The Community Terrestrial Systems Model

(and the Community Earth System Model)

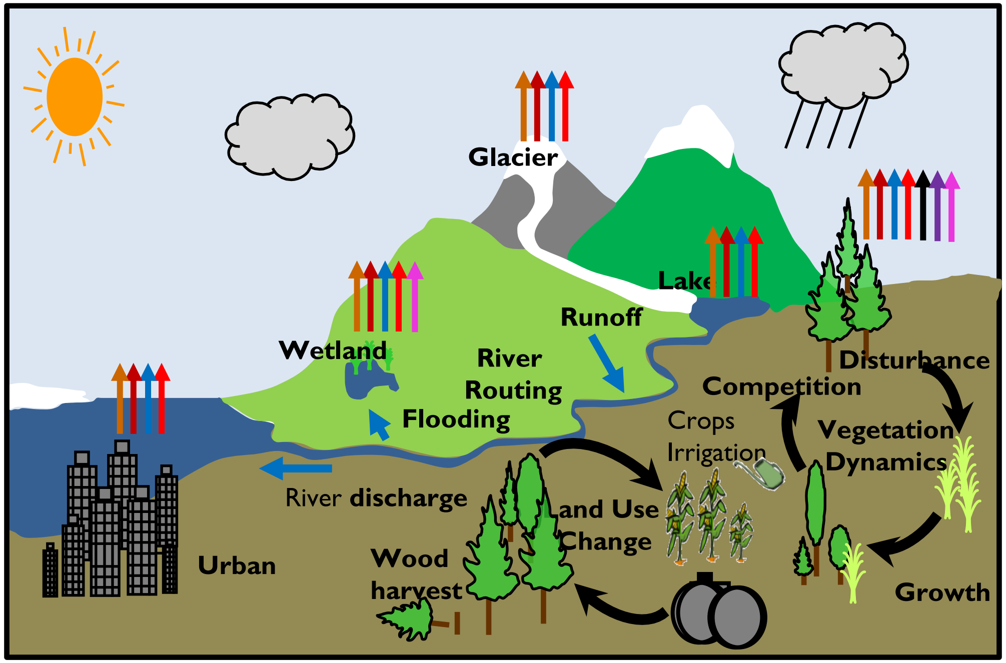
Representing terrestrial processes in the Earth System

David Lawrence

Co-chair of Land Model Working Group
Climate and Global Dynamics Lab
Terrestrial Sciences Section
dlawren@ucar.edu

NCAR is sponsored by the National Science Foundation

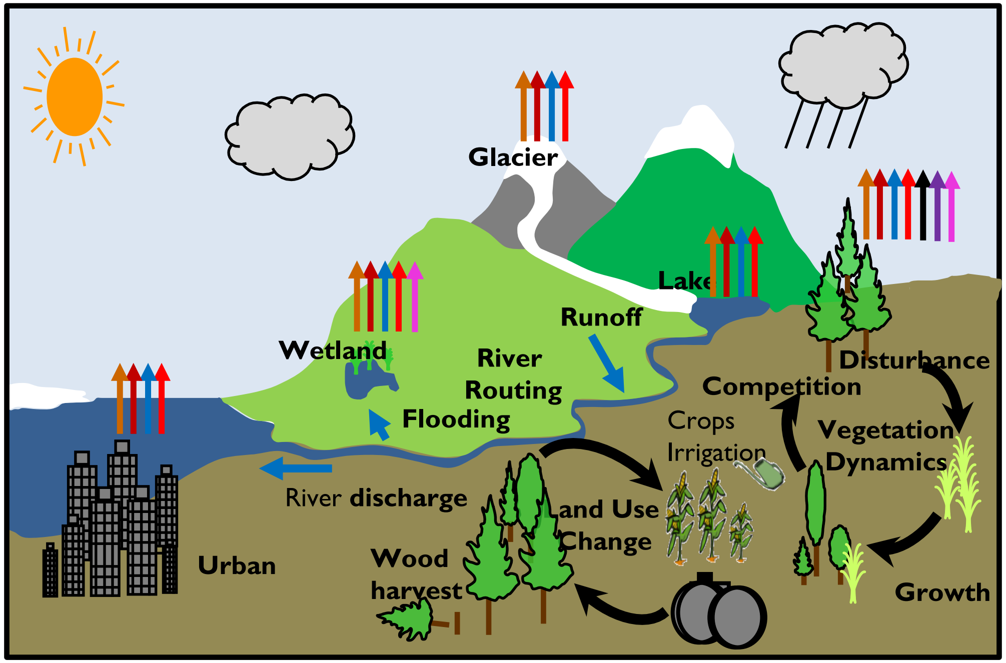
Land Modeling



"Why?"

"Are you sure this is necessary?"

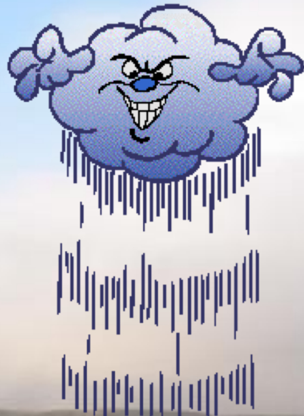
Land Modeling



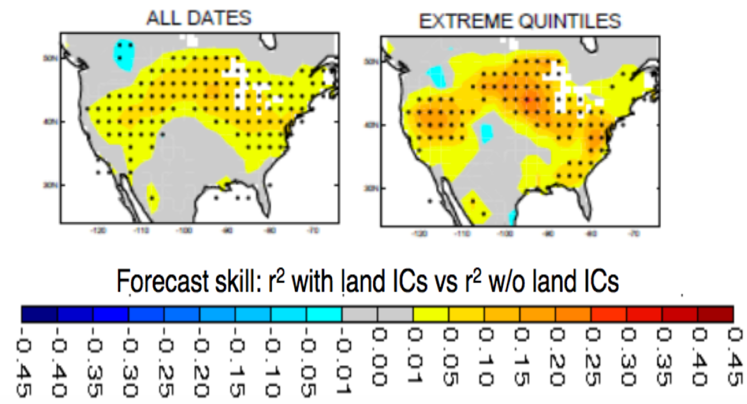
<u>Yes!</u>

Land is the critical interface through which humanity affects and is affected by, adapts to, and mitigates global environmental change

Land modelling, why? Land-atmosphere interactions



30-45 day forecast conditioned on SM

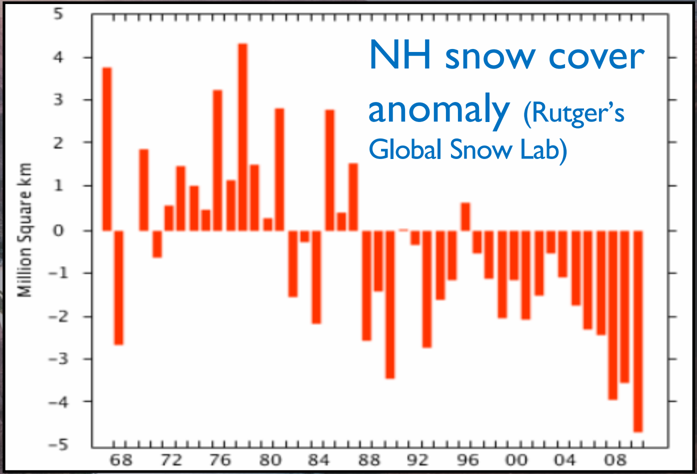


Koster et al., 2010

- When, where, and by how much do land fluxes influence atmosphere, surface temperature, clouds, precipitation, etc.?
- Land-driven predictability
  - Significant skill, especially when conditioned on amplitude of initial soil moisture anomaly
  - Increased land-atmosphere coupling in future warmer climate, increased land-driven skill?
- Land influence on extremes

Land modeling, why? Water

- Land feedbacks on droughts and floods
- Snow-albedo and snow-soil T feedbacks
- Water and food security
  - >1/6th world population dependent on water from seasonal snowpacks
- Water – plant interactions
  - Plant water use efficiency likely to increase with CO_2
- Streamflow prediction



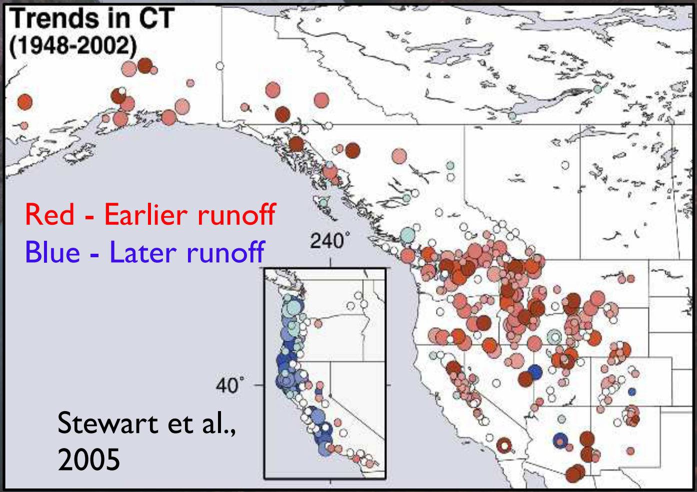
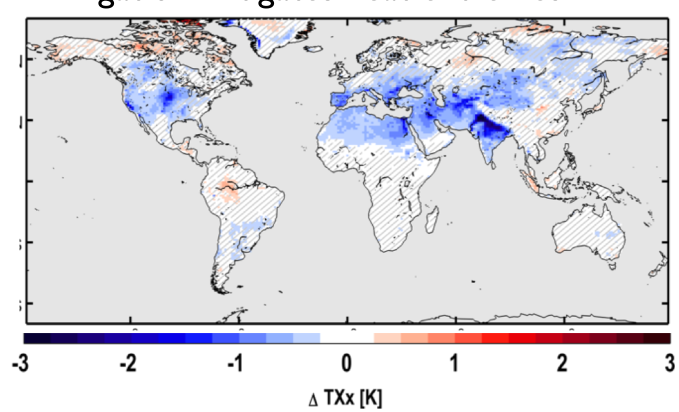


Image: Kimon Maritz

Land modeling why? Land-use and land-cover change

- ~25% non-ice land area undergone anthropogenic land-cover change
- ~80% non-ice land area under some form of land management, and with predicted growing demand for food and water, likely need for land use intensification
- Regionally, LULCC as impactful on surface climate as greenhouse gases
- And, LULCC source of ~1/3 of direct historic carbon emissions since 1993
- Address questions about effectiveness of afforestation and biofuels for CO_2 mitigation
- Urban-rural differences in climate change impacts, e.g. ,heat stress

Irrigation mitigates heat extremes



Thierry, Lawrence, et al., 2017

Image: Frans Lanting/Robert Harding Picture Library

Carbon and ecology

- High uncertainty in projected land C sink
  - Emissions driven RCP8.5: 795 to 1140 ppm (source of ±1.2C uncertainty on top of 3.7C projected change)
- Vulnerability of ecosystems to climate change as well as natural and human disturbances critical to understand C trajectory
- Can ecosystem stewardship help mitigate climate change?

Image: Joel Vodell

The interdisciplinary evolution of land models

The interdisciplinary evolution of land models

Land as a lower boundary to the atmosphere → **Land as an integral component of the Earth System**

