NCAR Earth System Laboratory

Lecture 5: Land Modeling I: Biogeophysics

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(With thanks to TSS group for their many contributions)

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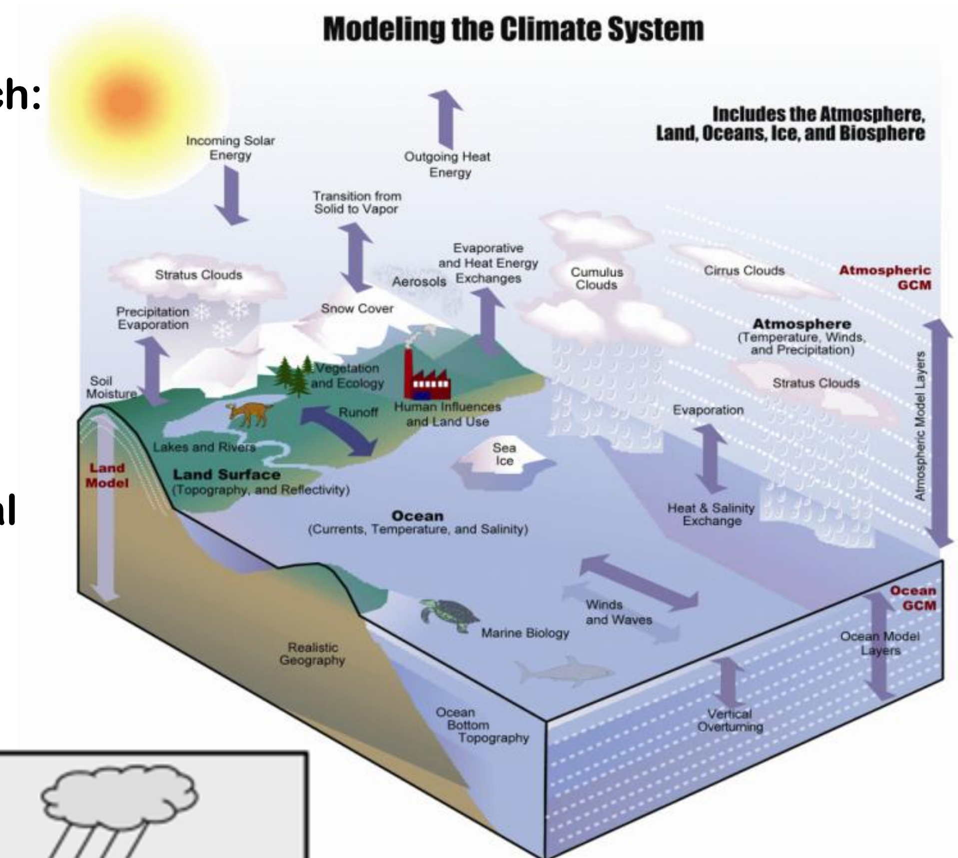
Understanding the Land Surface in the Climate System: Investigations with an Earth System Model (NCAR CESM)

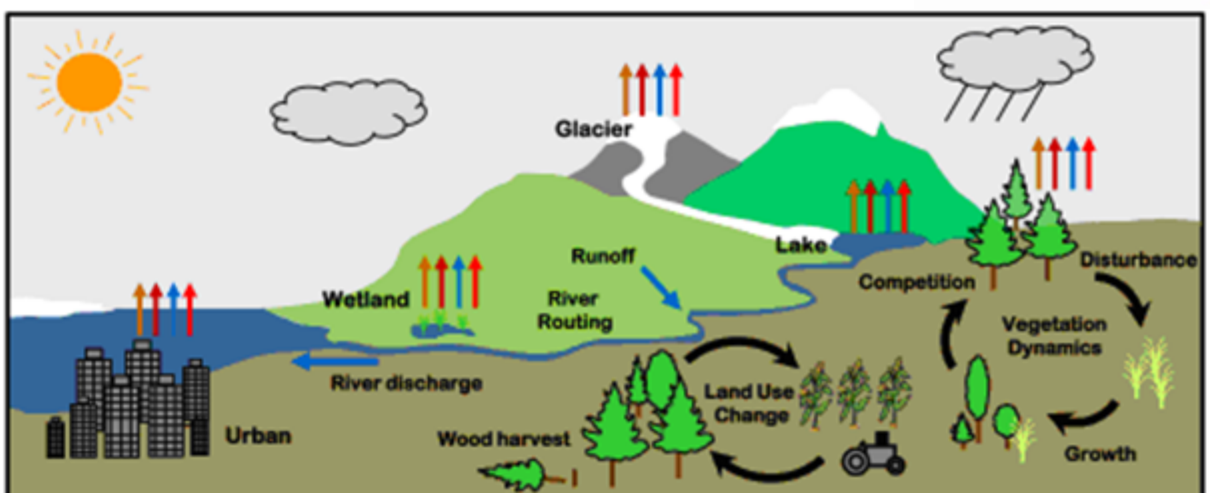


The land is a critical interface through which:

1. Climate and climate change impacts humans and ecosystems

and

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



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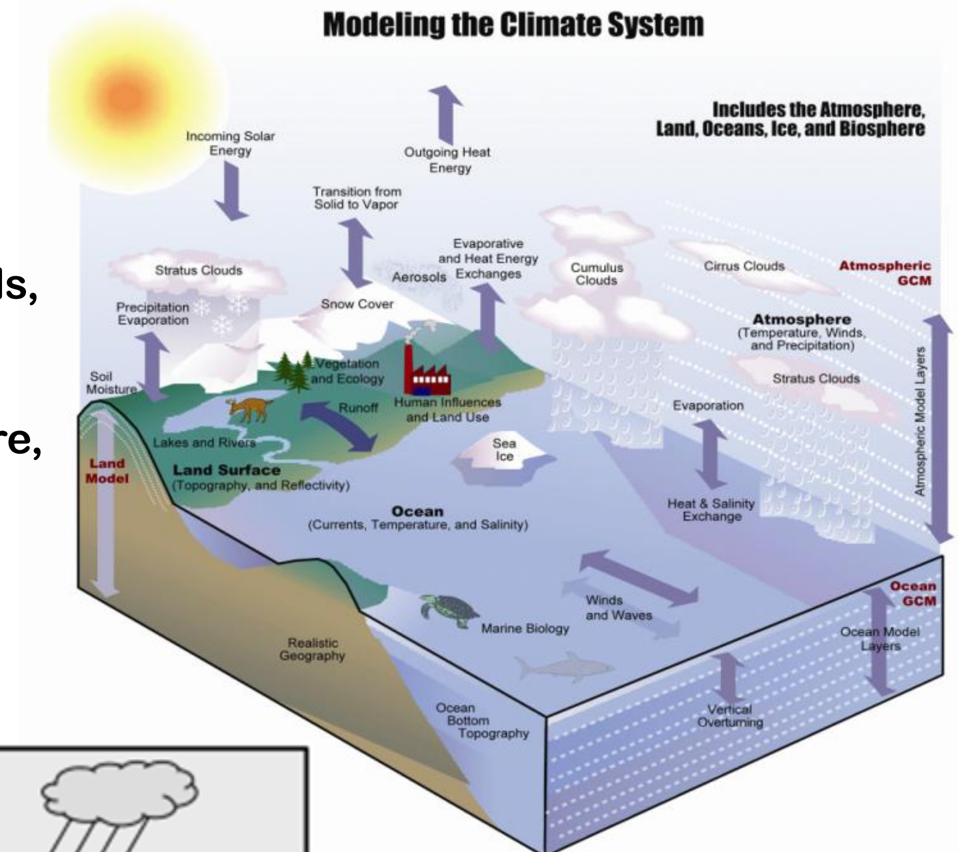
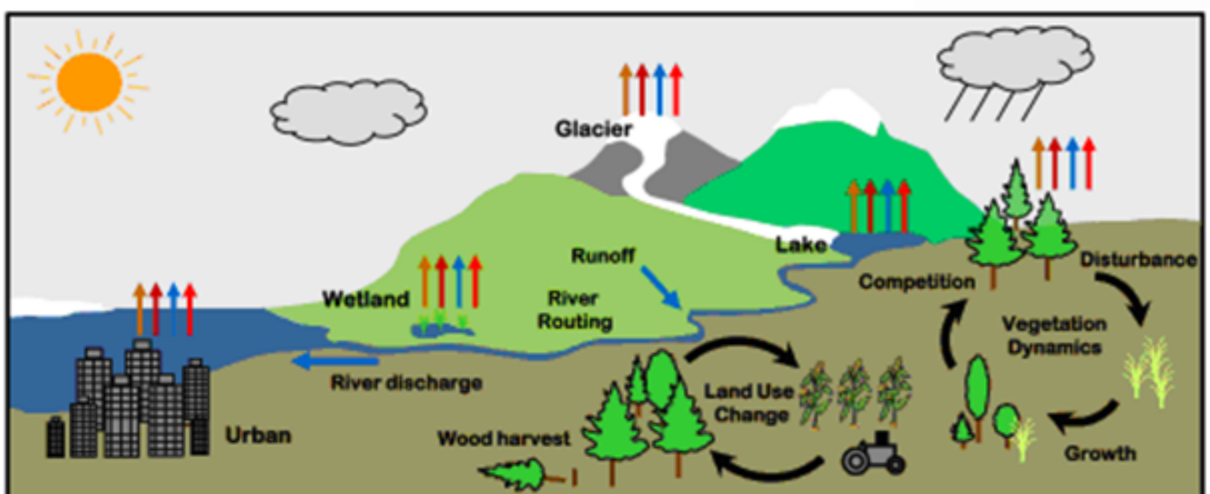


Land Surface Elements modeled in CESM:

- Glaciers, Lakes, Wetlands and Rivers

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

- Human Modified Landscapes of Agriculture, Forestry and Cities



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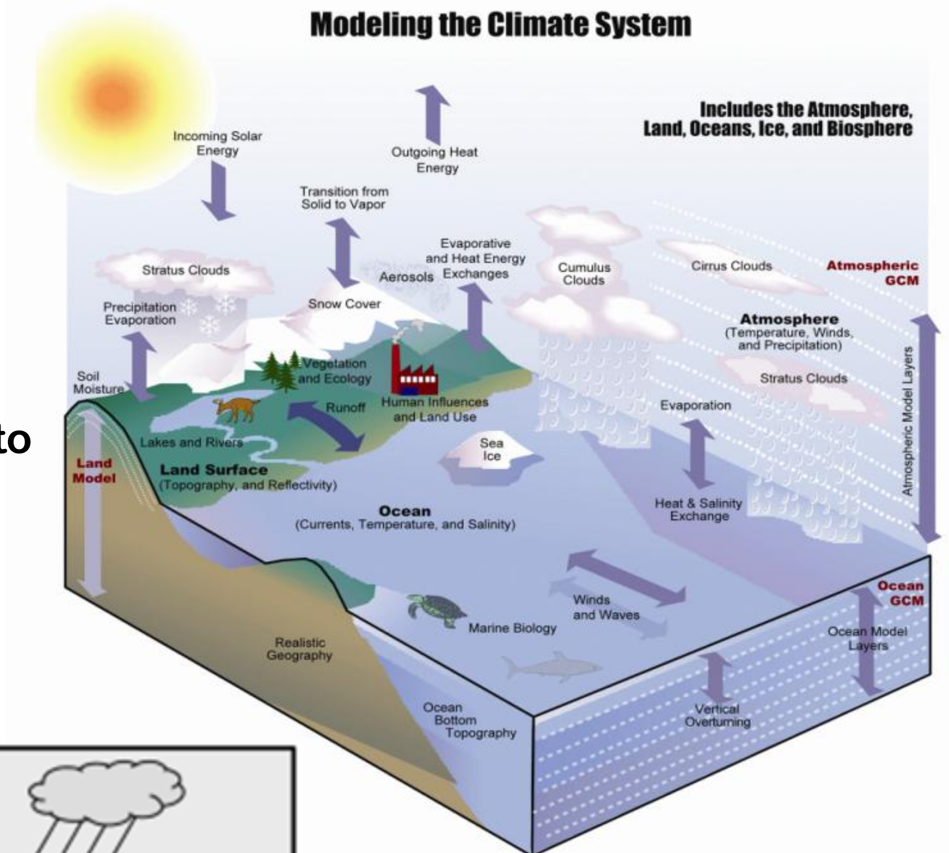
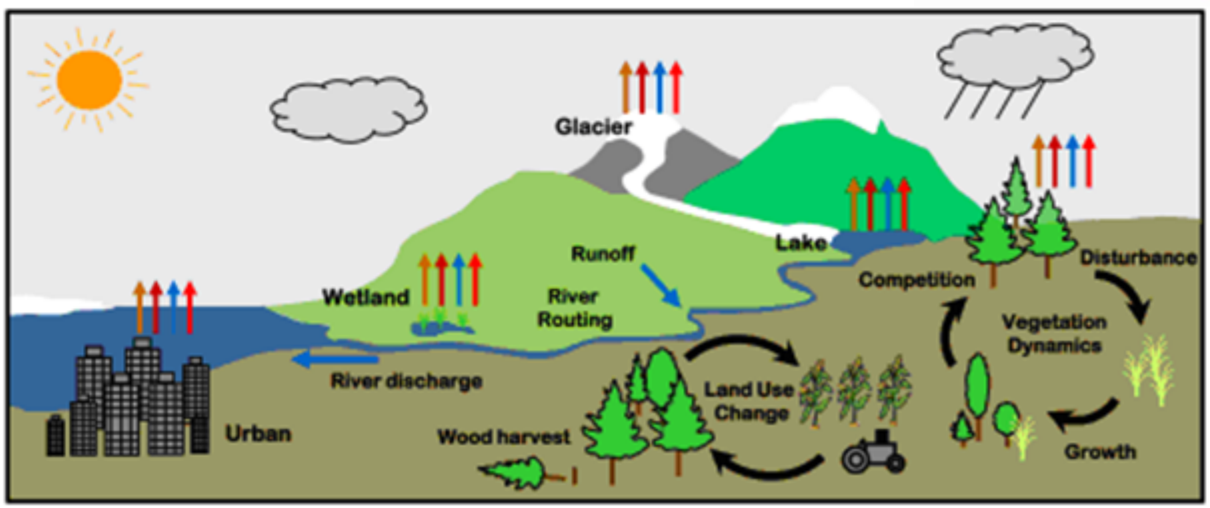


Global Environmental and Climate Change from the Land Surface in CESM:

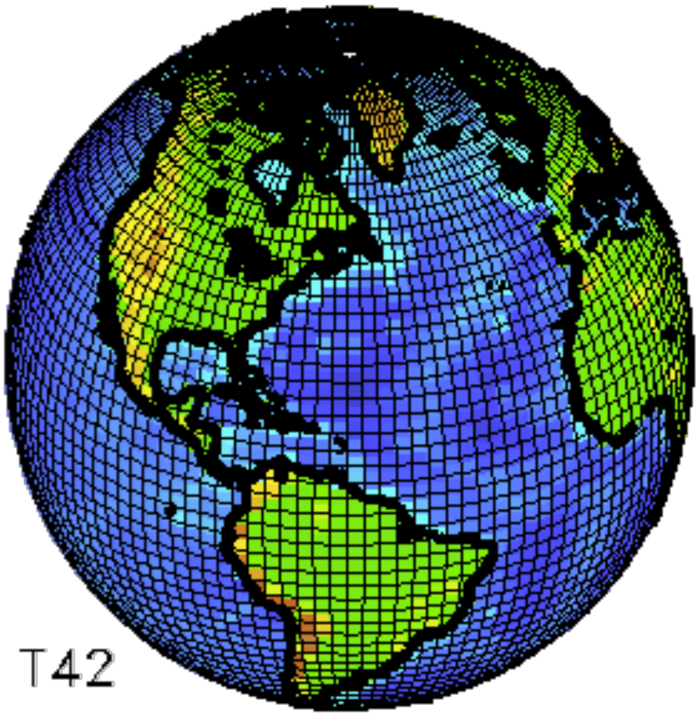
- Solar Radiation heating the land surface through snow, ice, vegetation, soils and cities

- 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



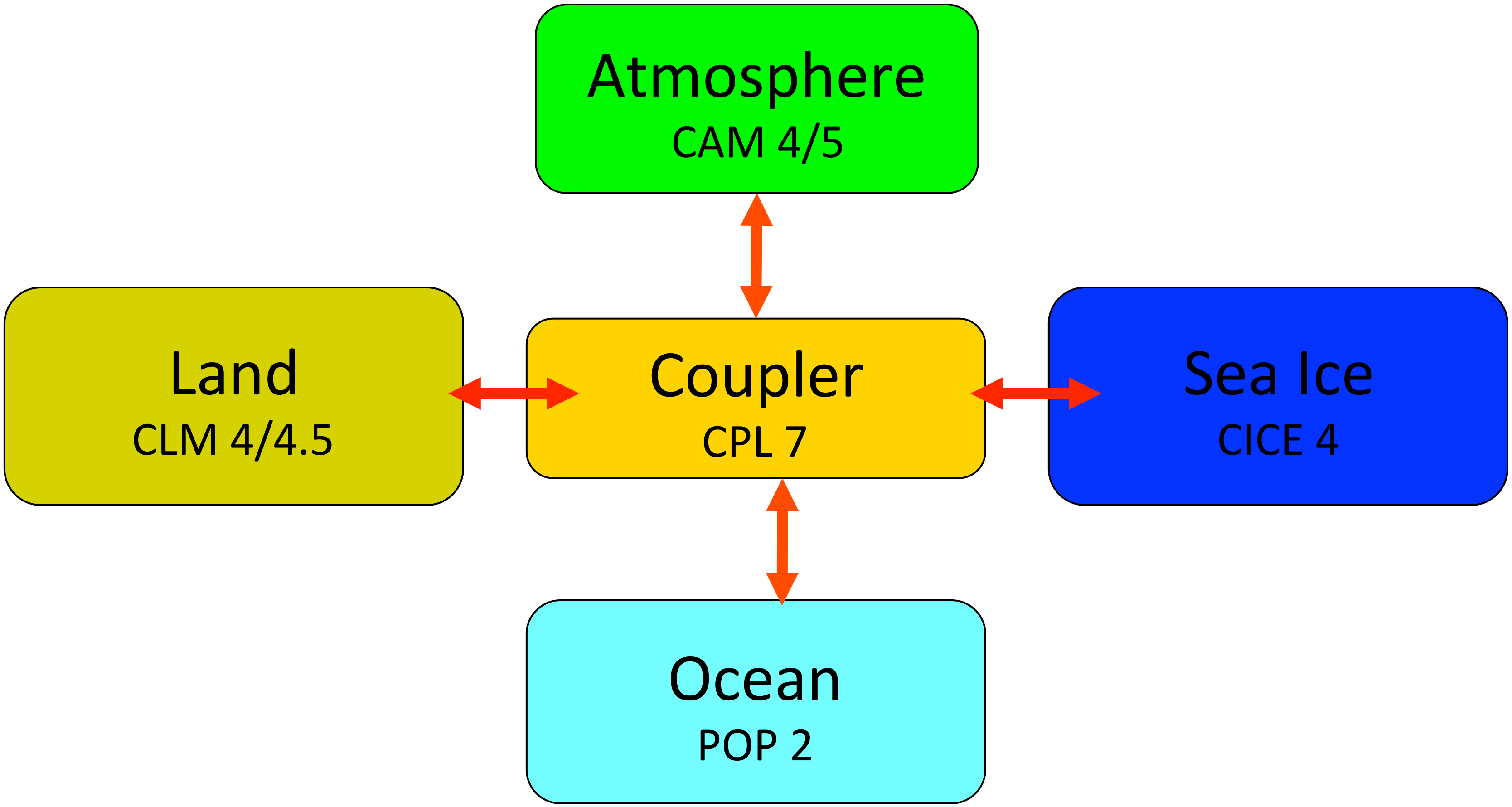
Community Earth System Model (CESM1)



