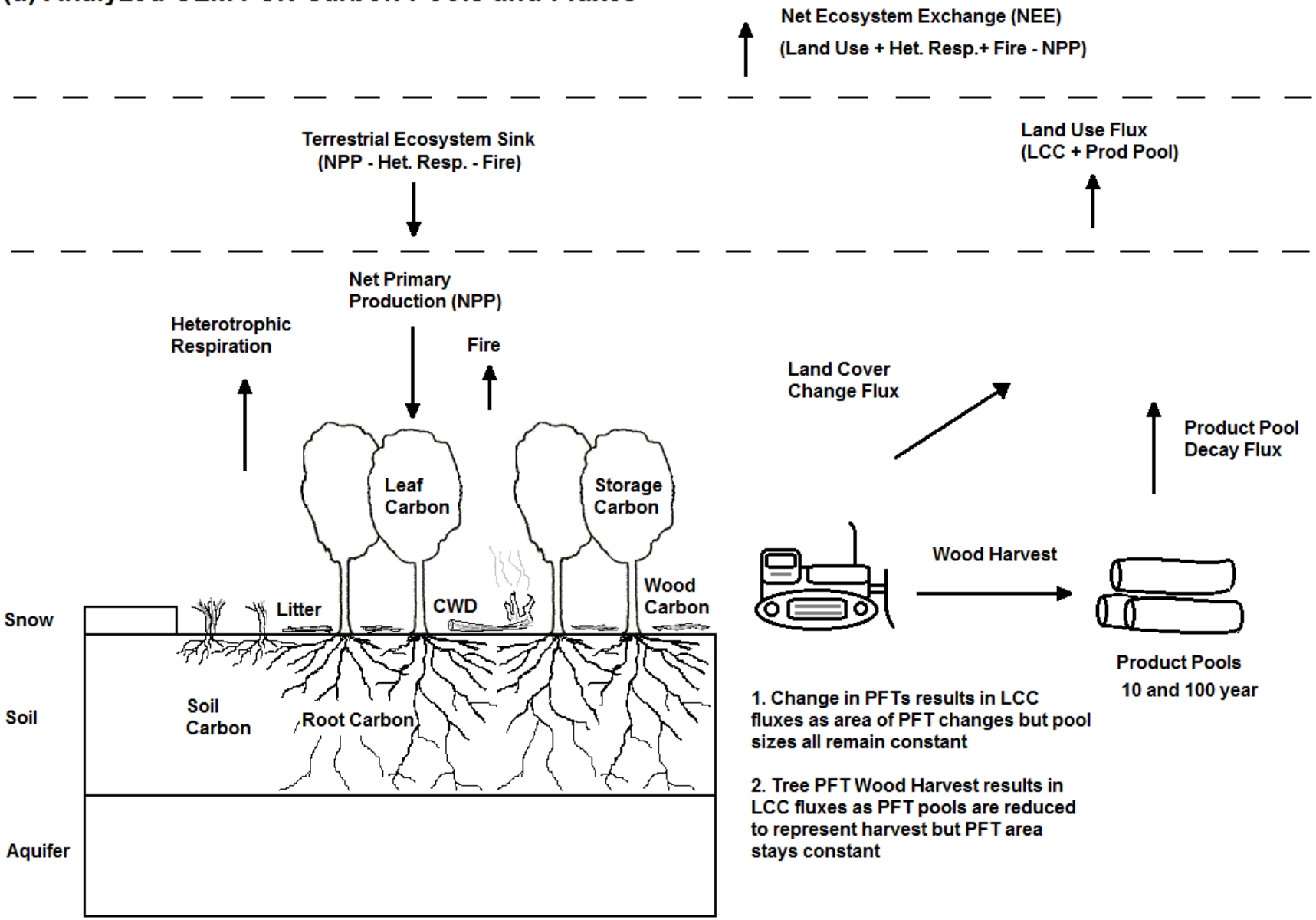
Land Cover Change Cropping and Forests in CLM4





Land Cover Change in (CLM4 CN)

(a) Analyzed CLM4 CN Carbon Pools and Fluxes



* Ecosystem Carbon = Leaf + Wood + Root + Storage + Litter + Coarse Woody Debris + Soil Carbon

** CWD = Coarse Woody Debris

Human Land Cover Change

1. Direct Biogeophysical Impacts:
- Albedo – Radiation (Snow Interactions)
- Surface Hydrology (Irrigation)
- Surface Roughness

2. Direct Biogeochemical Impacts:
- Vegetation and Soil Carbon Fluxes from Conversion Natural -> Human systems
- Harvesting from Forestry and Agriculture

3. Indirect Impacts:
- Increased Photosynthesis through higher CO_2, Nitrogen, Phosphorus and Potassium
- Atmospheric Responses in Temperature, Cloud, Precipitation and Larger Scale Circulation
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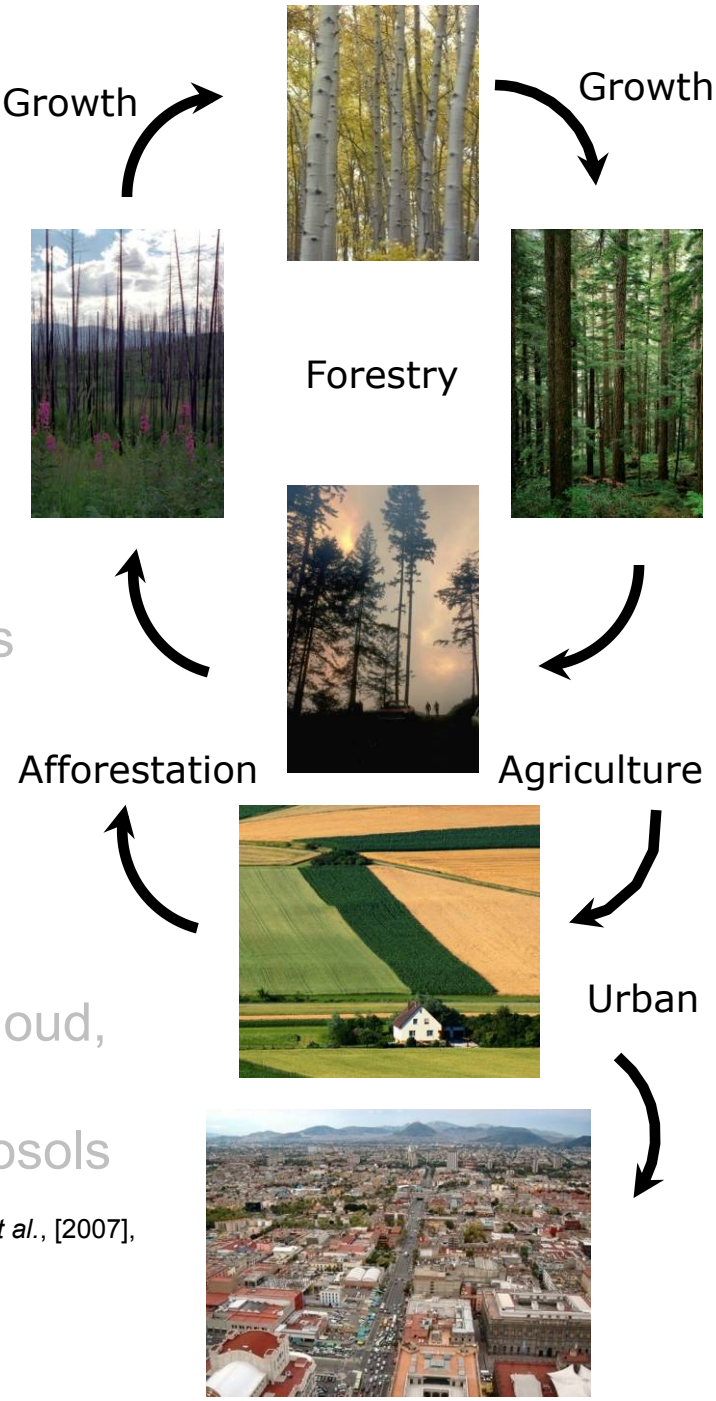