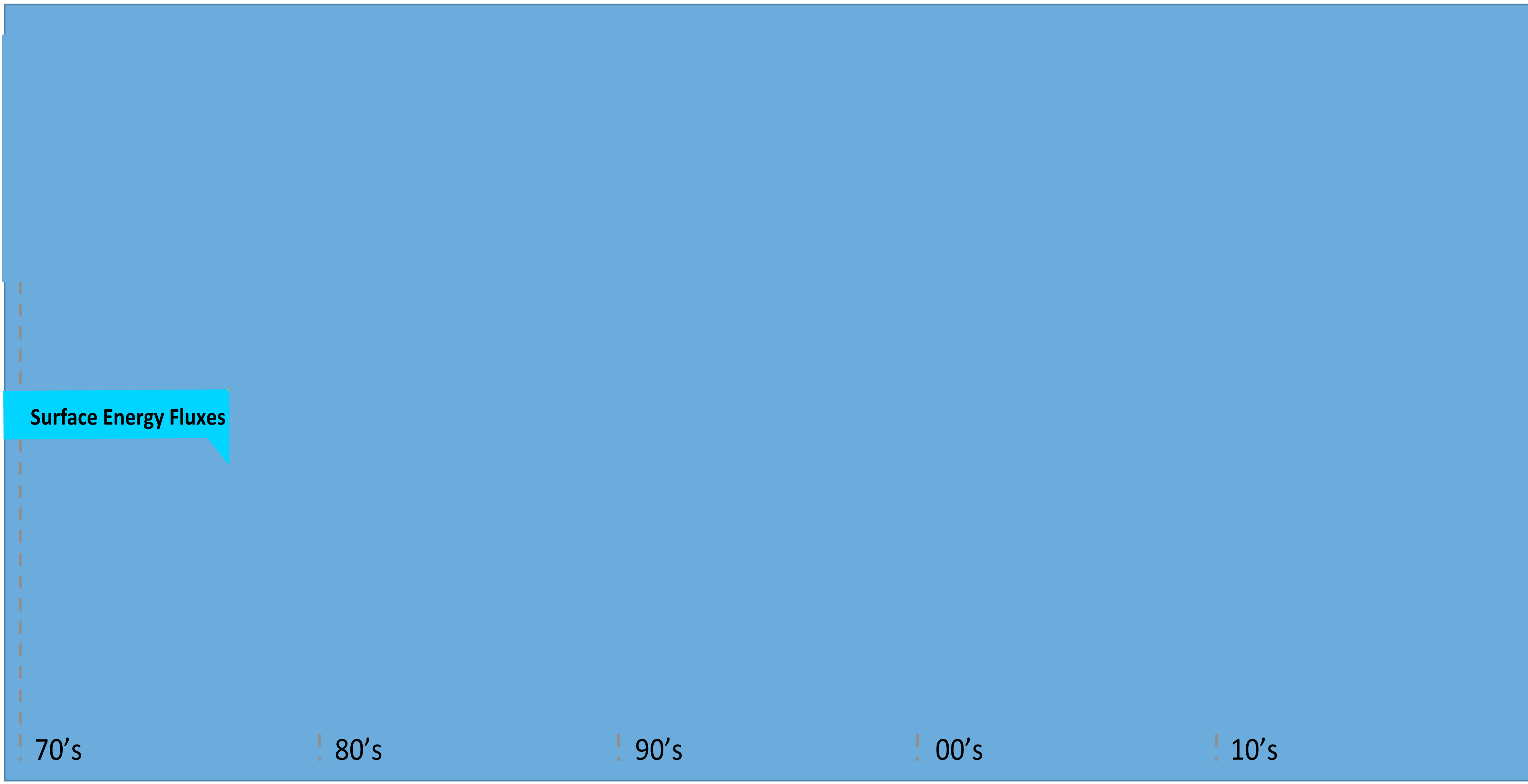
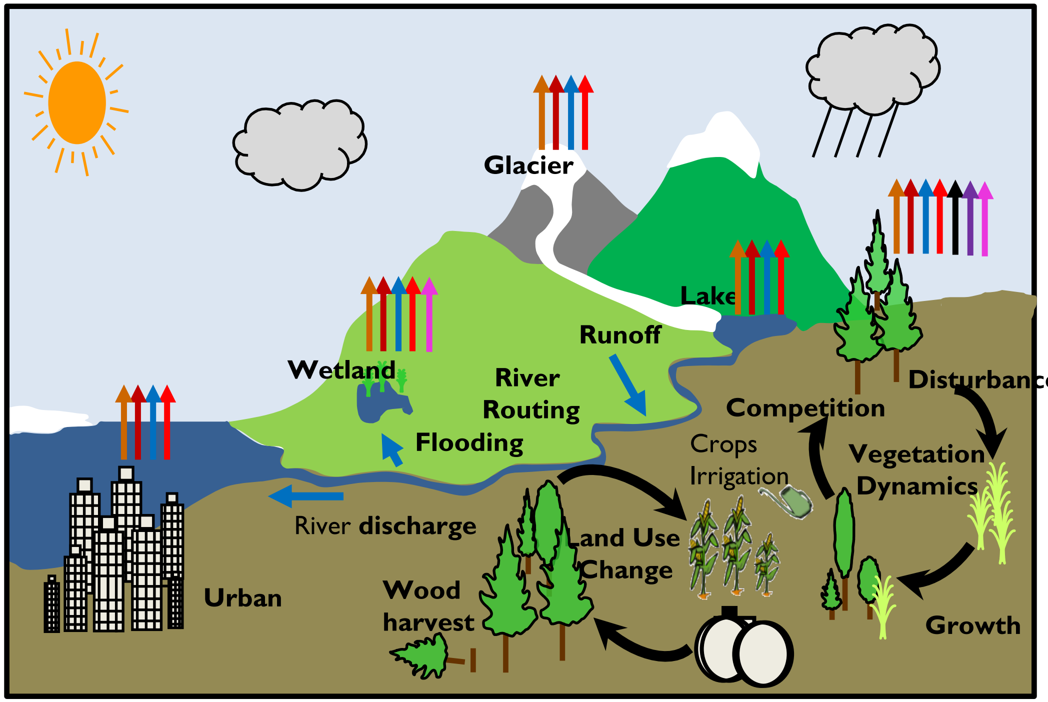
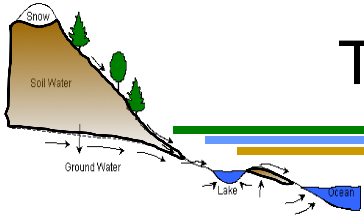


Figure: Fisher, Lawrence, Bonan, Clark, unpublished

Community Land Model (CLM)

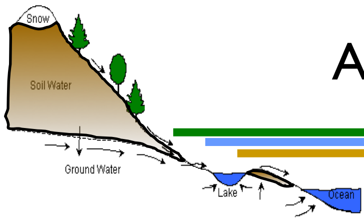


Comprehensive representations of land biogeophysics, hydrology, plant physiology, biogeochemistry, anthropogenic land use, and ecosystem dynamics

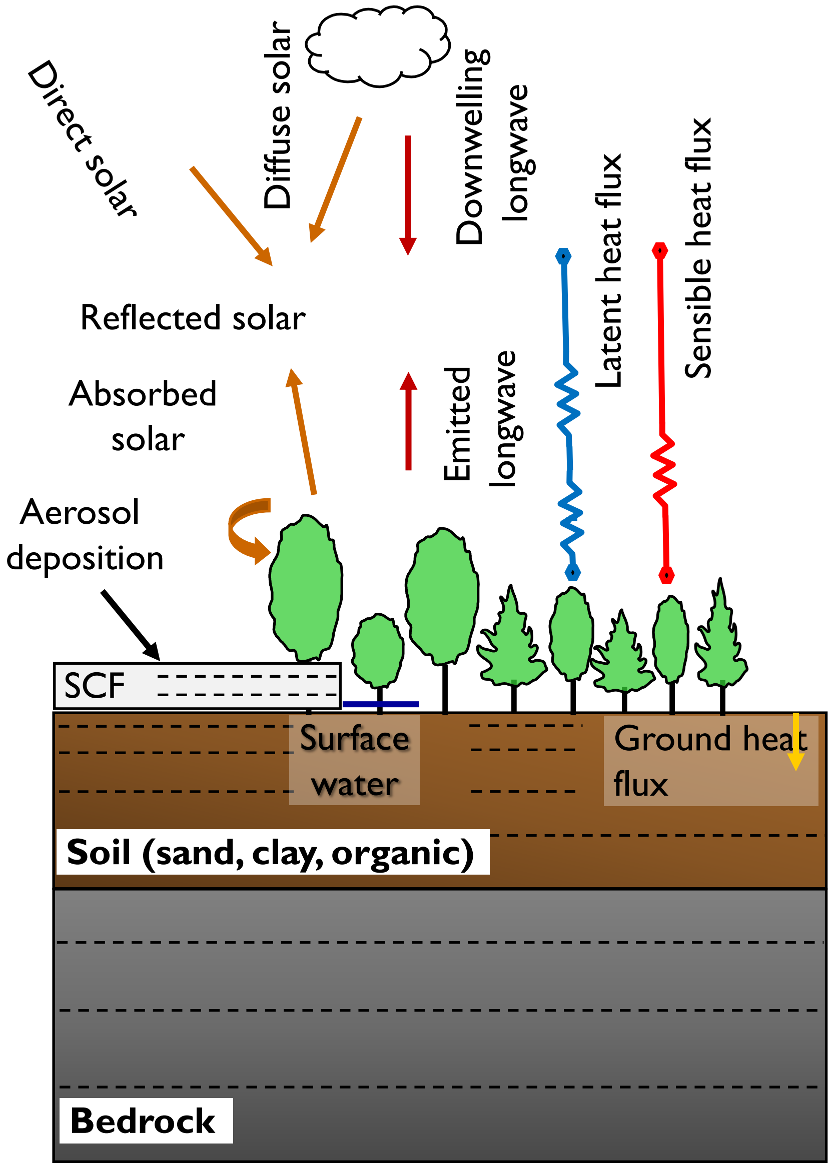


The role of a land model in an Earth System Model

- exchanges of momentum, energy, water vapor, CO_2, dust, and other trace gases/materials between land surface and the overlying atmosphere (and routing of runoff to the ocean)
- states of land surface (e.g., soil moisture, soil temperature, canopy temperature, snow water equivalent, C and N stocks in vegetation and soil)
- characteristics of land surface (e.g., soil texture, surface roughness, albedo, emissivity, vegetation type, cover extent, leaf area index, and seasonality)



At each time step the land model solves Surface Energy Balance



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

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

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

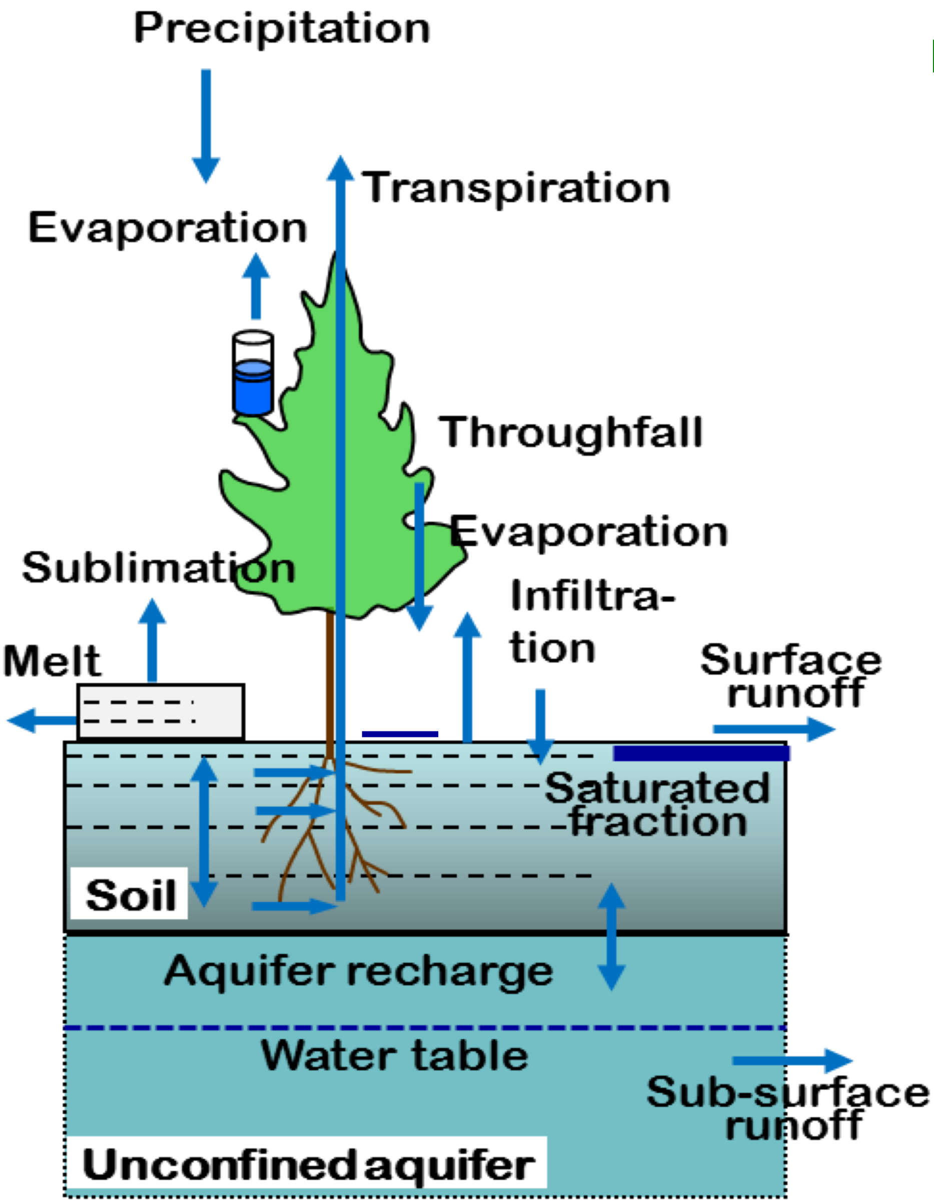
λ is latent heat of vaporization,

E is evaporation,

H is sensible heat flux

G is ground heat flux

… and the Surface Water Balance



$$P = E_S + E_T + E_C + R + (\Delta W_{soi} + \Delta W_{snw} + \Delta W_{sfcw} + \Delta W_{can}) / \Delta t$$