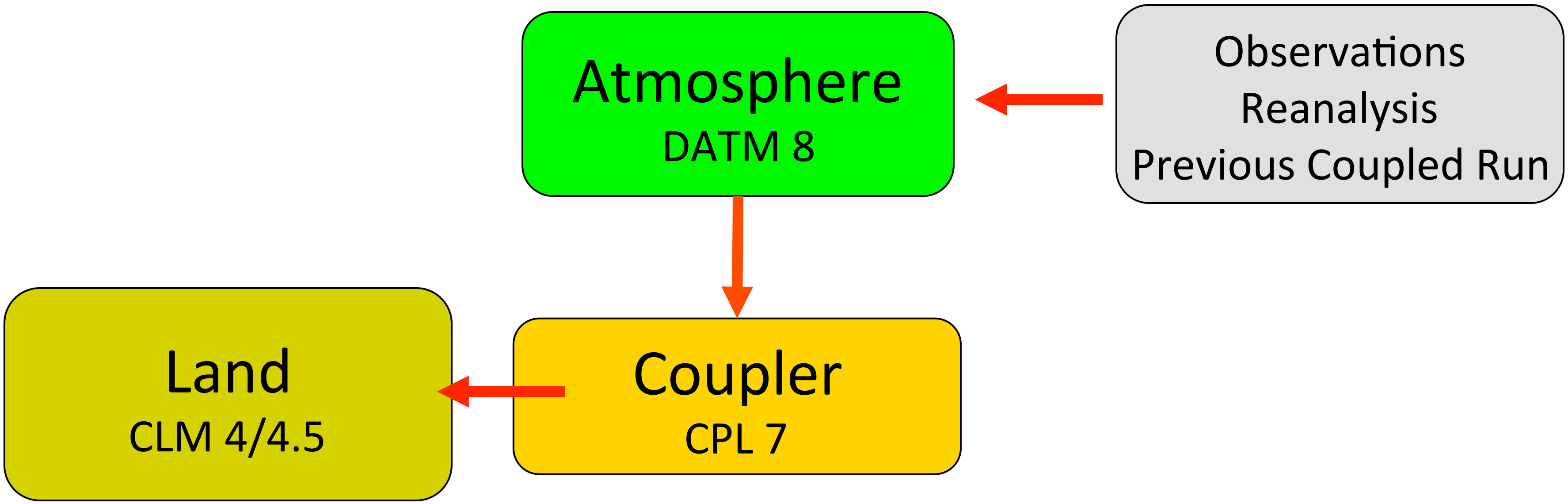
Core is a Coupled Ocean-Atmosphere-Land- Sea Ice model

- 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)

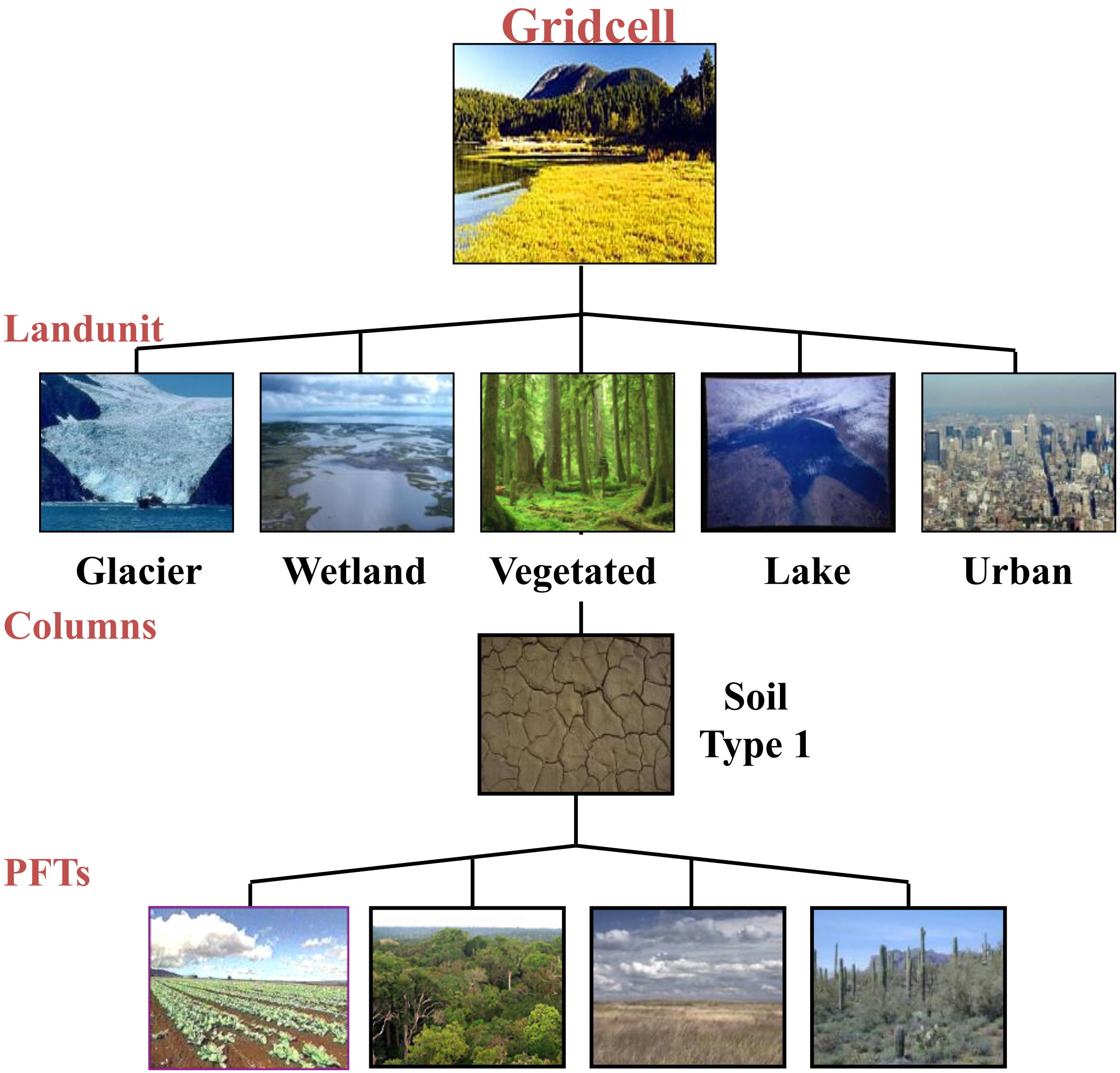
Configuration of CESM Fully Coupled

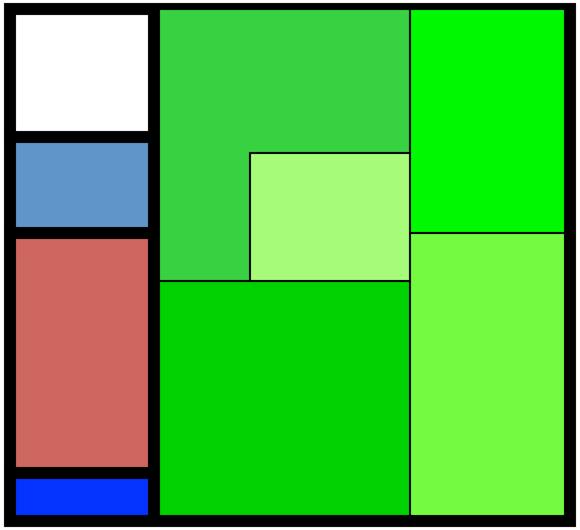


Configuration of CESM Prescribed Atmosphere



Community Land Model (CLM4) subgrid tiling structure





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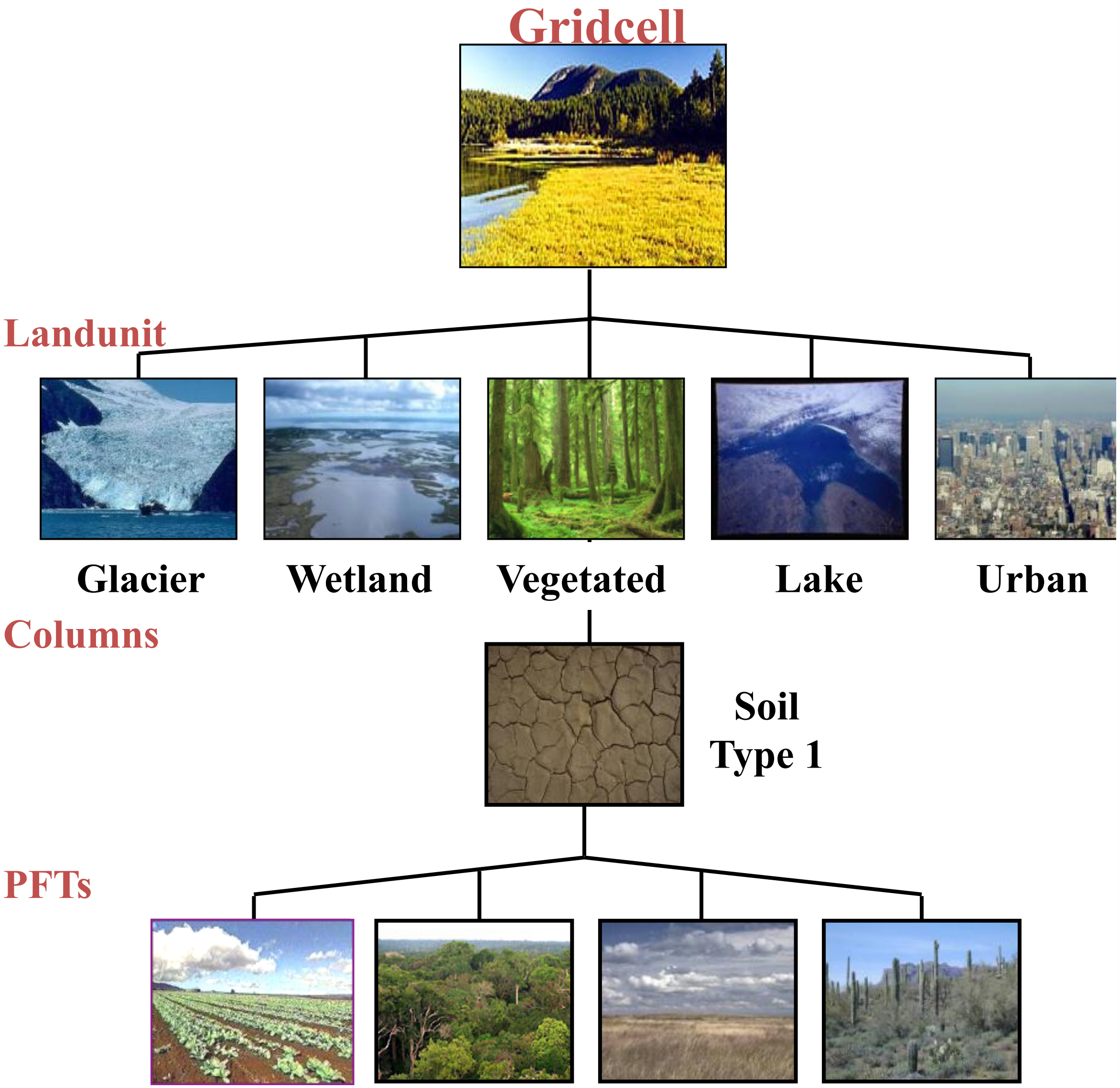


Plant Functional Types:

0. Bare

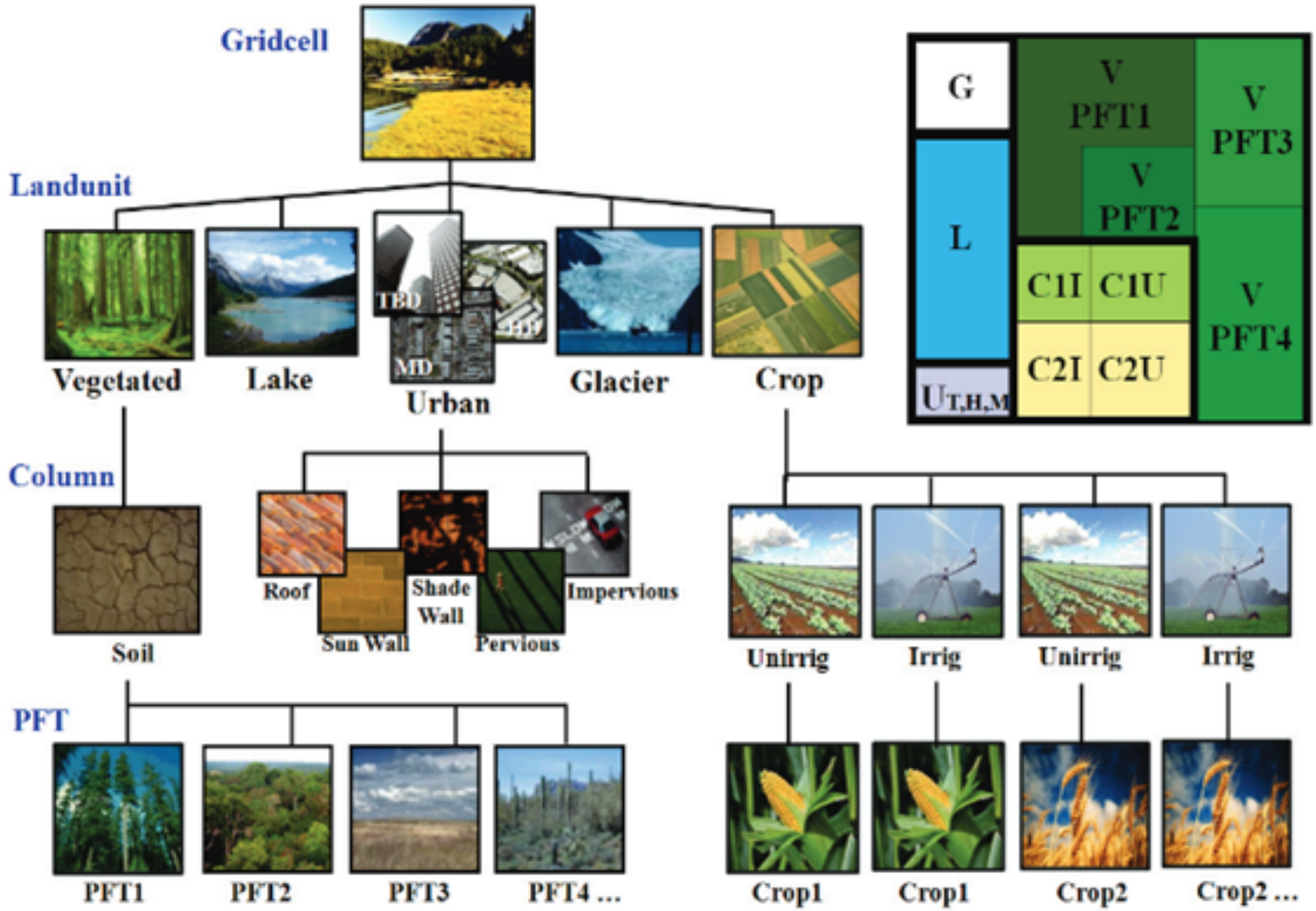
Tree:

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

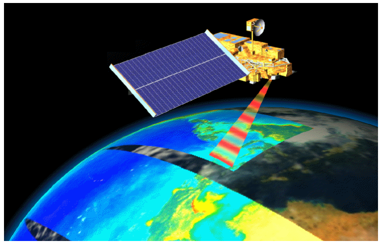
Community Land Model (CLM 4.5) subgrid tiling structure

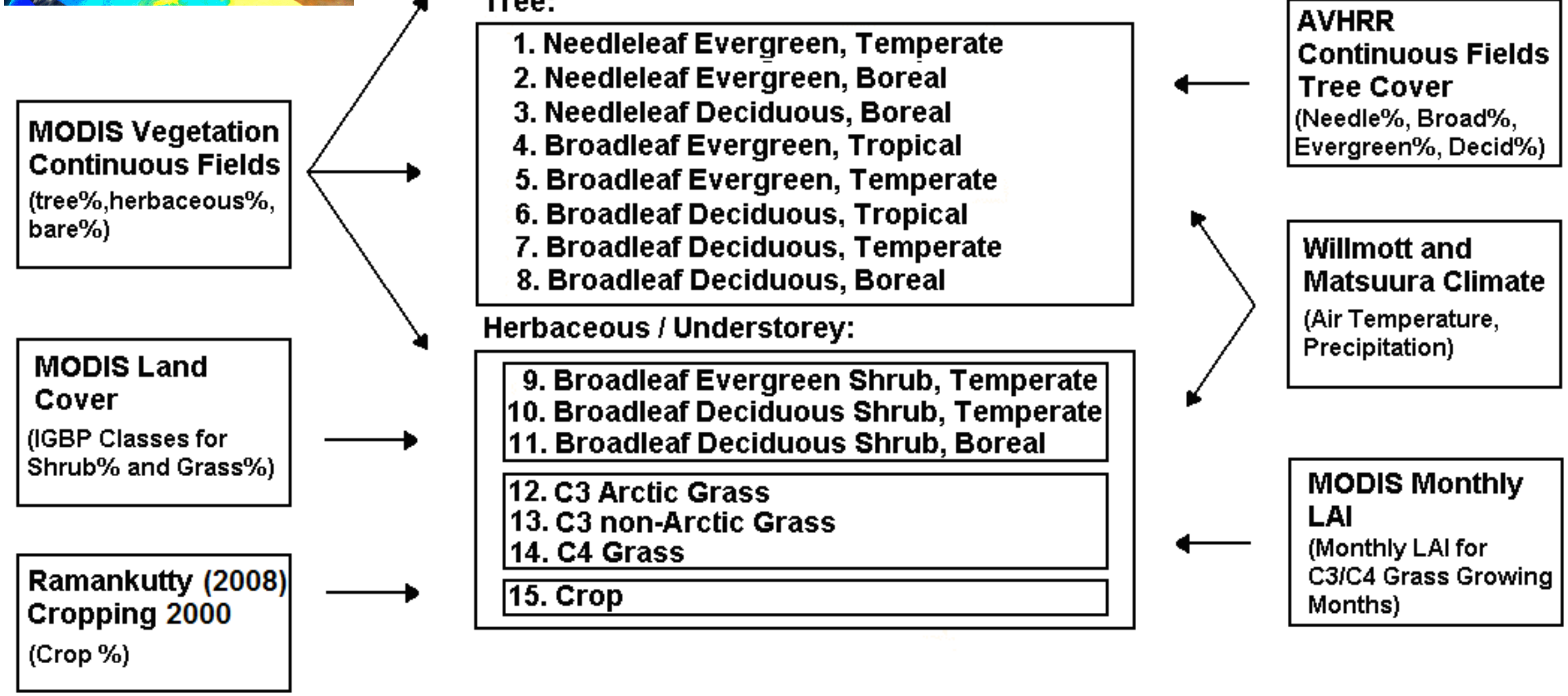


Plant Functional Type Parameters

- 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)

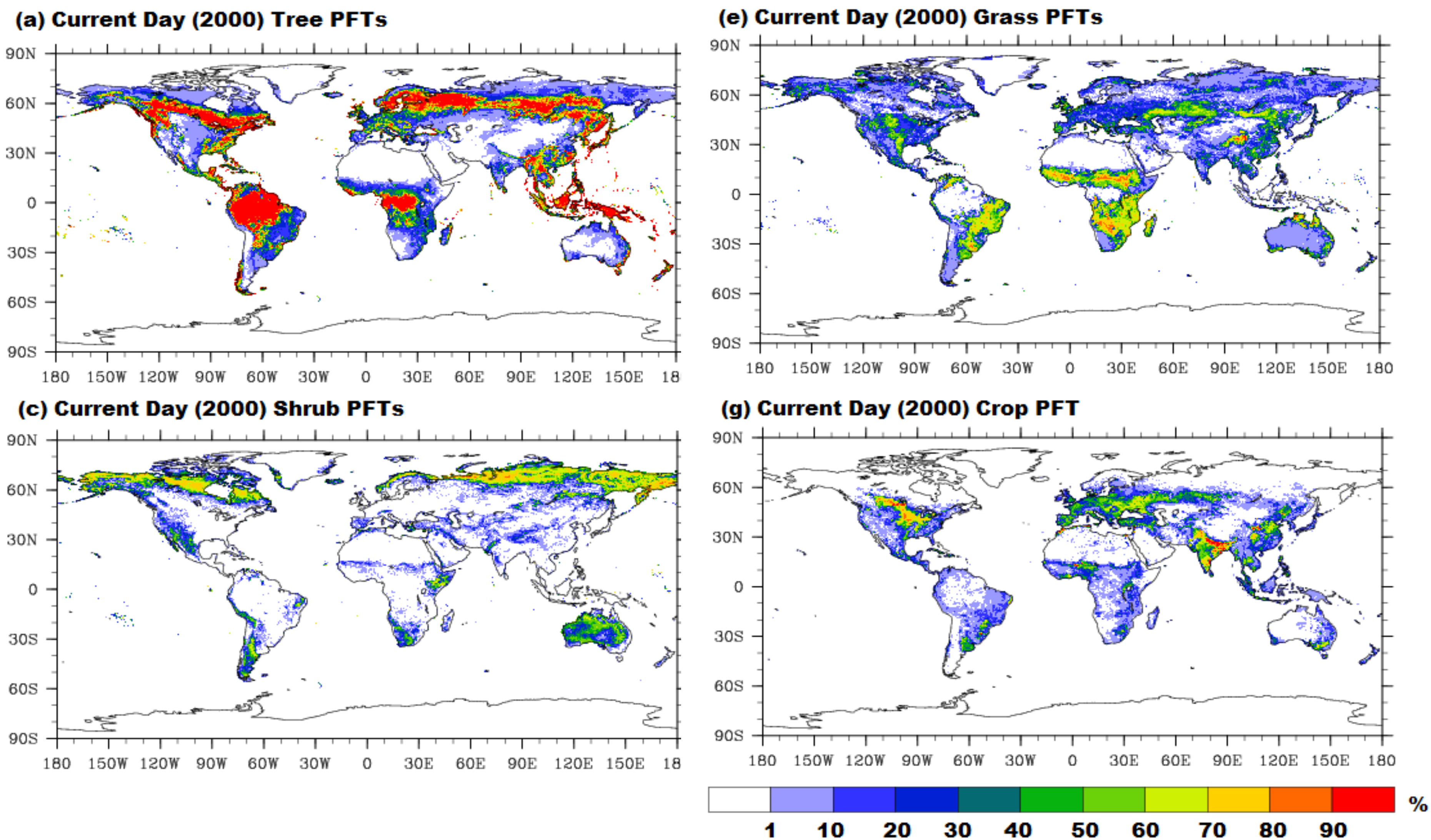
Current Day MODIS PFTs 0.05 degrees





Lawrence and Chase (2007)

