Overview of the Community Land Model (and the Community Earth System Model)

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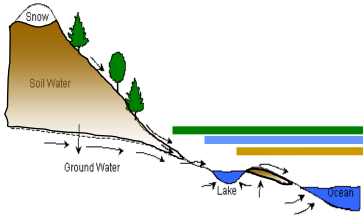
with input from members of LMWG and BGCWG

U.S. DEPARTMENT OF ENERGY

NSF

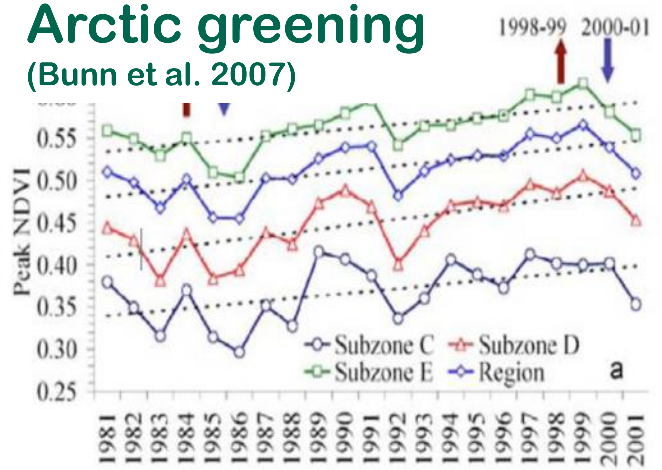
NESL

Terrestrial Processes within the Earth System

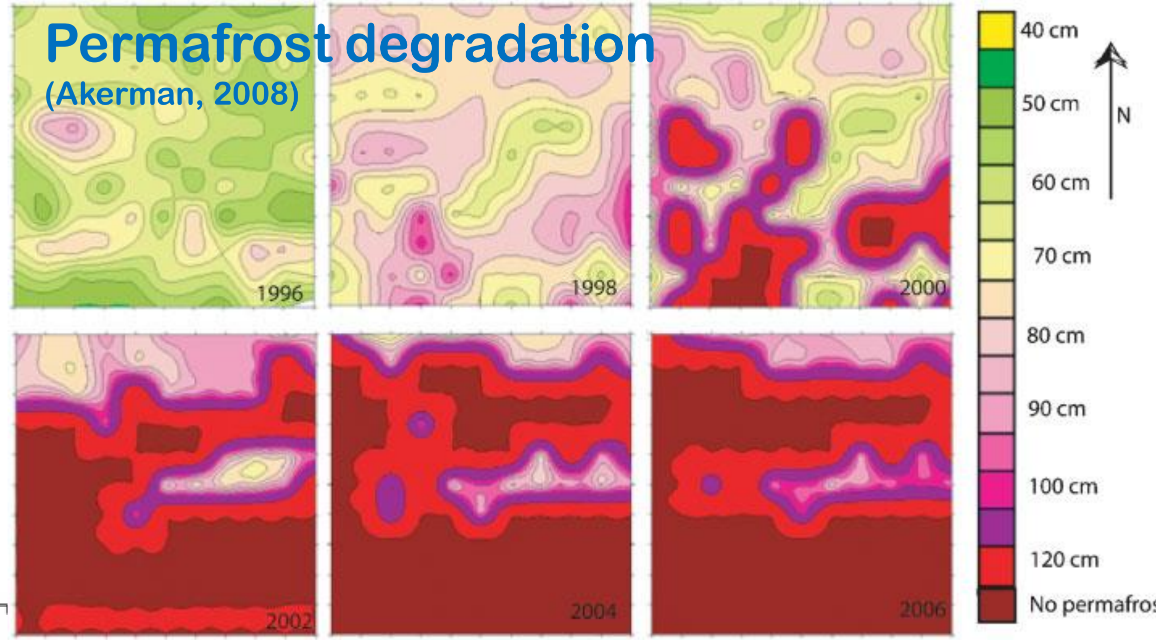


Observed terrestrial change

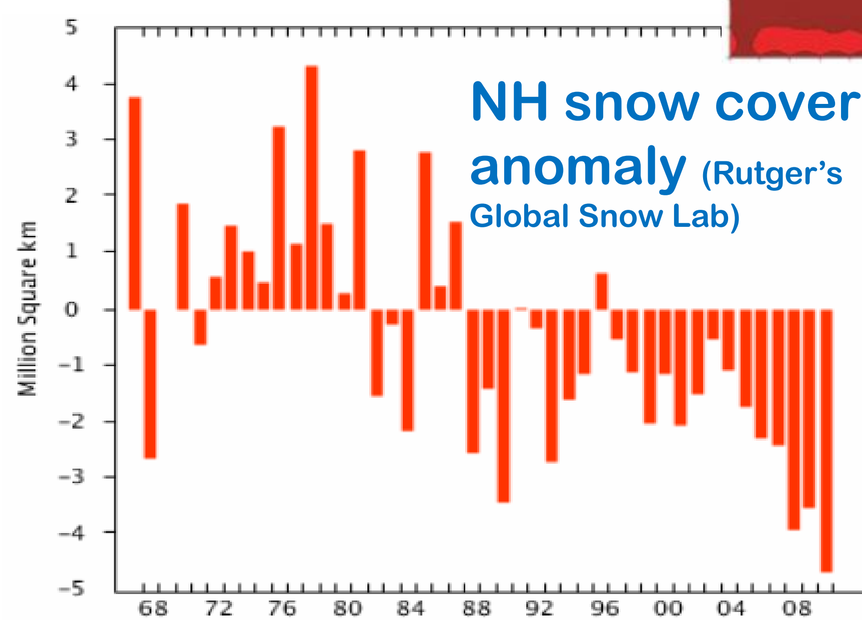
Arctic greening
(Bunn et al. 2007)



Permafrost degradation
(Akerman, 2008)



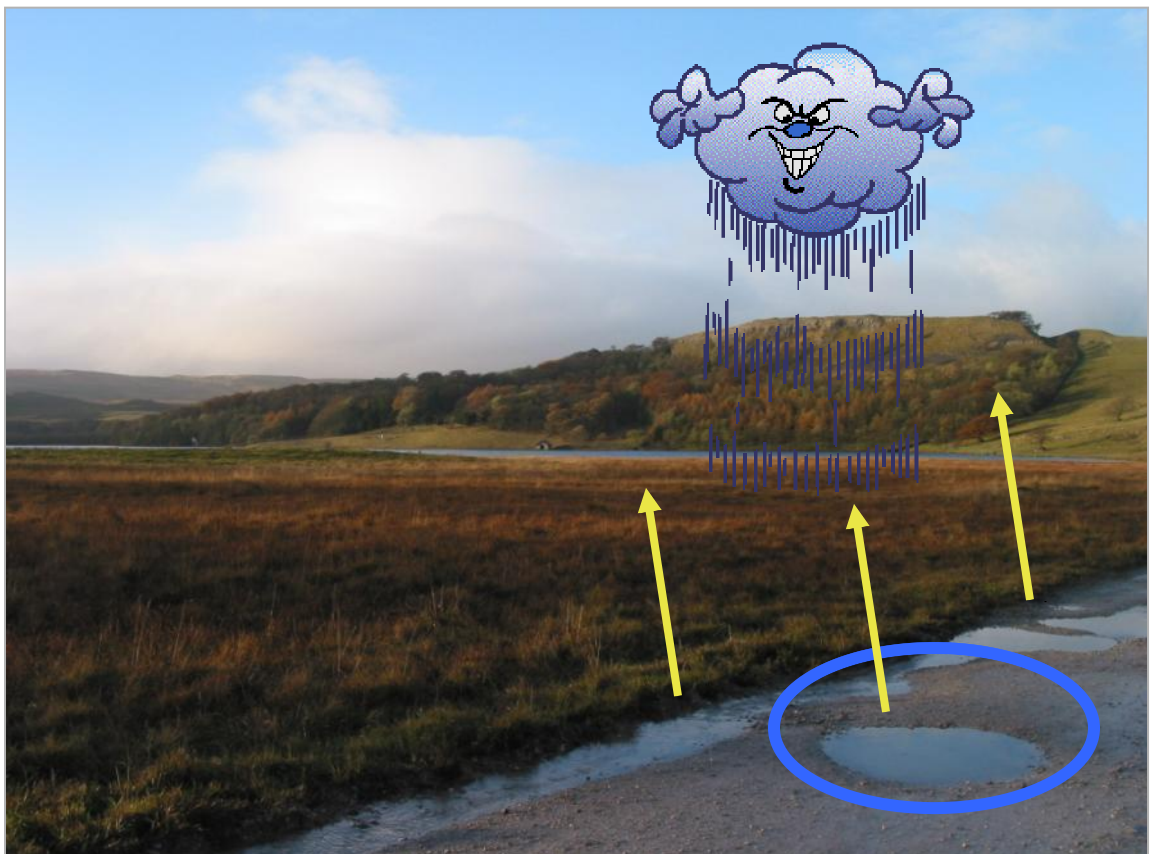
NH snow cover anomaly
(Rutger's Global Snow Lab)

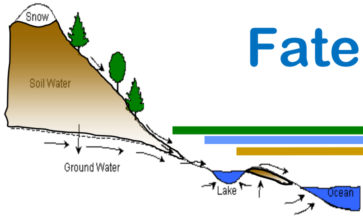


Deforestation

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?