P is rainfall/snowfall,

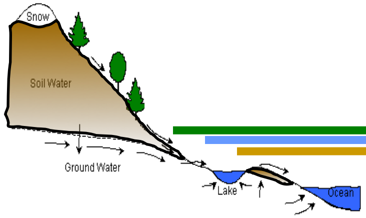
E_S is soil evaporation,

E_T is transpiration,

E_C is canopy evaporation,

R is runoff (surf + sub-surface),

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

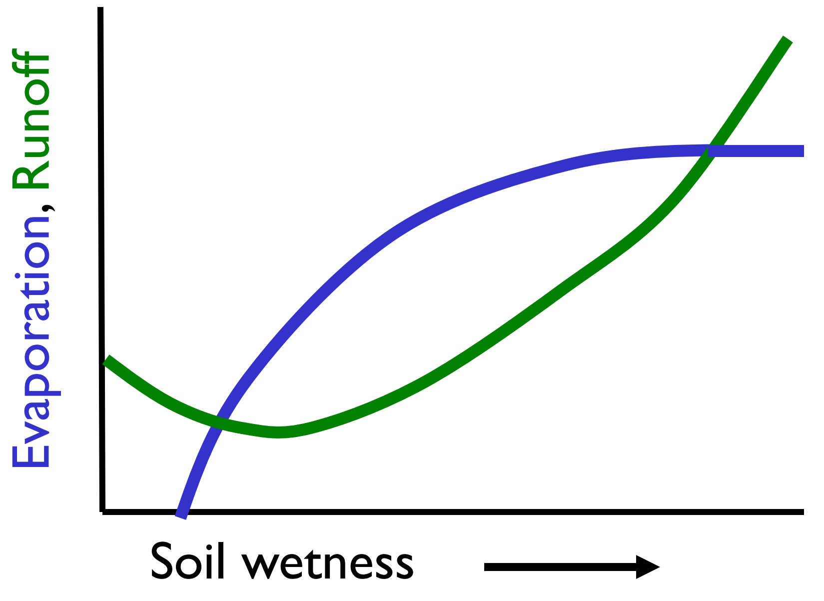


Land water and energy cycles intricately linked

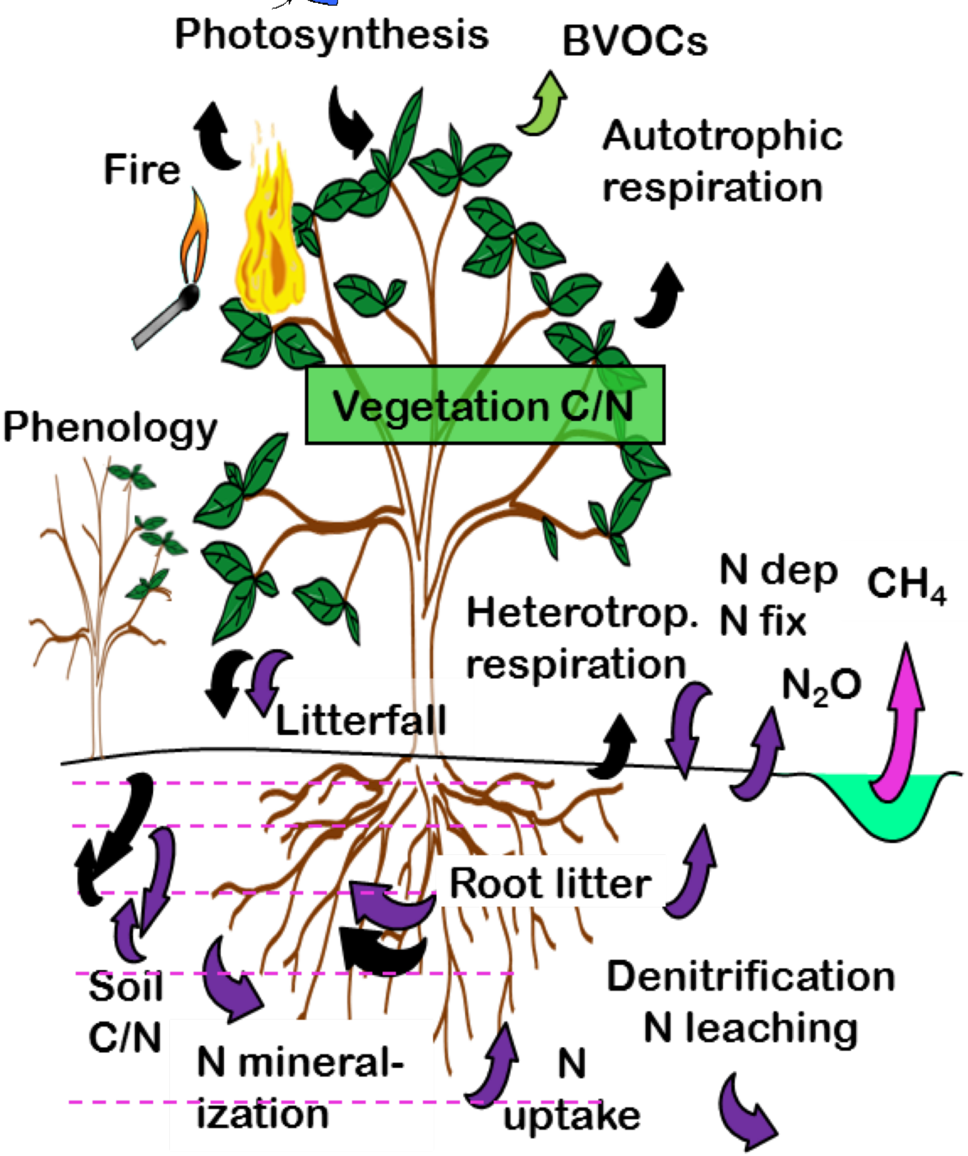
"The ability of a land-surface scheme to model evaporation correctly depends crucially on its ability to model runoff correctly. The two fluxes are intricately related through soil moisture."

(Koster and Milly, 1997).

Runoff and evaporation vary non-linearly with soil moisture



… and Surface Carbon Exchange



NEE = GPP – HR – AR – Fire – LUC

NEE is net ecosystem exchange

GPP is gross primary productivity

HR is heterotrophic respiration

AR is autotrophic respiration

Fire is carbon flux due to fire

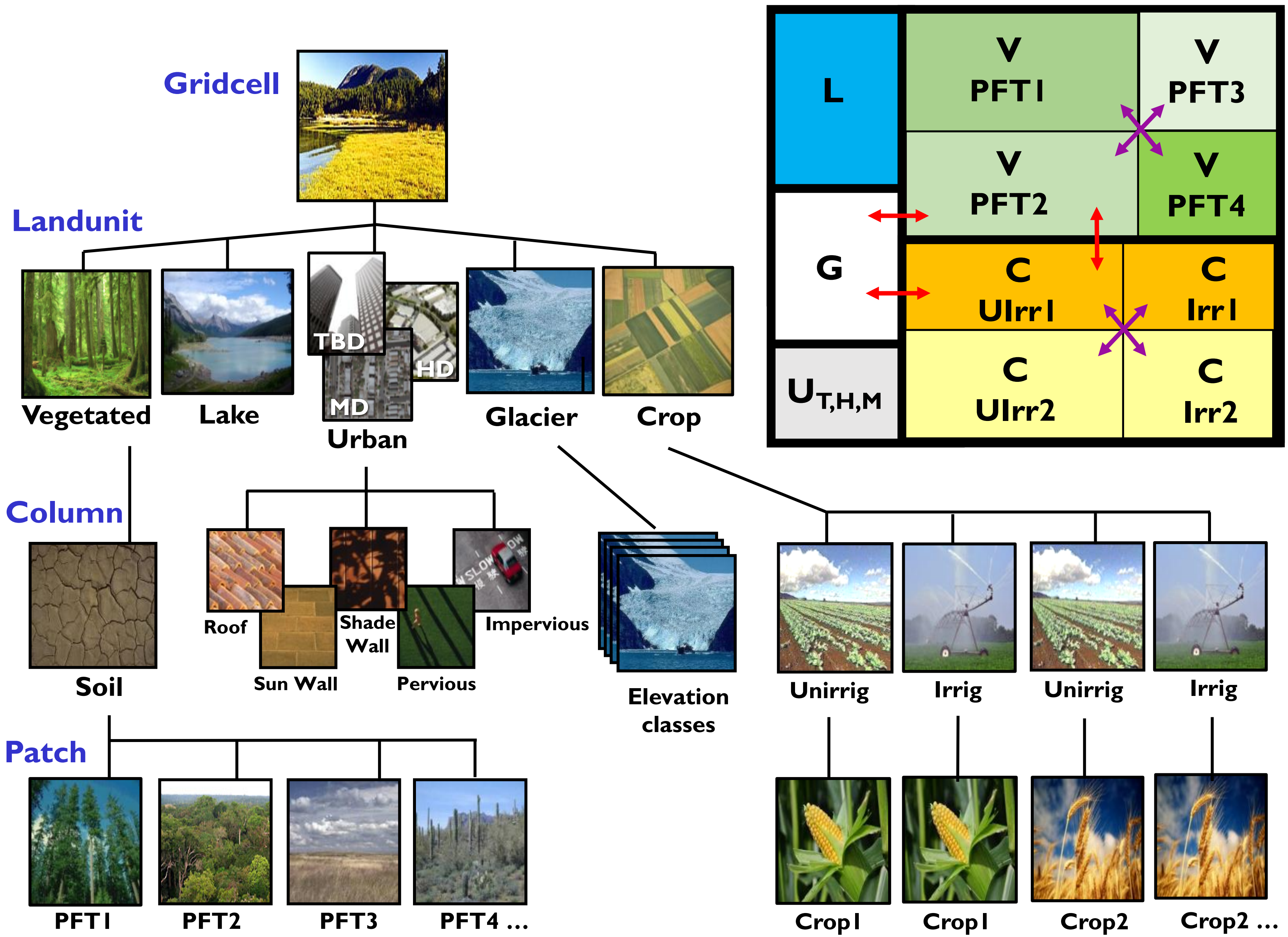
LUC is C flux due to land use change

Land complexity: Submodels of CLM

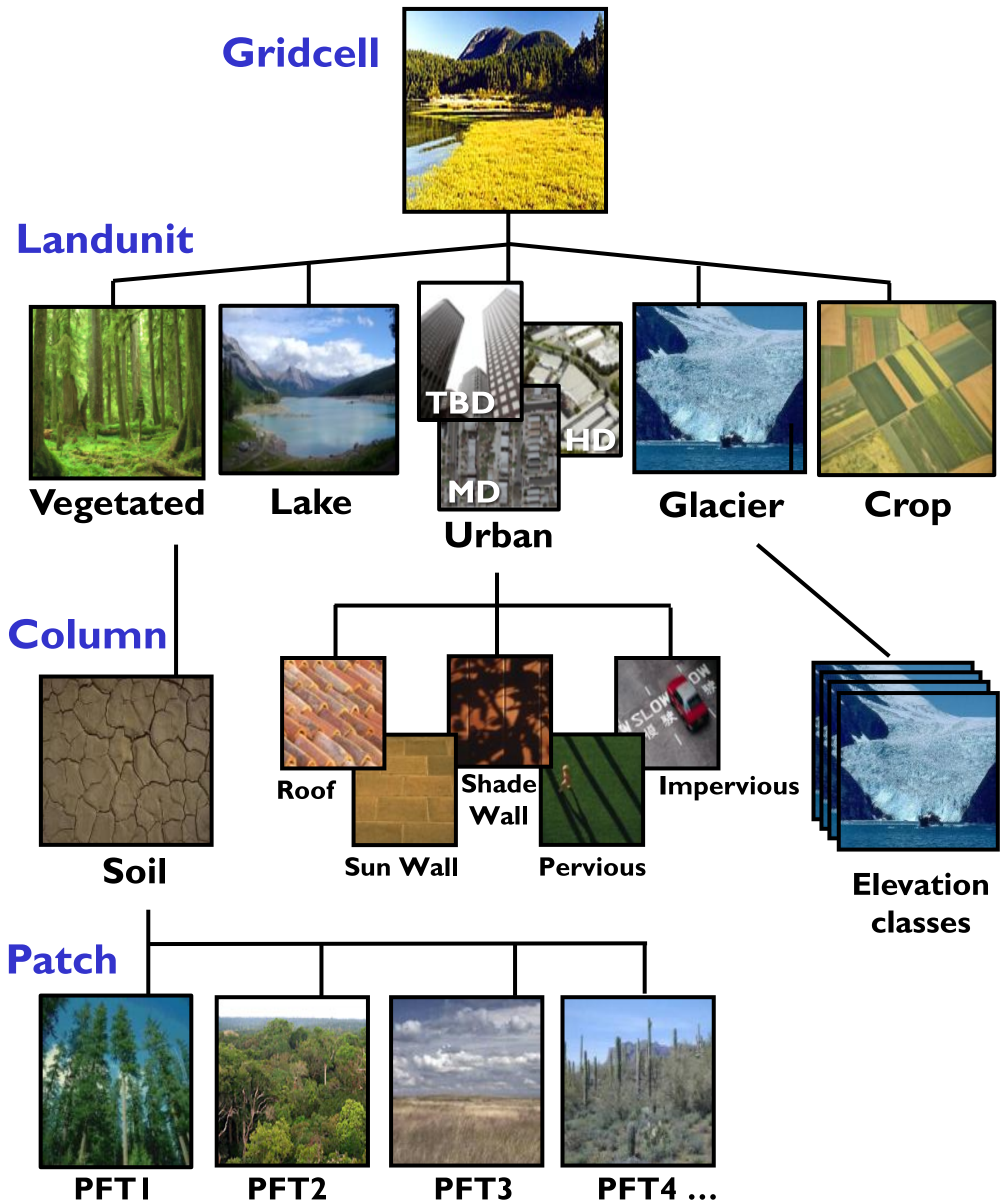
- Biogeophysics
  - Photosynthesis and stomatal resistance
  - Hydrology
  - Snow
  - Soil thermodynamics
  - Surface albedo and radiative fluxes
- Biogeochemistry
  - Carbon / nitrogen pools
  - Allocation, respiration
  - Vegetation phenology
  - Decomposition
  - Plant Mortality
  - External nitrogen cycle
- Vegetation dynamics
- Urban
- Lakes
- Glaciers and ice sheets
- Rivers
- Land use change
- Crops and irrigation
- Fire and fire emissions
- Dust emissions
- Biogenic Volatile Organic Compound emissions
- Methane production and emission

Key challenge: Land surface heterogeneity

Land surface heterogeneity: Subgrid tiling



Land surface heterogeneity: Subgrid tiling



Plant Functional Types:

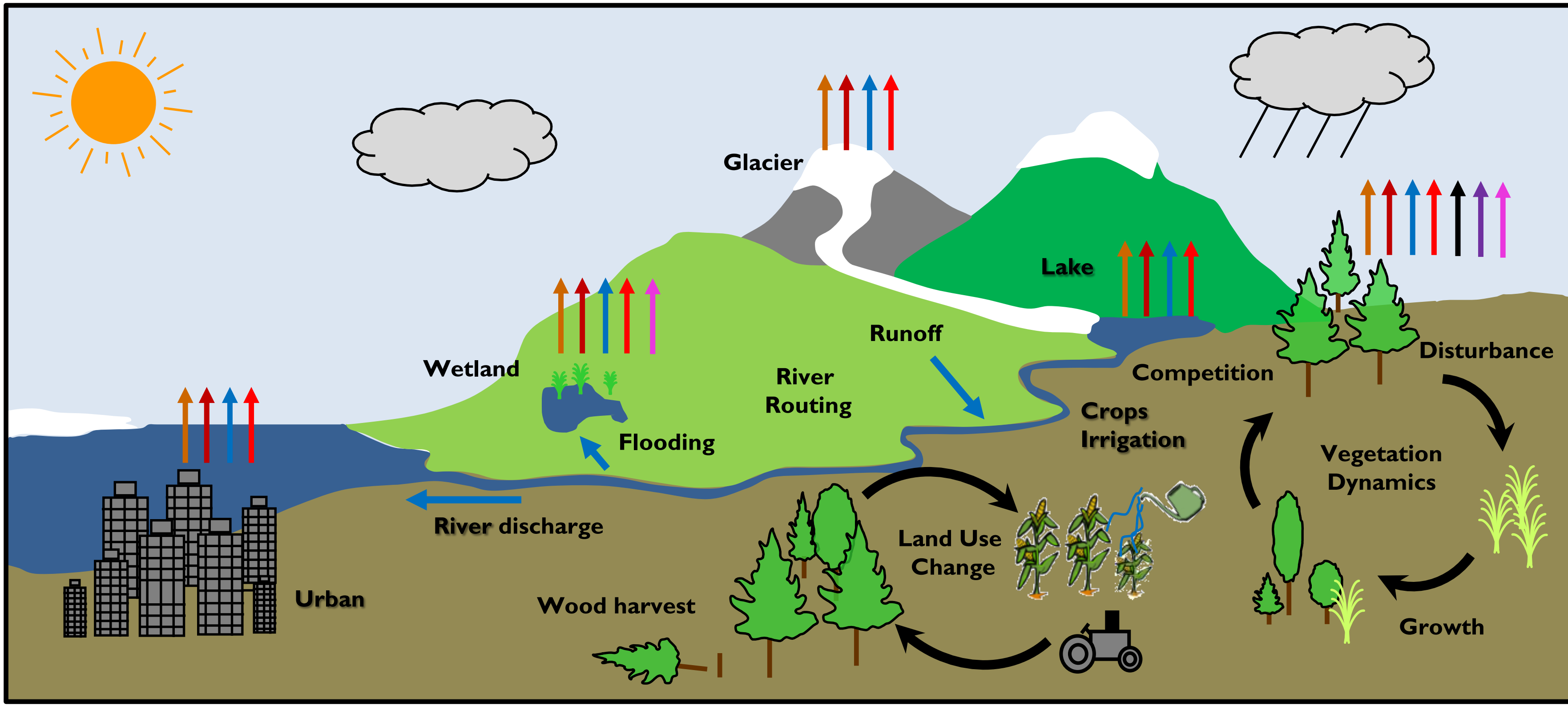
0. Bare

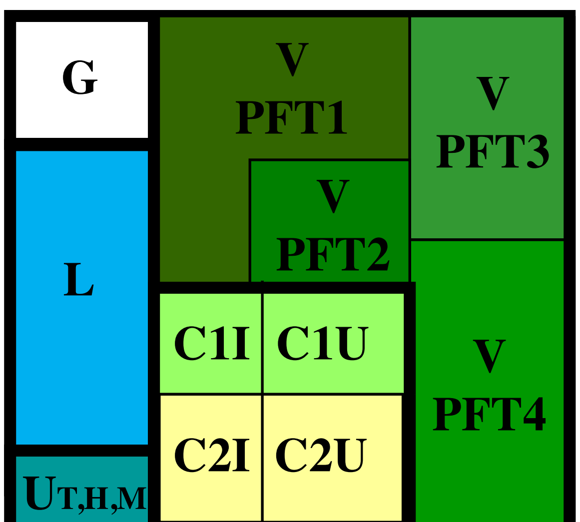
Tree:

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

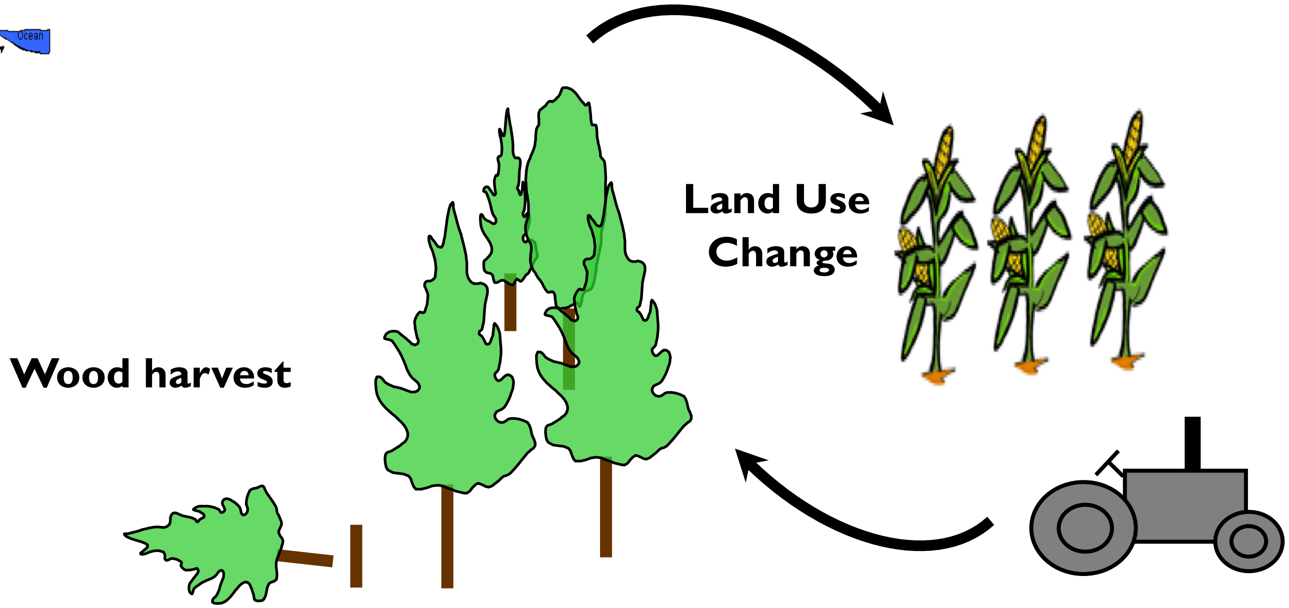


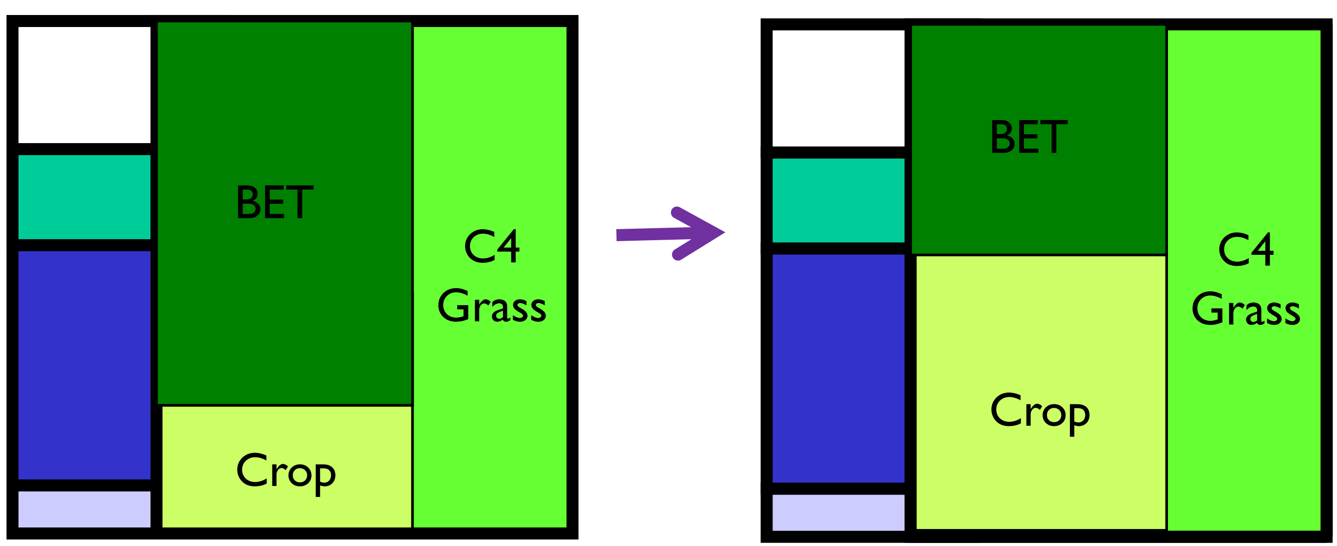


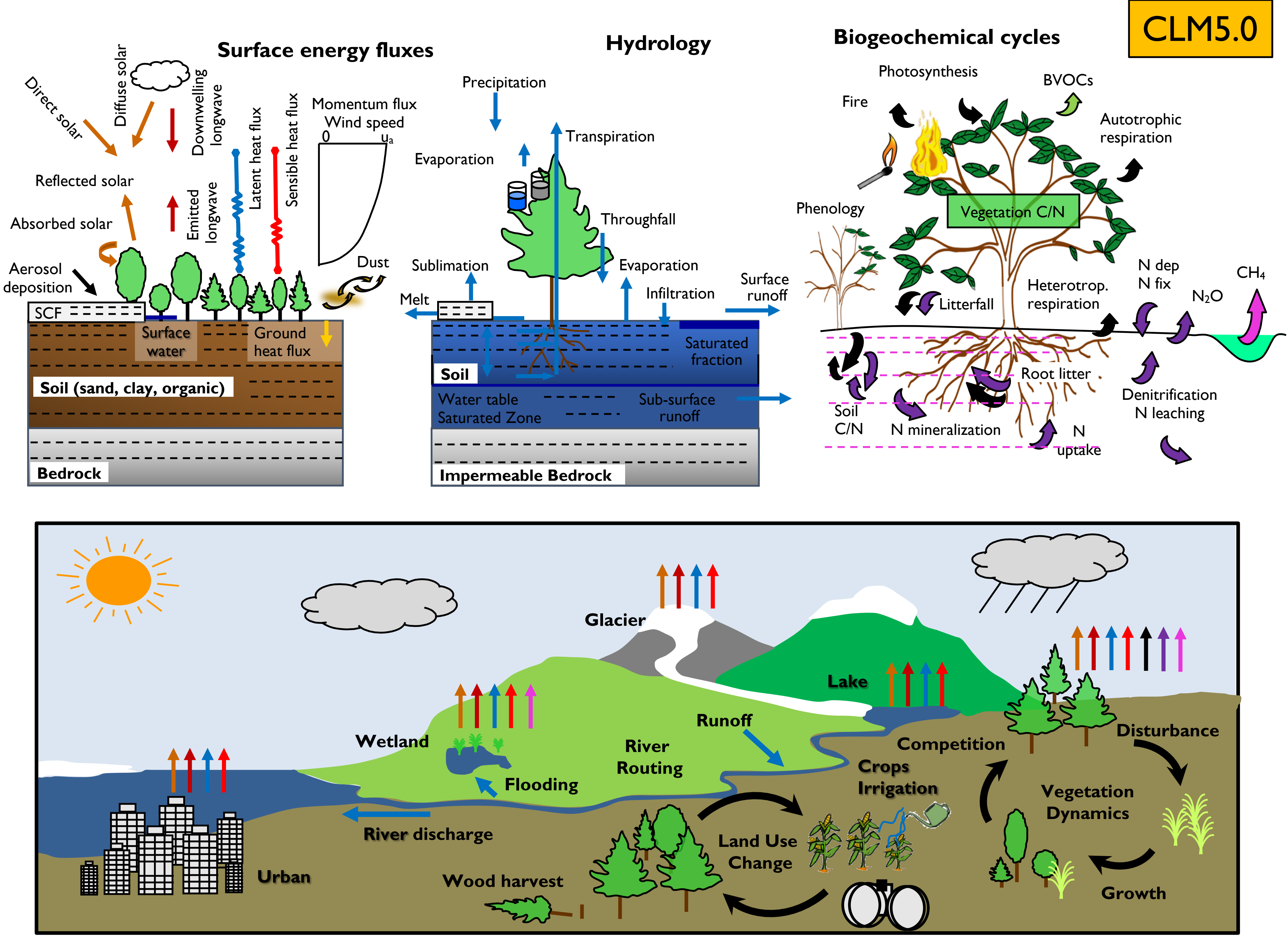
Landscape-scale dynamics

Long-term dynamical processes that affect fluxes in a changing environment (disturbance, land use, succession)

Land-cover / land-use change (prescribed)