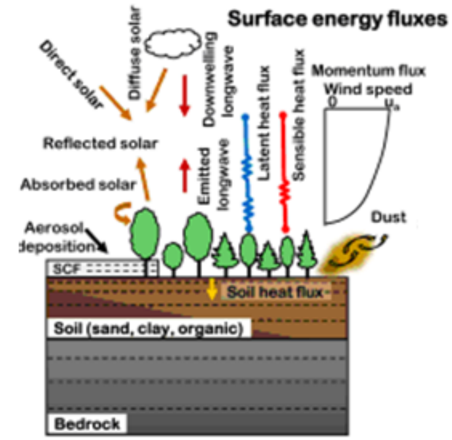
Plant Function Type distribution in CLM4 based on NASA MODIS Satellite/Crop datasets



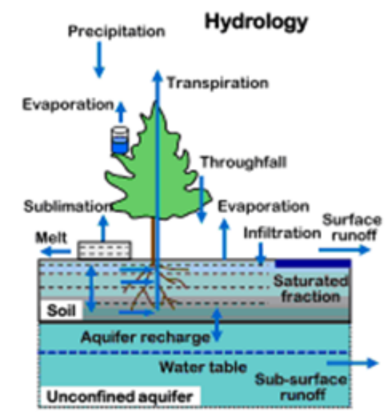
Lawrence and Chase, 2007

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)



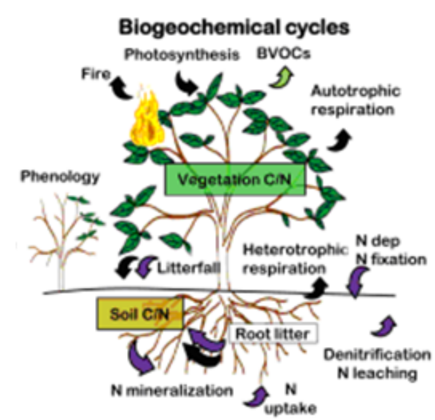
2. Surface Hydrology:
- Rain and Snow (Vegetation, Snow Pack, Runoff)
- Transpiration, Evaporation, Snow melt, Sublimation
- Soil Hydrology 10 Soil Layers in CLM (Richards Eqns)
- Deep Aquifer recharge and drainage (Top Model)



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

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

- 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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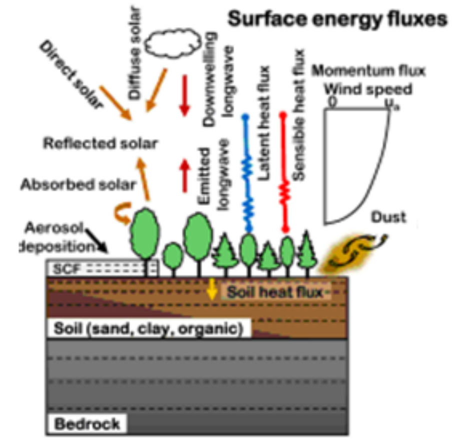

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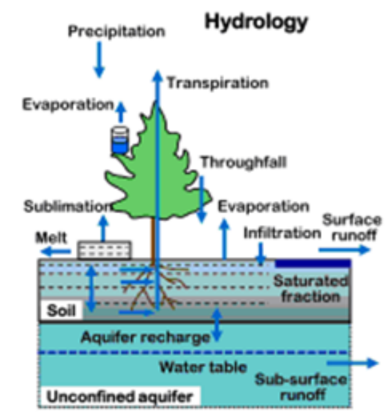

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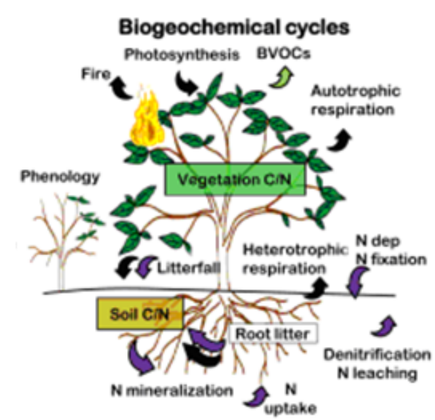

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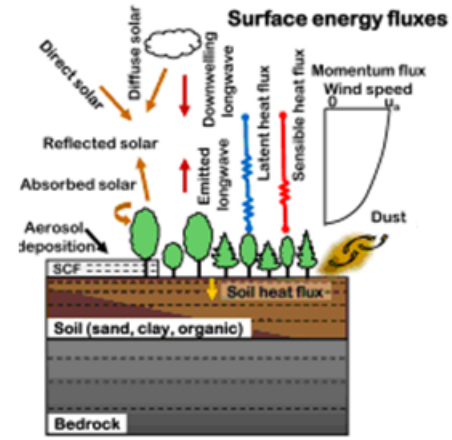

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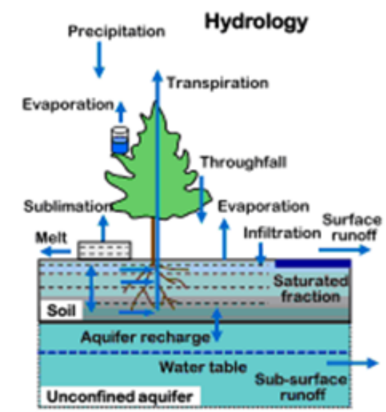

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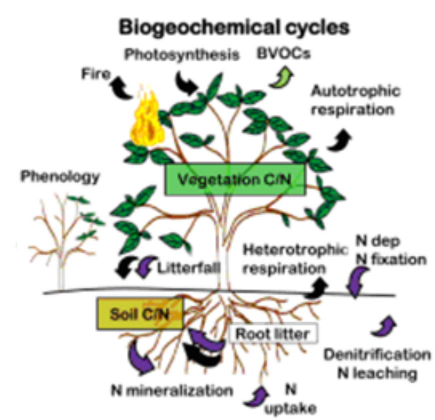


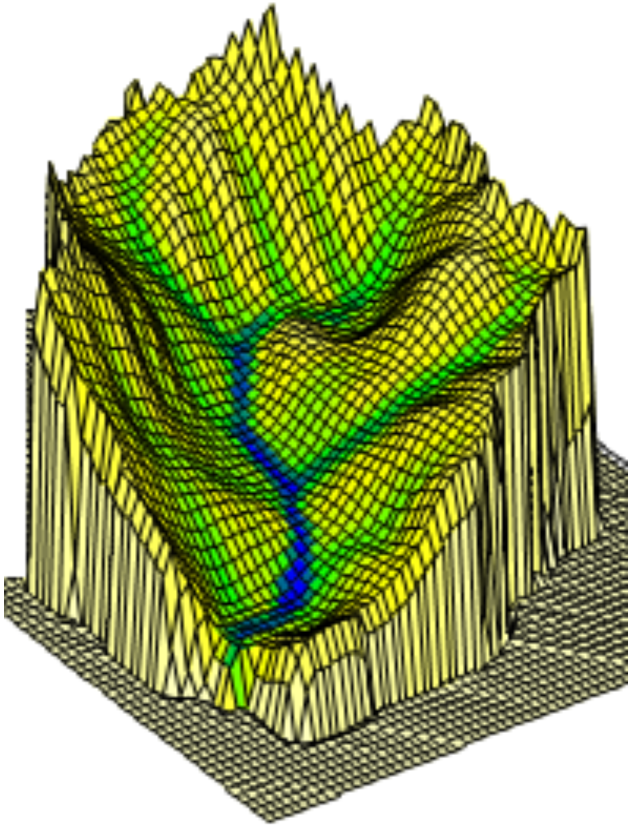
At each timestep the CLM land scheme solves …

- **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

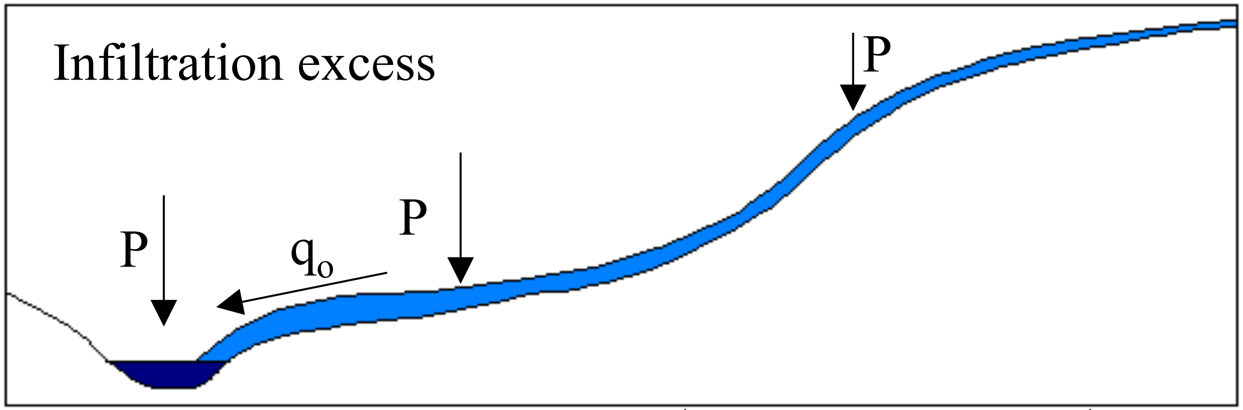
Subgrid-scale soil moisture heterogeneity

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.

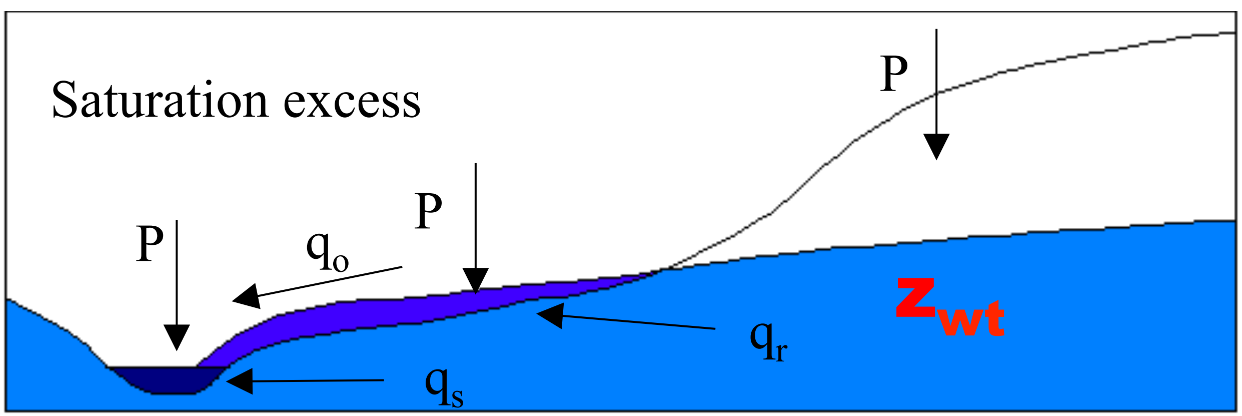


Three main sources of runoff:
- **Infiltration excess occurs over the unsaturated fraction**
- **Saturation excess occurs over the saturated fraction**
- **Baseflow (drainage)**

SIMTOP: Simple TOPMODEL-based runoff model



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

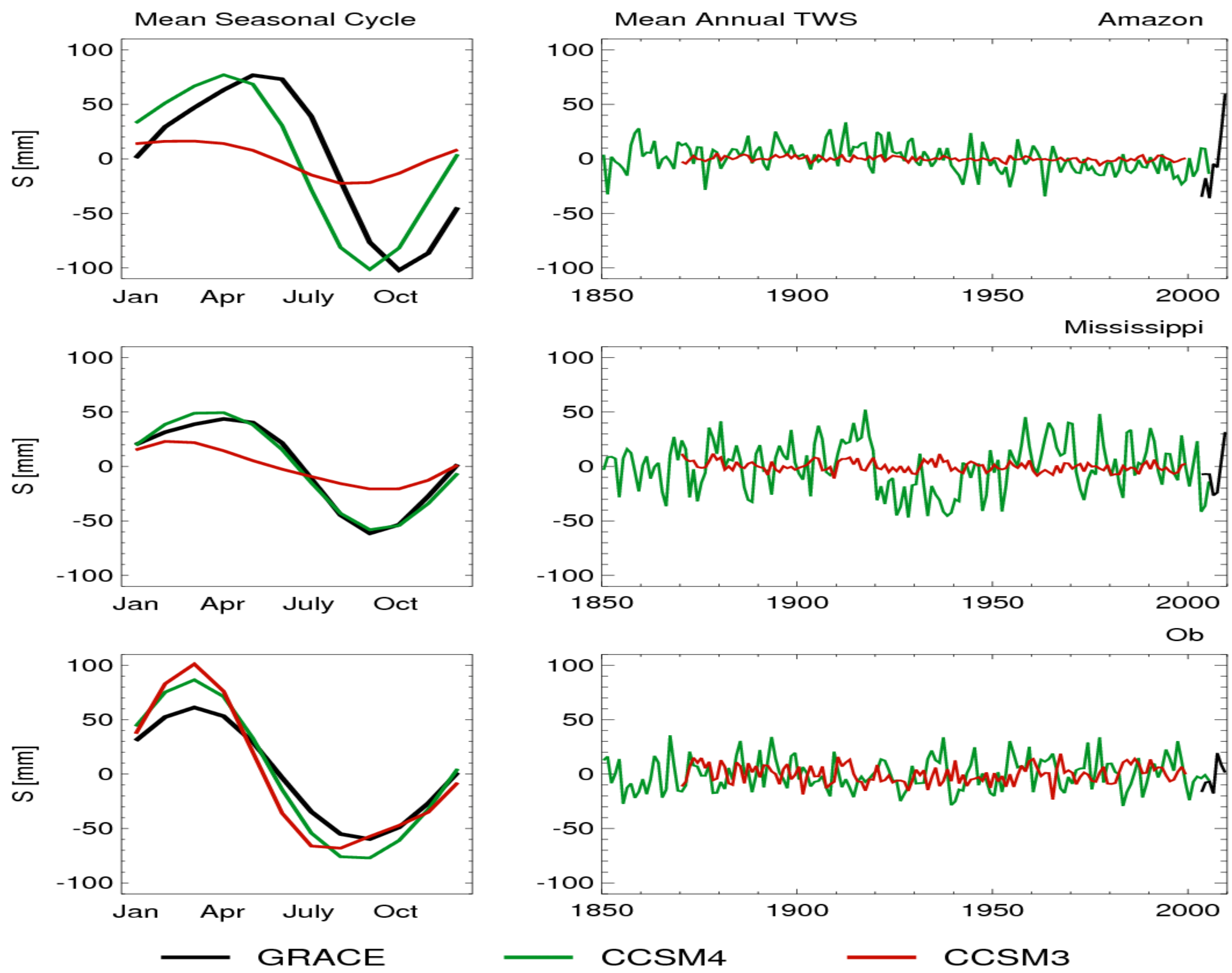


$$q_{over} = f_{sat} q_{liq,0}$$

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

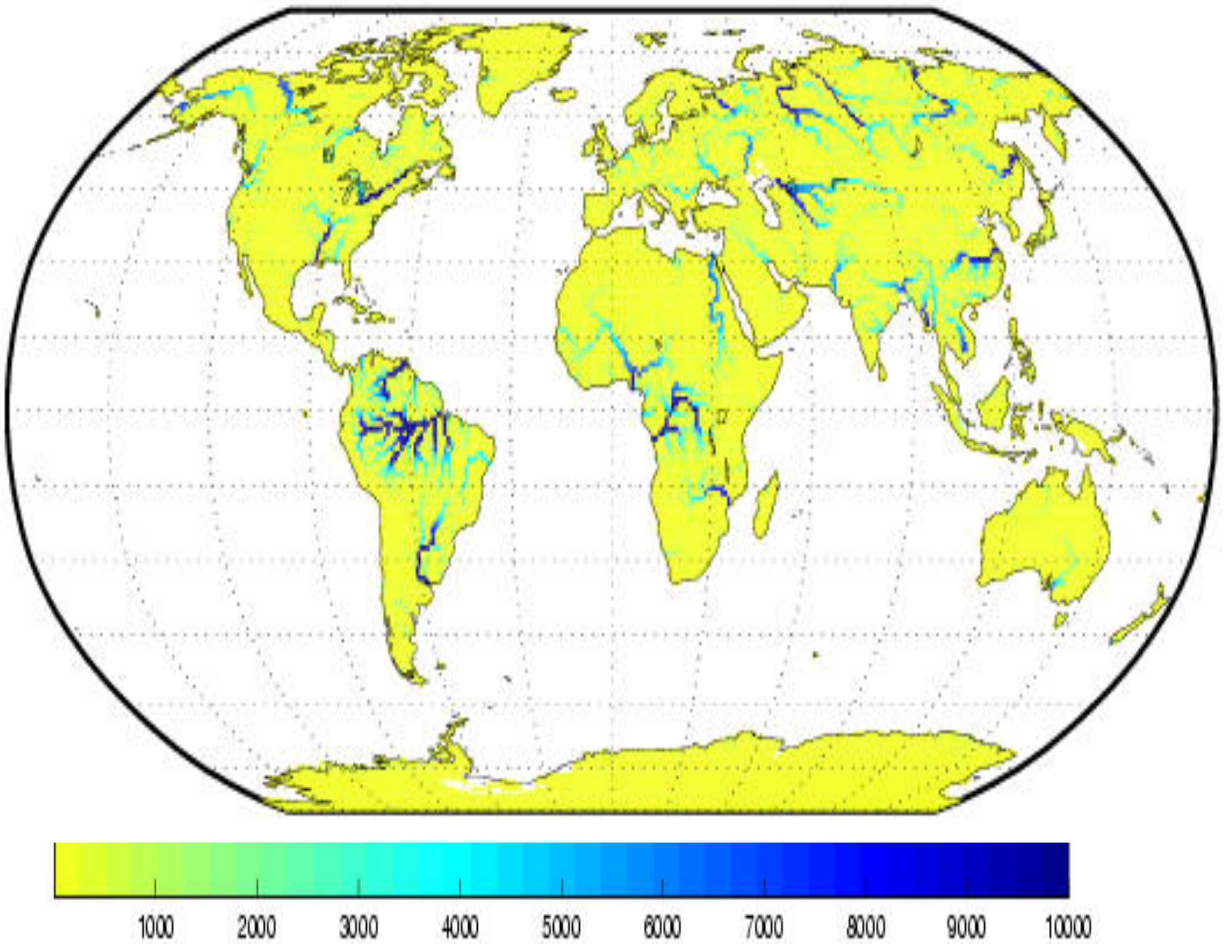
Niu et al. 2005

Total Land Water Storage (CCSM vs GRACE)