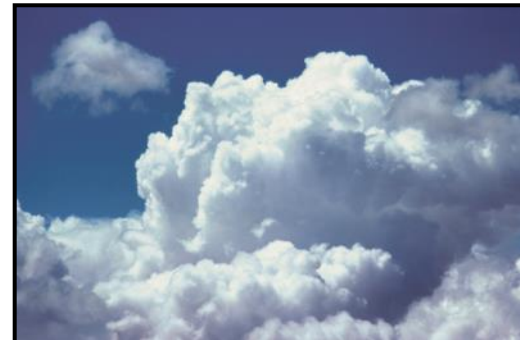
Fate of anthropogenic CO_2 emissions (2002-2011 average)

8.3±0.4 PgC/yr 90%

1.0±0.5 PgC/yr 10%

+

4.3±0.1 PgC/yr
46%



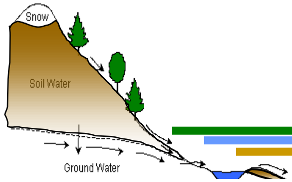
2.6±0.8 PgC/yr
28%
Calculated as the residual
of all other flux components

26%
2.5±0.5 PgC/yr

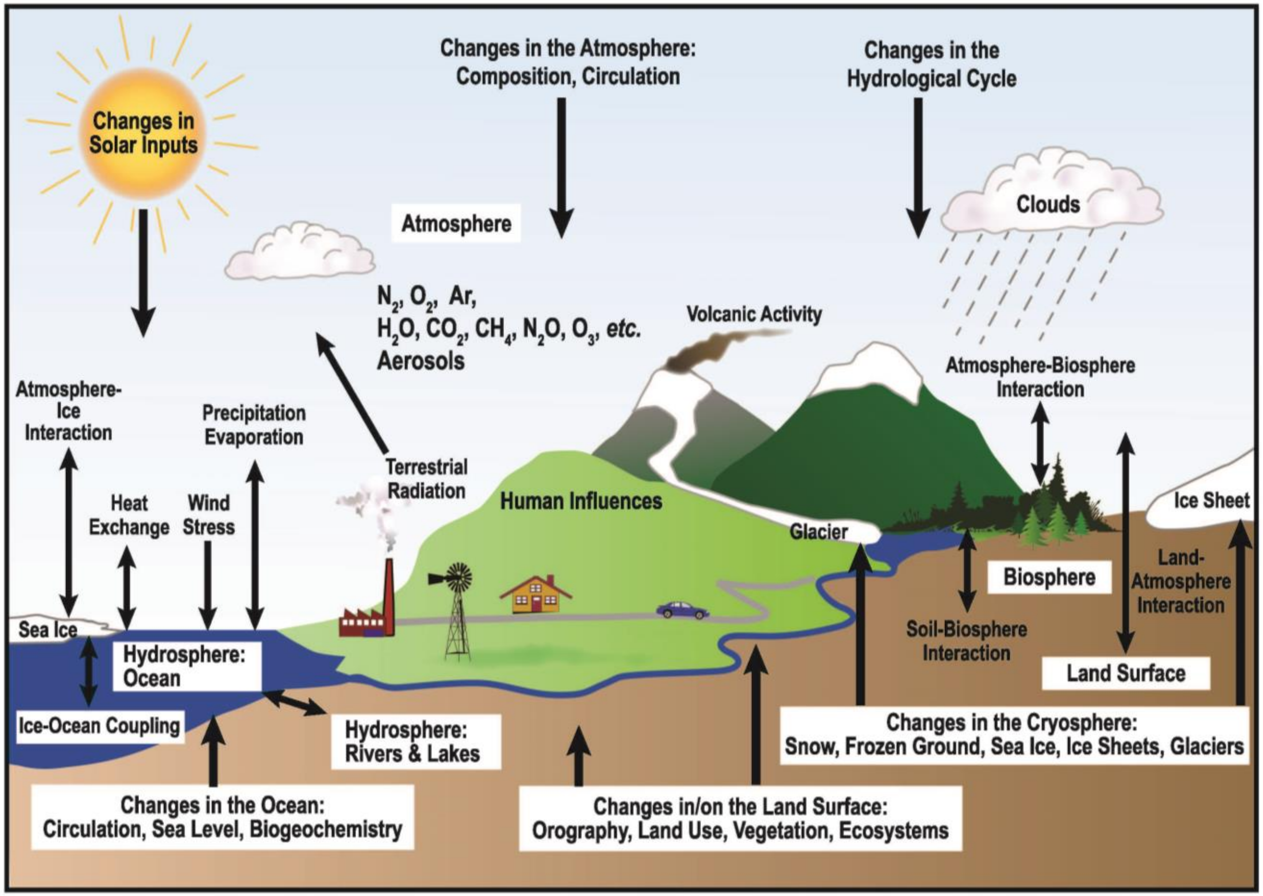
Source: Le Quéré et al. 2012; Global Carbon Project 2012

Earth System Models

Community Earth System Model (CESM)



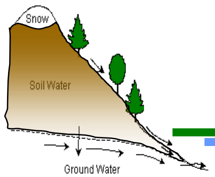
Earth System Model



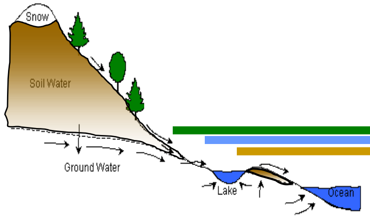
Earth System Models are utilized to support a vast and expanding array of scientific research into the climate system

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

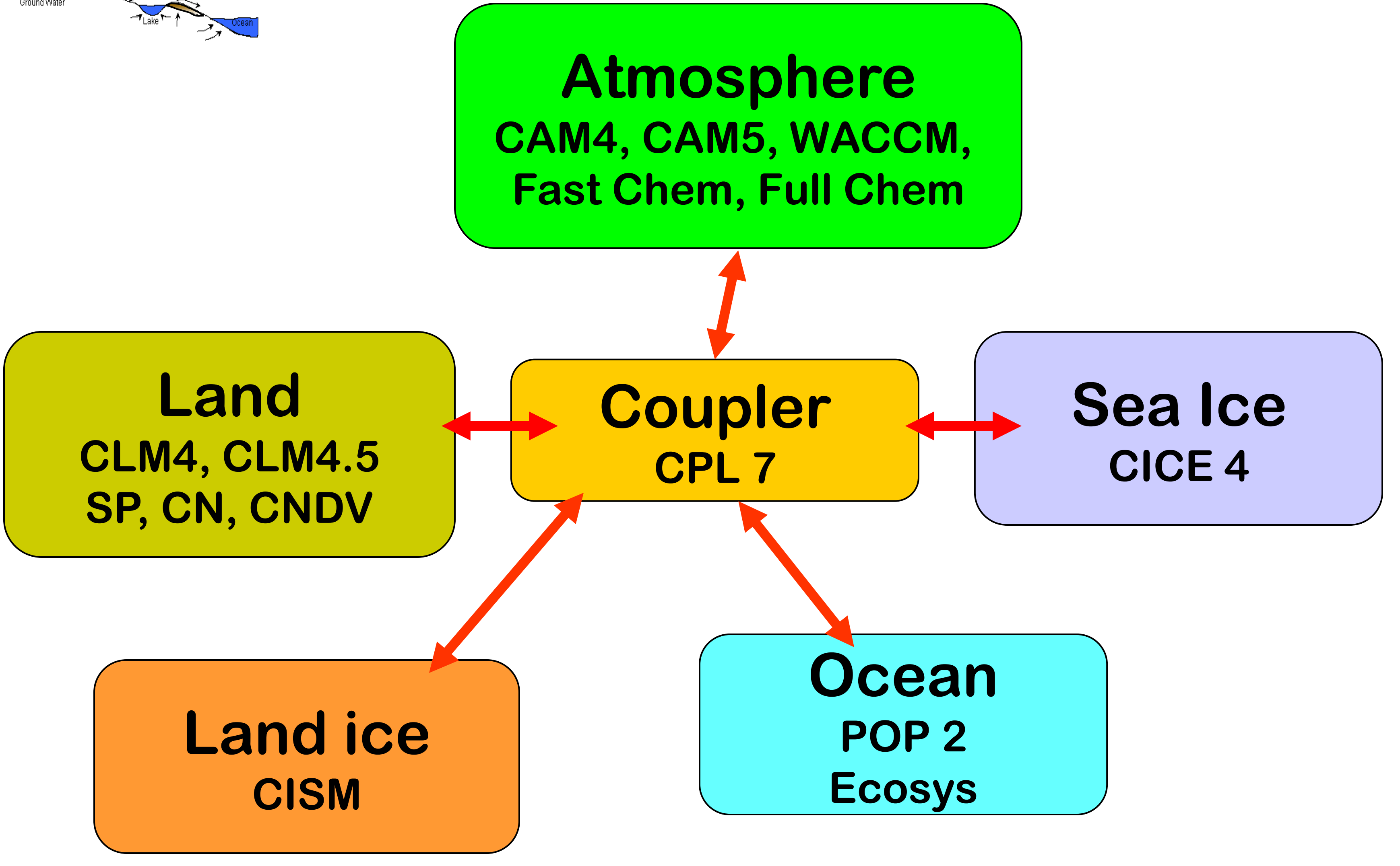
History of Climate Model to Earth System Model Development
http://www.aip.org/history/climate/GCM.htm

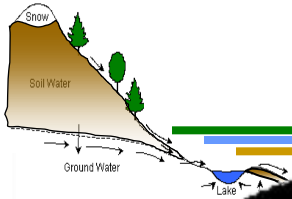


Mid-1960s	Mid 1970s-1980s	1990s	2000s	2010s
Atmosphere/ Land Surface	Atmosphere/ Land Surface/ Vegetation	Atmosphere/ Land Surface/ Vegetation	Atmosphere/ Land Surface/ Vegetation	Atmosphere/ Land Surface/ Vegetation
Ocean	Ocean	Ocean	Ocean	Ocean
	Sea Ice	Sea Ice	Sea Ice	Sea Ice
	Coupled Climate Model	Coupled Climate Model	Coupled Climate Model	Coupled Climate Model
		Sulfate Aerosol	Sulfate Aerosol	Sulfate Aerosol
		Carbon Cycle	Carbon Cycle	Carbon Cycle
			Dust/Sea Spray/Carbon Aerosols	Dust/Sea Spray/Carbon Aerosols
			Interactive Vegetation	Interactive Vegetation
			Biogeochemical Cycles	Biogeochemical Cycles
				Ice Sheet