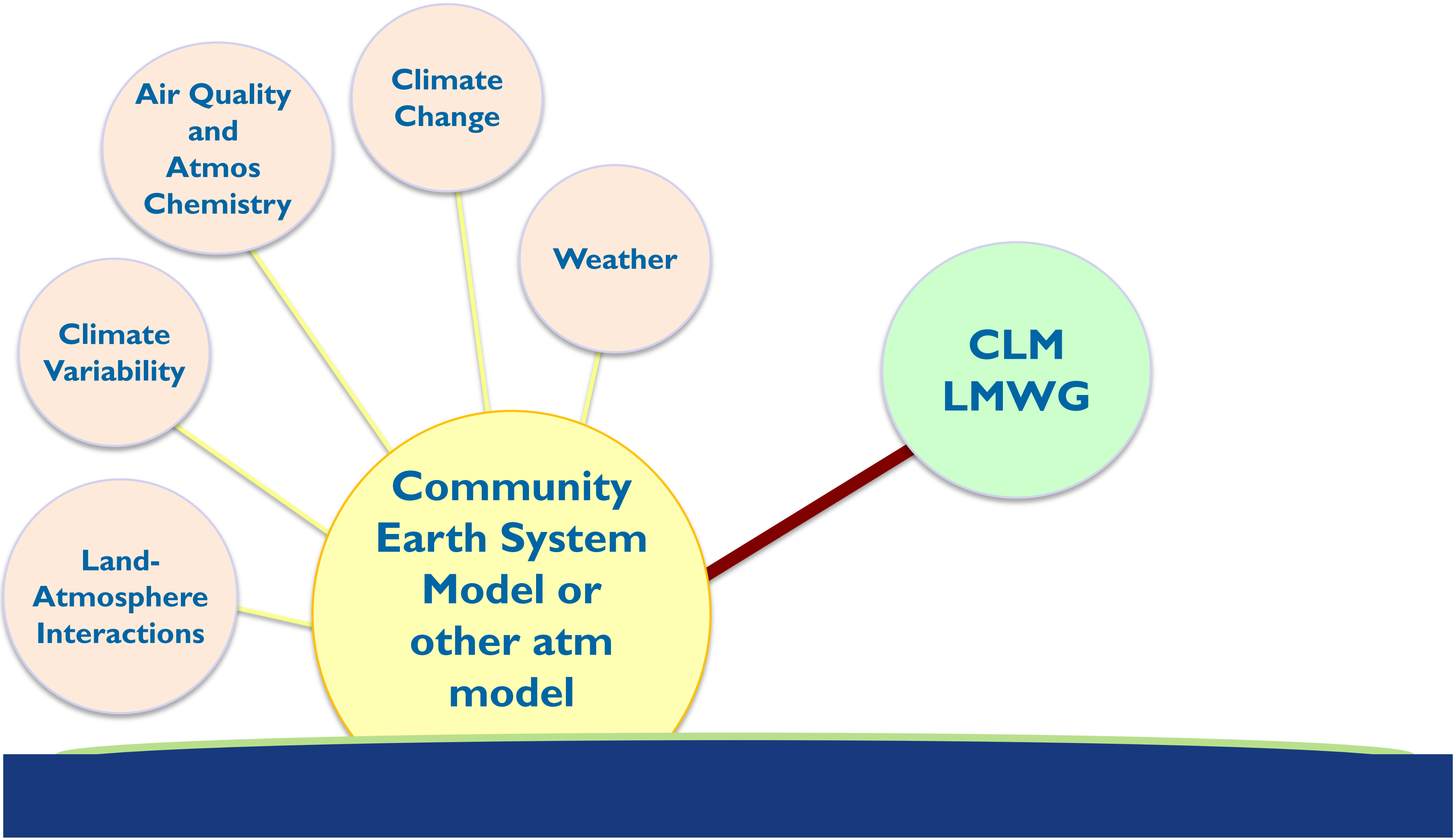






CLM5.0
Surface energy fluxes
Hydrology
Biogeochemical cycles
Direct solar
Diffuse solar
Downwelling longwave
Reflected solar
Absorbed solar
Emitted longwave
Latent heat flux
Sensible heat flux
Momentum flux
Wind speed
0
u_a
Aerosol deposition
Dust
SCF
Surface water
Ground heat flux
Soil (sand, clay, organic)
Bedrock
Precipitation
Transpiration
Evaporation
Throughfall
Sublimation
Evaporation
Melt
Infiltration
Surface runoff
Soil
Saturated fraction
Water table
Saturated Zone
Sub-surface runoff
Impermeable Bedrock
Photosynthesis
BVOCs
Fire
Autotrophic respiration
Phenology
Vegetation C/N
Litterfall
Heterotrop. respiration
N dep
N fix
N_2O
CH_4
Root litter
Soil C/N
N mineralization
N uptake
Denitrification
N leaching
Glacier
Lake
Wetland
Runoff
River Routing
Flooding
River discharge
Urban
Wood harvest
Land Use Change
Crops
Irrigation
Competition
Disturbance
Vegetation Dynamics
Growth

CLM as a community modeling tool



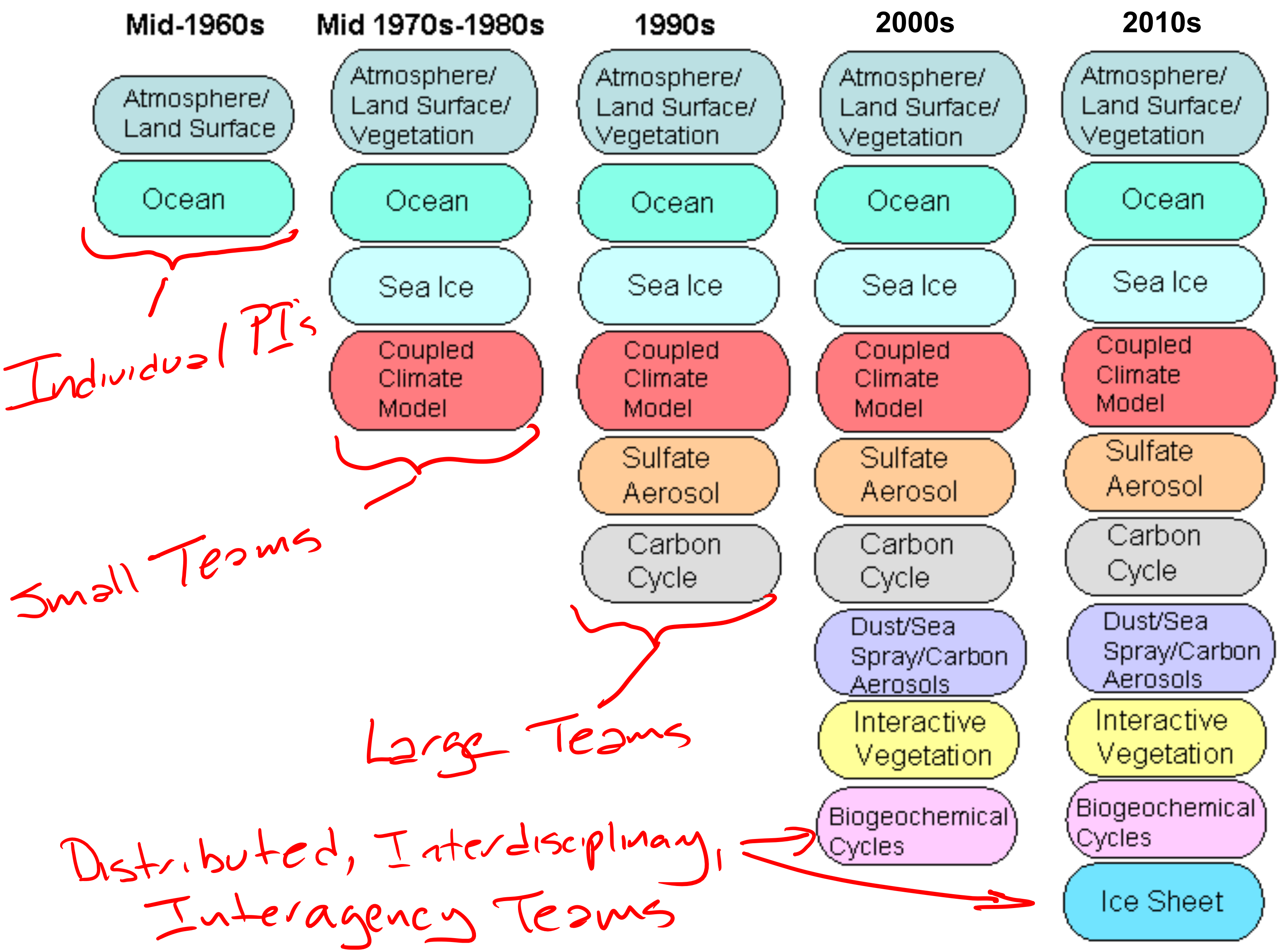
www2.cesm.ucar.edu

The Community Earth System Model: A Framework for Collaborative Research
J.W. Hurrell, M.M. Holland, P.R. Gent, S. Ghan, J.E. Kay, P.J. Kushner, J.-F. Lamarque, W.G. Large, D. Lawrence, K. Lindsay, W.H. Lipscomb, M.C. Long, N. Mahowald, D.R. Marsh, R.B. Neale, P. Rasch, S. Vavrus, M. Vertenstein, D. Bader, W. D. Collins, J.J. Hack, J. Kiehl, S. Marshall, **Bulletin American Meteorological Society**, 2013.

Graphic courtesy of Steve Ghan and DOE Graphics team

History of Climate Model to Earth System Model Development

http://www.aip.org/history/climate/GCM.htm



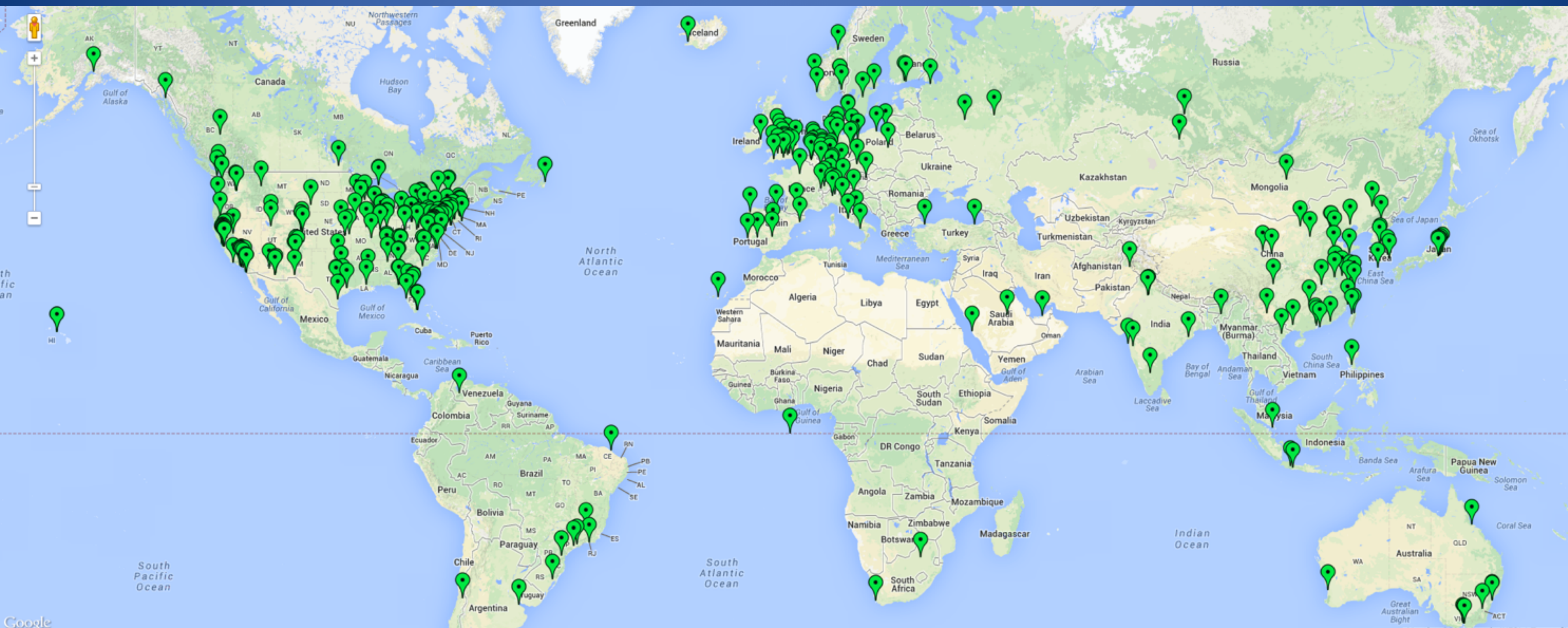
CESM Project

Based on 20+ Years of Model development and application

CESM is primarily sponsored by the National Science Foundation and the Department of Energy