Lawrence et al., [2011], *Lawrence and Chase*, [2010], *Feddema, et al.*, [2005], *Findell, et al.*, [2007], *IPCC*, [2007], *Bonan*, [2008], and *Canadell, et al.*, [2007]

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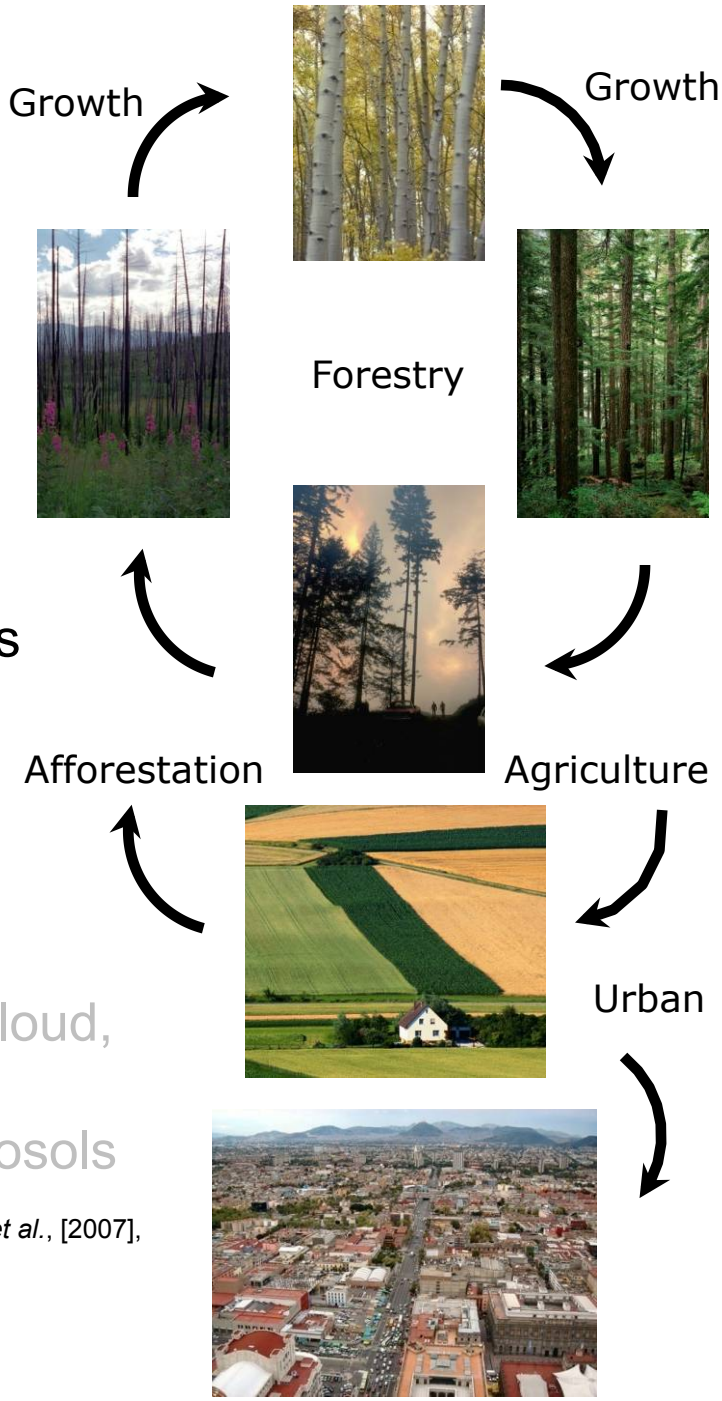

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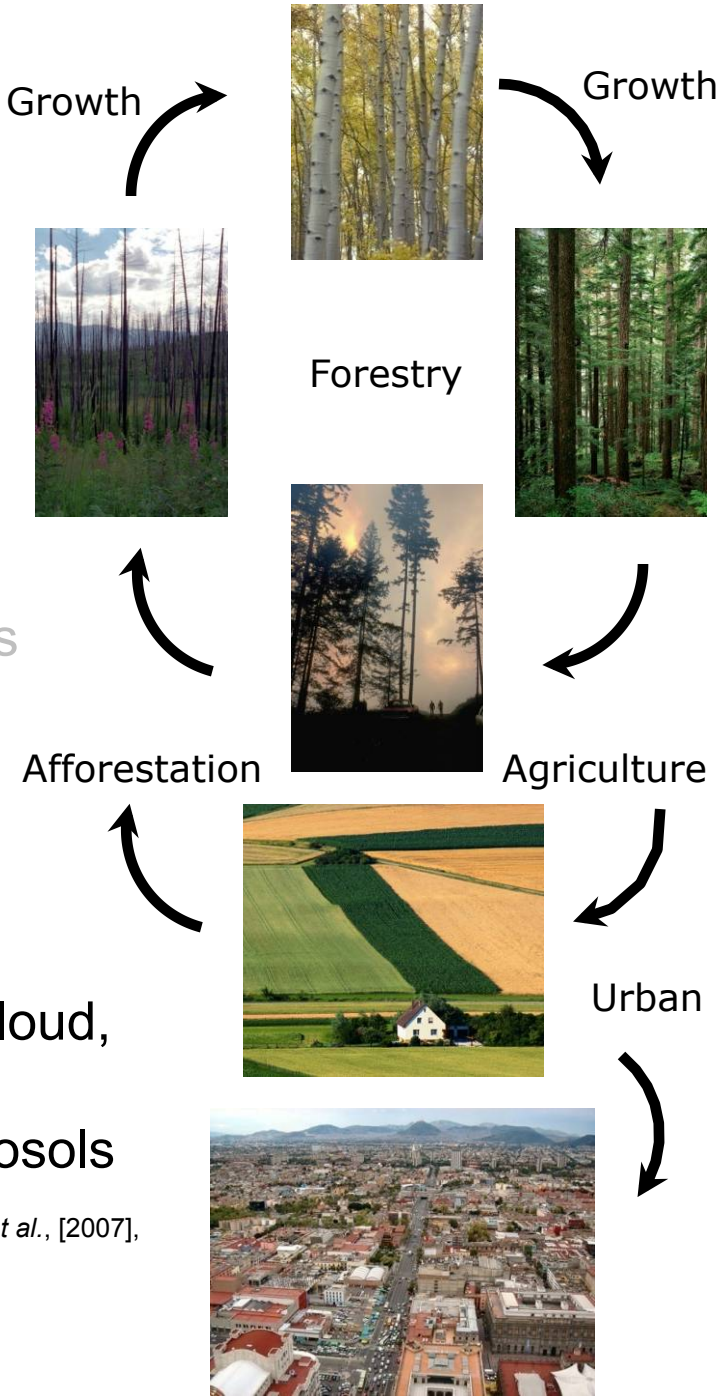