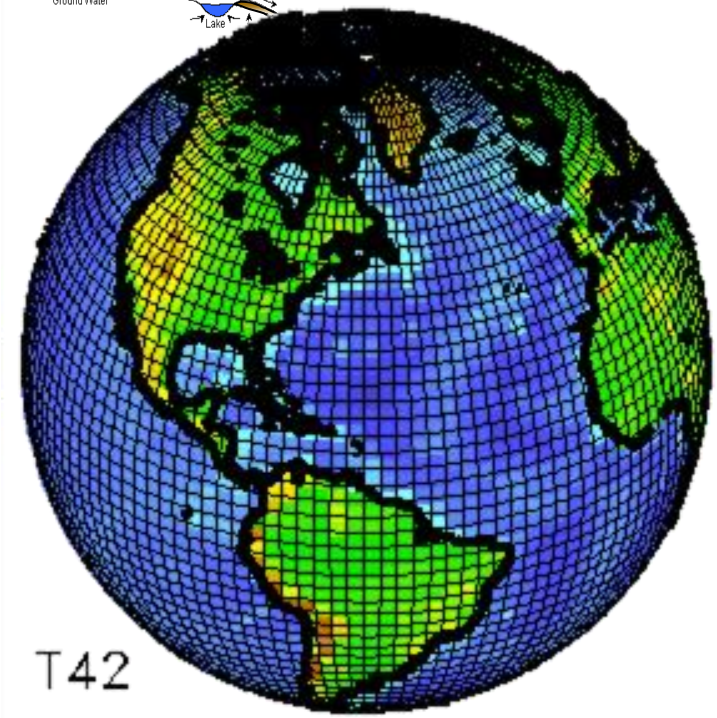


Community Earth System Model
Coupled modeling framework



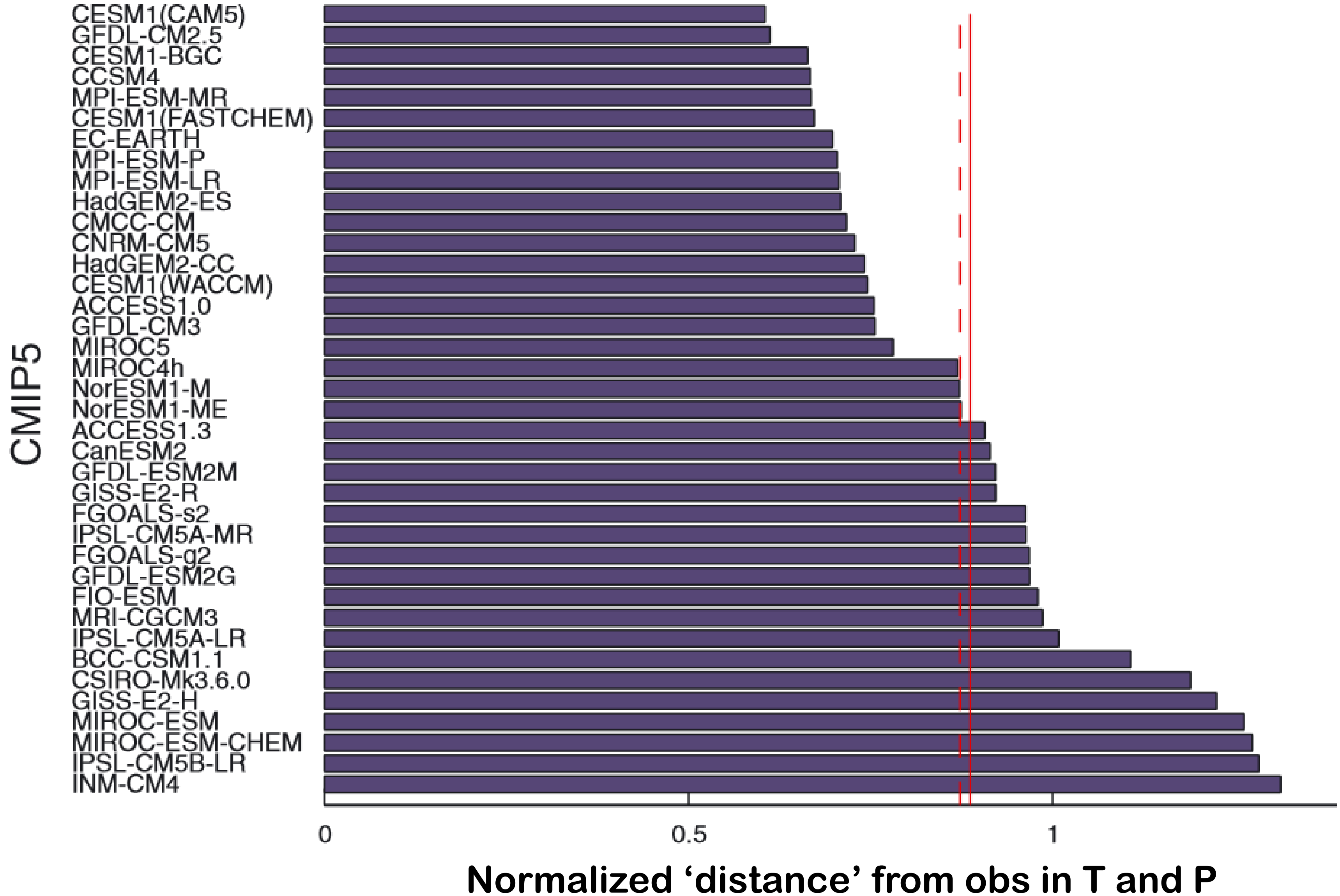


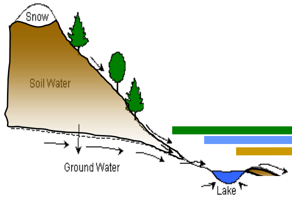
Community Earth System Model (CESM1)



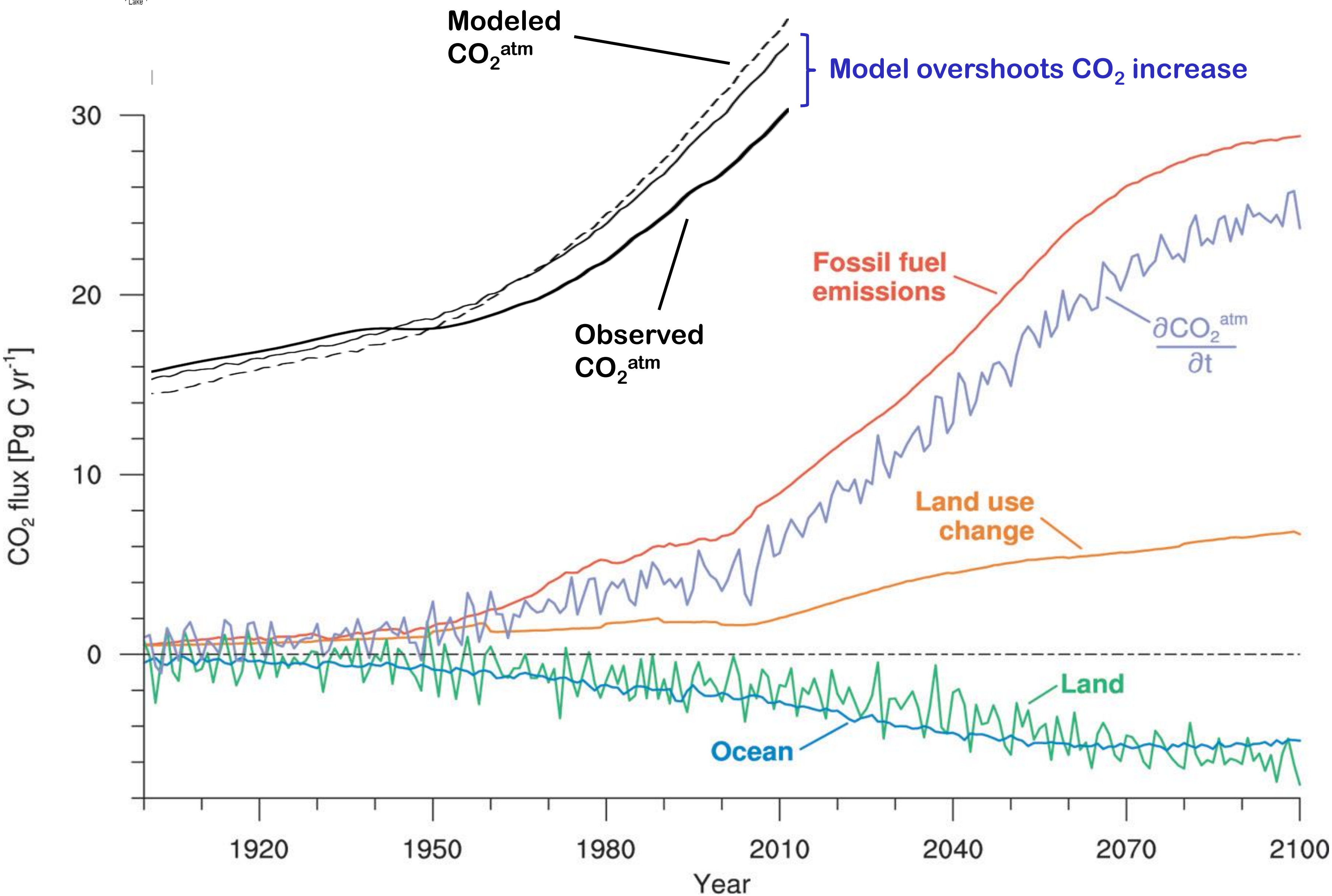
- 0.25°, 0.5°, 1° , 2° resolutions
- 30 minute time step
- 26 atmosphere levels
- 60 ocean levels
- 15 ground layers
- ~5 million grid boxes at 1° resolution
- ~1.5 million lines of computer code
- Data archived (monthly, daily, hourly) for hundreds of geophysical fields (over 400 in land model alone)
- Utilized by hundreds of scientists all around the world

CESM in Coupled Model Intercomparison Project (CMIP5)





Carbon cycle in CESM



Community Land Model

www.cesm.ucar.edu/models/lnd

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

Goals of CESM Land Model and Biogeochemistry Working Groups:

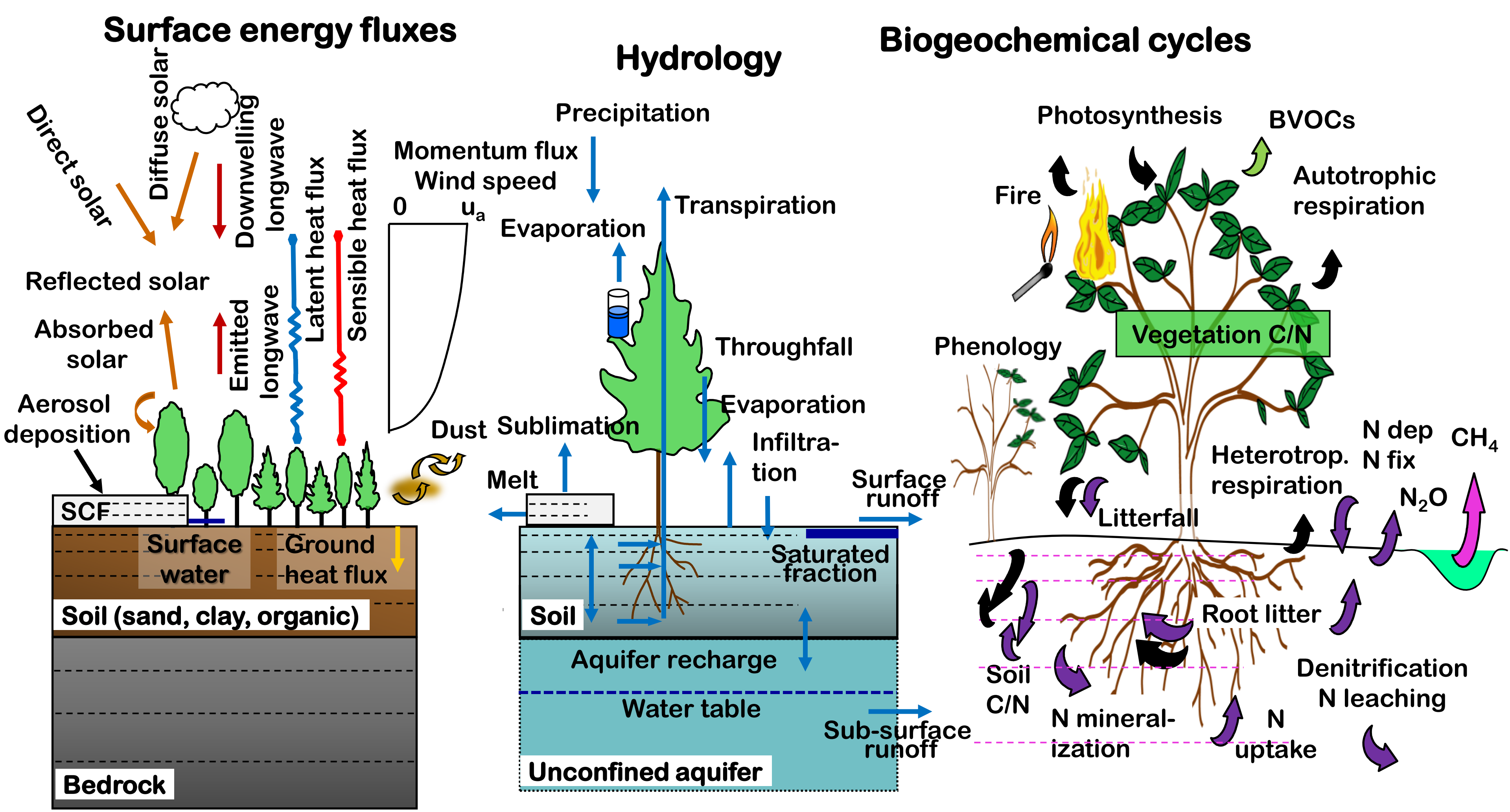
Improve and expand our capability to simulate ecological, hydrological, biogeochemical, and socioeconomic forcings and feedbacks in the earth system

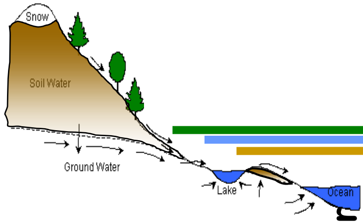
Submodels of CLM

- Biogeophysics
  - Photosynthesis and stomatal resistance
  - Hydrology
  - Snow
  - Soil thermodynamics
  - Surface albedo and radiative fluxes
- Biogeochemistry
  - Carbon / nitrogen pools, allocation, respiration
  - Vegetation phenology
  - Decomposition
  - Plant Morality
  - External nitrogen cycle
  - Methane production

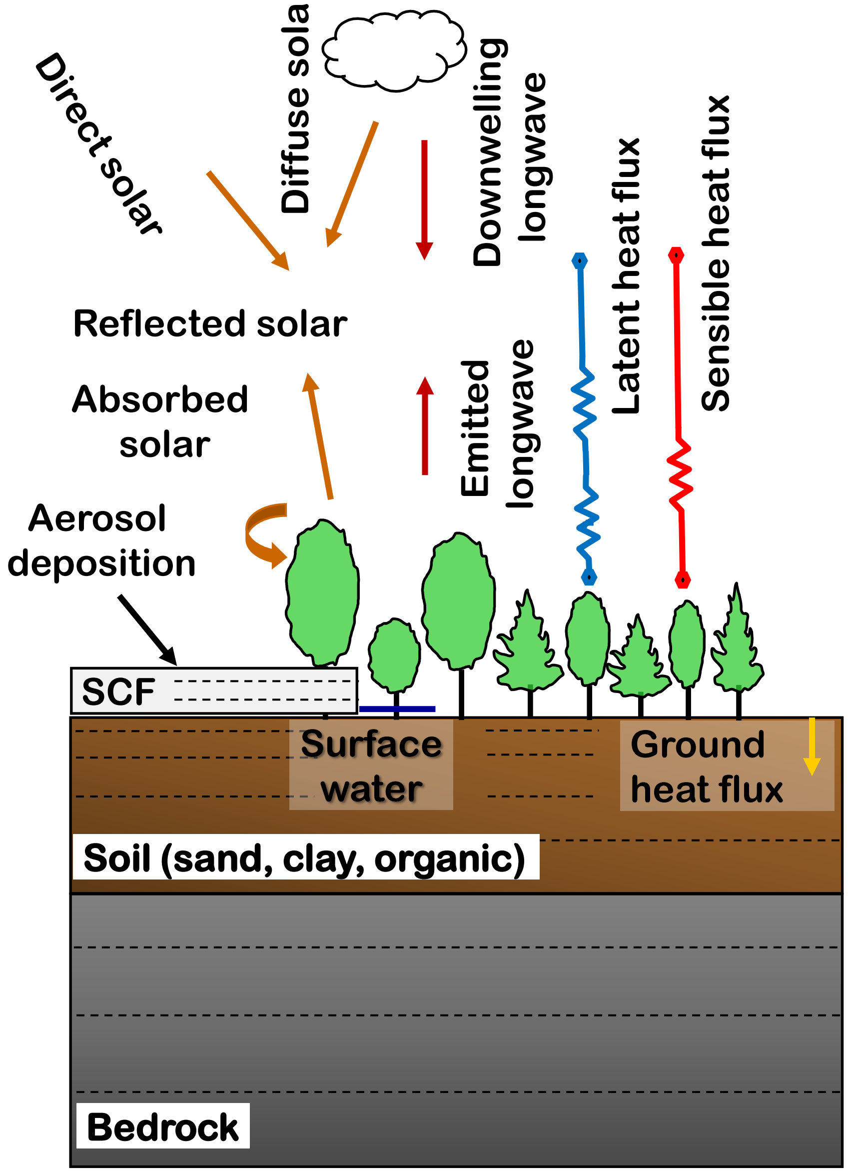
- Urban model
- Crop and irrigation model
- Lake model
- Glacier model
- Fire model
- Dust emissions model
- River model
- Biogenic Volatile Organic Compounds model

Community Land Model (CLM4.5)





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,

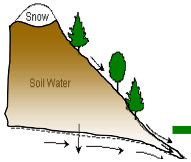
$L^{\uparrow}$, $L^{\downarrow}$ are up(down)welling longwave rad,

λ is latent heat of vaporization,

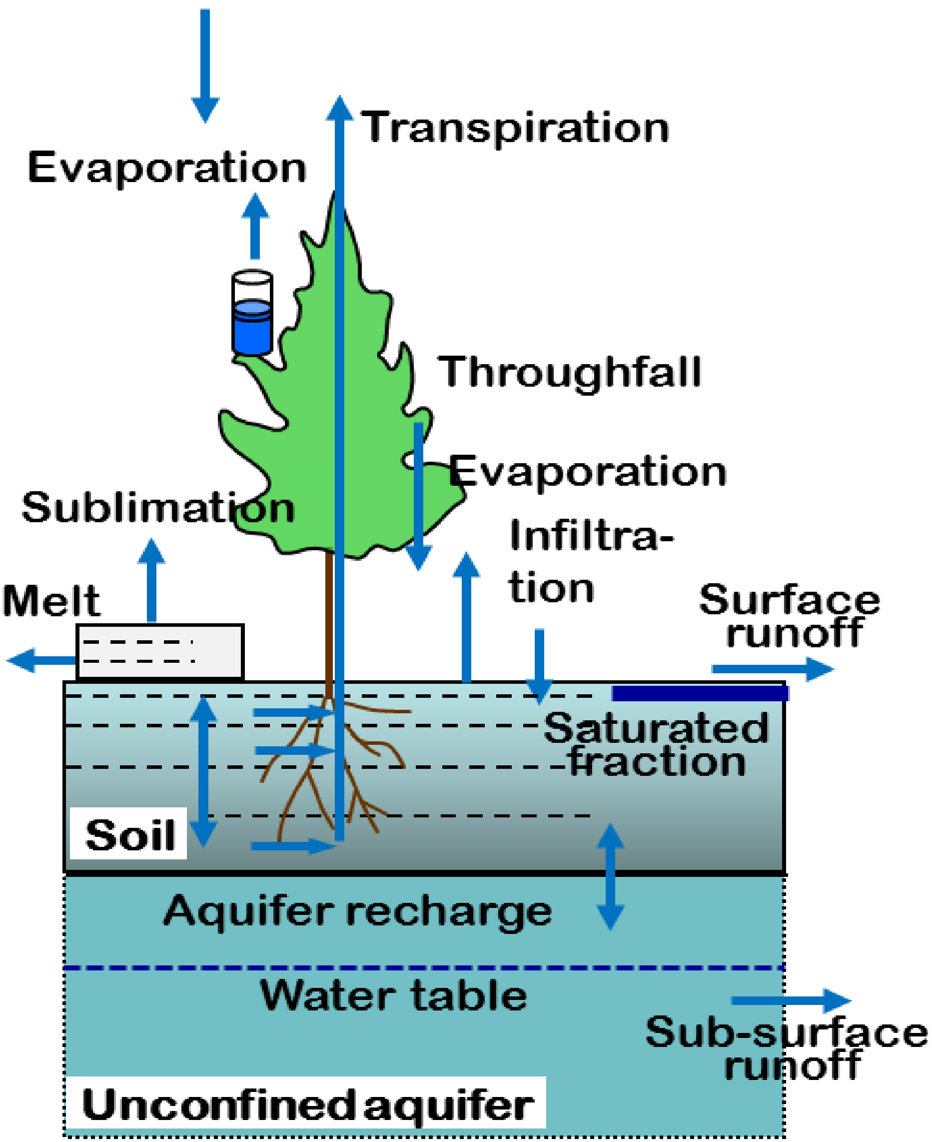
E is evaporation,

H is sensible heat flux

G is ground heat flux

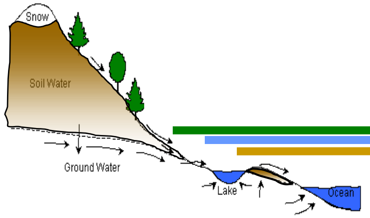


Surface water balance



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

- P is rainfall/snowfall,
- E_S is soil evaporation,
- E_T is transpiration,
- E_C is canopy evaporation,
- R is runoff (surf + sub-surface),
- $\Delta W_{soi} / \Delta t$, $\Delta W_{snw} / \Delta t$, $\Delta W_{can} / \Delta t$ are the changes in soil moisture, snow, and canopy water, water over a timestep