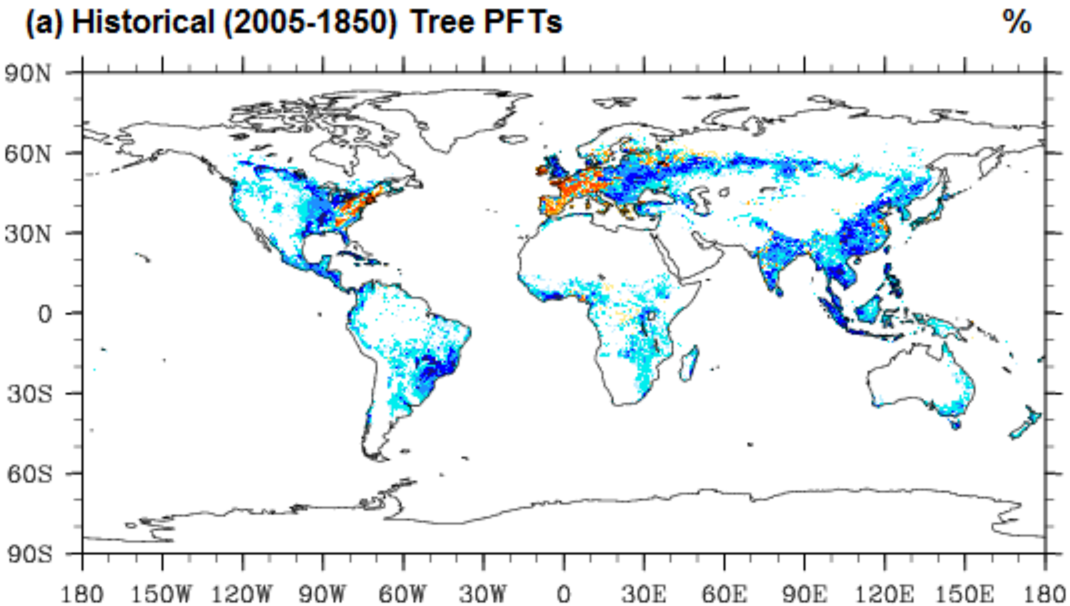


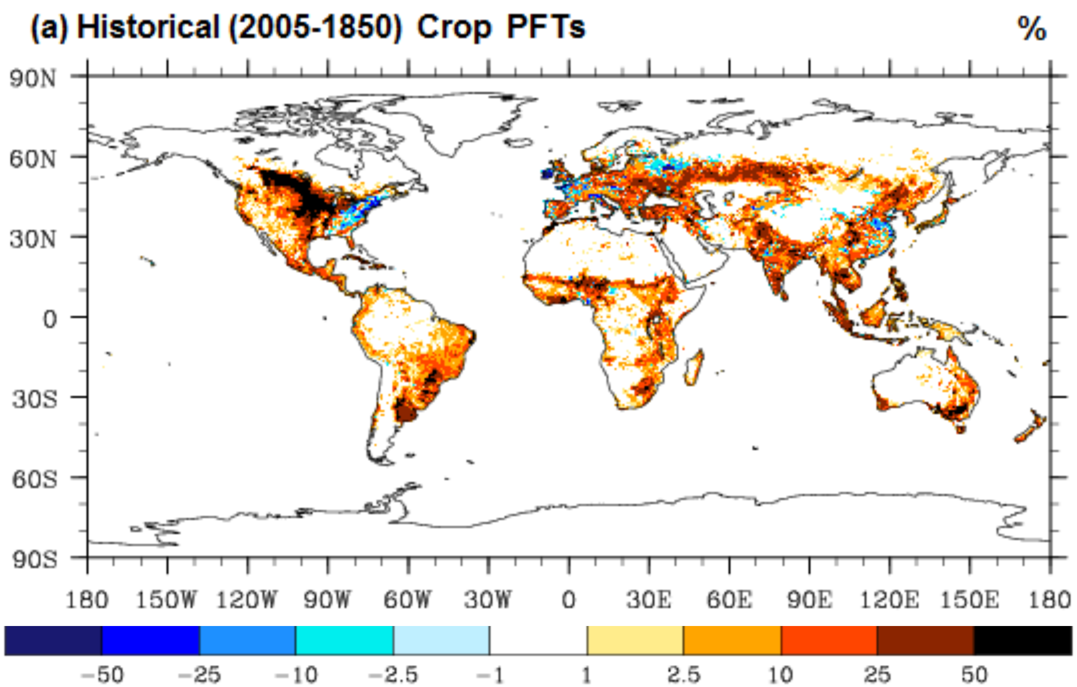
River Transport Model (RTM)

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



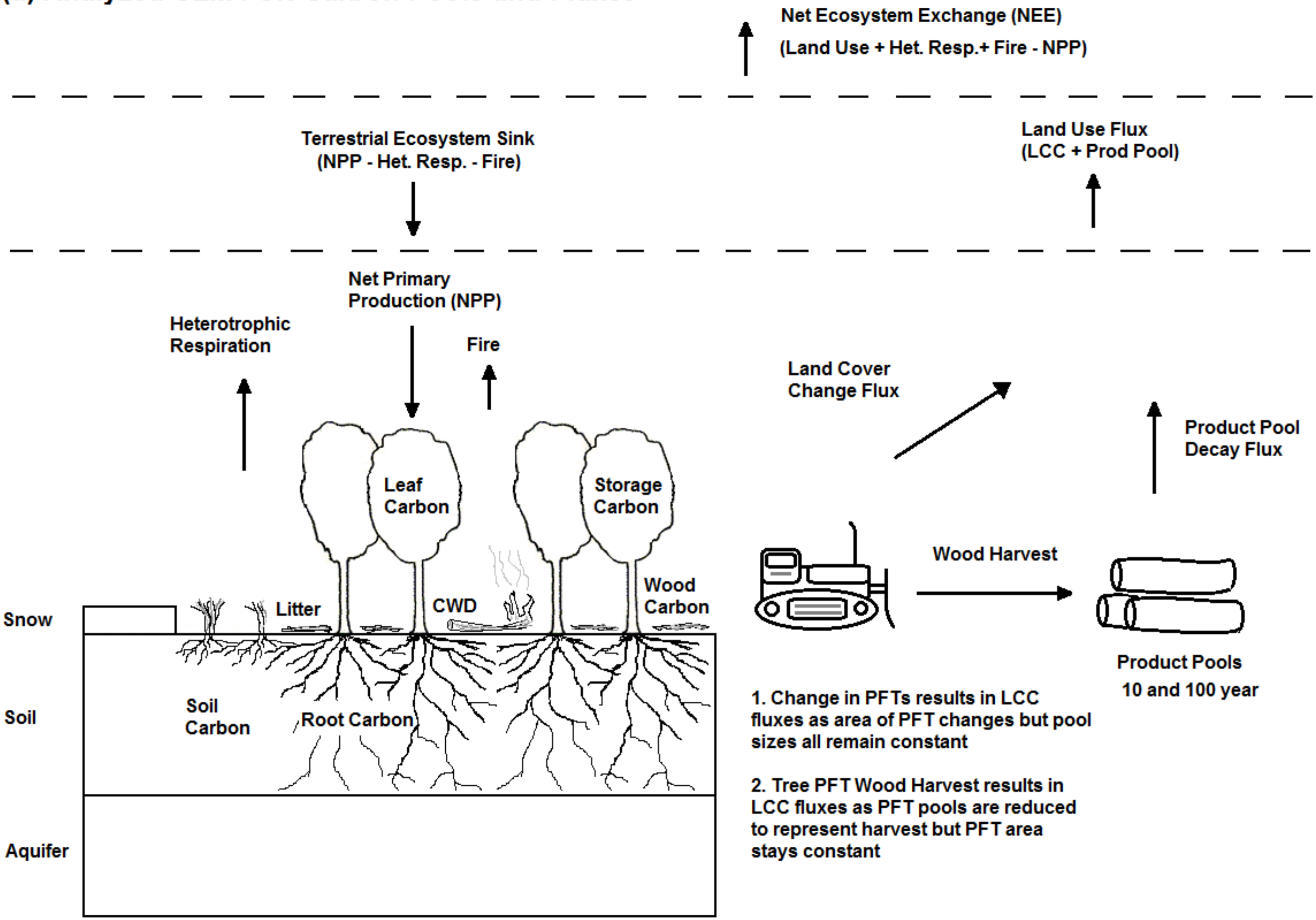
Land Cover Change Cropping and Forests in CLM4





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

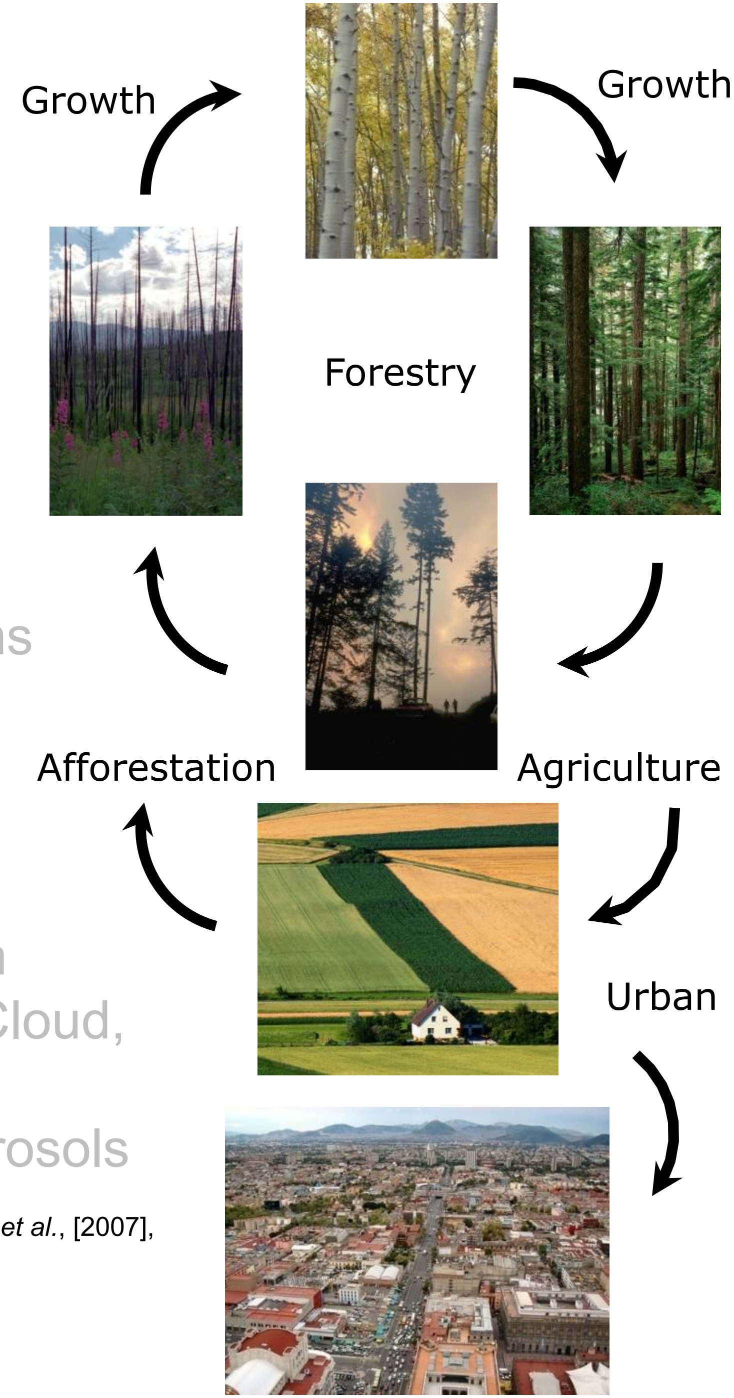
Human Land Cover Change

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
- Fire, Methane, Dust, Volatile Organics, Aerosols

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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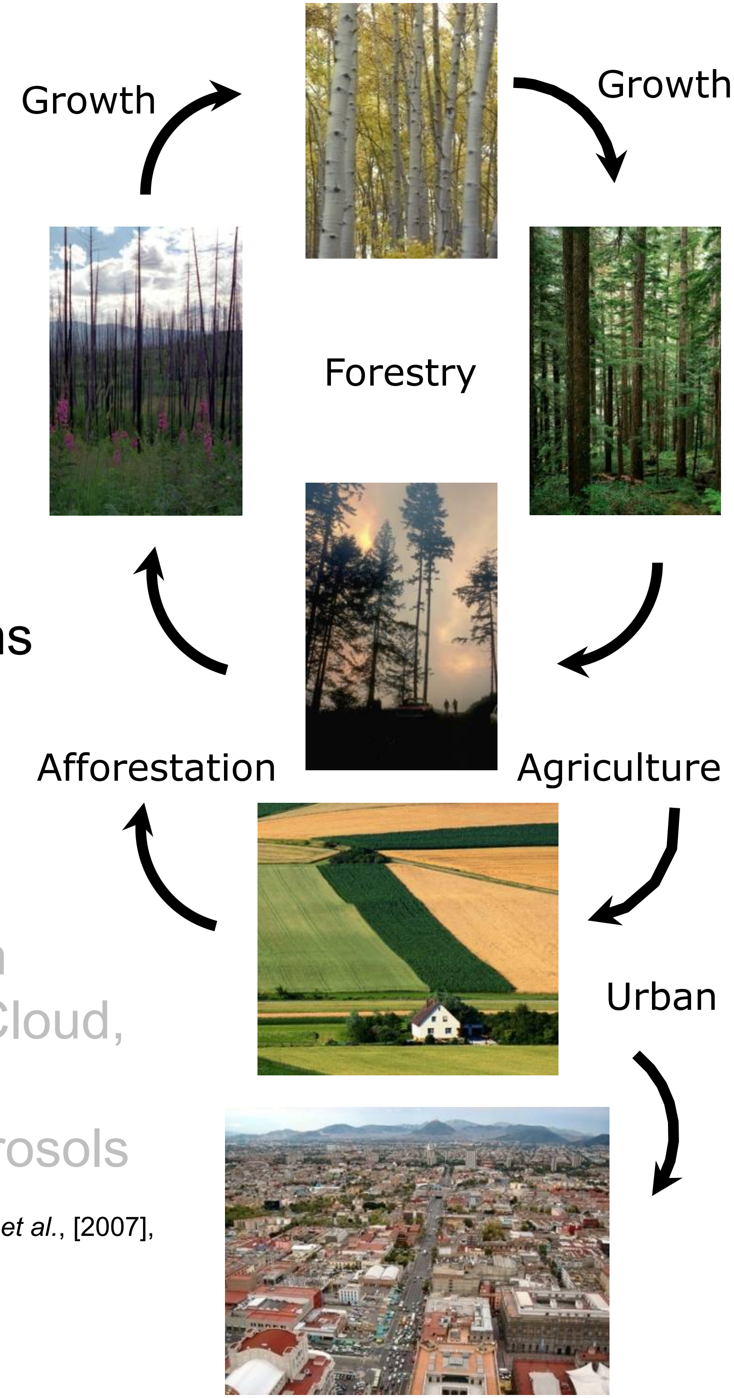

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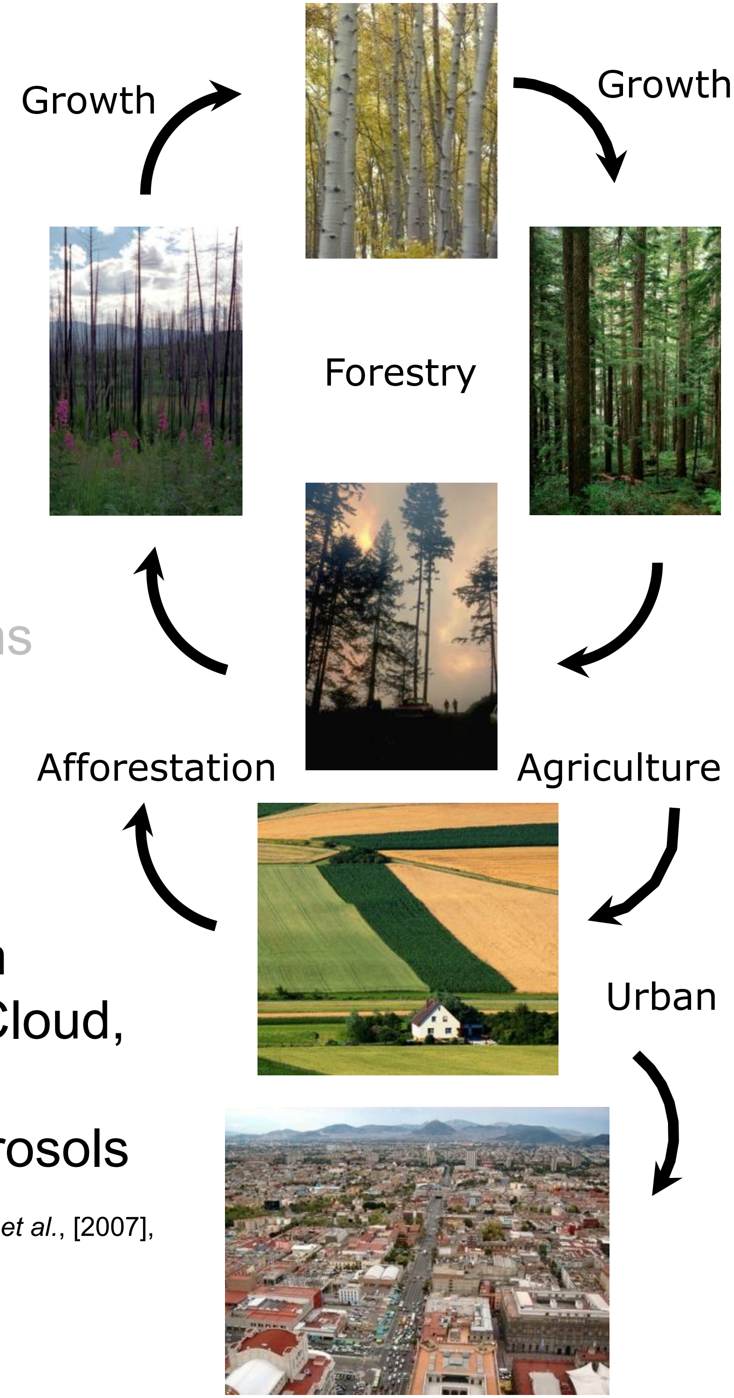


CLM4 Land Cover Change Climate Experiments

1. Current Day Climate and Land Cover Change sensitivity experiments in CESM

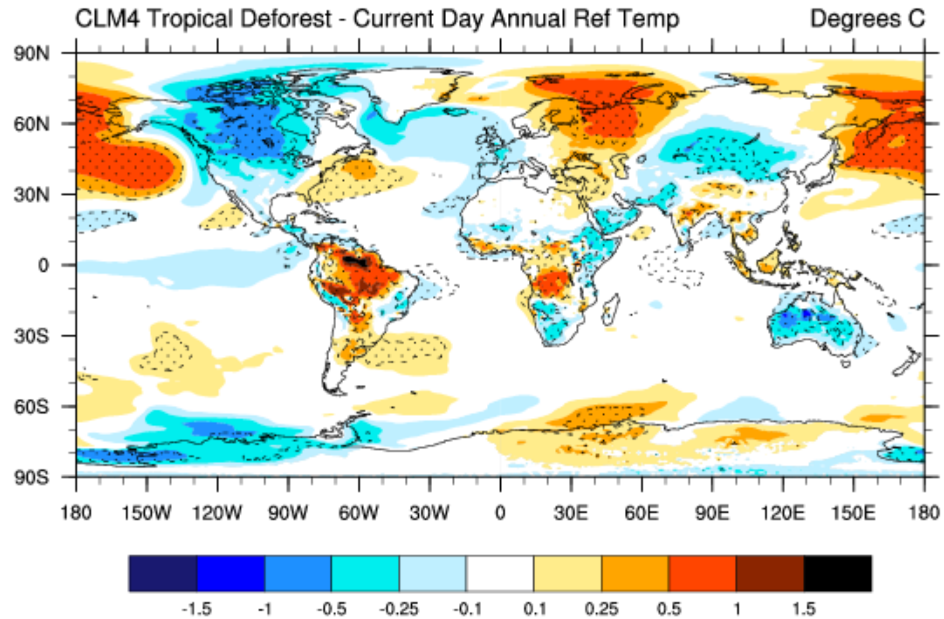
2. Fully Coupled Current Day Climate simulations with:

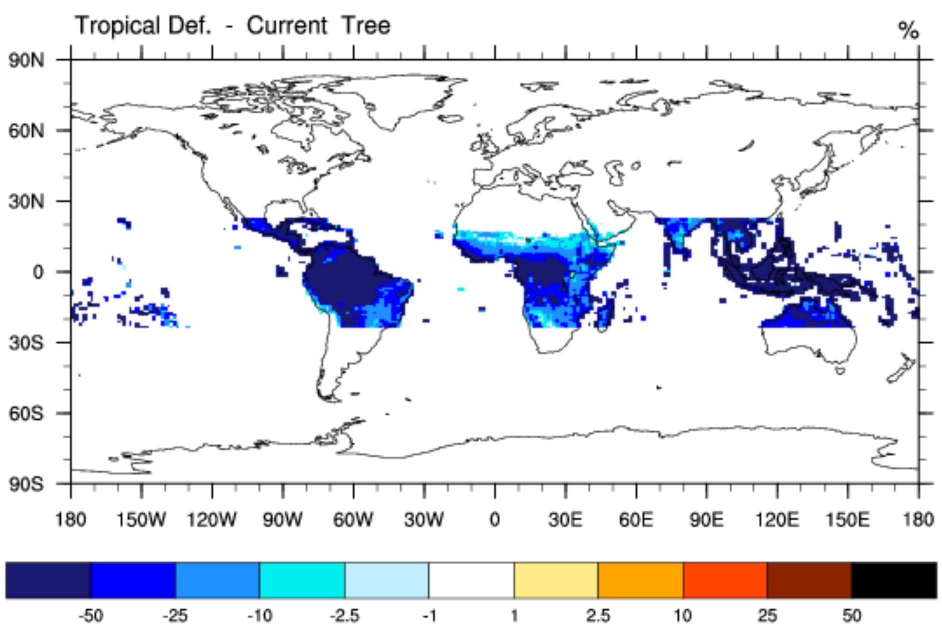
   a. Current Day Vegetation
   b. Tropical Deforestation
   c. Boreal Deforestation

3. Each simulation run with CESM 1.2 with CAM4 for 50 years of present day climate with year 2000 CO_2 and Aerosols then compared to same simulation with current day vegetation

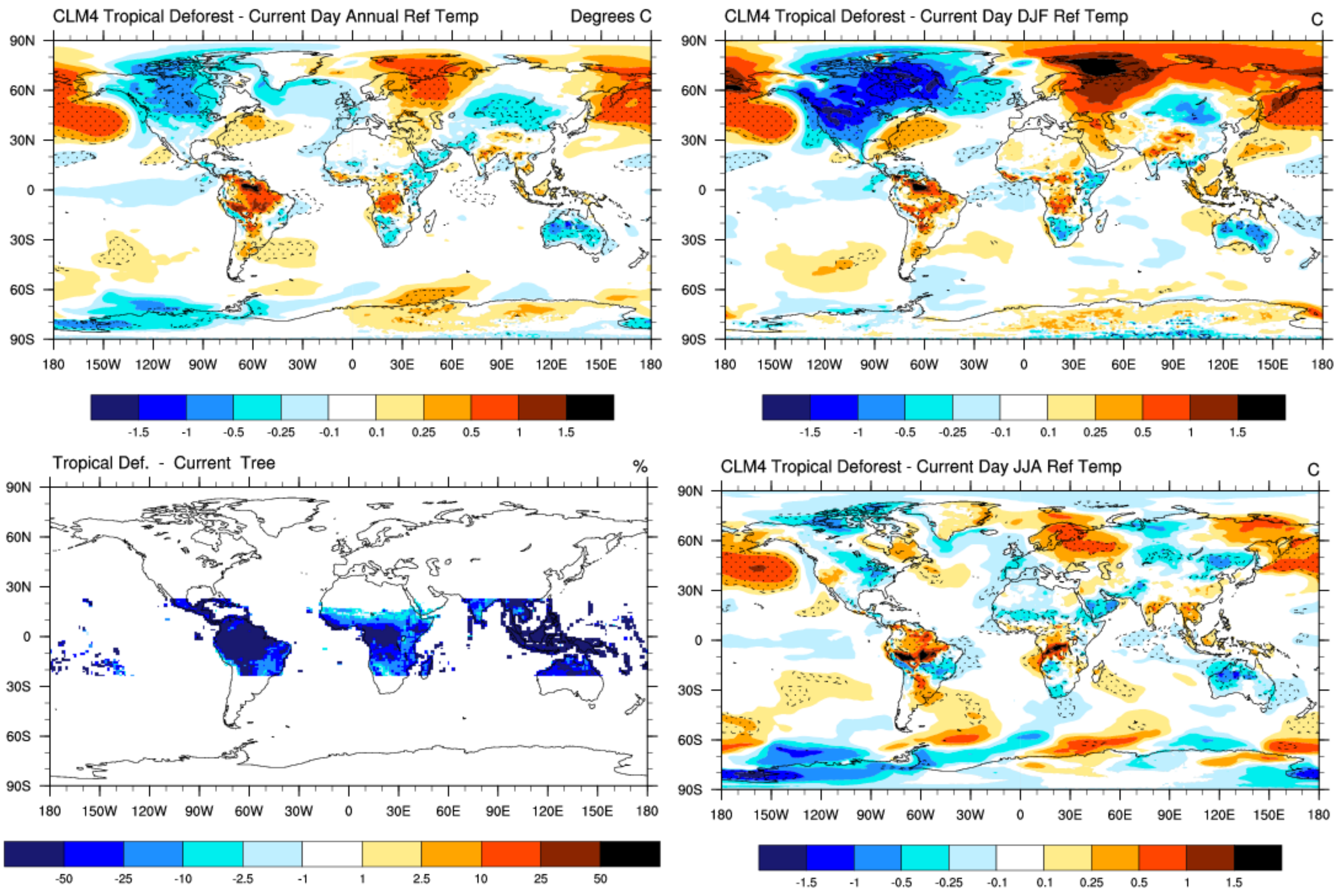
4. Investigate the climate changes between Current Day Vegetation simulation and each of the Deforestation simulations

Current Day – Tropical Deforestation – Annual Temperature

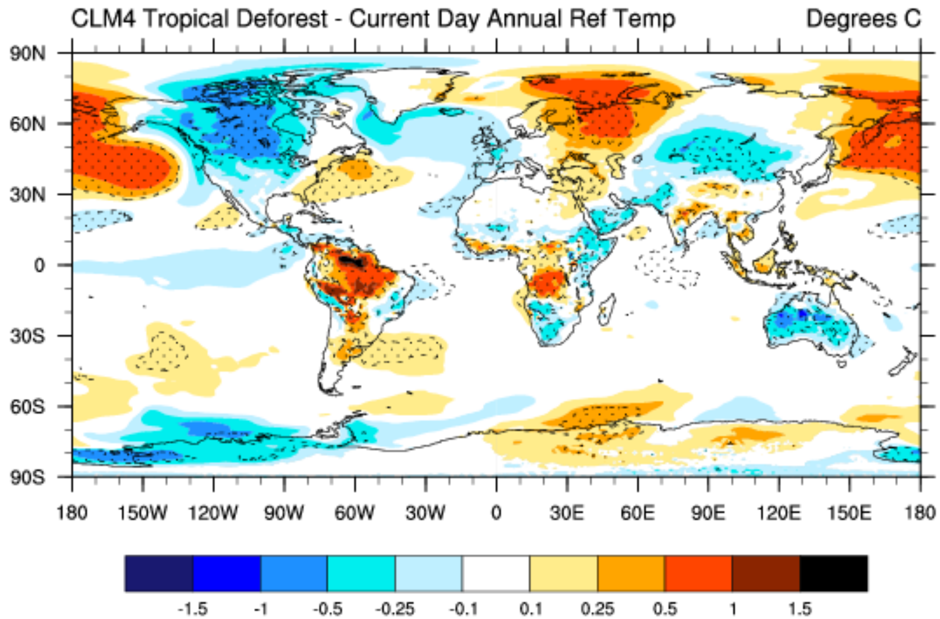


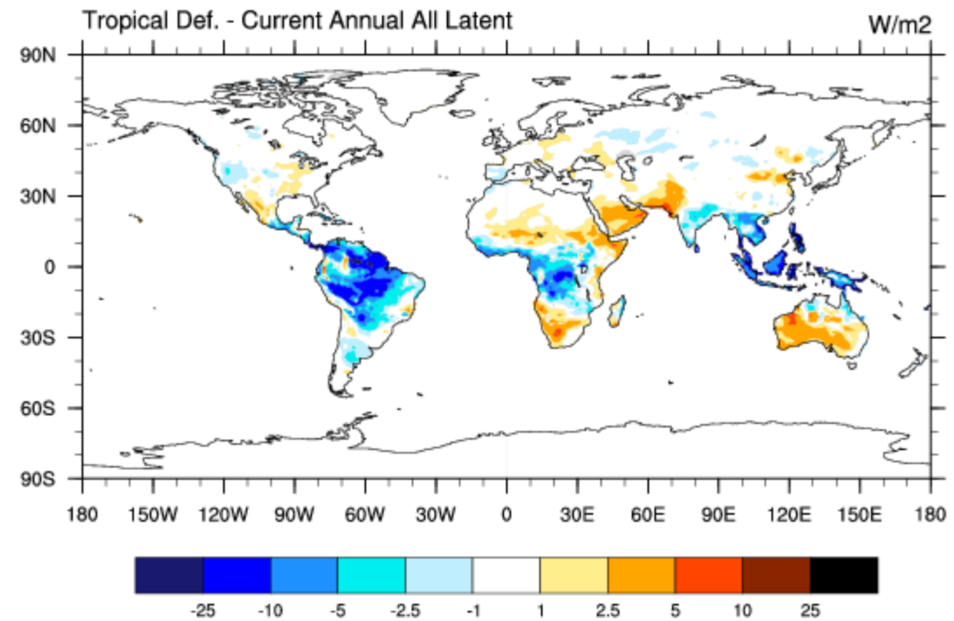


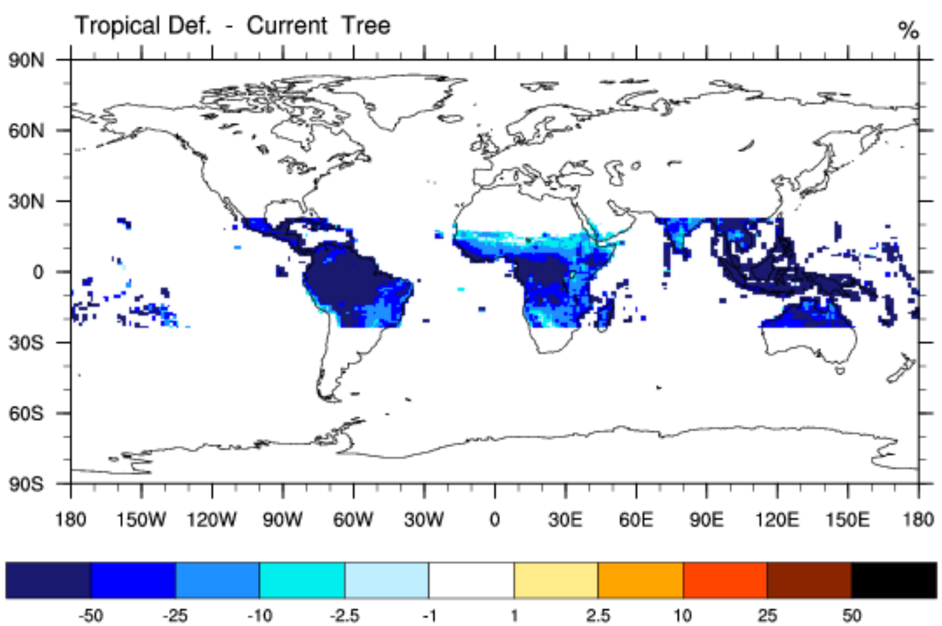
Current Day – Tropical Deforestation – Seasonal Temp.