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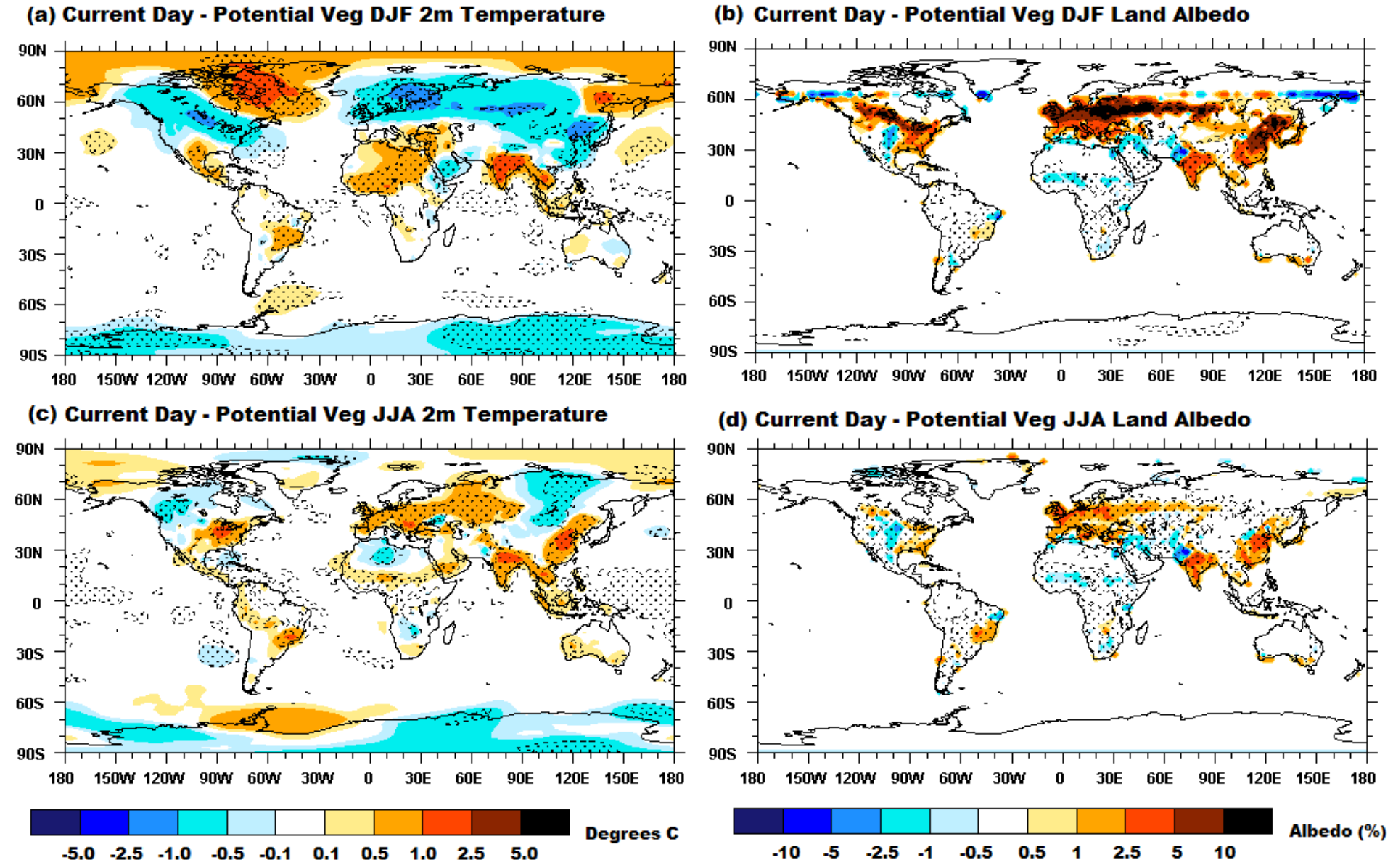
CCSM Land Cover Change Climate Experiments

1. The biogeophysical climate impacts of changing land cover from precleared vegetation to current day vegetation were investigated with the CCSM 3.0 model in *Lawrence and Chase* (2010)

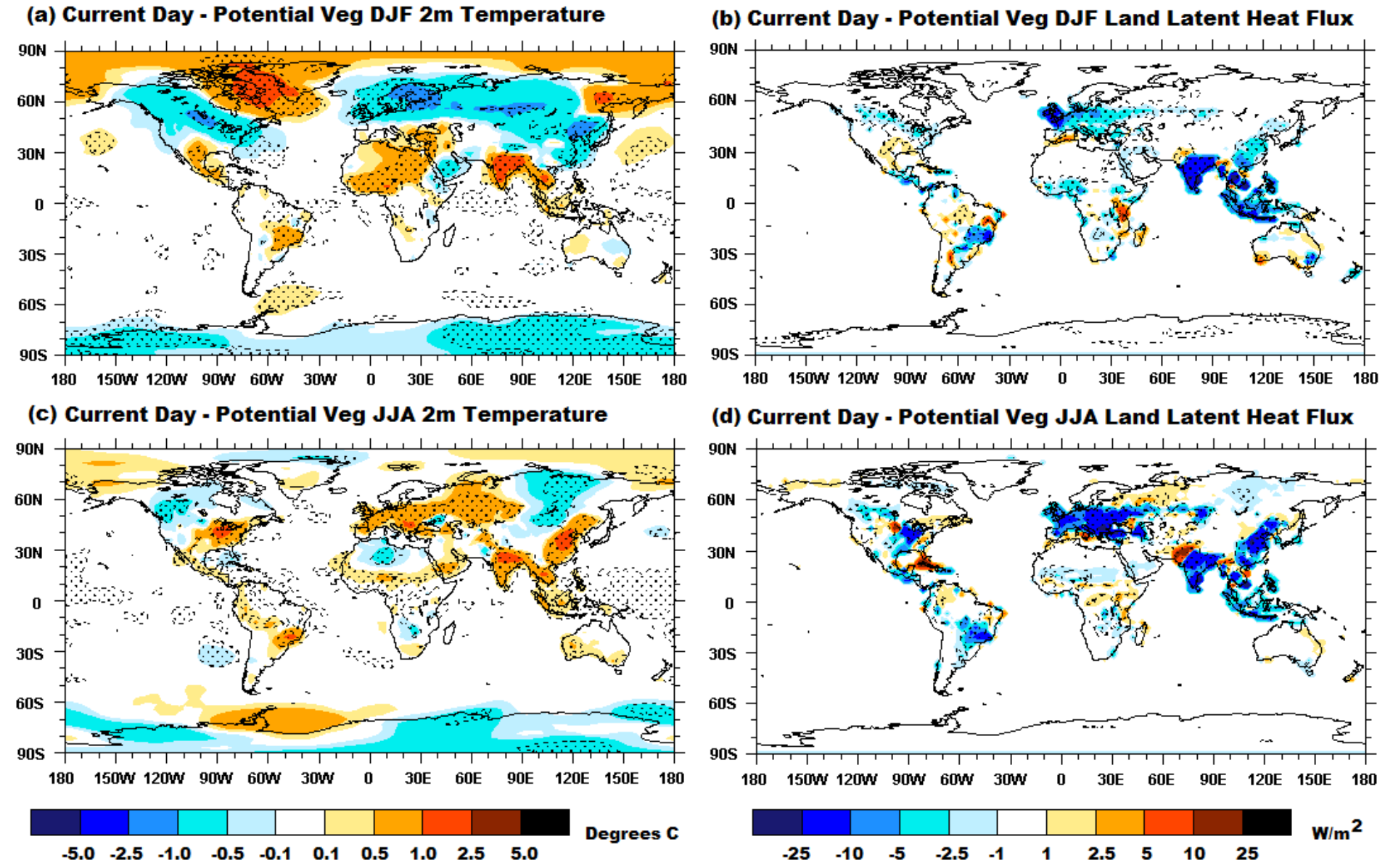
2. The investigation compared six ensemble members of 30 years of current day equilibrium climate simulated in the fully coupled CCSM 3.0 model with Precleared Vegetation land surface parameters, against the same climate simulated with Current Day land surface parameters

3. The Land Surface Hydrology representation in CLM 3.0 was modified as described in *Lawrence and Chase* (2009) to address modeling biases.