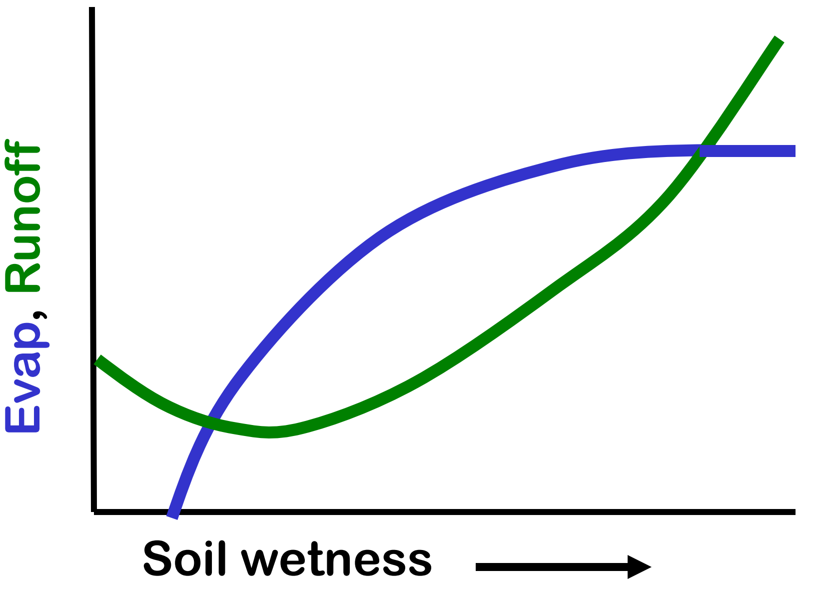


Modeling evaporation and runoff

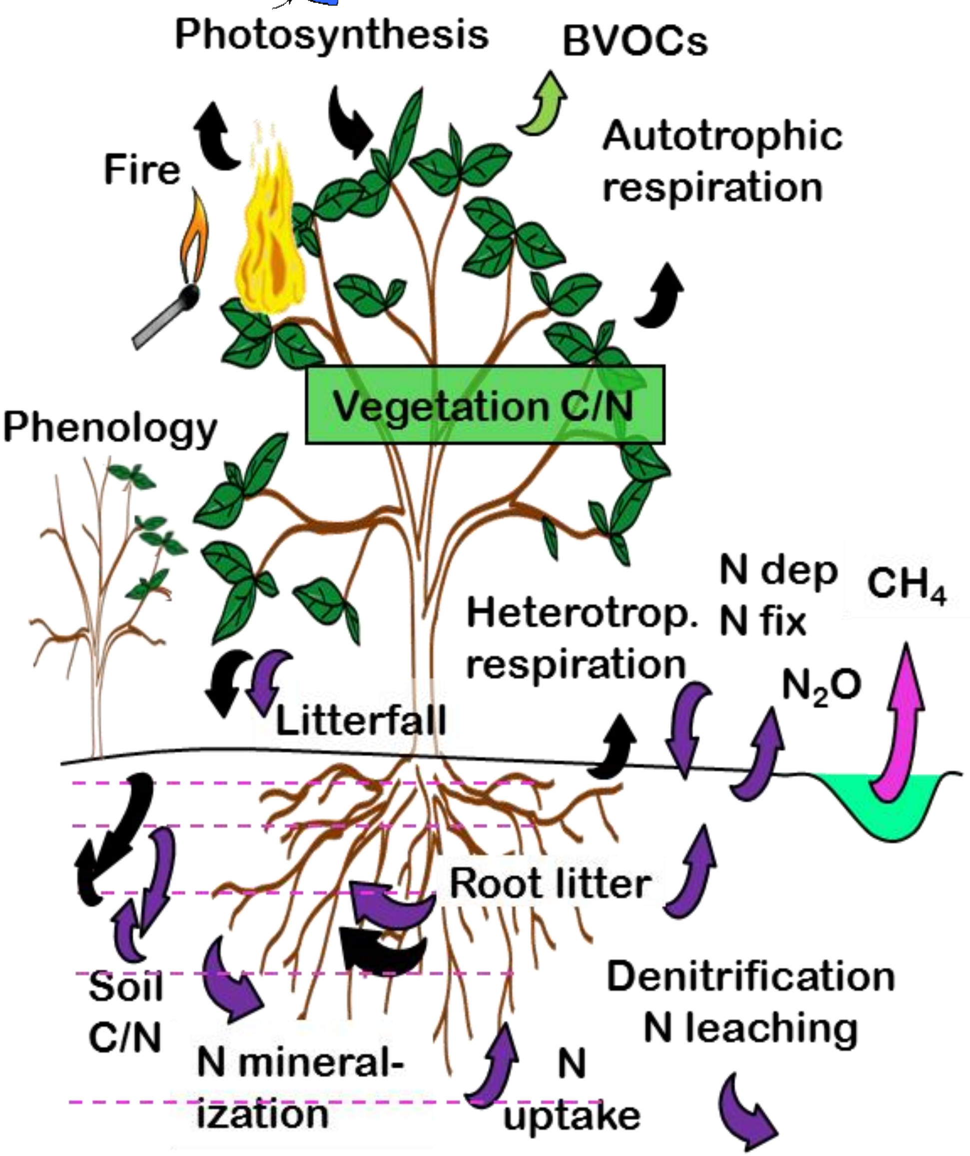
"The ability of a land-surface scheme to model evaporation correctly depends crucially on its ability to model runoff correctly. The two fluxes are intricately related."

(Koster and Milly, 1997).