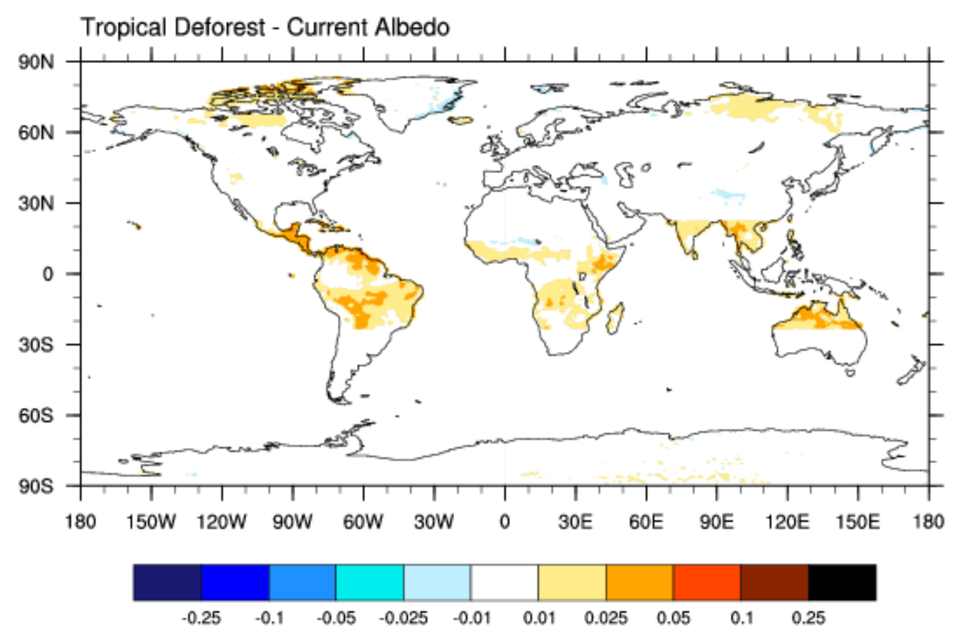


Current Day – Tropical Deforestation – Latent Heat & Albedo

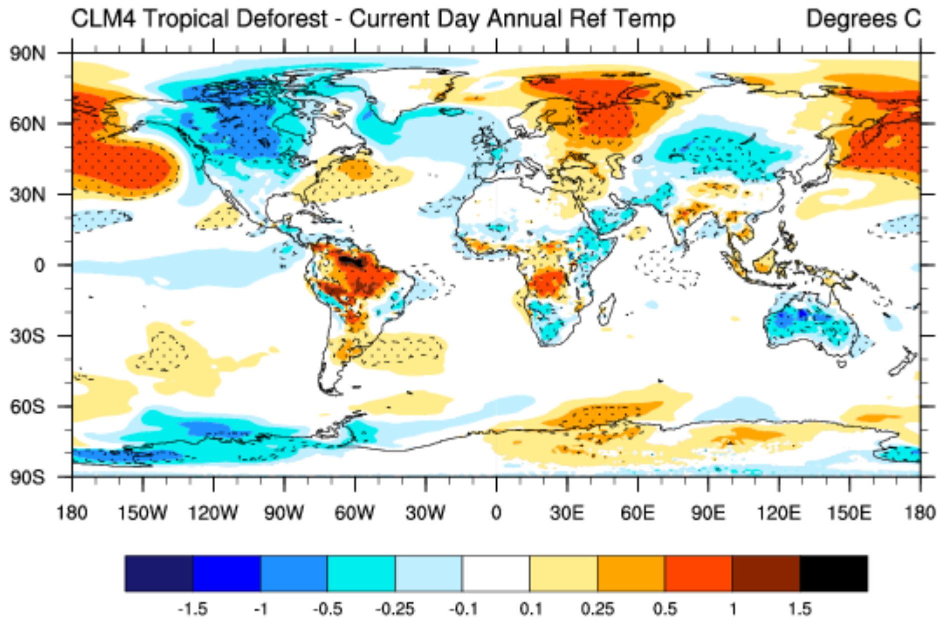


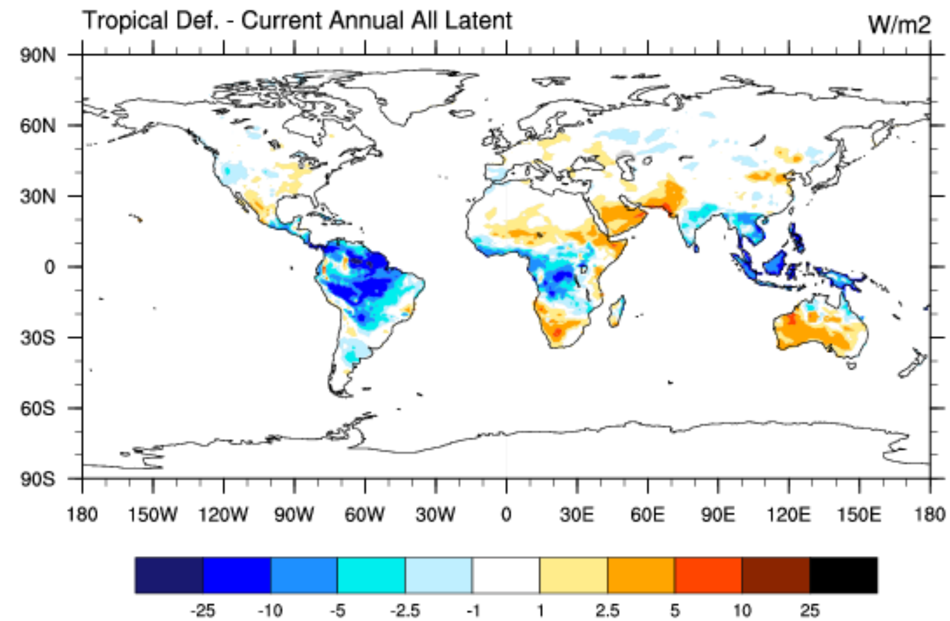


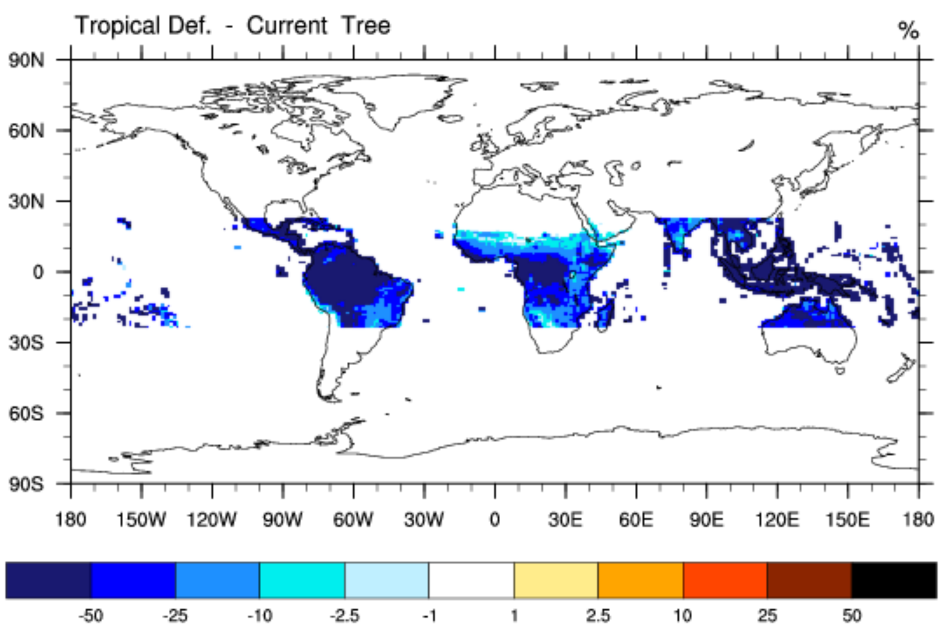


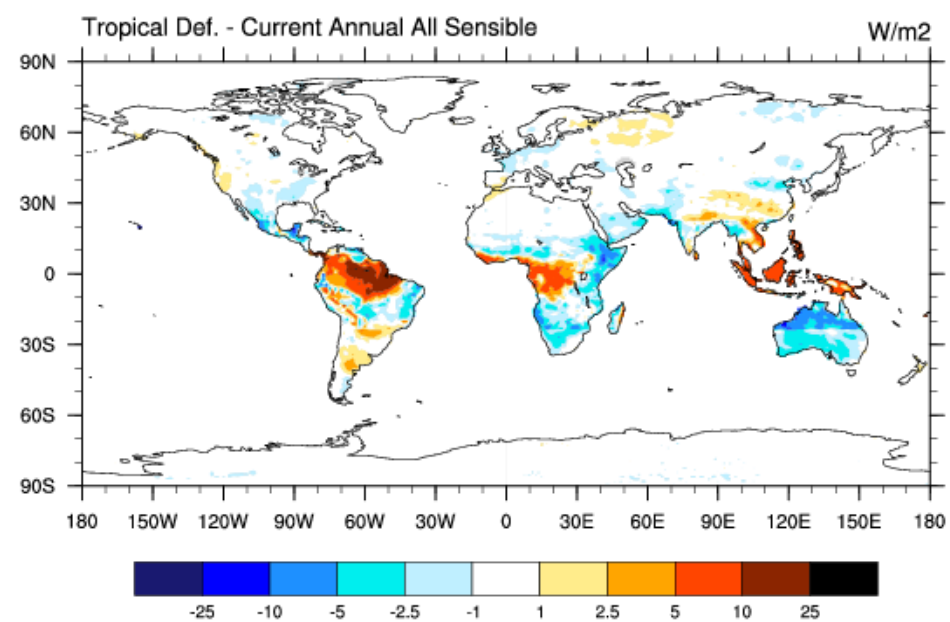


Current Day – Tropical Deforestation – Latent and Sensible

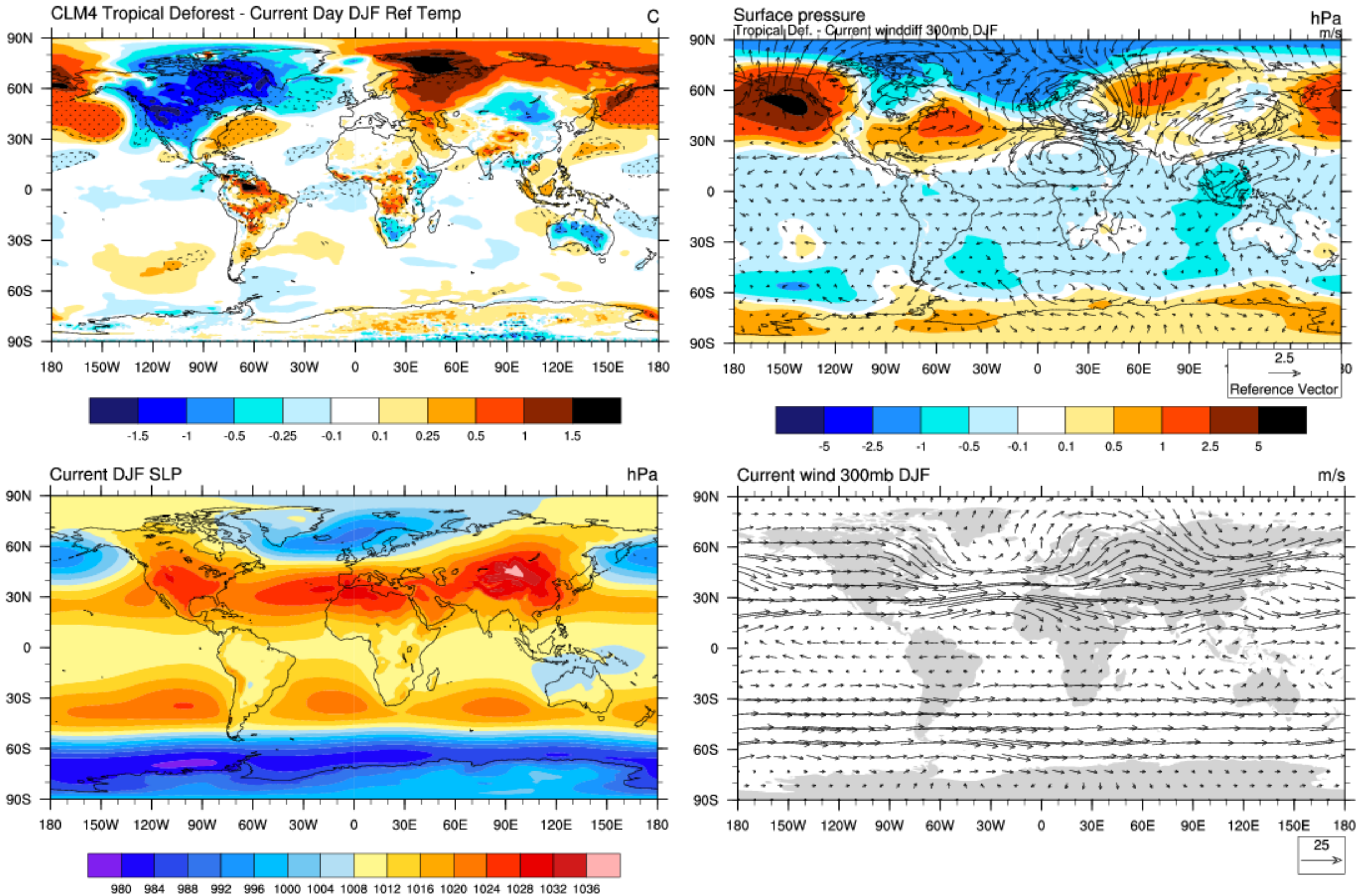




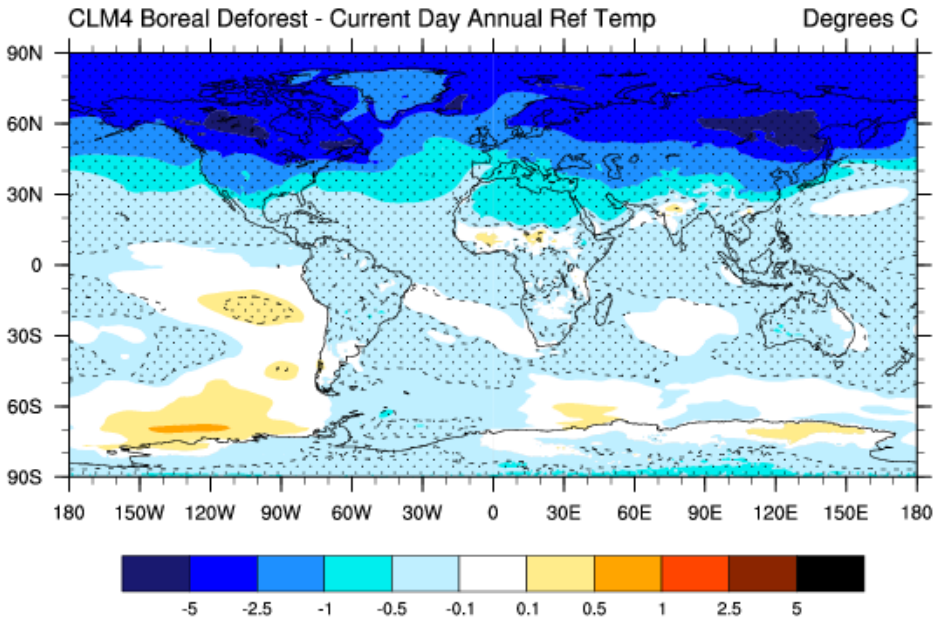


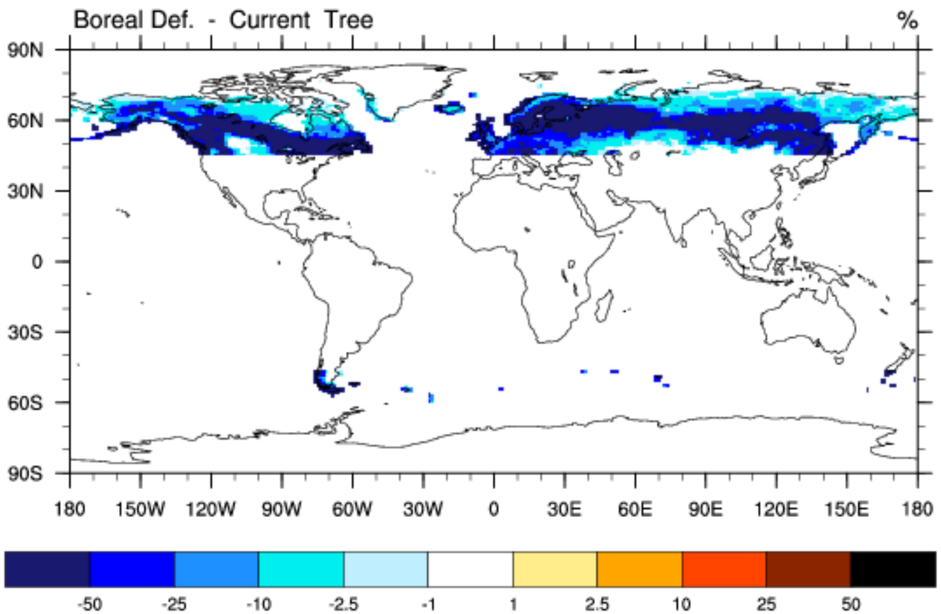


Current Day – Tropical Deforestation – Circulation Changes

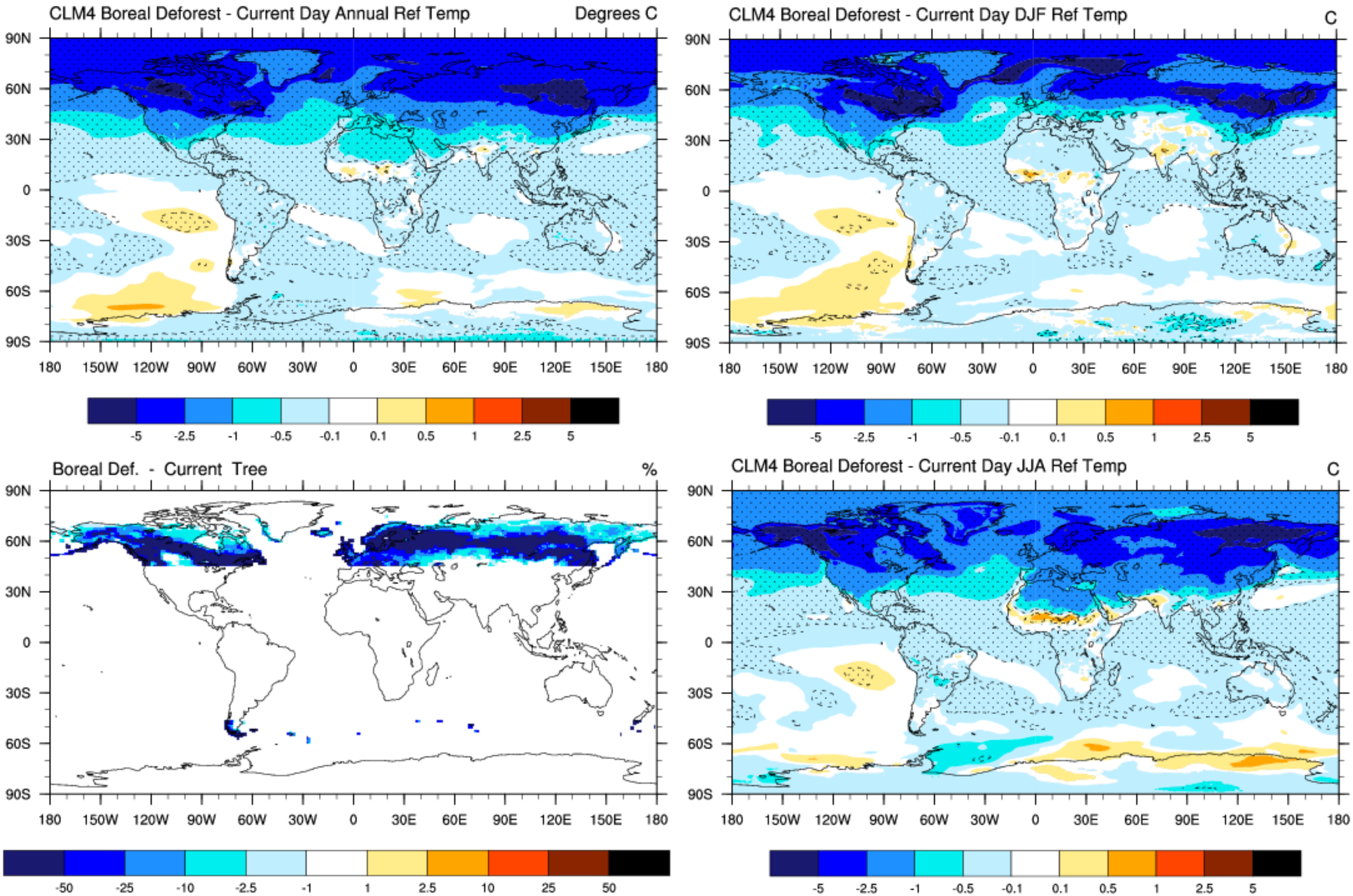


Current Day – Boreal Deforestation – Annual Temp

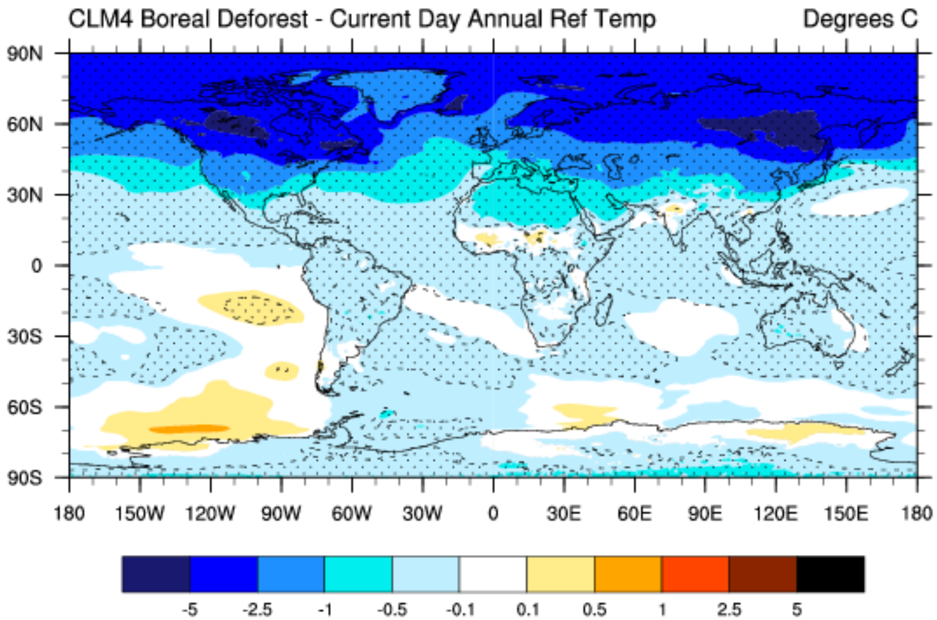


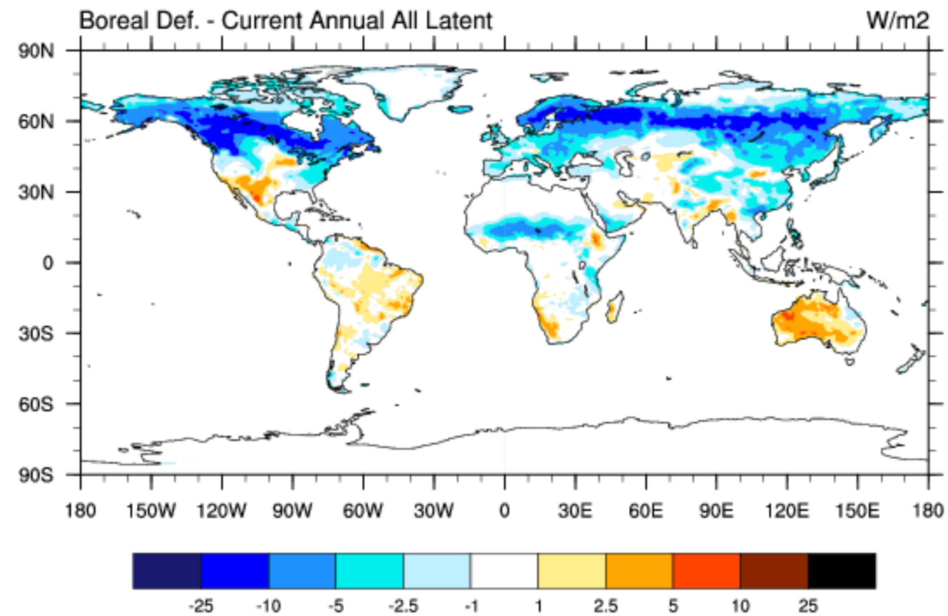


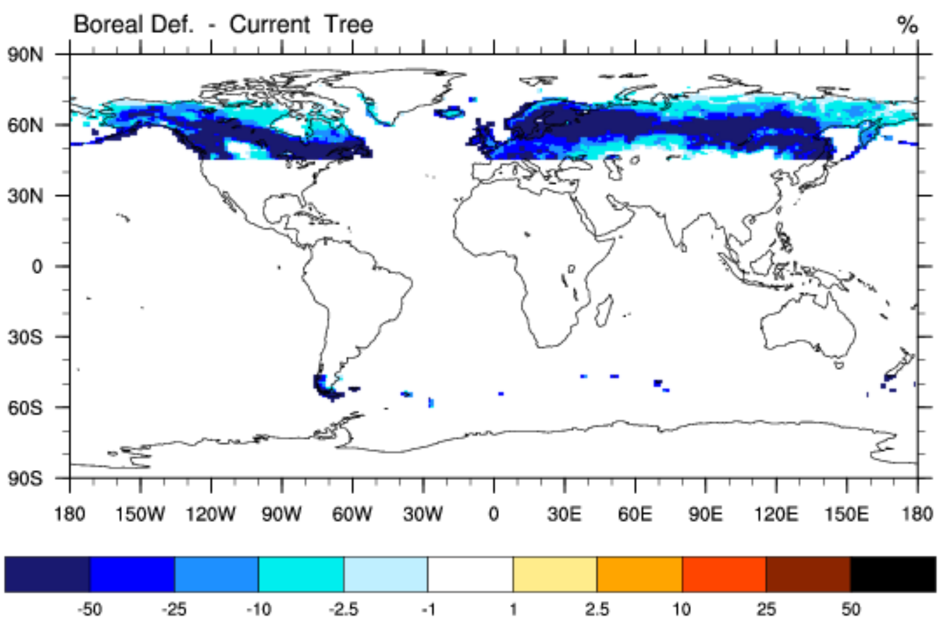
Current Day – Boreal Deforestation – Seasonal Temp