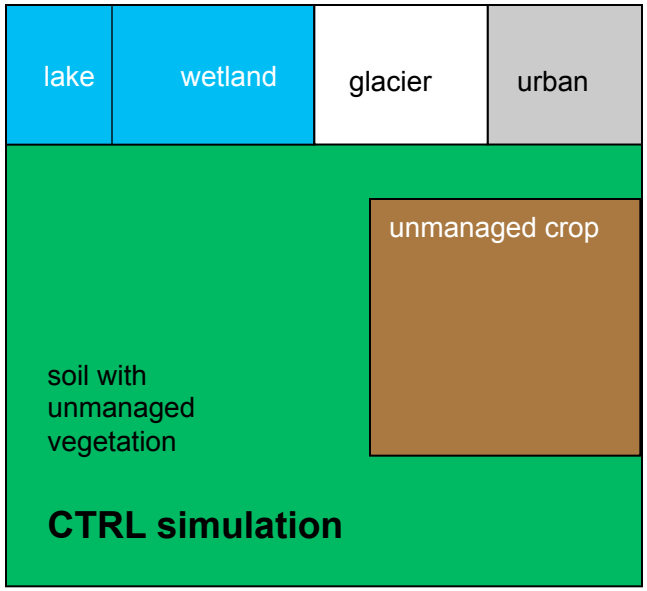
Current Day – Preclear Vegetation CCSM Climate-Albedo

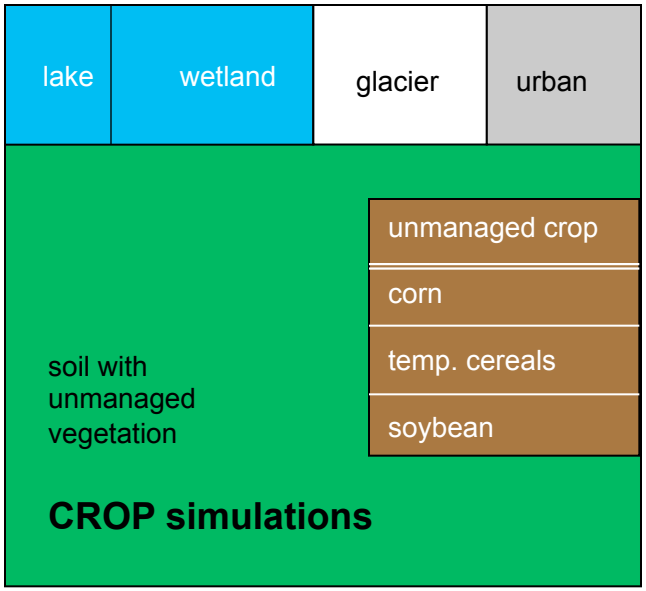


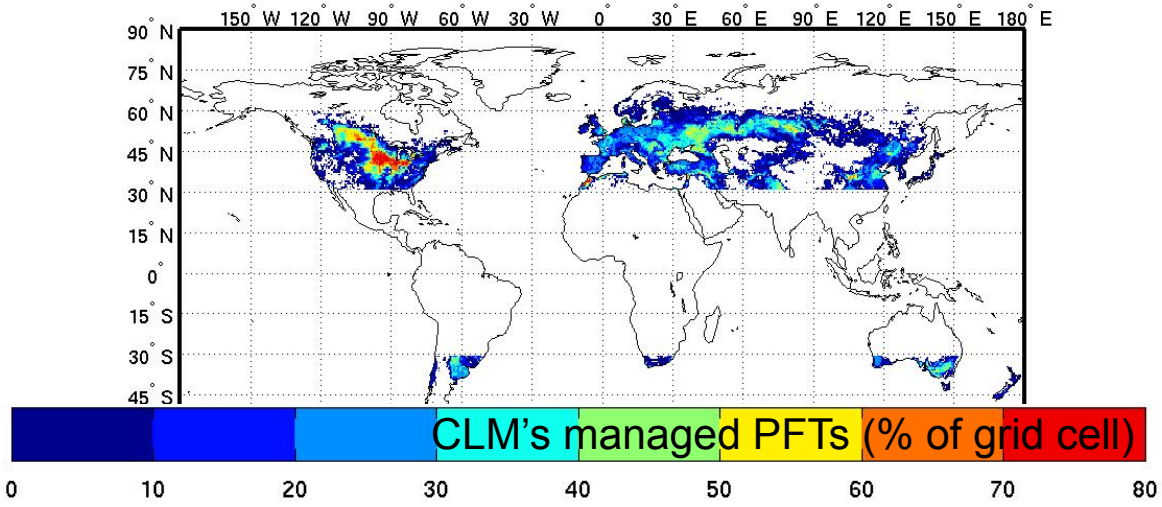
Current Day – Preclear Vegetation CCSM Climate-Latent