Runoff and evaporation vary non-linearly with soil moisture



Carbon exchange



NEE = GPP – HR – AR – Fire – LUC

NEE is net ecosystem exchange

GPP is gross primary productivity

HR is heterotrophic respiration

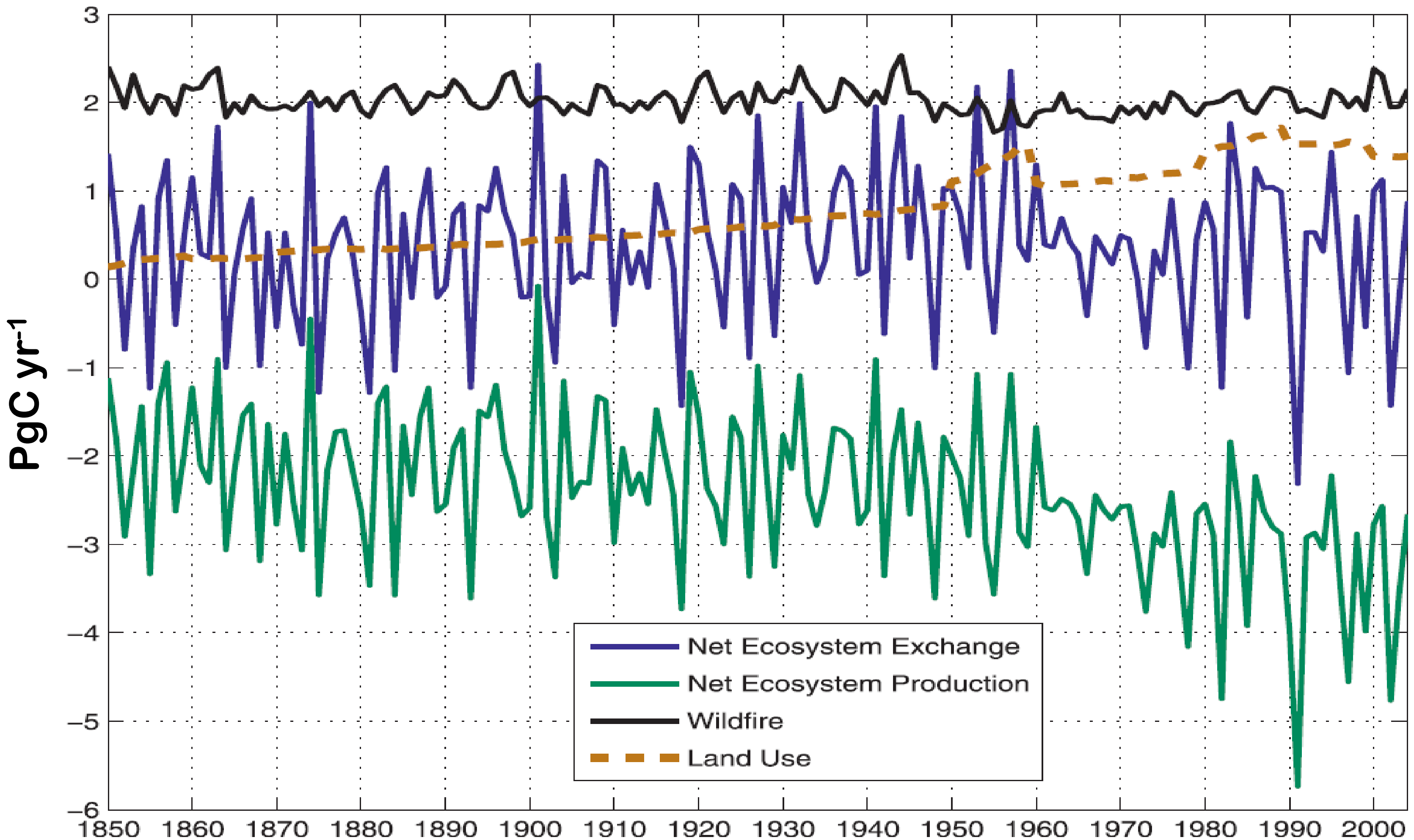
AR is autotrophic respiration

Fire is carbon flux due to fire

LUC is C flux due to land use change

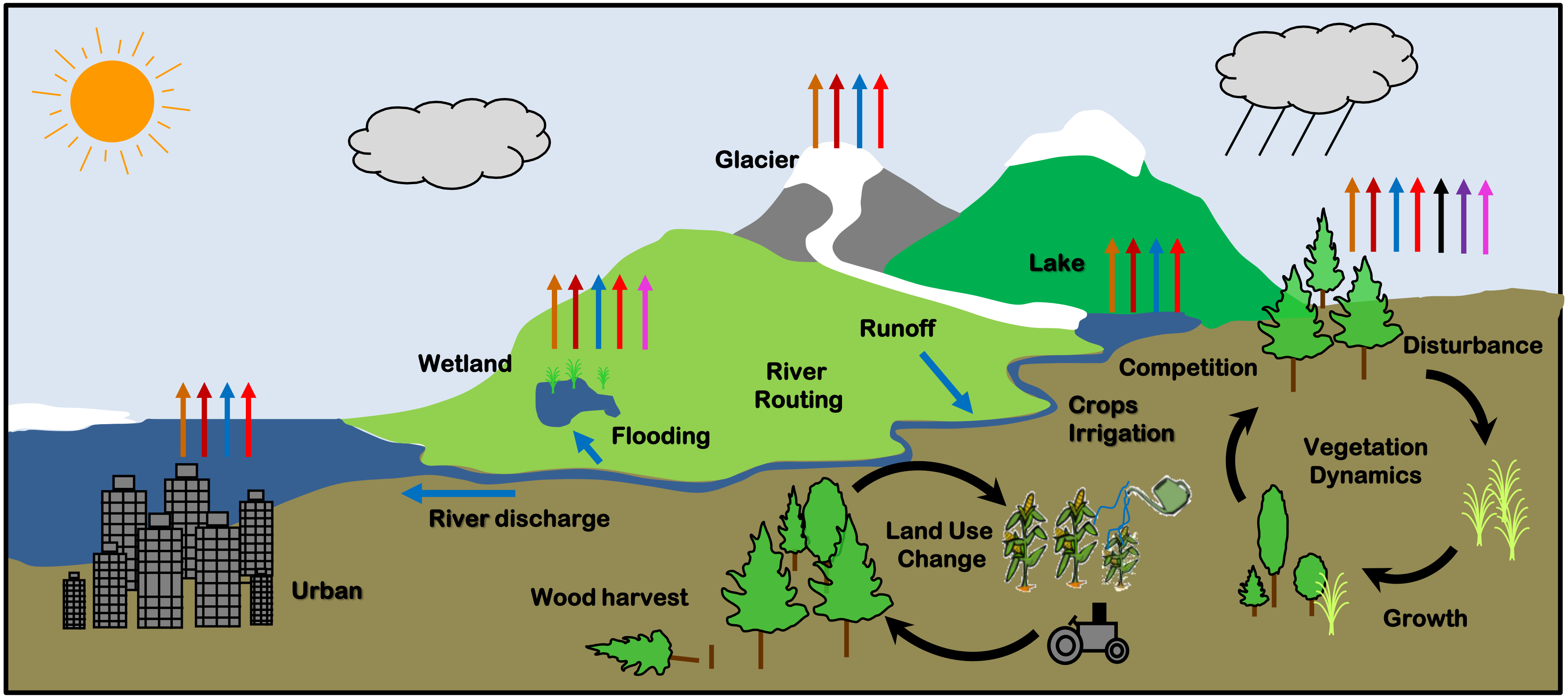
Carbon exchange

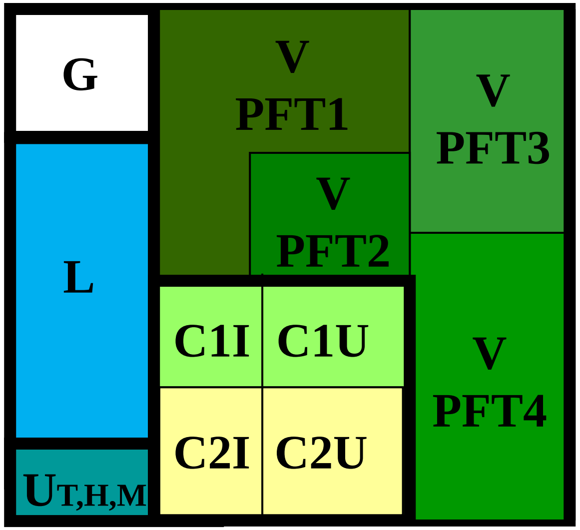
NEE = GPP – HR – AR – Fire – LUC



Features of the Community Land Model

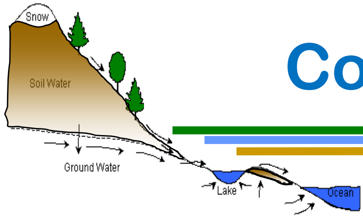
- Submodels and parameterizations
- Structural aspects (surface and input datasets)
  - Heterogeneity of landscape (vegetated, urban, lake, glacier, crop)
  - Plant Functional Types and associated parameters (optical, morphological, photosynthetic)
  - Soil texture (sand, silt, clay, organic matter) and color (albedo)
  - River directional map and mean slope
  - Urban characteristics
  - CO_2
  - Land cover/use change (changes in PFTs over time, wood harvest)
  - Aerosol and nitrogen deposition datasets
  - Population density and Gross Domestic Productivity