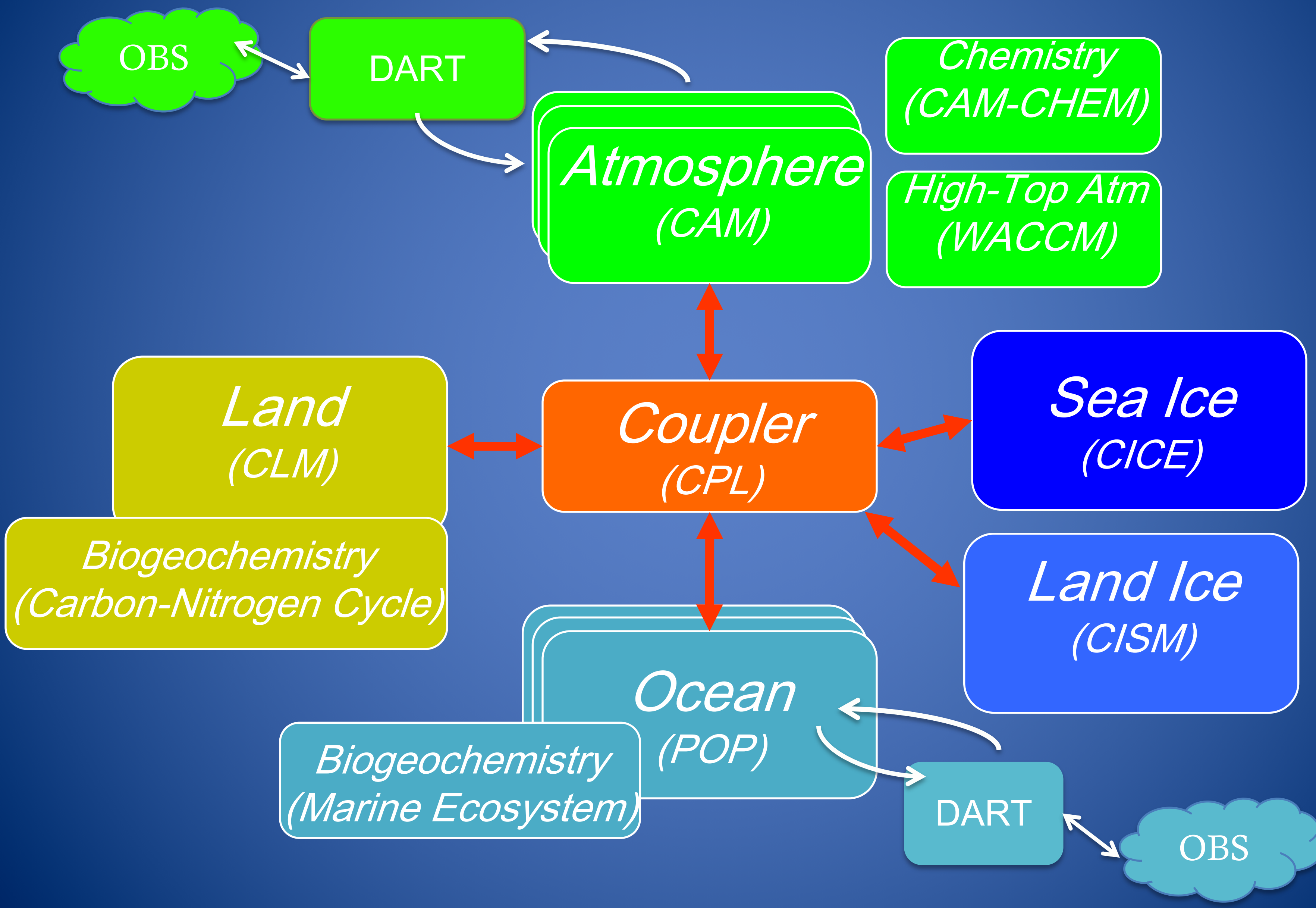
Most working groups have winter/spring meetings. Annual meeting in June (≈400 participants).

A truly global community

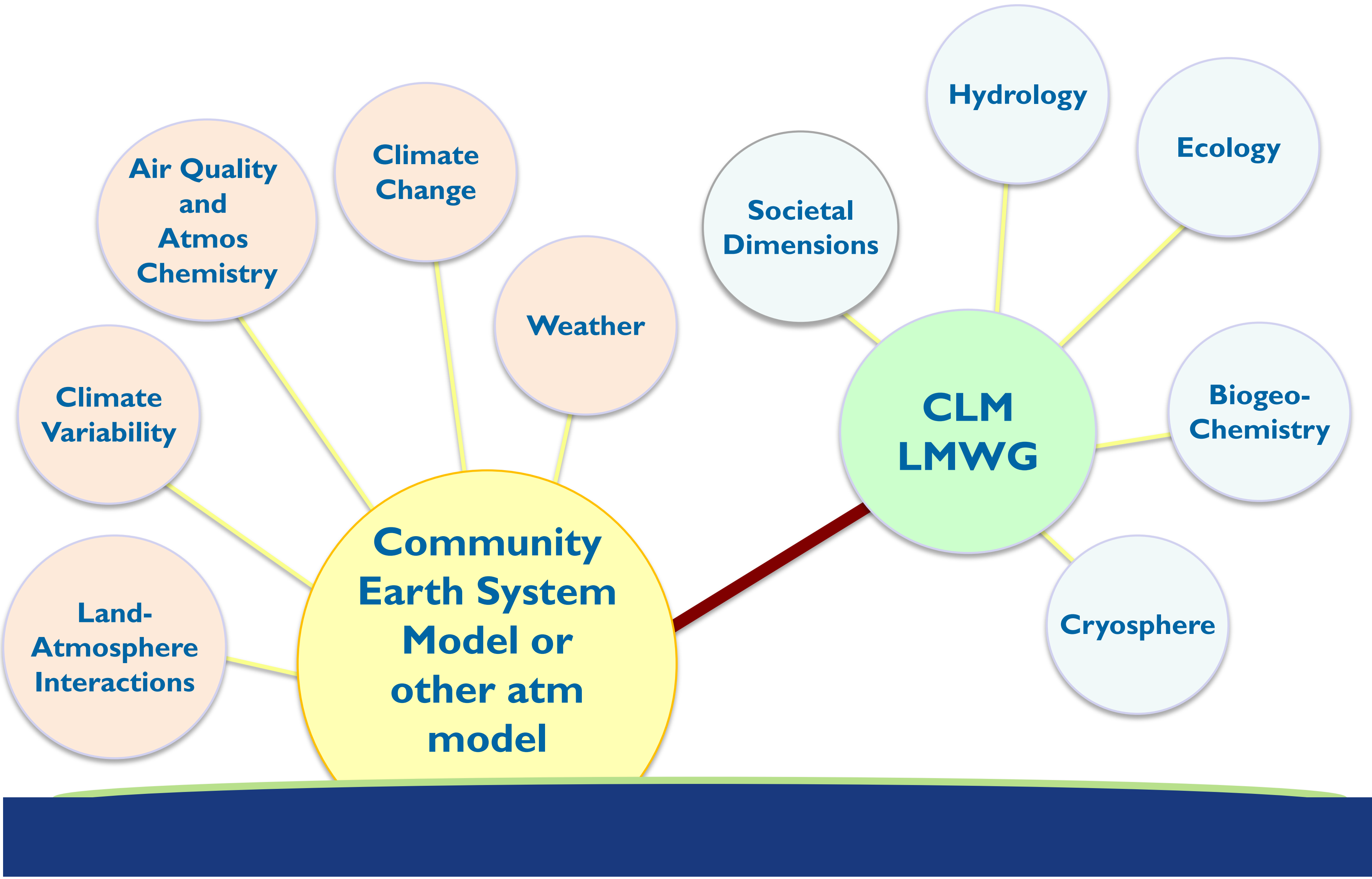


Download of released version since 2010

CESM Prediction System



CLM as a community modeling tool



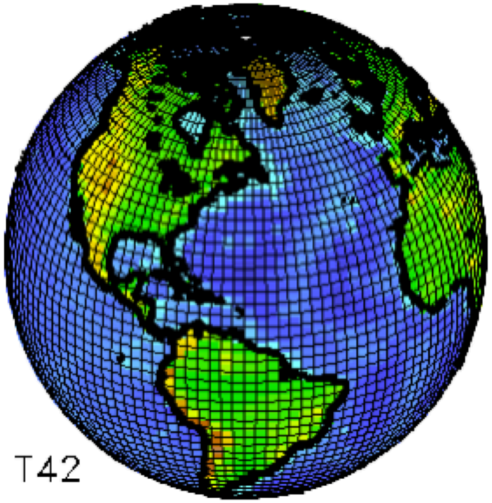
CLM/CTSM as a research tool

Model configurations

- SP (satellite phenology, prescribed vegetation)
- BGC (prognostic carbon, vegetation)
- BGC-crop (default in CESM2, same as BGC with crops)
- BGC no-anthro
- + many options for individual parameterizations (i.e., can revert to CLM4.5

Spatial configurations

- Global (low and high resolution)
- Regional
- Single point (tower site)
- Irregular grids (cubed sphere, *basin*)



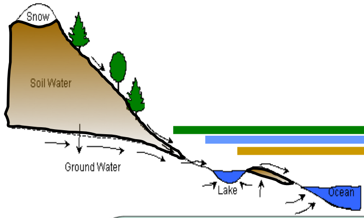
CLM/CTSM as a research tool

Options to reduce complexity (i.e., can be turned off or switched)

- CH_4 emissions
- Carbon isotopes
- land-use change
- VOC emissions
- Plant Hydraulics
- Soil structure (15-level vs 25-level)

Options to increase complexity

- Representative hillslopes
- FATES (Ecosystem dynamics)
- Fire trace gas emissions
- Additional land management
- Flooding
- Ozone damage to plants
- *Water tracers (available soon)*



Model Development Process

- Model release (CESM2/CLM5)
- Detailed model assessment (identify strengths and weaknesses)
- LMWG members develop parameterizations or add features
- Present ideas/results at LMWG meetings
- Publish papers
- Evaluate competing parameterizations
- Plans for next (and next next) model version discussed at LMWG meetings
- Build and test beta version of offline model
- Finalize and test within CESM
- Document, perform control integrations

Use model for scientific studies

CLM Development Process

CLM4 (June 2010) CLM4.5 (June 2013)

- Carbon and nitrog
  prognostic vegetat
- Transient land cove
  wood harvest
- 'Permafrost-enable
  deep ground
- Aerosol depositior
- Simple groundwate
- Urban model

- Vertically-resolved soil C/N
- Co-limitation and acclimation of photosynthesis
- Variable river flow rates
- Natural CH_4 emissions
- Human triggering and suppression of fire
- Cold region hydrology
- Revised lake model
- Multiple urban density classes

What's New for CLM5

https://github.com/ESCOMP/ctsm

A LOT!

More than 50 researchers from 15 different institutions have been involved in development of CLM5

Parallel focus on mechanistic improvements and expansion of capabilities

- hydrology more consistent with state-of-art understanding
- more ecologically relevant plant nutrient, carbon, and water dynamics
- land management including global crop model, wood harvest, urban environments
- prognostic Greenland ice sheet model
- …

CLM4 (June 2010)

- Carbon and nitrog
  prognostic vegetat
- Transient land cove
  wood harvest
- ‘Permafrost-enable
  deep ground
- Aerosol depositior
- Simple groundwate
- Urban model

CLM4.5 (June 2013)

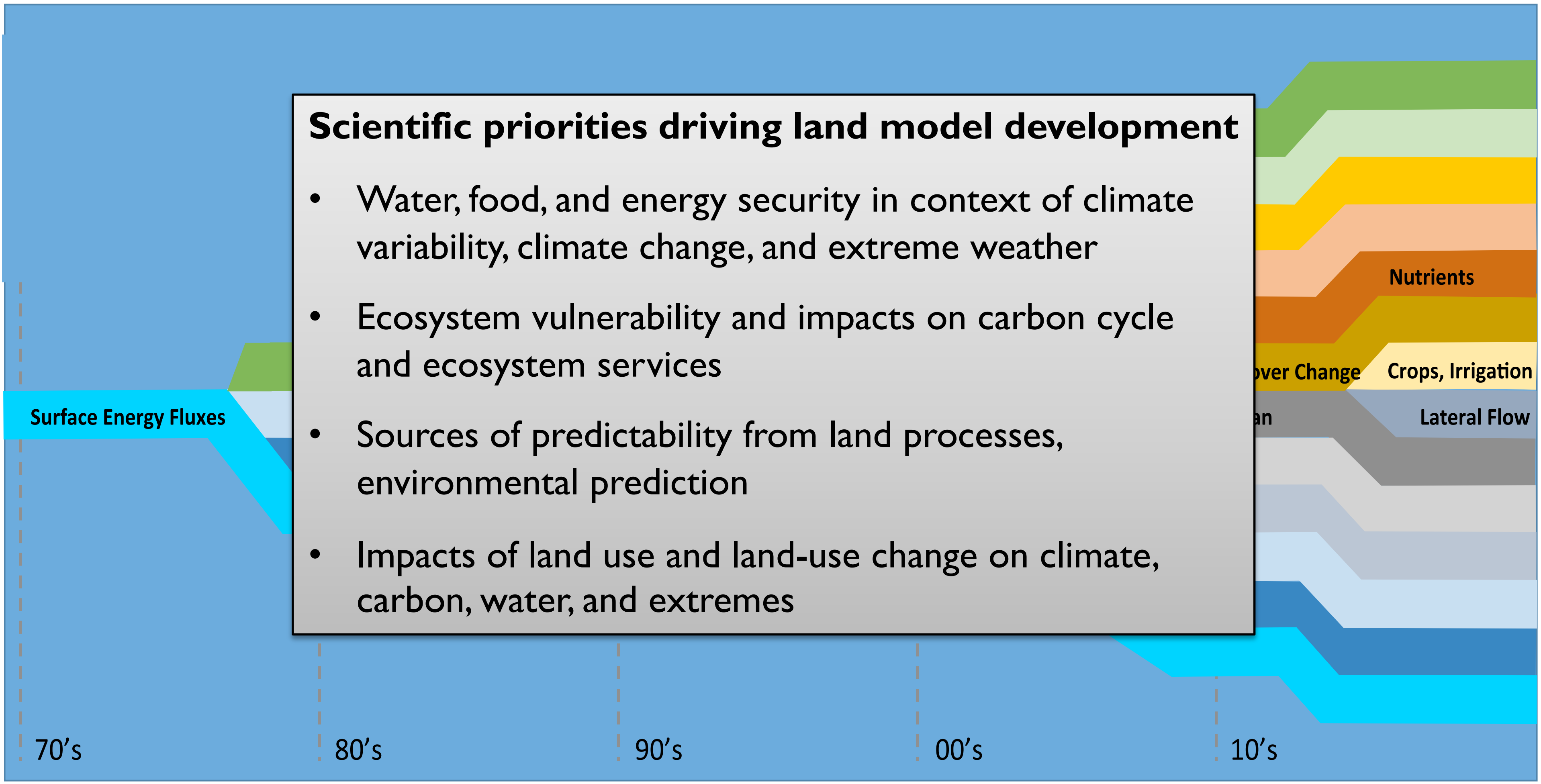
- Vertically-
- Co-limitat
  of photosy
- Variable ri
- Natural C
- Human tri
  suppressic
- Cold regic
- Revised la
- Multiple u
  classes