Interactive crop management CLM4CNcrop

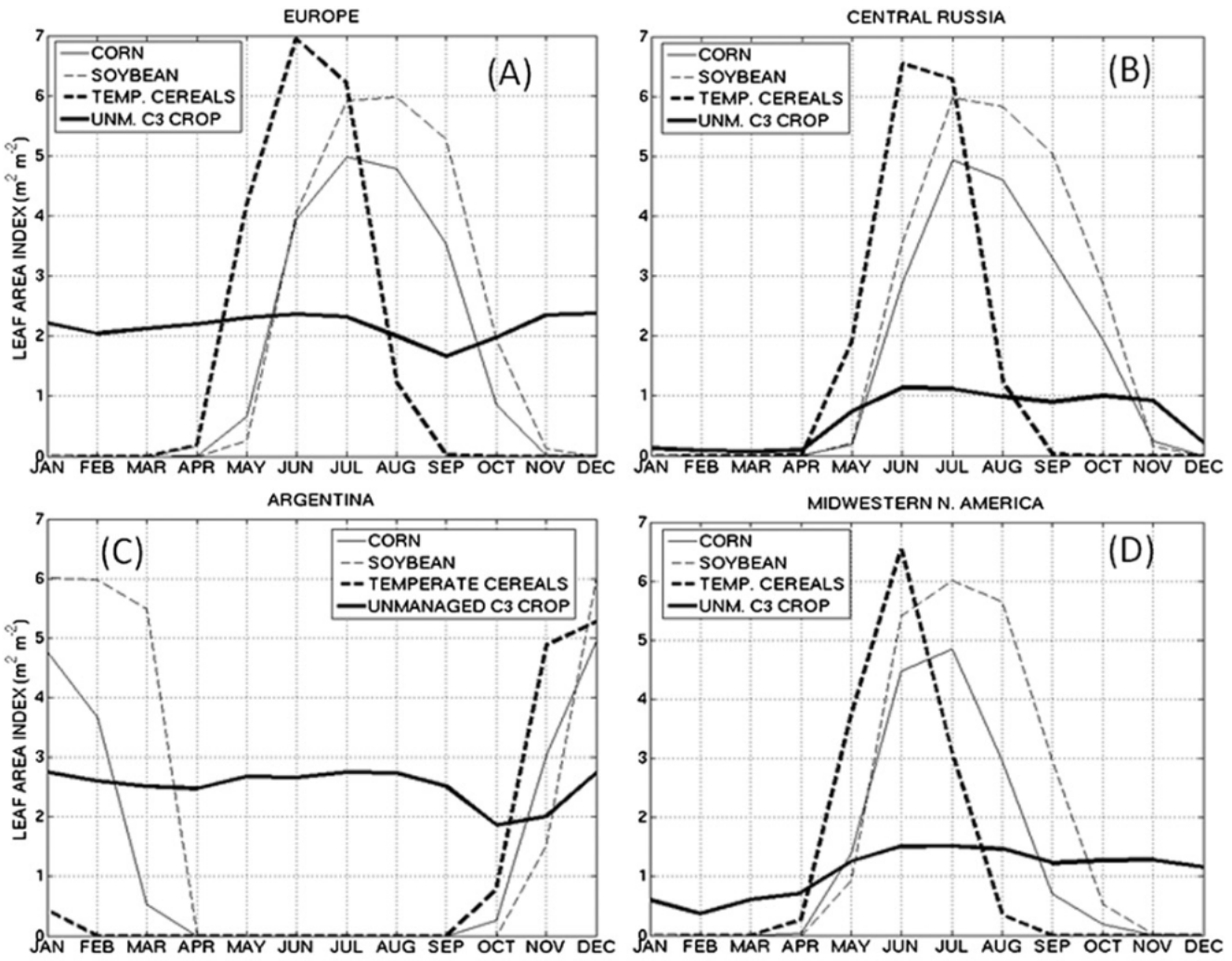






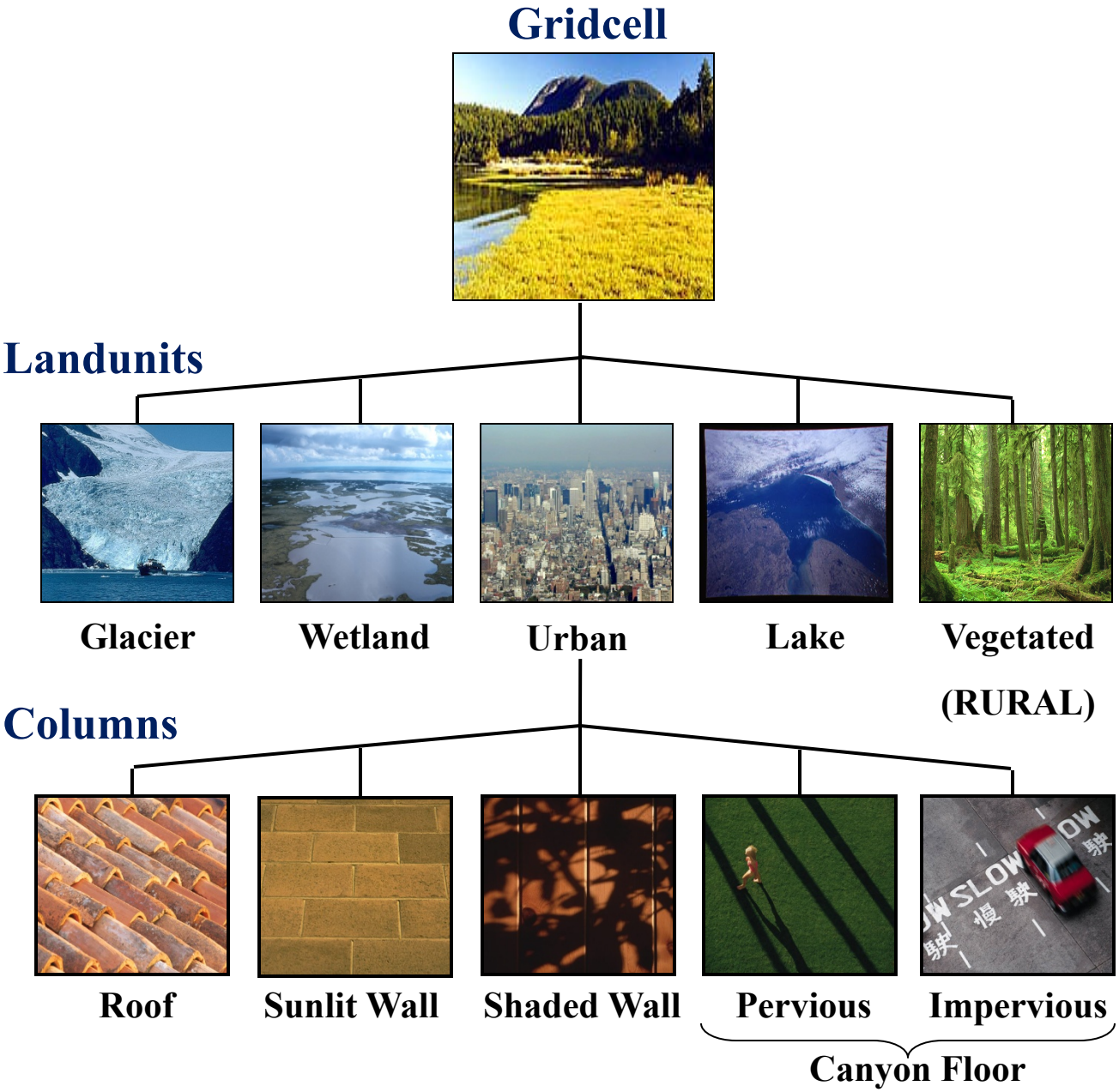
Levis *et al. 2012*

Interactive crop management CLM4CNcrop



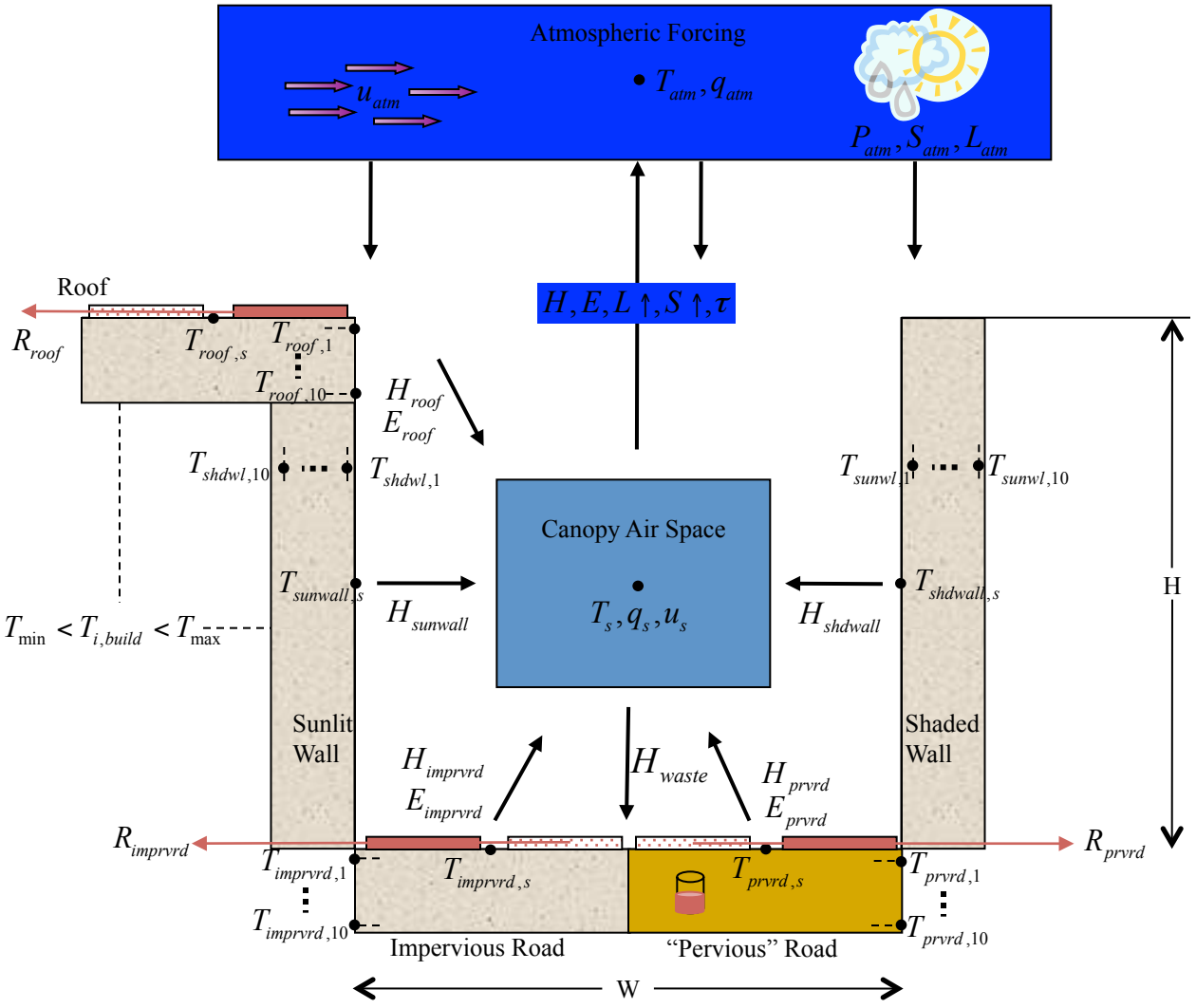
Levis *et al. 2012*

Urban Areas in a Climate Model



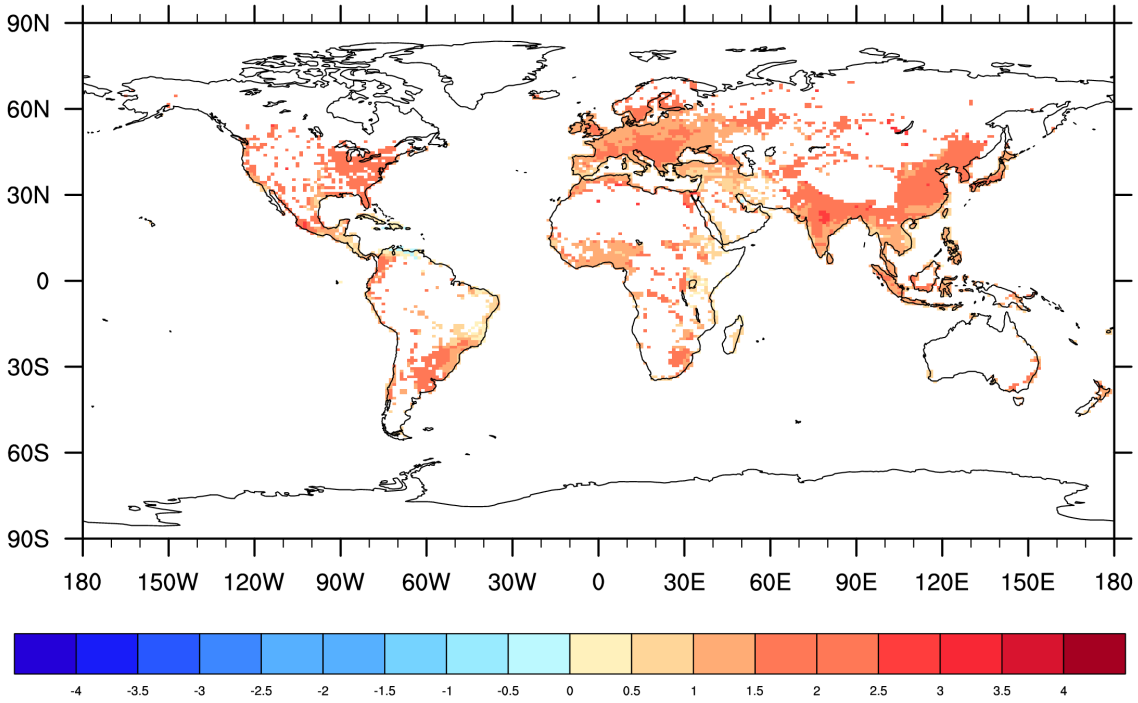
Community Land Model – Urban (CLMU)