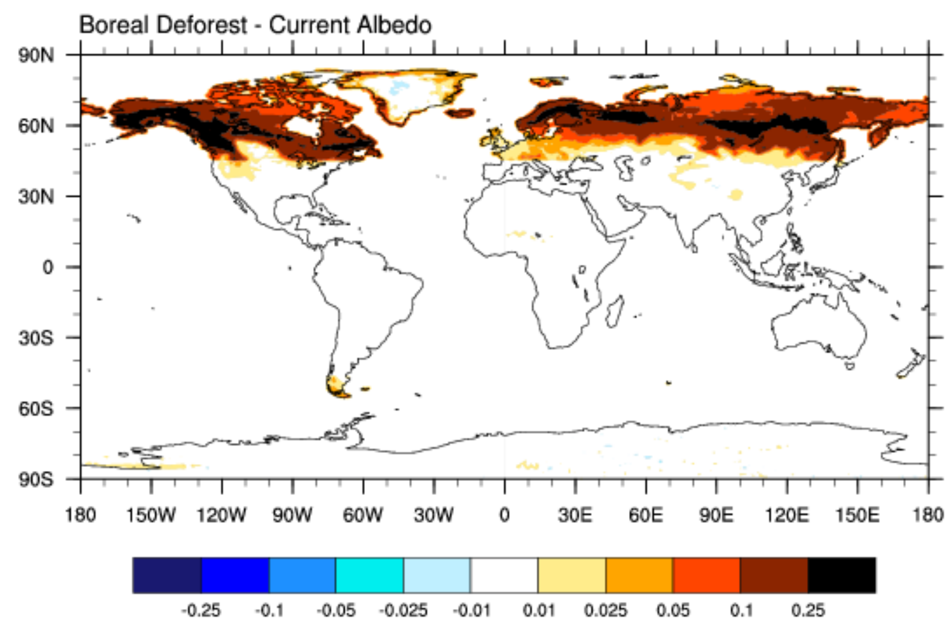


Current Day – Boreal Deforestation – Latent & Albedo

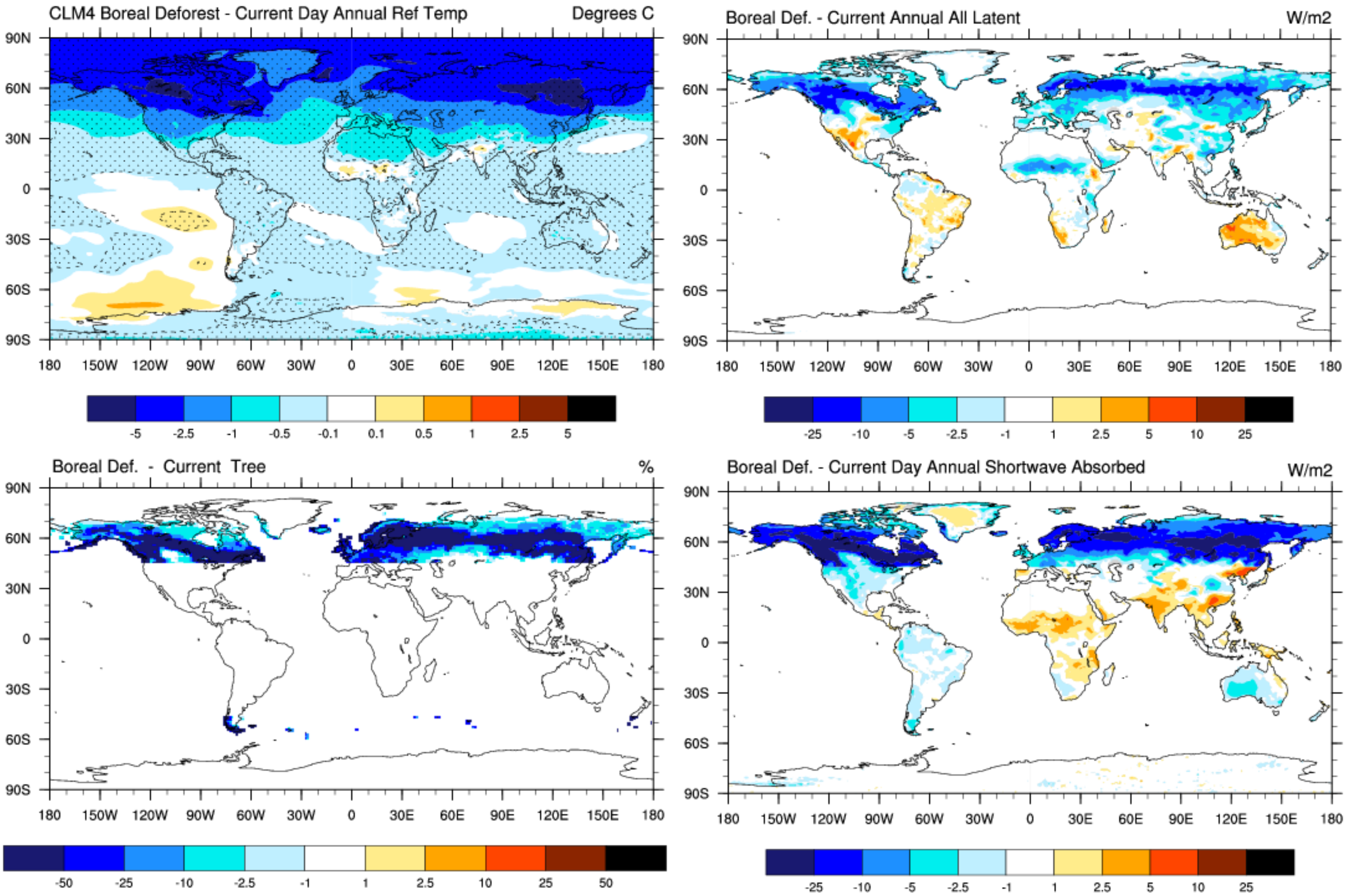




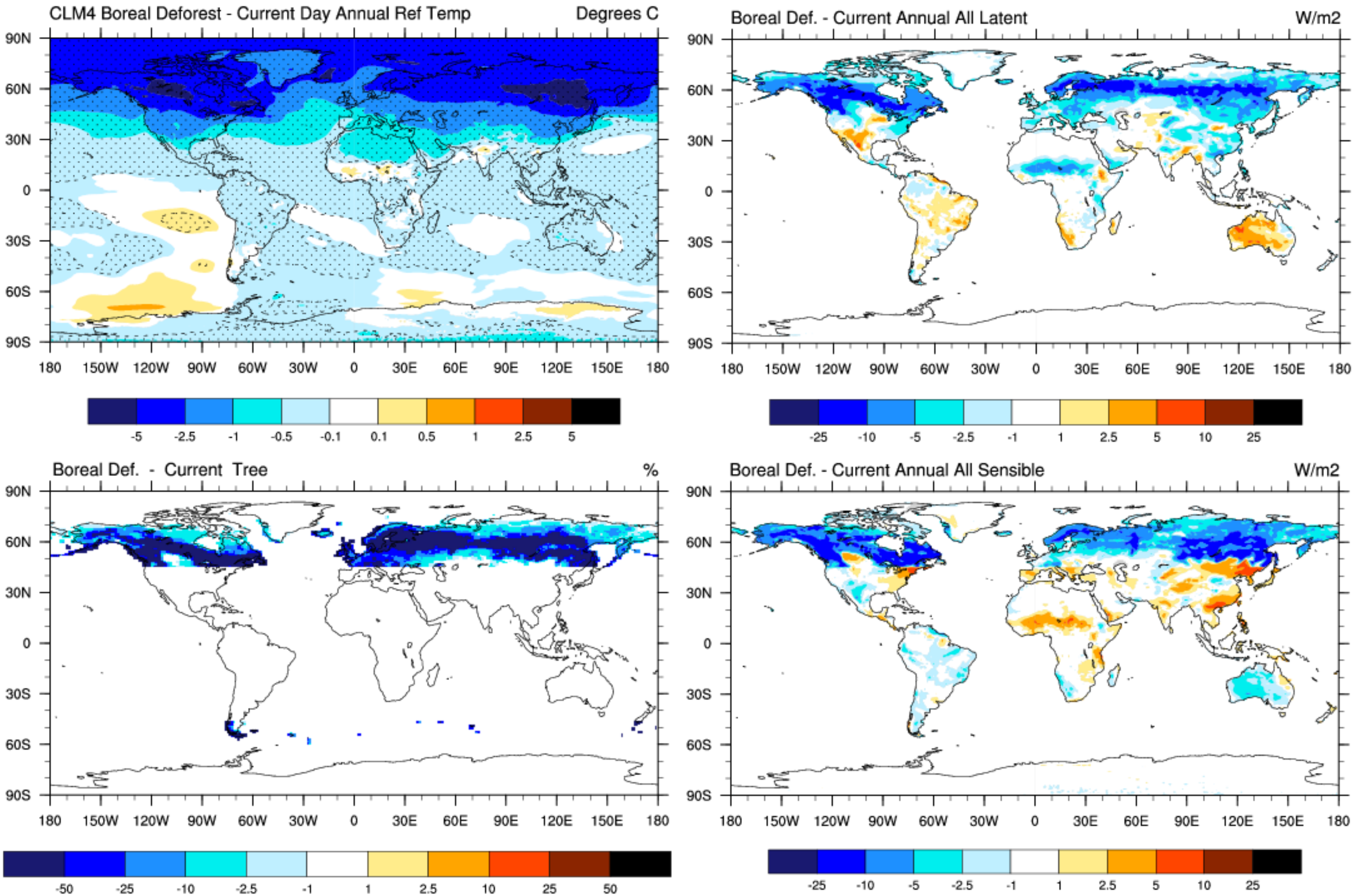




Current Day – Boreal Deforestation – Latent & Shortwave



Current Day – Boreal Deforestation – Latent & Sensible



CLM4 Land Cover Change Climate Experiments

1. Climate Impacts of Land Cover Change simulations.

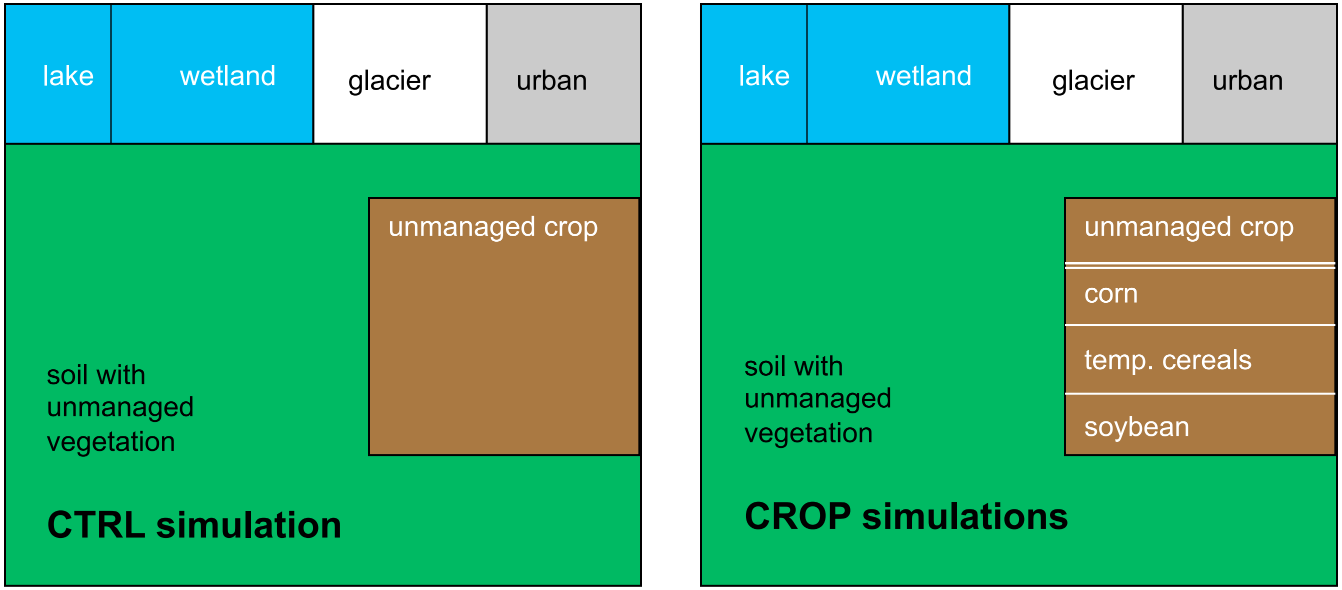
    a. Tropical Deforestation – Regional warming with teleconnections
    b. Boreal Deforestation – Strong regional cooling

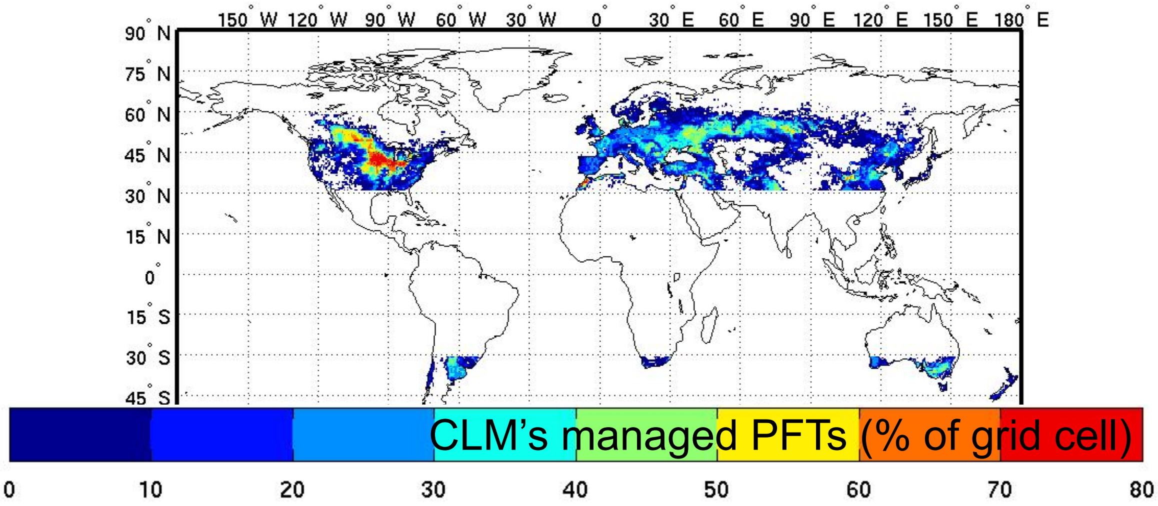
2. Tropical warming from reduced latent heat flux that has a greater impact than albedo in tropical forests but mixed in other areas.

3. Teleconnections in global circulation have impacts on the jet stream at higher latitudes with both regional cooling and warming.

4. Boreal cooling from higher albedo reduces shortwave absorbed by surface. Both sensible and latent heat fluxes decrease reducing energy transferred to the atmosphere.