CLM5 (Feb 2018)

- Flexible leaf stoichiometry, leaf N optimize for photosynthesis
- Carbon costs for plant N uptake
- Plant hydraulics w/ hydraulic redistribution, *Ecosystem demography (FATES), ozone damage*
- Spatially explicit soil depth (0.4 – 8.5m), dry surface layer, revised GW, canopy interception, *representative hillslopes*
- MOSART river model (hillslope → tributary → main channel)
- Canopy snow, snow dens (T, wind), simple firn model
- Global crop model (8 crop types), transient irrigation and fertilization, *shifting cultivation*
- Dynamic landunits (nat veg ←→ crop, *glacier ←→ nat veg*,)
- Urban heating and AC, heat stress indices
- Carbon isotopes
- *Coupled fire trace gas emissions*

The interdisciplinary evolution of land models

Land as a lower boundary to the atmosphere → **Land as an integral component of the Earth System**



Scientific priorities driving land model development

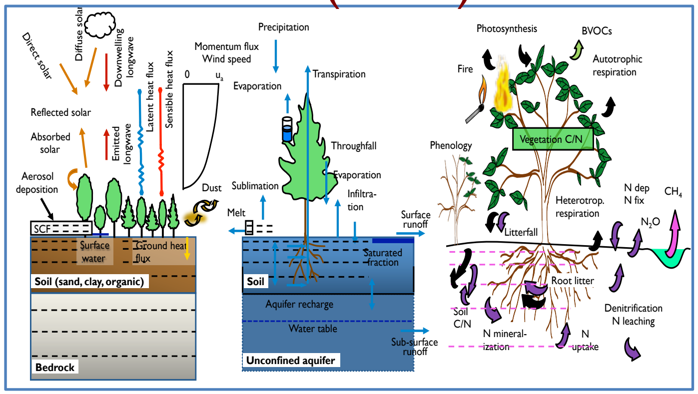
- Water, food, and energy security in context of climate variability, climate change, and extreme weather
- Ecosystem vulnerability and impacts on carbon cycle and ecosystem services
- Sources of predictability from land processes, environmental prediction
- Impacts of land use and land-use change on climate, carbon, water, and extremes

Figure: Fisher, Lawrence, Bonan, Clark, unpublished

The Community Terrestrial System Model

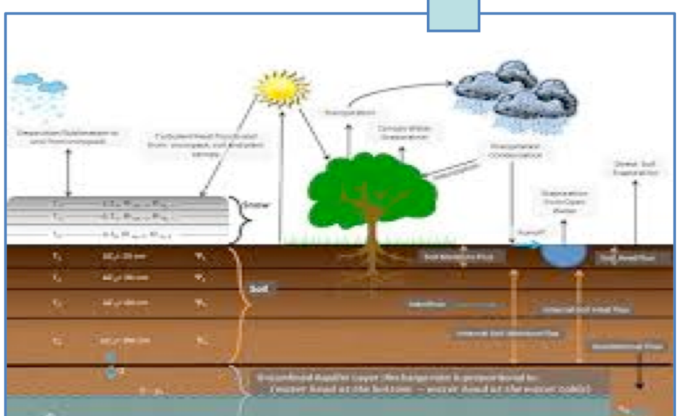
a unified model for research and prediction in climate, weather, water, and ecosystems

CLM (CGD)



SUMMA concepts

CTSM

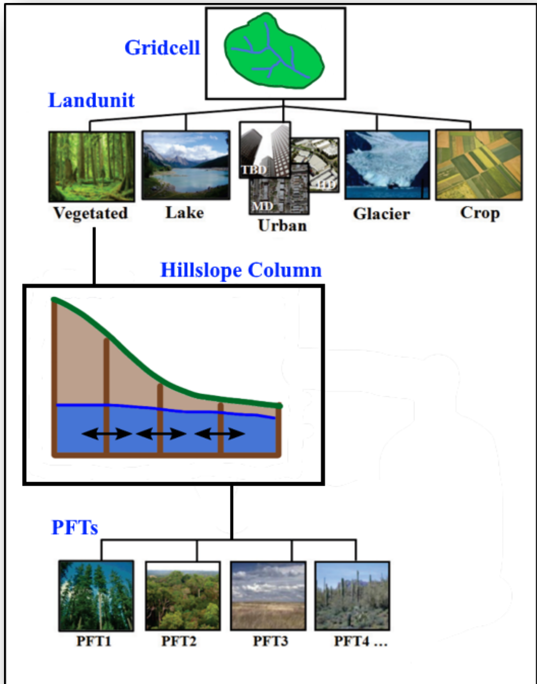


Noah-MP, WRF-Hydro (RAL)

- **CTSM (unification) benefits:**
  - extend NCAR leadership in community modeling
  - reverse trends of model proliferation and shantytown syndrome
  - more efficient use of NCAR and community model development resources
  - integrate and expand land modeling research
  - accelerate advances, improve science through multiple hypothesis testing

- **CTSM software improvement goals:**
  - reduce accumulated technical debt
  - clean separation of flux parameterizations and numerical solution
  - modularity; alternative hypotheses
  - hierarchy of complexity (climate, NWP, water, and ecology applications)
  - flexibility of spatial disaggregation

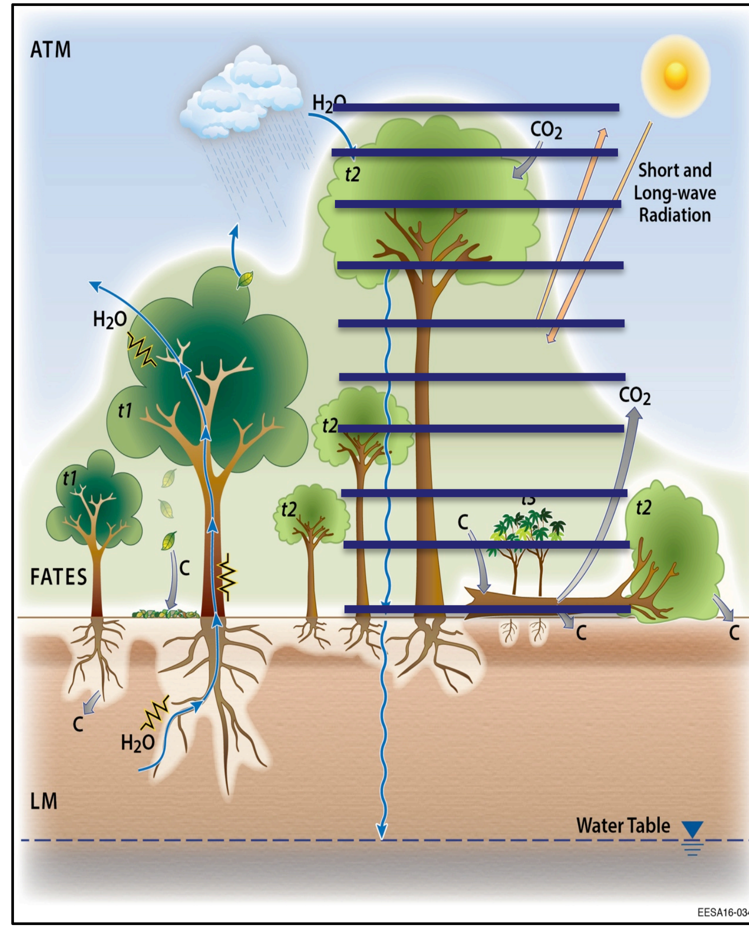
CTSM will help pave wave way for next-generation land model



Lateral fluxes of water

Water and land management

Ecosystem Demography (FATES)
Multi-layer canopy



Where to find information about CLM/CTSM

www.cesm.ucar.edu/models/cesm2/land

CLM5 Documentation

Introduction

CLM5.0 is the latest in a series of land models developed through the CESM project. More information on the CLM project and access to previous released CLM model versions and documentation can be found via the CLM Web Page. Note that CLM4.5 biogeophysics and biogeochemistry can be run from this release code. A new river model (MOSART) is also included. *This release is a land-only release*. The capability to run CLM5.0 within CESM2.0 will be included in the CESM2.0 release.

The Functionally Assembled Terrestrial Ecosystem Simulator [FATES] is available within the CLM5 release as a research option.

Access

- CLM5.0 is publicly available through the Community Terrestrial System Model (CTSM) git repository
- Download the code by executing the following commands:

```
$ git clone -b release-clm5.0 https://github.com/ESCOMP/ctsm.git clm5.0
$ cd clm5.0
$ ./manage_externals/checkout_externals
```

Documentation

- CLM5.0 Technical Description [HTML] [PDF]
- What's new in CLM5.0 Description [Text] [Image]
- CLM5.0 User's Guide
- CESM2.0 Quickstart Guide *Note that same script commands used for CLM land-only

CESM Project

CESM is a fully-coupled, community, global climate model that provides state-of-the-art computer simulations of the Earth's past, present, and future climate states.

CESM is sponsored by the National Science Foundation (NSF) and the U.S. Department of Energy (DOE). Administration of the CESM is maintained by the Climate and Global Dynamics Laboratory (CGD) at the National Center for Atmospheric Research (NCAR).

CESM2 Quicklinks

Quick Start Guide

Downloading The Code

Scientifically Validated Configurations

› Prognostic Components

CESM Software Engineering

Related Information

Data Management & Distribution Plan

Development Project Policies & Terms of Use

Tutorials

- CLM/CTSM Tutorial Announcement (2019)
- FATES Tutorial (Feb, 2018)
- CLM Tutorial (Sept, 2016)

Model Design and Development

All future CLM development will occur within the framework of **CTSM**. CLM will be an instantiation of CTSM.

- Development Guide

  CTSM development guidelines, workflow, and coding standards provided at CTSM github wiki page

Model output and diagnostic plots

- CLM5.0, CLM4.5, and CLM4.0 land-only control simulations are published on the Earth System Grid at: CLM Simulations on the ESG (http://doi.org/10.5065/d6154fwh)

  *PFT-level, daily, and hourly data available for selected fields and simulations
- CLM Diagnostic package plots
- ILAMB package plots
- CESM Postprocessing Tool: Quick Start, User's Guide, and Workflow

References

Bibliography of papers utilizing and/or developing CLM * Last update: Feb/15/2018

CLM5

Lawrence, D.M. R.A. Fisher, C.D. Koven, K.W. Oleson, S.C. Swenson, G. Bonan, N. Collier, B. Ghimire, L. van Kampenhout, D. Kennedy, E. Kluzek, P.J. Lawrence, F. Li, H. Li, D. Lombardozzi, W.J. Riley, W.J. Sacks, M. Shi, M. Vertenstein, W.R. Wieder,, C. Xu, A.A. Ali, A.M. Badger, G. Bisht, M.A. Brunke, S.P. Burns,, J. Buzan, M. Clark, A. Craig, K. Dahlin, B. Drewniak, J.B. Fisher, M. Flanner, A.M. Fox, P. Gentine, F.Hoffman, G. Keppel-Aleks, R., Knox, S. Kumar, J. Lenaerts, L.R. Leung, W.H. Lipscomb, Y. Lu, A., Pandey, J.D. Pelletier, J. Perket,, J.T. Randerson, D.M. Ricciuto, B.M., Sanderson, A. Slater, Z.M. Subin, J. Tang, R.Q. Thomas, M. Val Martin, and X. Zeng, 2018: The Community Land Model version 5: Description of new features, benchmarking, and impact of forcing uncertainty. *Submitted to J. Adv. Model. Earth Syst.*

github.com/ESCOMP/ctsm

ESCOMP / ctsm

Unwatch 25 | Unstar 58 | Fork 69

Code | Issues 314 | Pull requests 14 | Projects 8 | Wiki | Insights

Community Terrestrial Systems Model (includes the Community Land Model of CESM) http://www.cesm.ucar.edu/models/cesm2...

land model climate hydrology ecosystem ncar cesm clm

1,633 commits | 7 branches | 573 releases | 1 environment | 18 contributors | View license

Branch: master | New pull request | Create new file | Upload files | Find file | Clone or download

billsacks Merge branch 'minor_fixes' ... Latest commit f1c4d8f 9 days ago

.github	Add a note about what's expected for the bug summary	6 months ago
bld	Remove some more clm4-specific things	25 days ago
cime_config	Output cpl hist files in SSP test	14 days ago
doc	Update ChangeLog	9 days ago

README.rst

CTSM

The Community Terrestrial Systems Model.

This includes the Community Land Model (CLM5.0 and CLM4.5) of the Community Earth System Model.