Oleson et al. 2008a, b, *JAMC*



Urban Heat Island in CCSM4

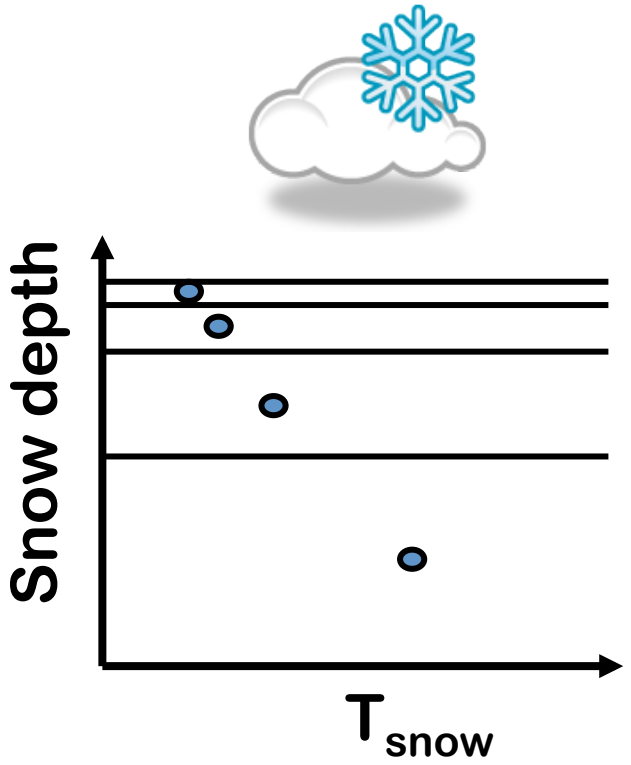
Present day Urban Heat Island (UHI) simulated by CLM Urban (°C)



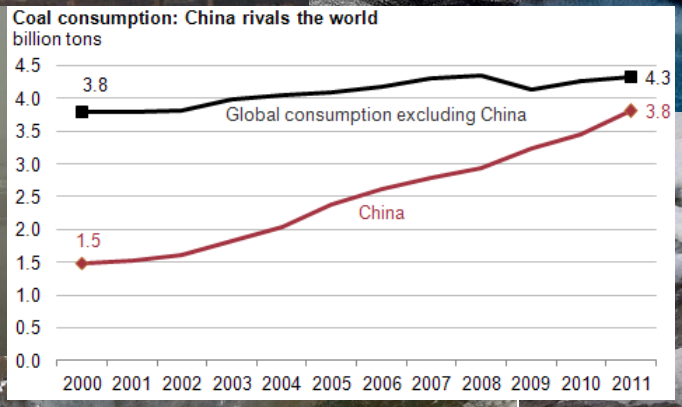
Modeled UHI ranges from near-zero up to 4°C with spatial and seasonal variability controlled by urban to rural contrasts in energy balance.