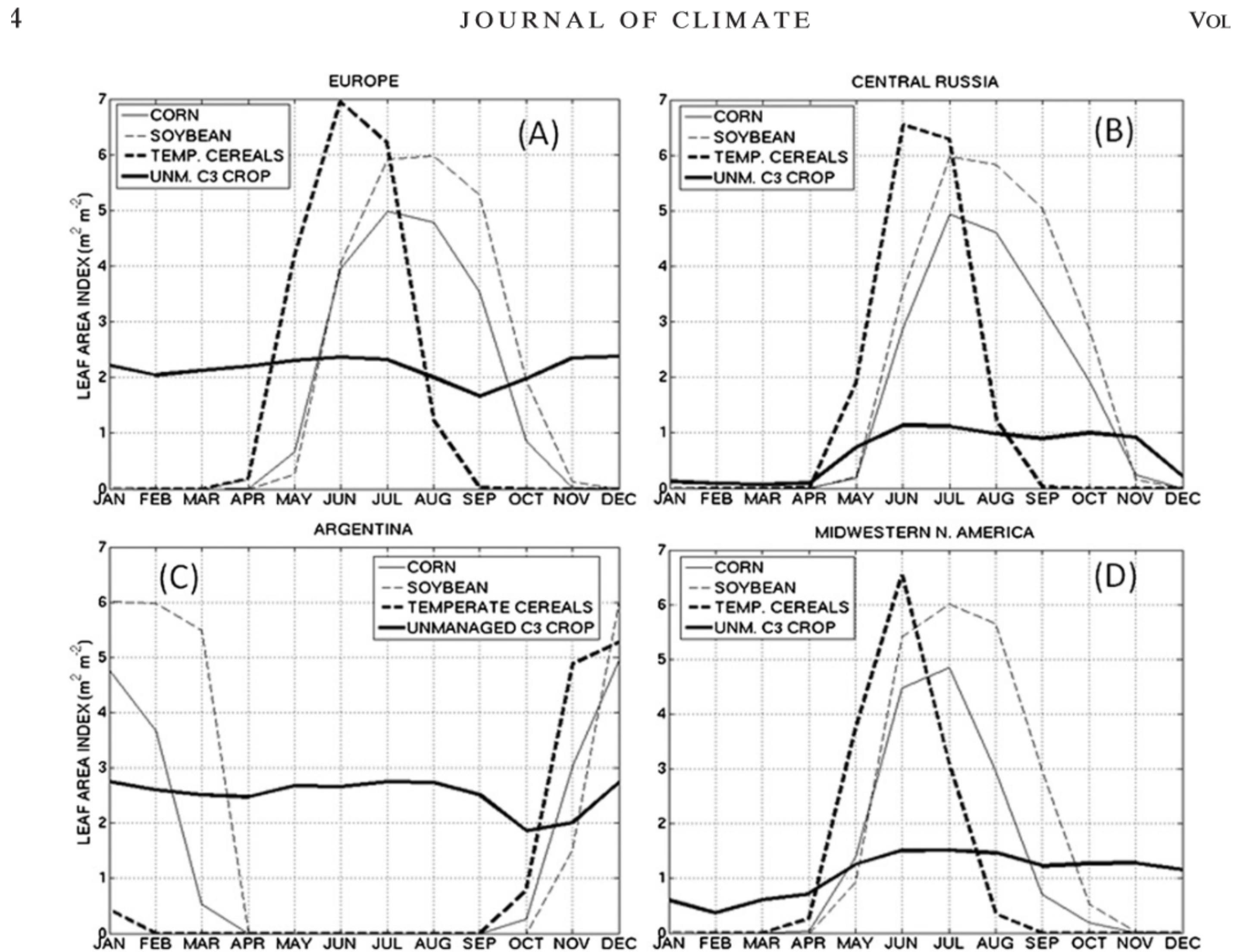
Interactive crop management CLM4CNcrop





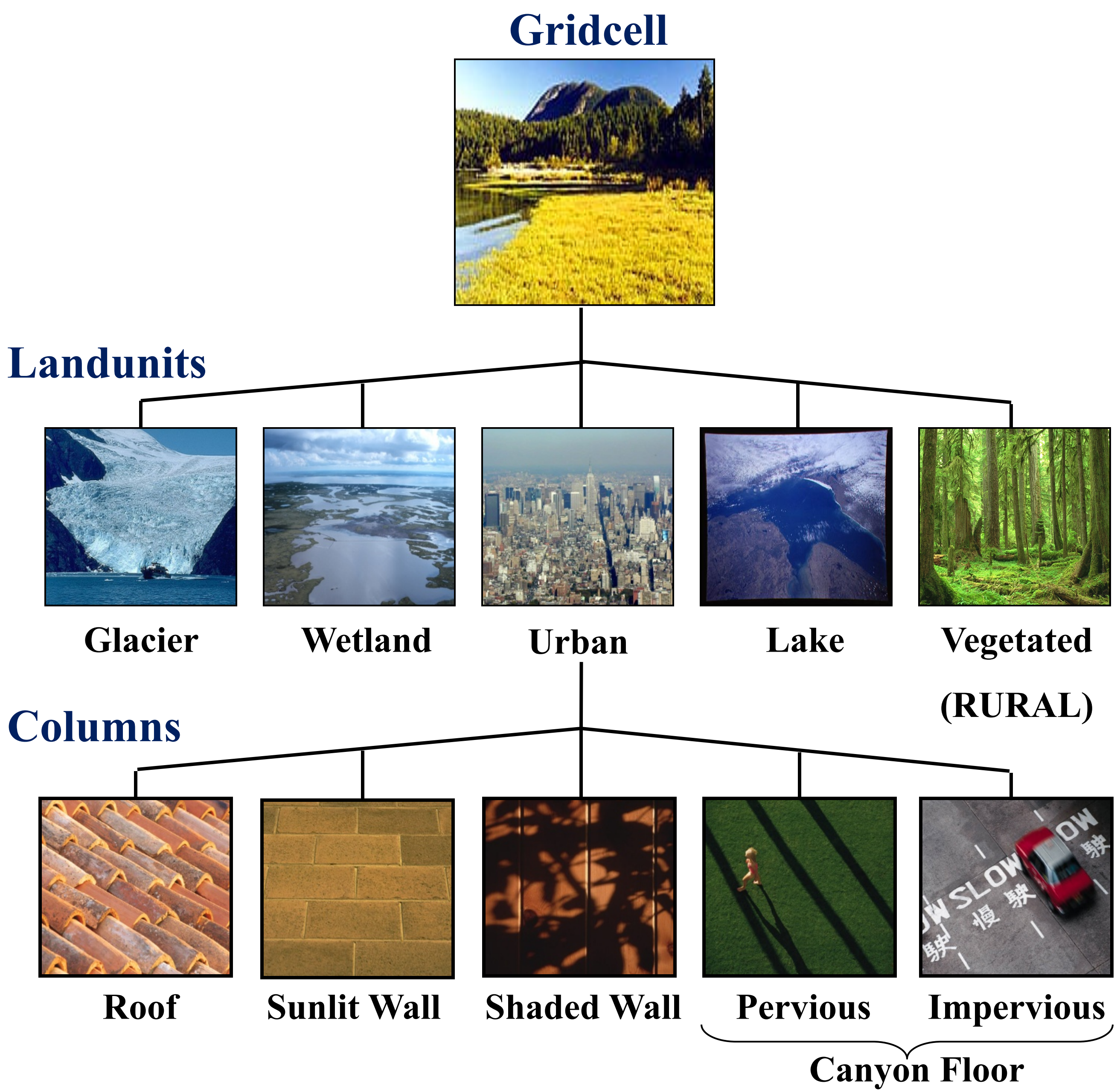
Levis *et al.* 2012

Interactive crop management CLM4CNcrop



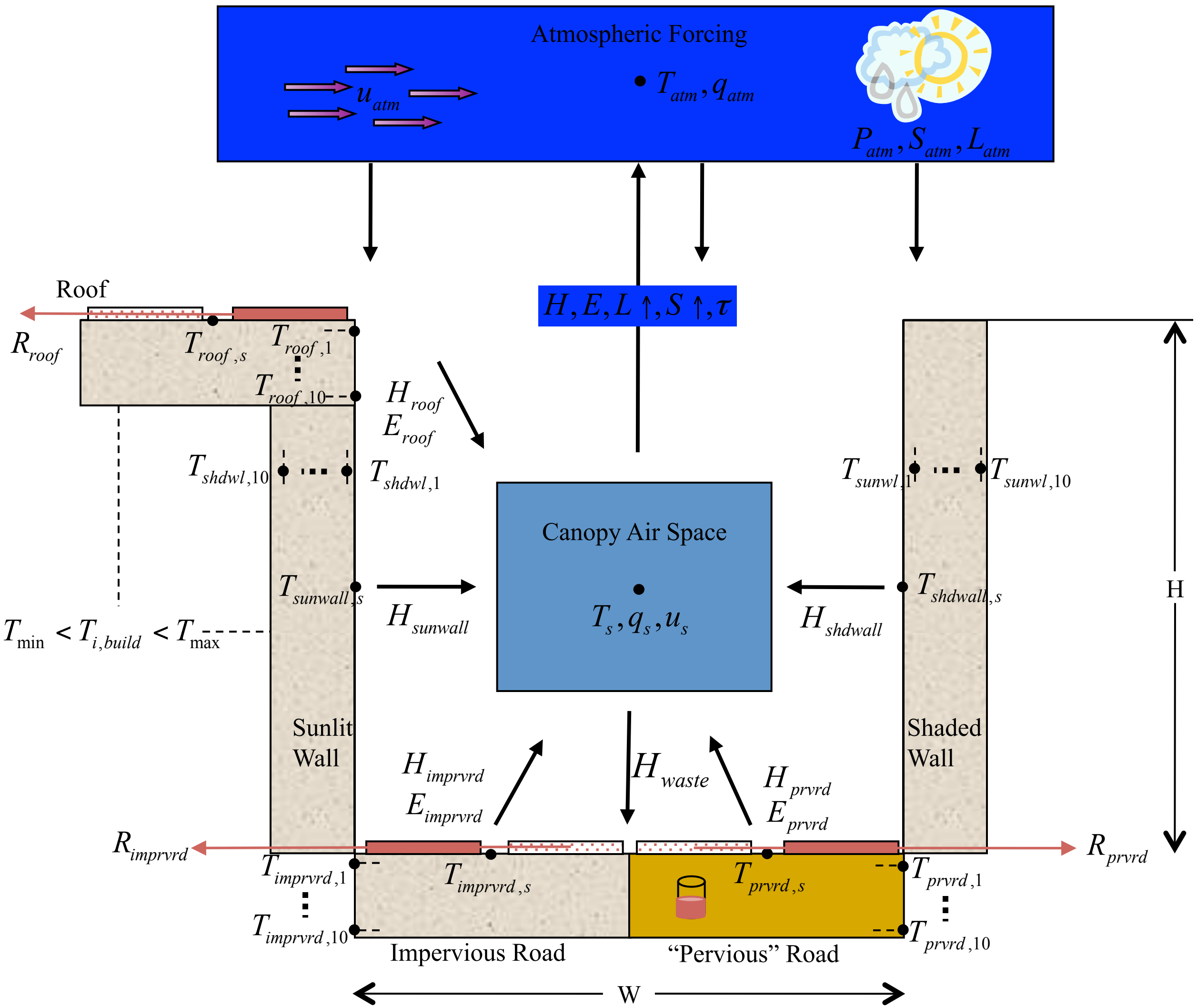
Levis *et al. 2012*

Urban Areas in a Climate Model



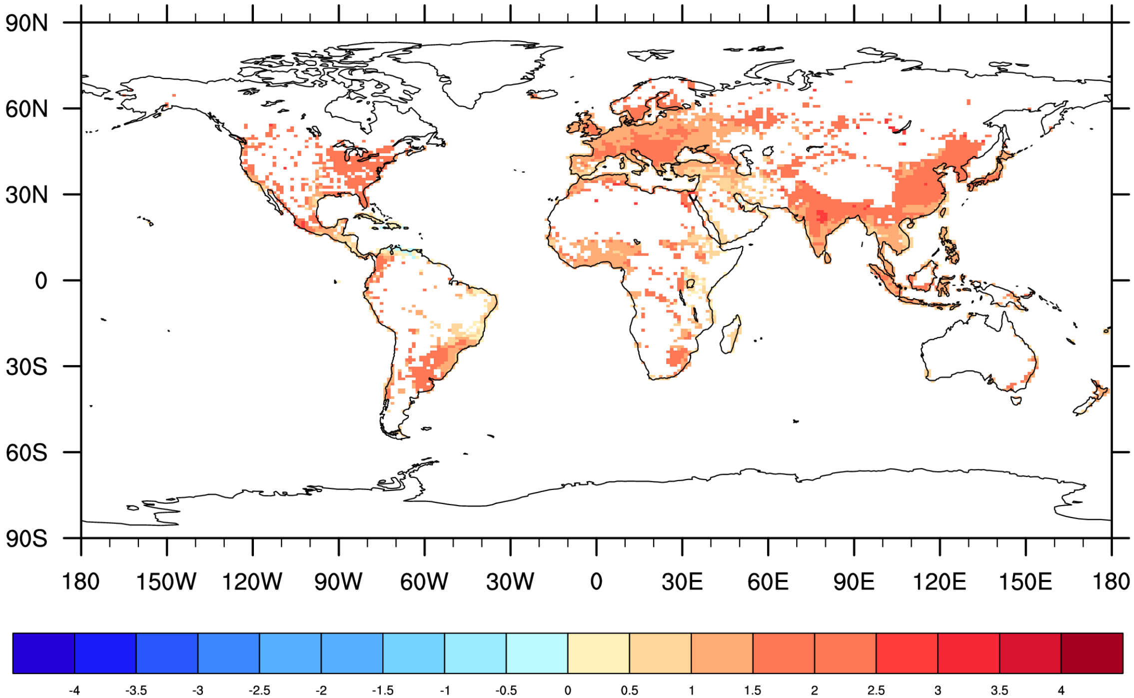
Community Land Model – Urban (CLMU)

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



Urban Heat Island in CCSM4

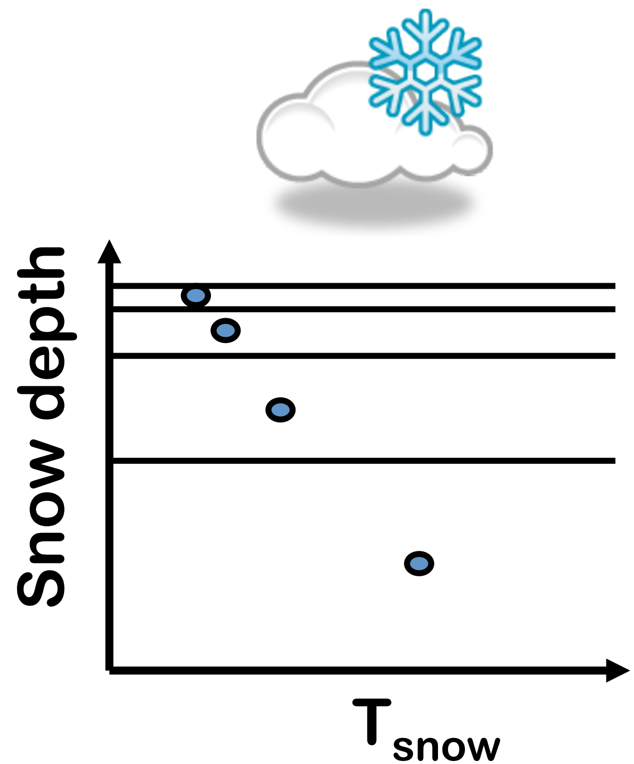
Present day Urban Heat Island (UHI) simulated by CLM Urban (°C)



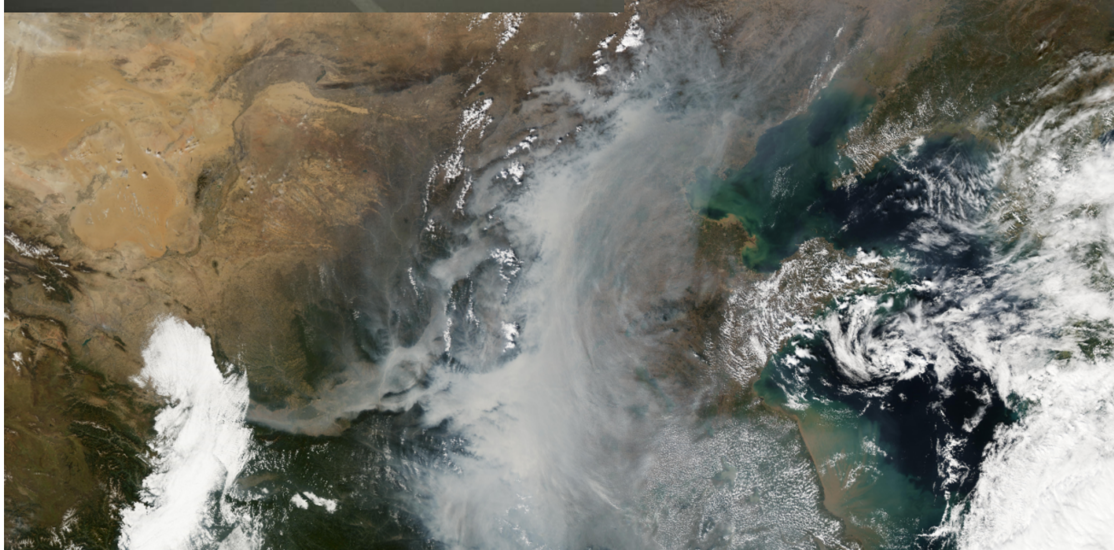
Modeled UHI ranges from near-zero up to 4°C with spatial and seasonal variability controlled by urban to rural contrasts in energy balance.

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

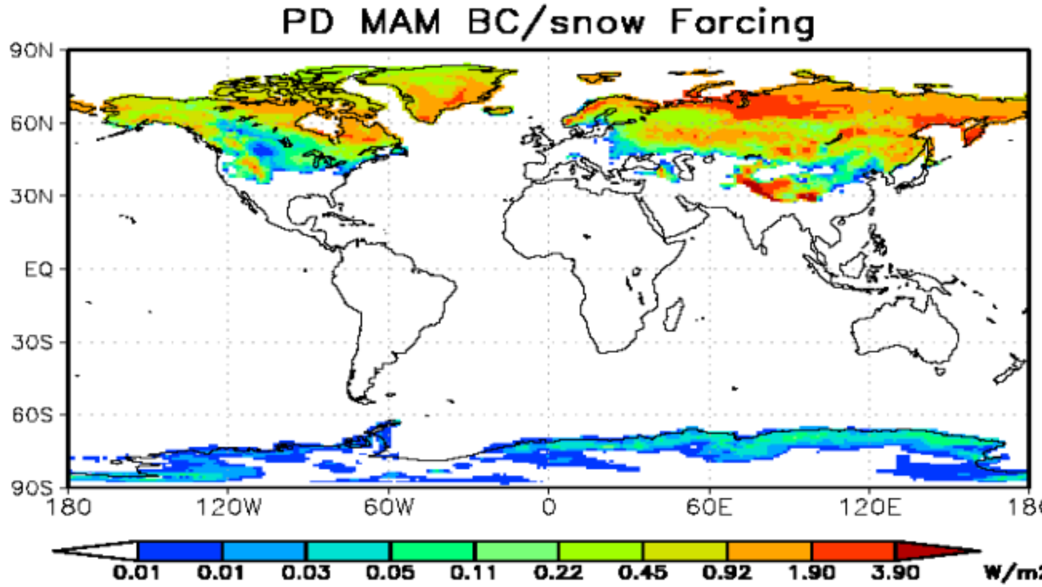


Black Carbon on Snow and Albedo – Greenland Icesheet – Cryoconite



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*

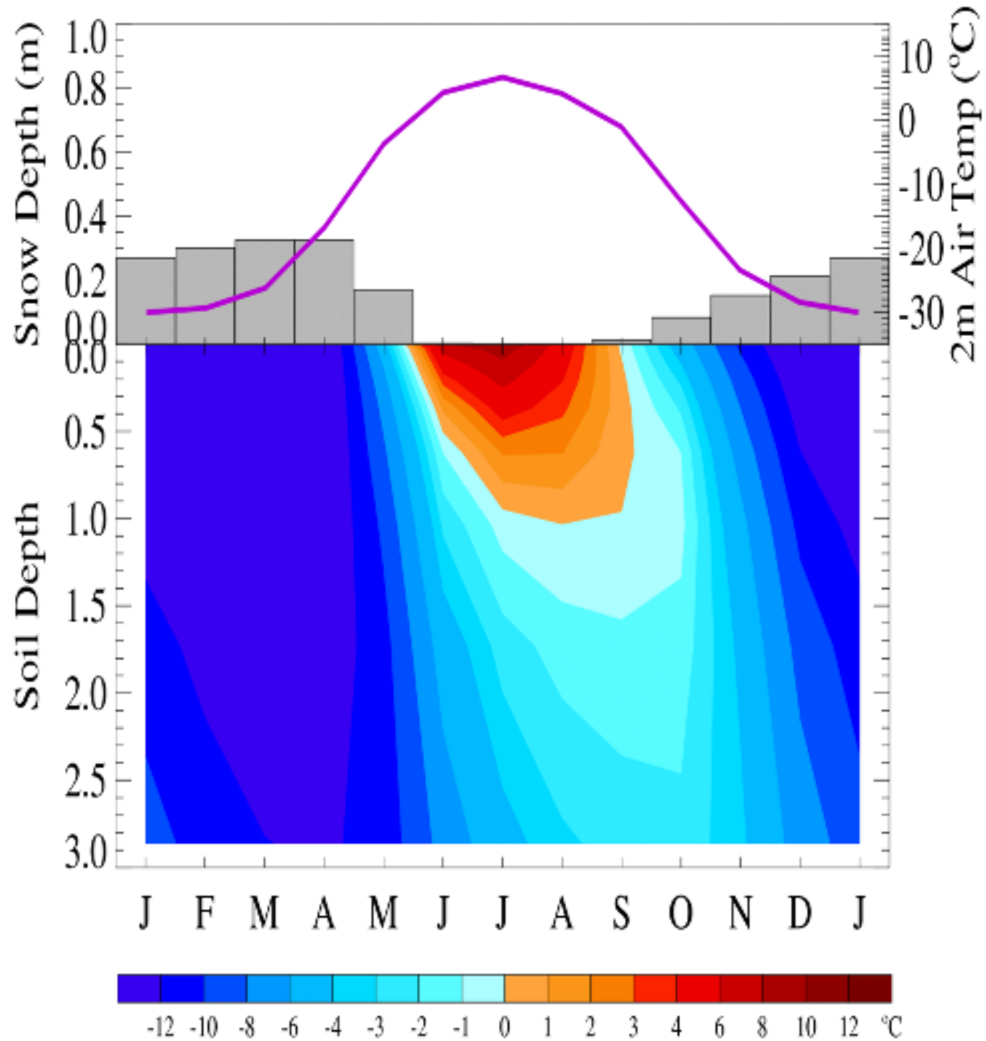
Snow/Soil thermodynamics

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

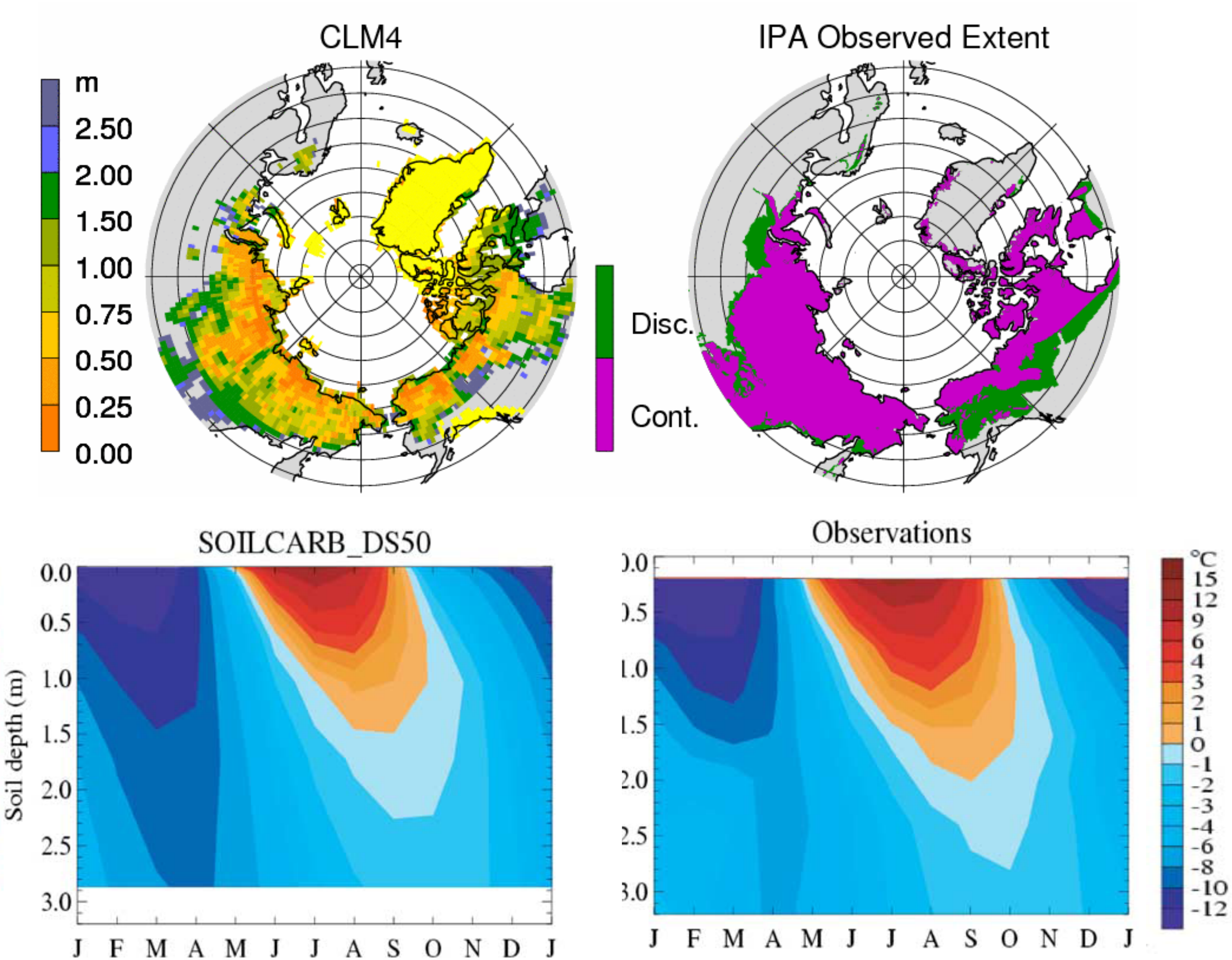
$$C_p \frac{\partial T}{\partial t} = \frac{\partial}{\partial z}\left(K \frac{\partial T}{\partial z}\right)$$

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

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

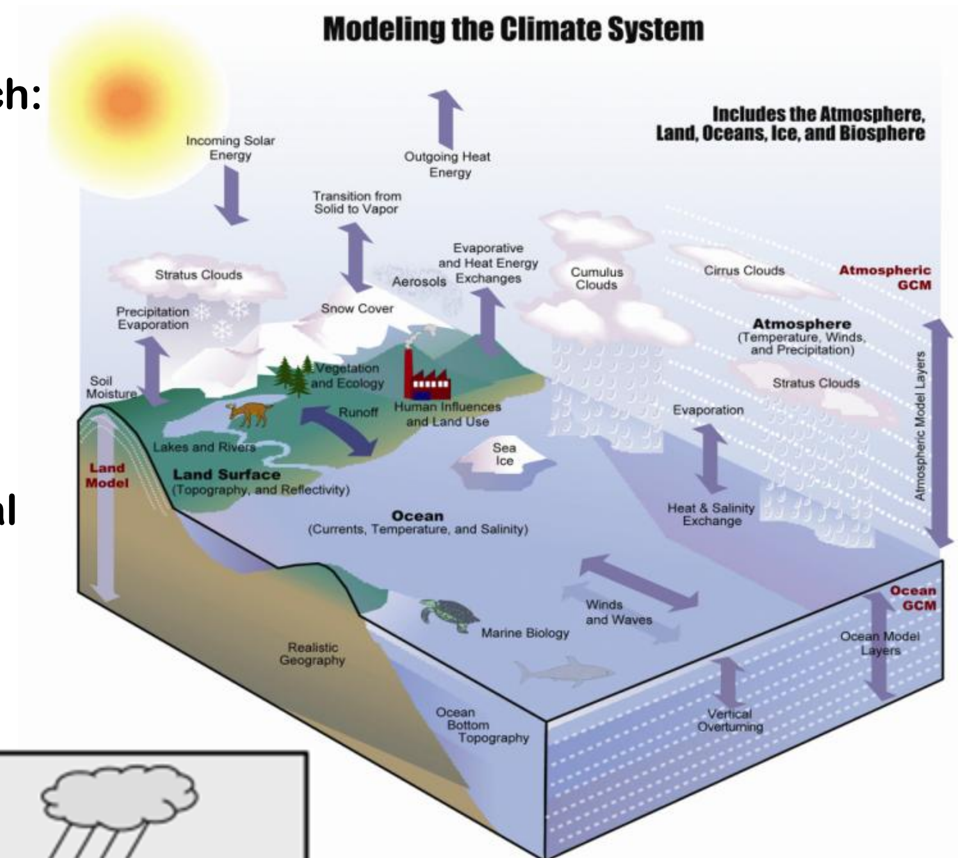


Modeling Permafrost in CLM



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