For documentation, quick start, diagnostics, model output and references, see

http://www.cesm.ucar.edu/models/cesm2.0/land/

and

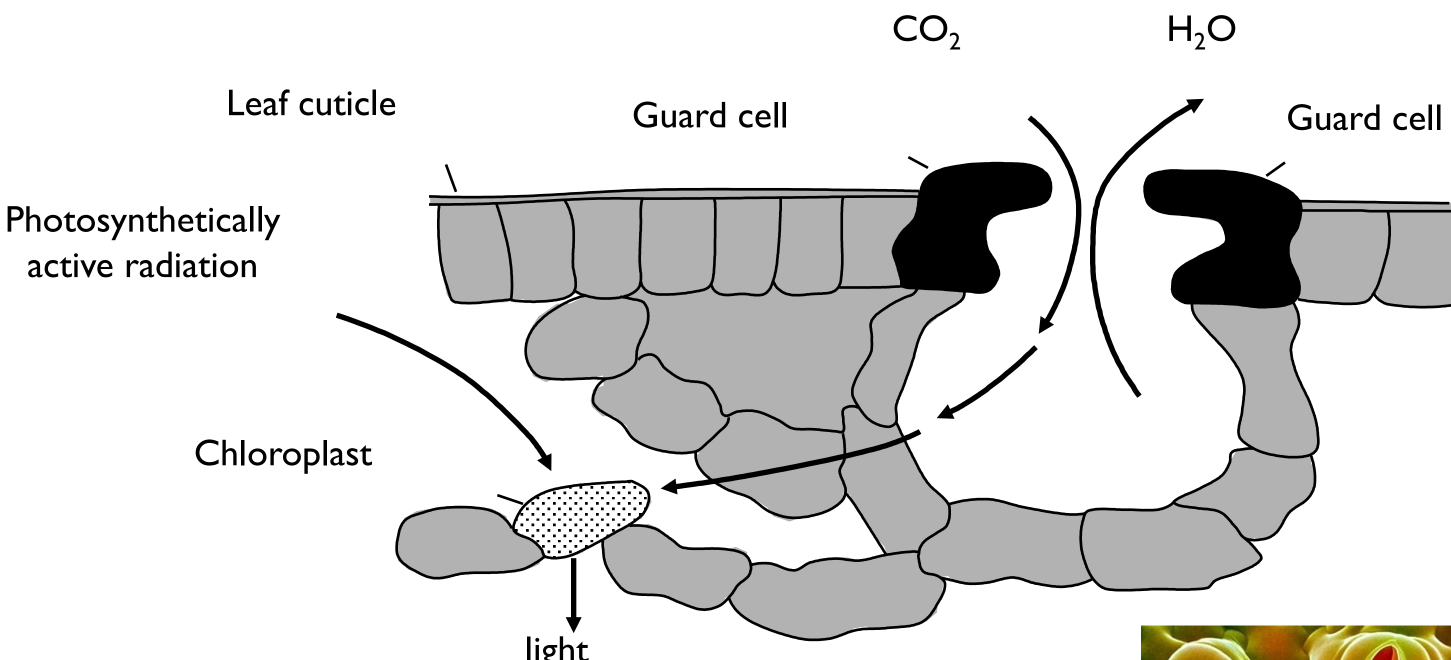
Welcome to the CTSM/CESM research community!

Questions?

Photosynthesis model

Plant physiological controls on CO_2 exchange and transpiration

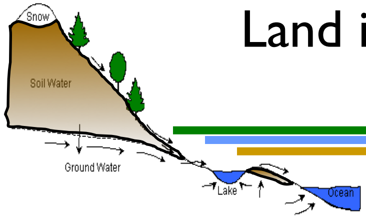
Function of solar radiation, humidity deficit, soil moisture, [CO2], temperature, leaf N content



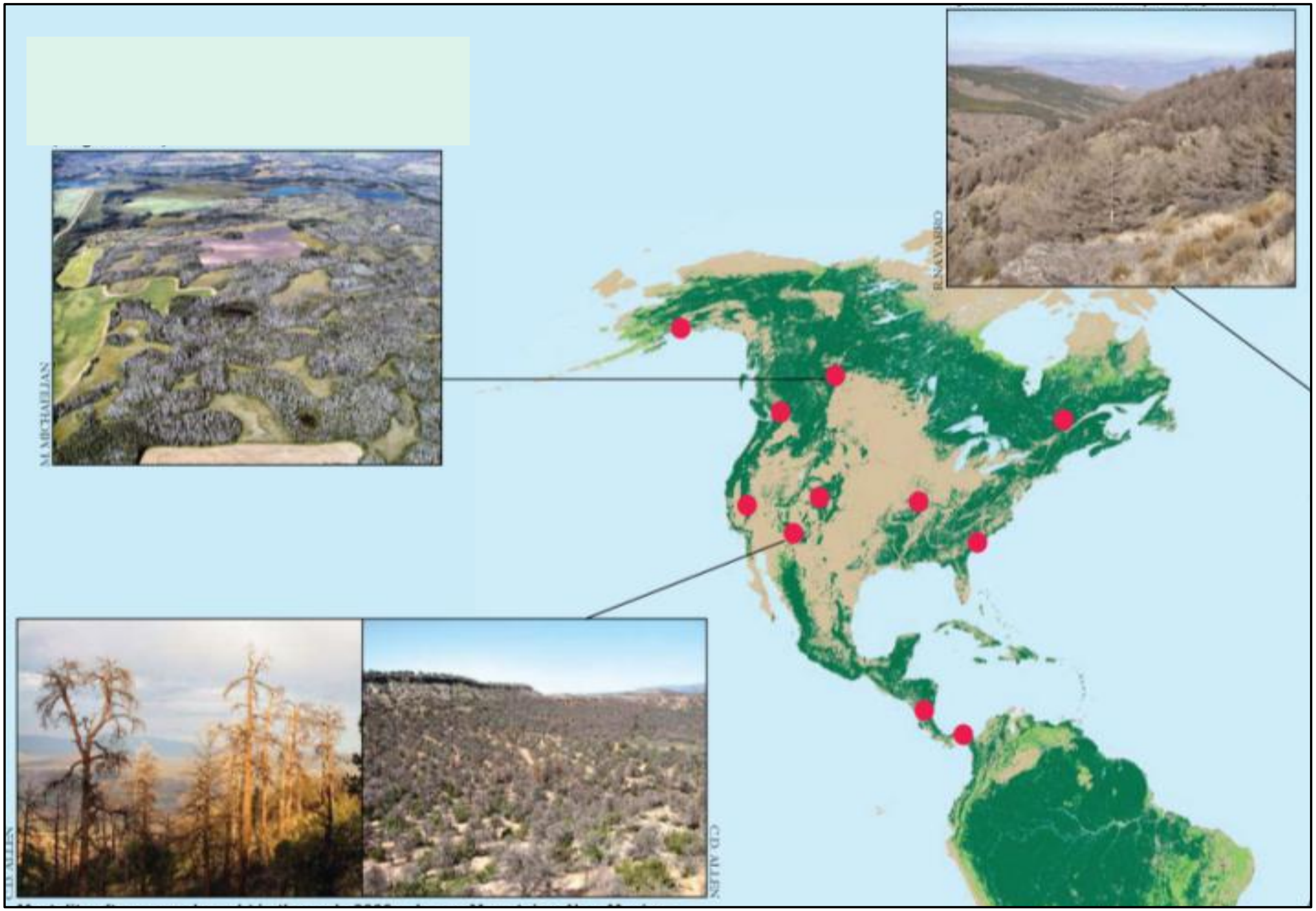
$$CO_2 + 2\,H_2O \rightarrow CH_2O + O_2 + H_2O$$

Figure courtesy G. Bonan

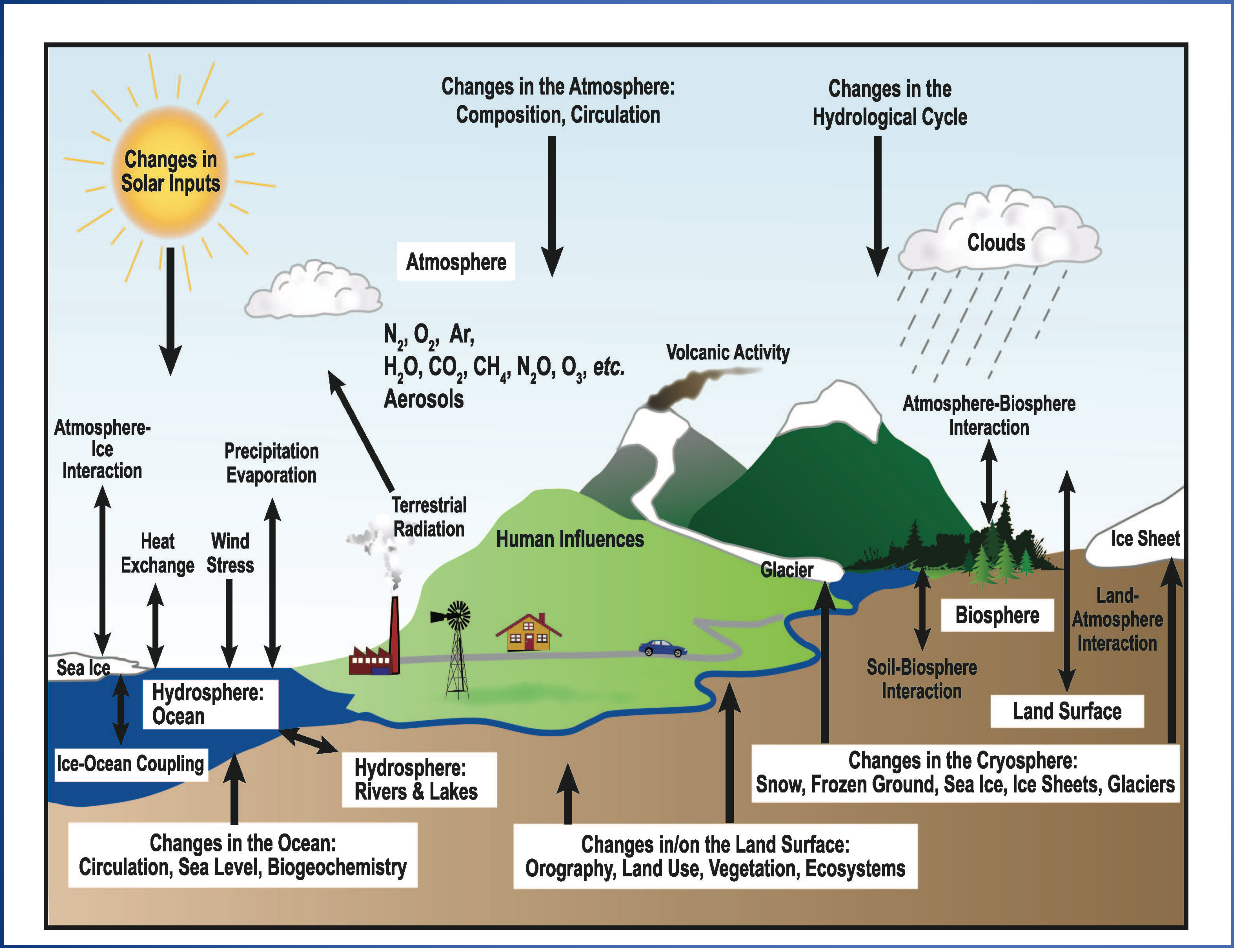
Bonan (1995) JGR 100:2817-2831
Denning et al. (1995) Nature 376:240-242
Denning et al. (1996) Tellus 48B:521-542, 543-567
Cox (1999)



Land in Earth System: But, trees (carbon sinks) are dying due to fire, drought, insects, and deforestation

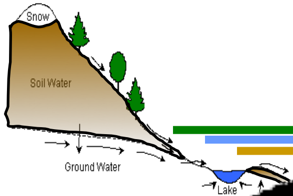


Earth System Models

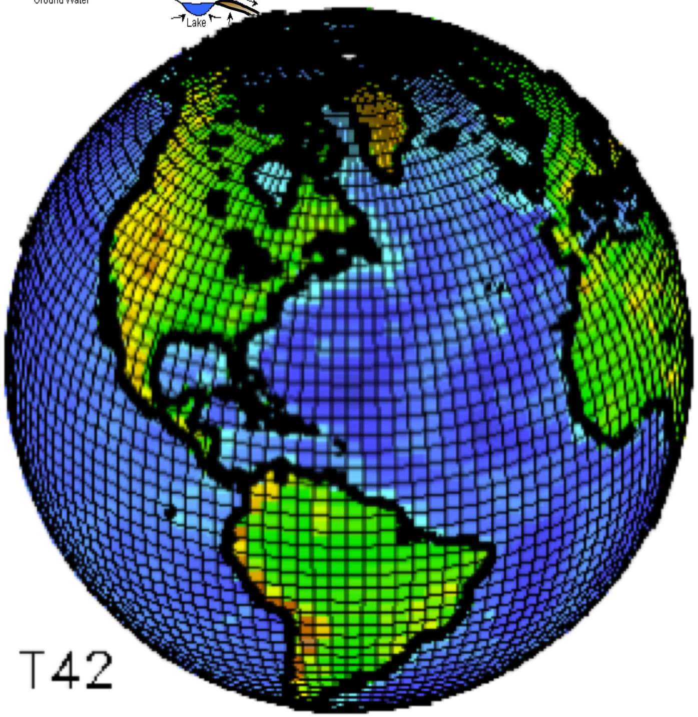


Earth System Models are utilized to support a vast and expanding array of scientific research into the climate system

- climate change feedbacks and attribution
- climate variability
- roles of clouds, aerosols, sea ice, ocean, land use, ozone, etc on climate
- climate change impacts on humans and ecosystems



Community Earth System Model (CESM2)



- 0.25°, 1° , 2°, and regionally-refined grids
- 30 minute time step
- 31 atmosphere levels
- 60 ocean levels
- 25 ground layers
- ~5 million grid boxes at 1° resolution
- ~2 million lines of computer code
- Data archived (monthly, daily, hourly) for hundreds of geophysical fields (over 450 in land model alone)
- Utilized by hundreds of scientists all around the world