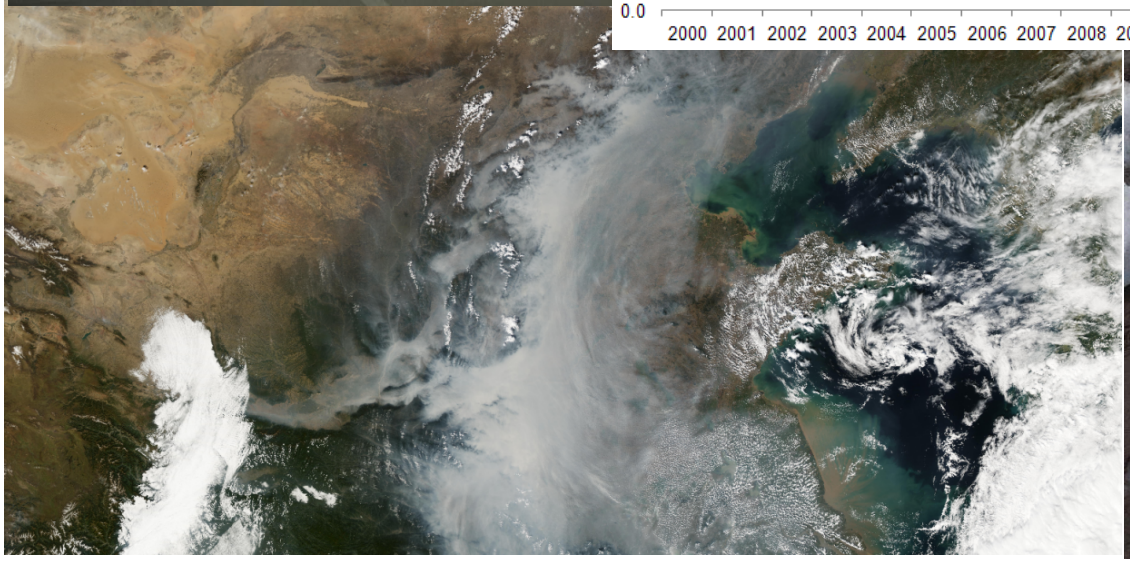
Model components: Snow Model

- 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



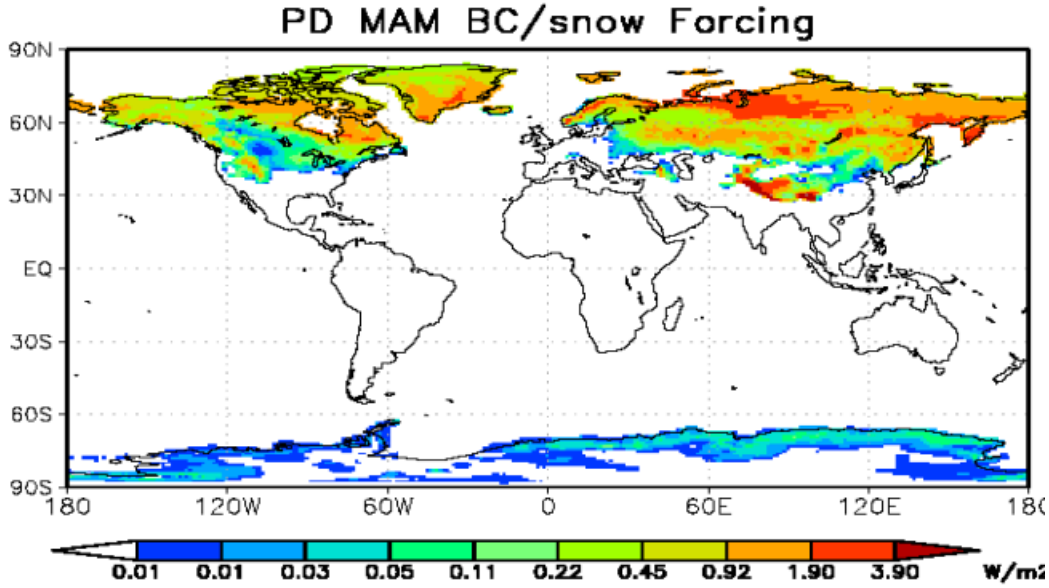
China – Black Carbon on Snow and Albedo – Greenland Icesheet – Cryoconite