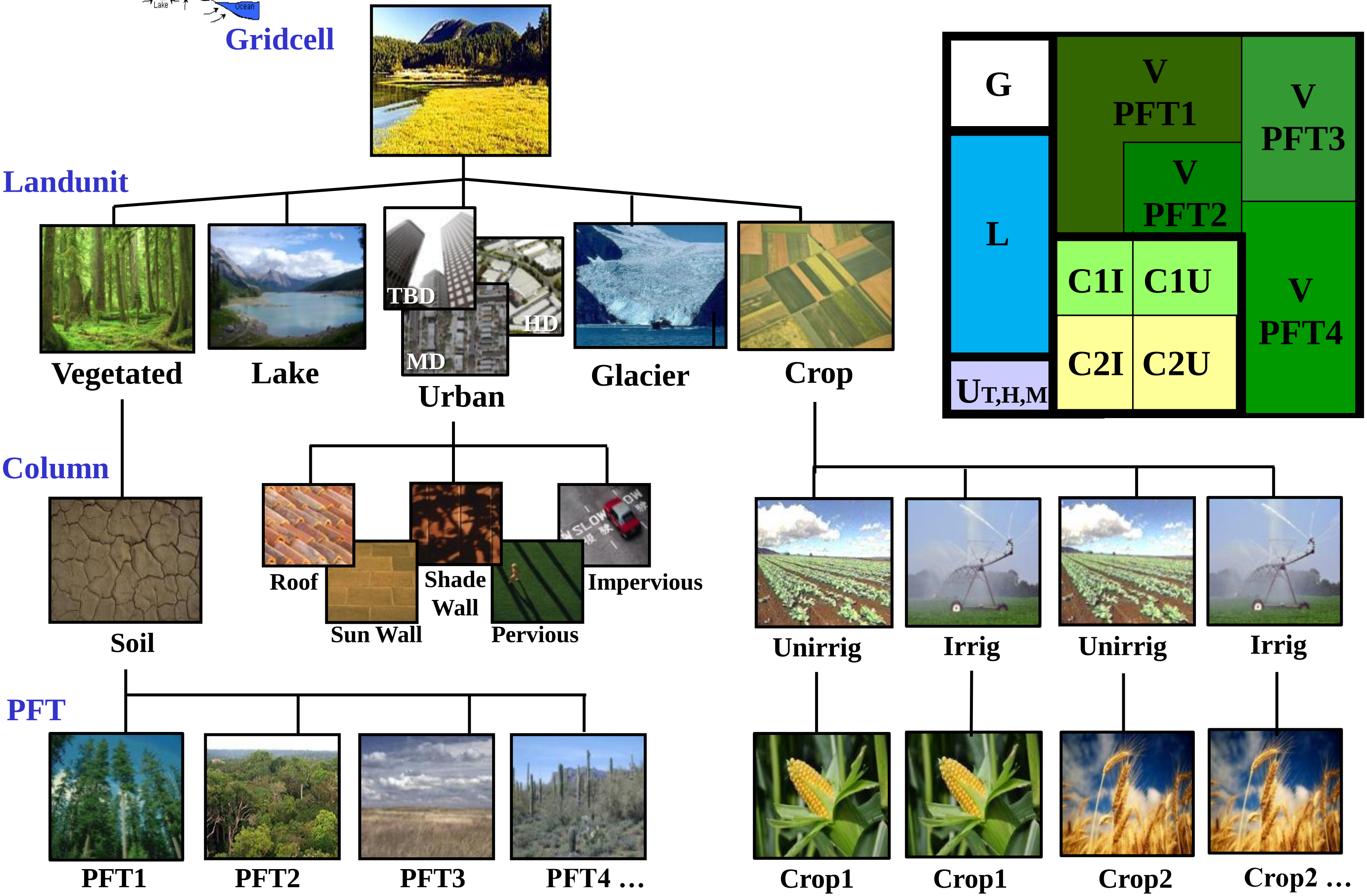


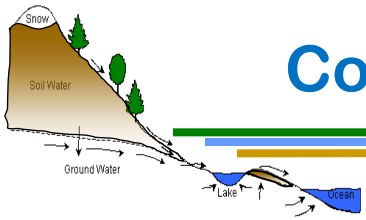
Landscape-scale dynamics

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

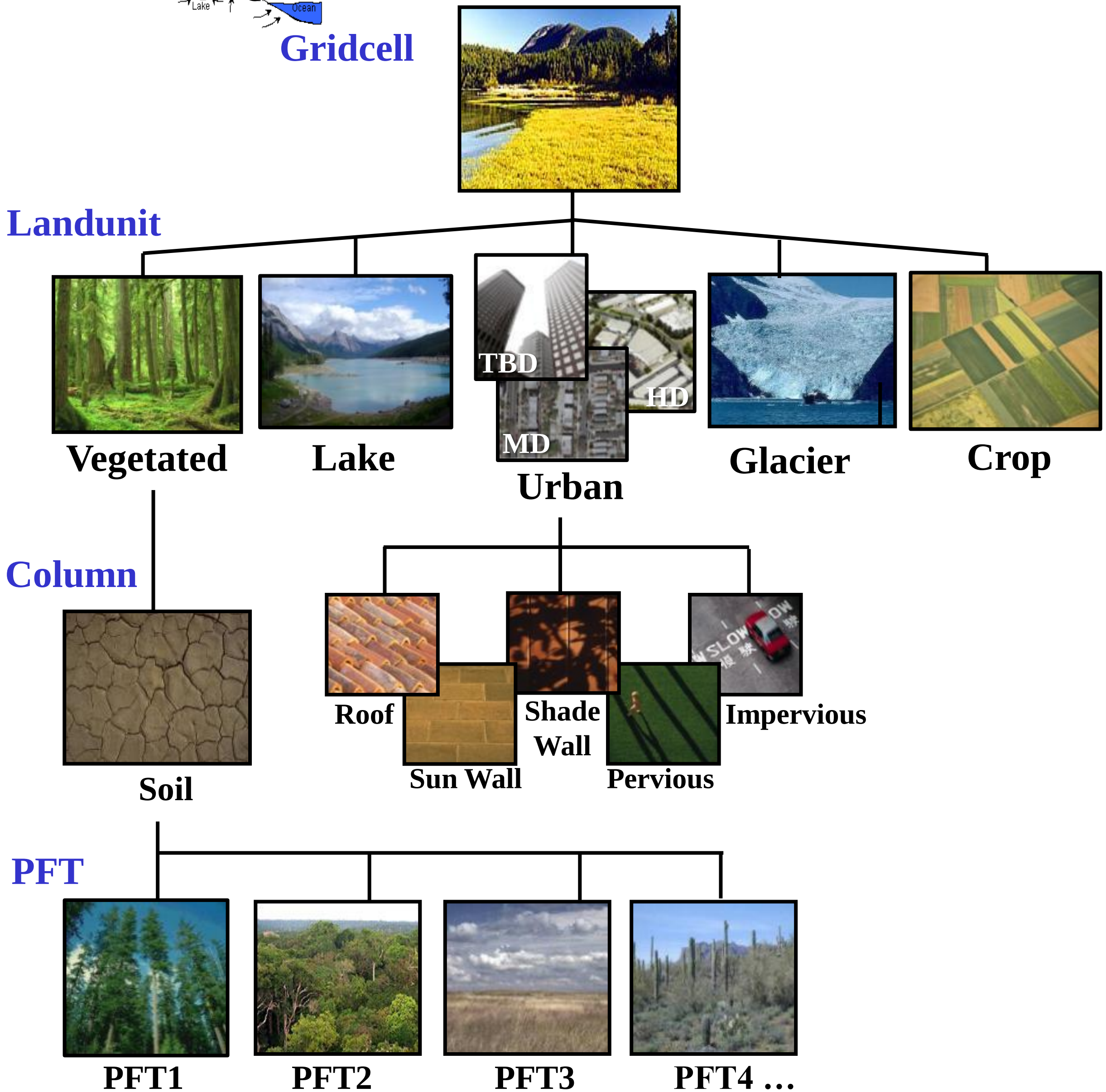


Community Land Model subgrid tiling structure





Community Land Model subgrid tiling structure



Plant Functional Types:

0. Bare

Tree:

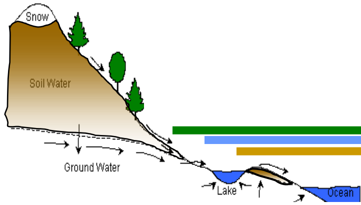
1. Needleleaf Evergreen, Temperate
2. Needleleaf Evergreen, Boreal
3. Needleleaf Deciduous, Boreal
4. Broadleaf Evergreen, Tropical
5. Broadleaf Evergreen, Temperate
6. Broadleaf Deciduous, Tropical
7. Broadleaf Deciduous, Temperate
8. Broadleaf Deciduous, Boreal

Herbaceous / Understorey:

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

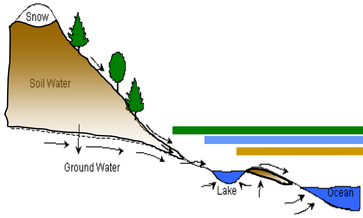
CLM Development

http://www2.cesm.ucar.edu/working-groups/lmwg/developer-guidelines



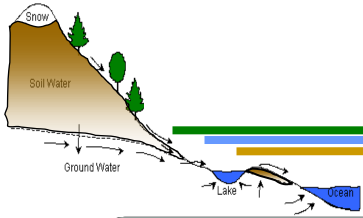
Scientific goals driving CLM development and use

- Improve understanding of carbon and nitrogen cycle interactions and their impact on long term trajectory of terrestrial carbon sink
- Assess response and vulnerability of ecosystems to climate change and disturbances (human and natural)
- Evaluate utility of ecosystem management as mechanism to mitigate climate change
- Ascertain vulnerability of water resources under climate change; establish role of land in drought and flood
- Quantify land feedbacks to climate change: e.g. permafrost-carbon, snow- and vegetation-albedo, soil moisture-ET feedbacks



Scientific goals driving CLM development and use

- **Assess urban-rural differences in climate change impacts**
- **Prognose anthropogenic and natural land cover/land use change and LULCC impact on climate and trace gas emissions**
- **Investigate role of surface heterogeneity in land-atmosphere interaction and carbon cycling, including scale issues**
- **Model – data fusion; Exploitation of experimental ecosystem data**
- **Uncertainty Quantification, parameter optimization**



Model Development Process

Model release (CESM1/CLM4)

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

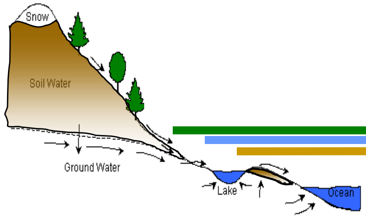
Plans for next (and next next) model version discussed at LMWG meetings