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*

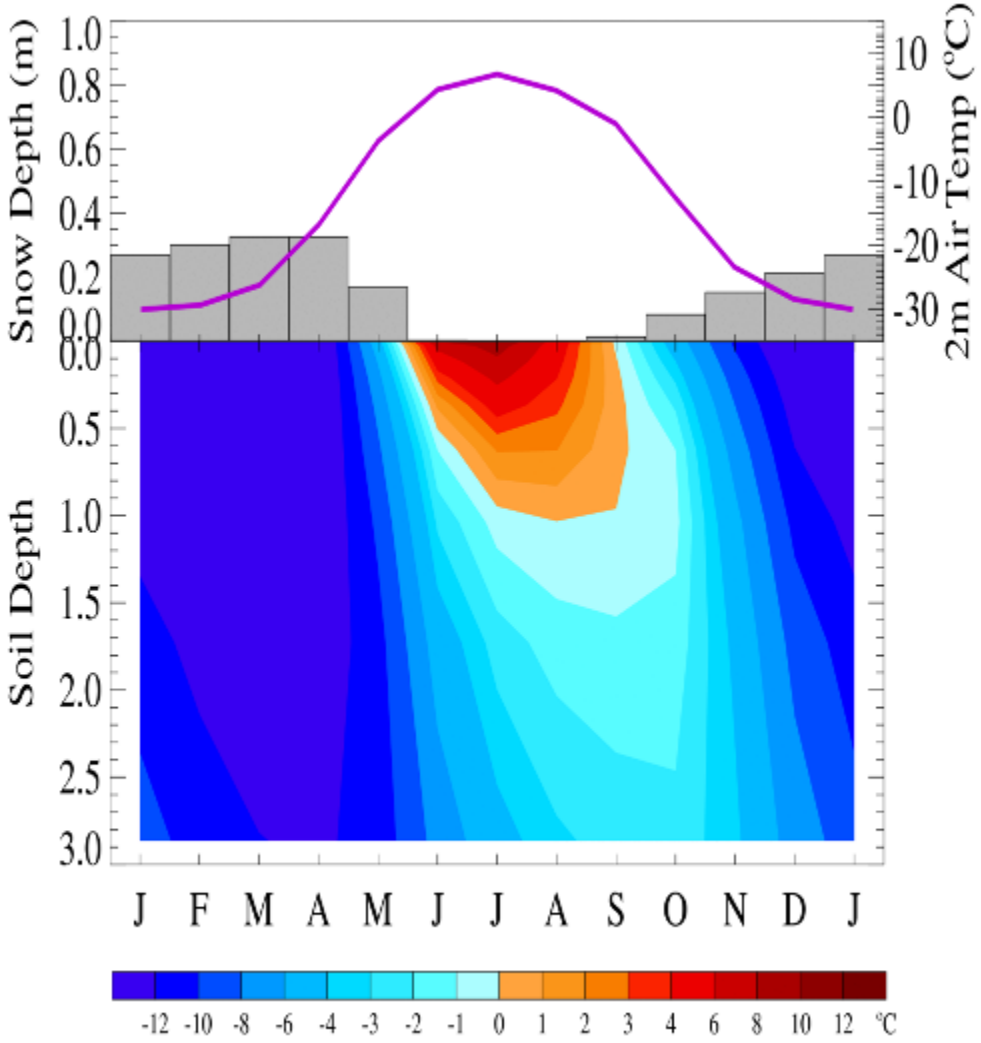
Snow/Soil thermodynamics

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

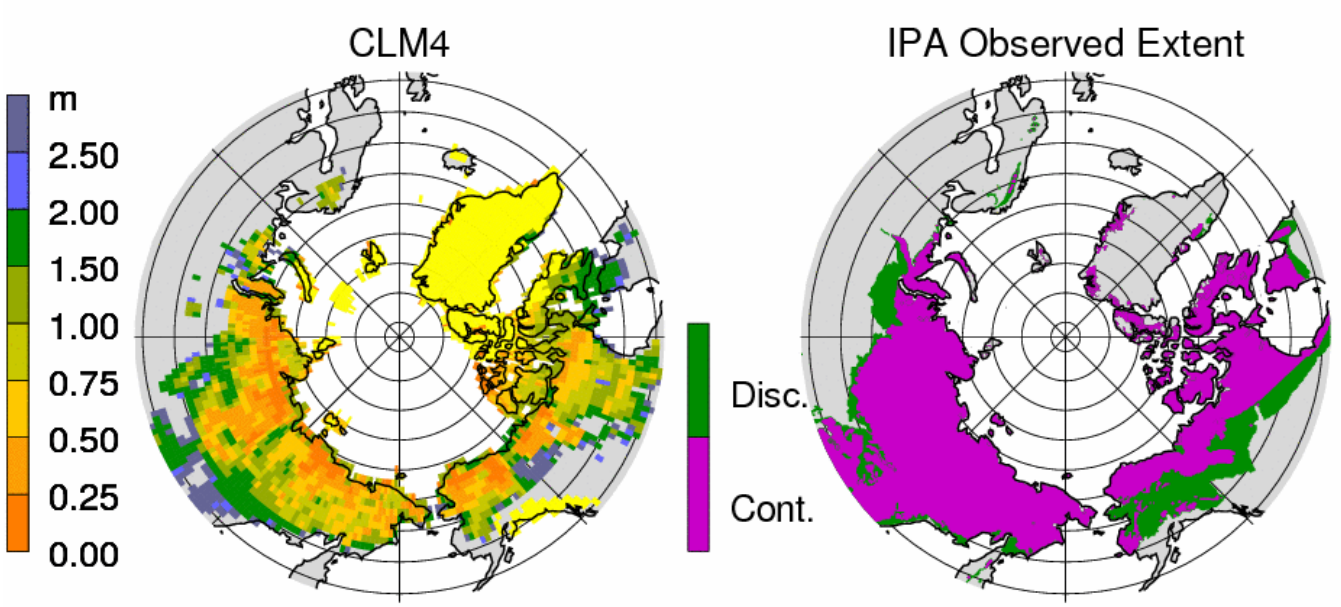
$$C_p \frac{\partial T}{\partial t} = \frac{\partial}{\partial z}\left(K \frac{\partial T}{\partial z} \right)$$

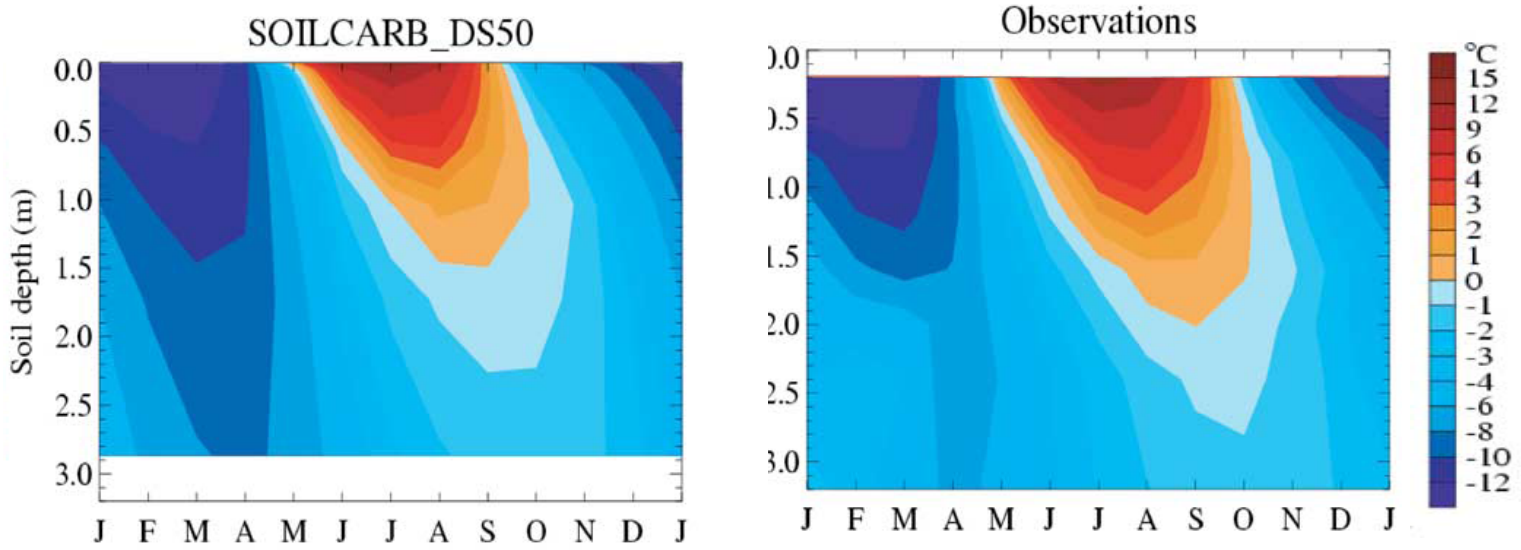
where C_p (heat capacity) and K (thermal conductivity) are functions of:

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



Modeling Permafrost in CLM





Lawrence et al., J. Climate, 2011

Understanding the Land Surface in the Climate System: Investigations with an Earth System Model (NCAR CESM)

The land is a critical interface through which:

1. Climate and climate change, impacts humans and ecosystems

and

2. Humans and ecosystems can force global environmental and climate change