Build and test beta version of offline model

Finalize and test within CESM

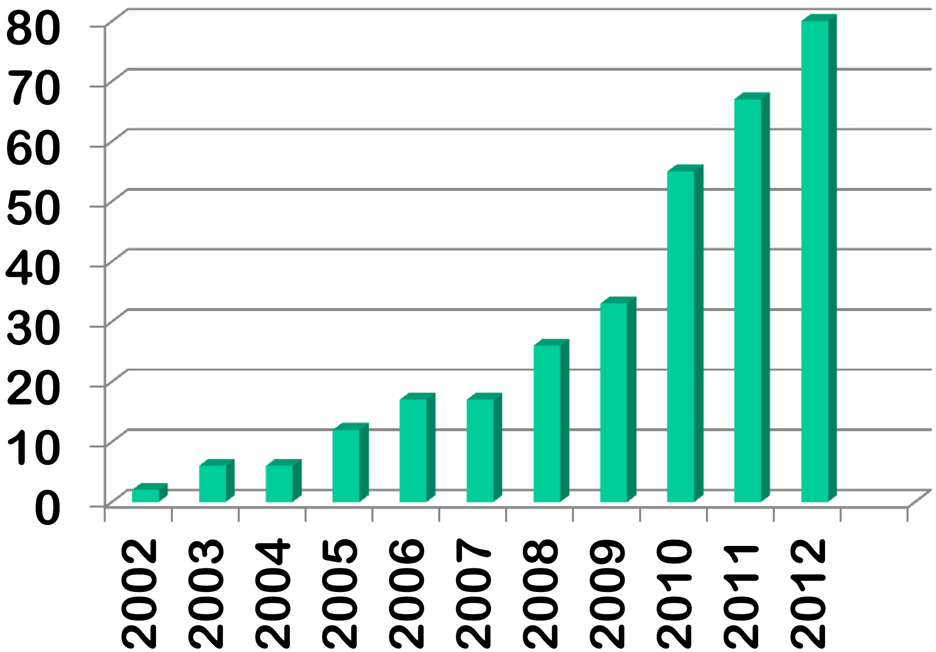
Document; Control integrations

Use model for scientific studies

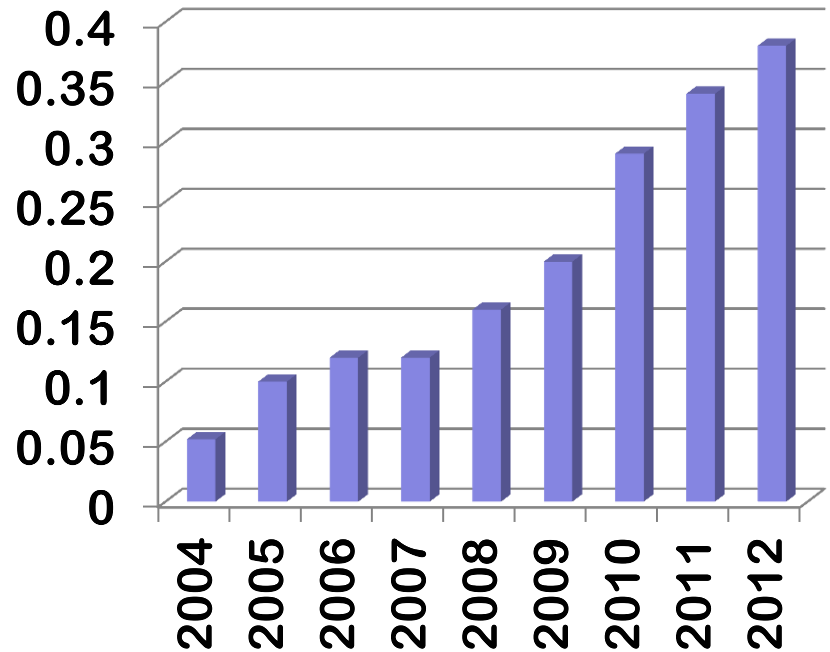


CLM as a community modeling tool

AGU presentations with CLM in abstract or title

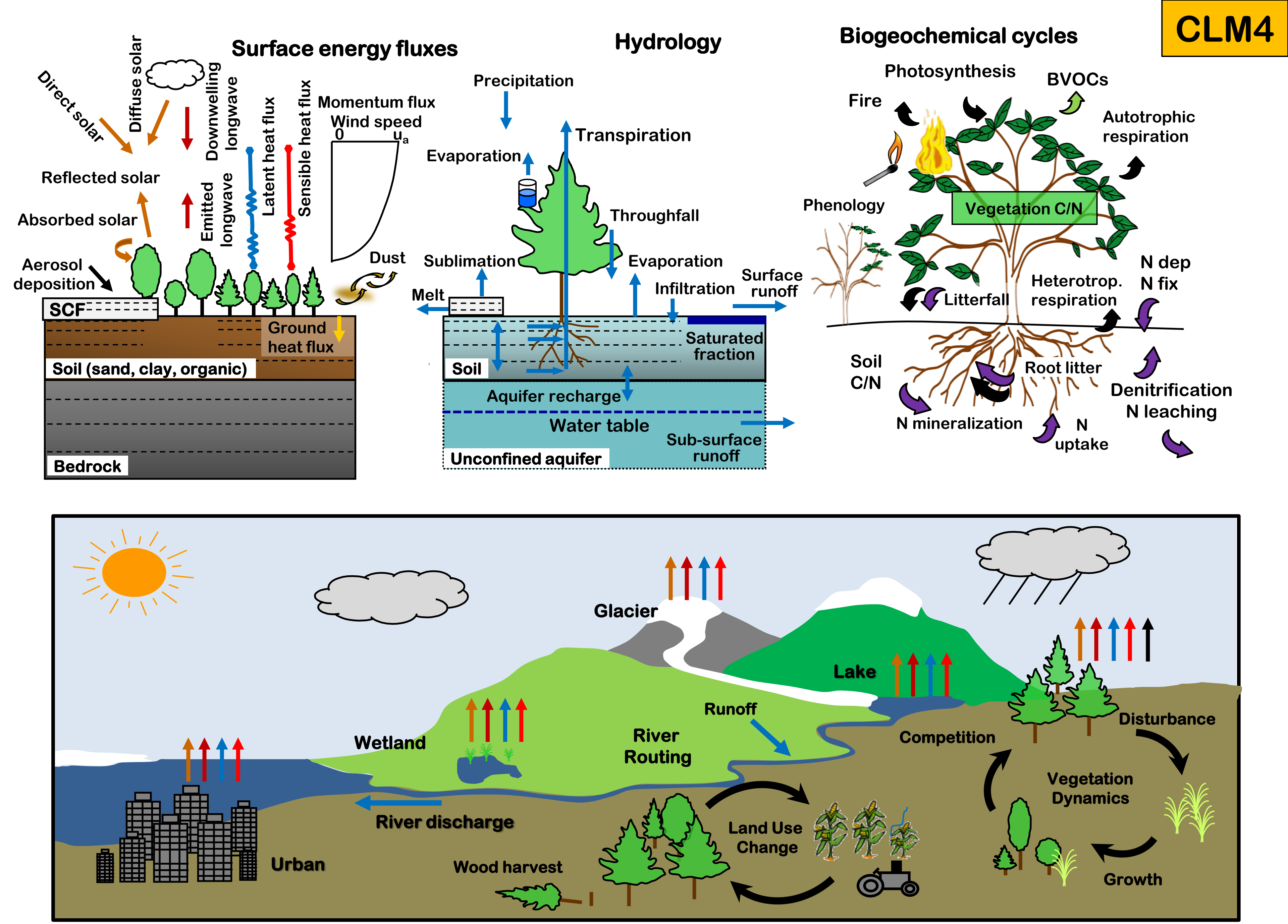


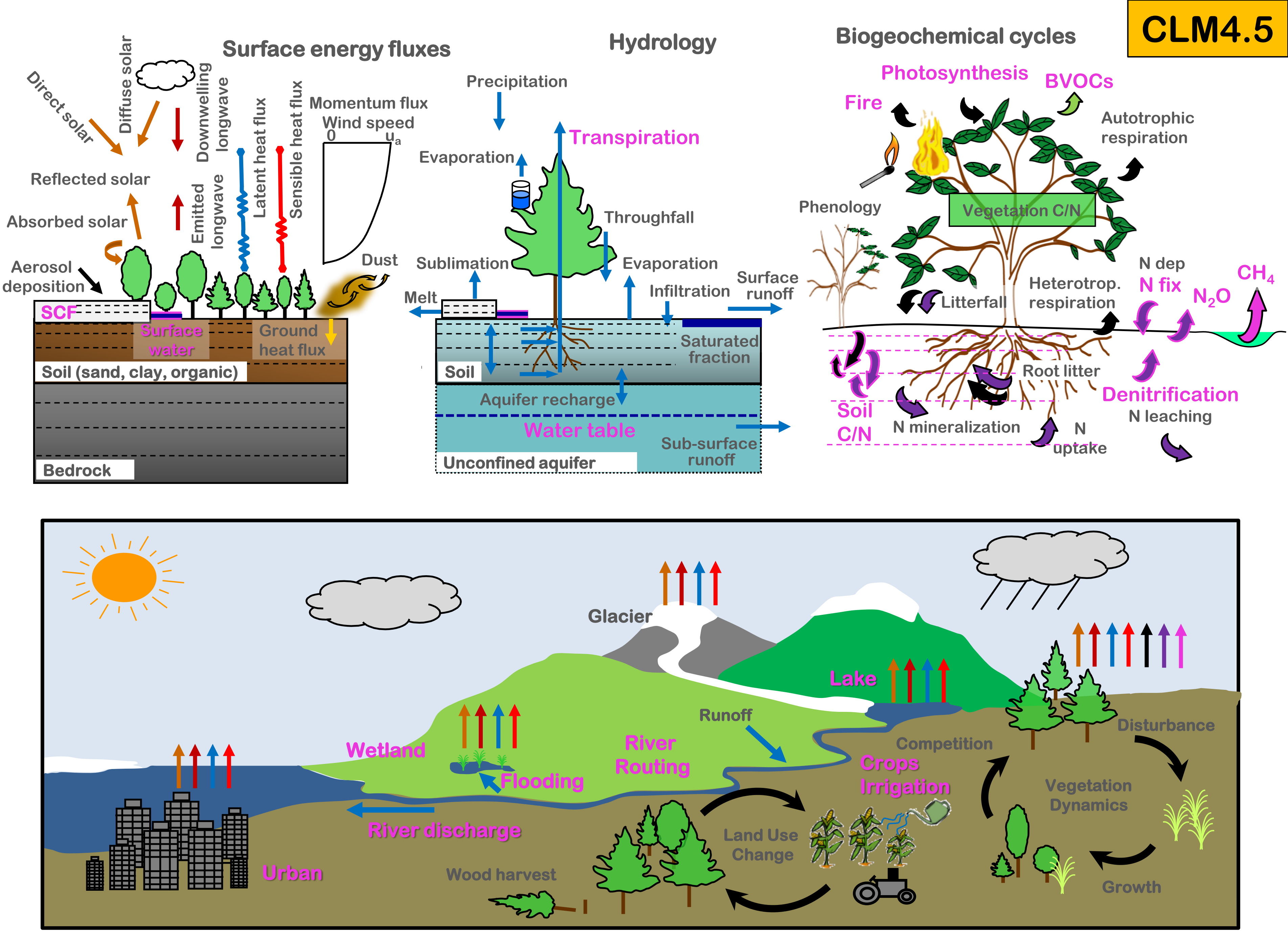
% of AGU presentations that included CLM



CLM3.5 [Oleson et al., 2008] (236 citations)

CLM4.0 [Lawrence et al., 2011] (164 citations)


CLM4
Surface energy fluxes
Hydrology
Biogeochemical cycles
Direct solar
Diffuse solar
Downwelling longwave
Latent heat flux
Sensible heat flux
Momentum flux
Wind speed
0
u_a
Reflected solar
Absorbed solar
Emitted longwave
Aerosol deposition
Dust
SCF
Ground heat flux
Soil (sand, clay, organic)
Bedrock
Precipitation
Transpiration
Evaporation
Throughfall
Sublimation
Evaporation
Melt
Infiltration
Surface runoff
Soil
Saturated fraction
Aquifer recharge
Water table
Sub-surface runoff
Unconfined aquifer
Photosynthesis
BVOCs
Fire
Autotrophic respiration
Phenology
Vegetation C/N
Litterfall
Heterotrop. respiration
N dep
N fix
Soil C/N
Root litter
Denitrification
N leaching
N mineralization
N uptake
Glacier
Lake
Wetland
Runoff
River Routing
Competition
Disturbance
Vegetation Dynamics
Growth
River discharge
Urban
Wood harvest
Land Use Change


CLM4.5
Surface energy fluxes
Direct solar
Diffuse solar
Downwelling longwave
Reflected solar
Absorbed solar
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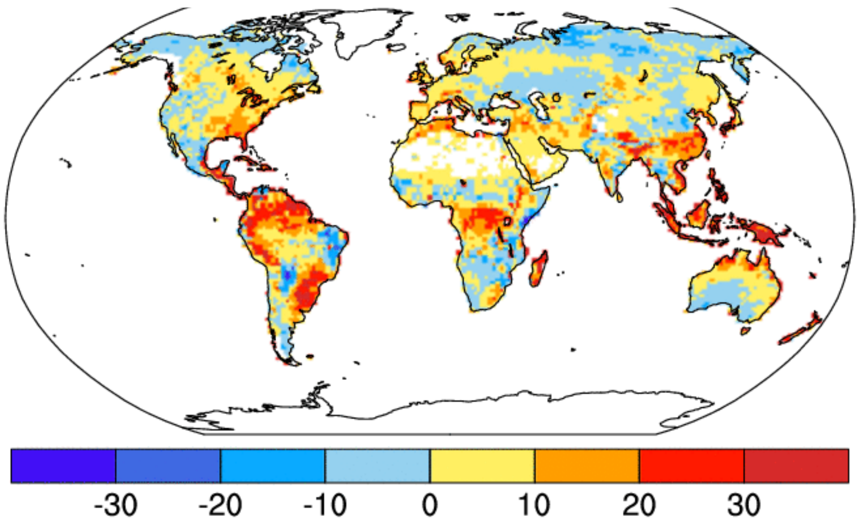
Competition
Crops
Irrigation
Disturbance
Vegetation Dynamics
Growth

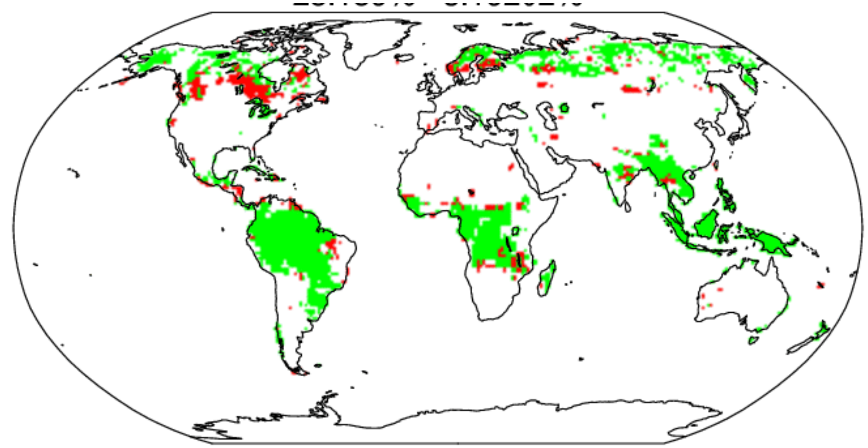
Reduced biases in CLM4.5

ANN Latent Heat bias (obs: FLUXNET MTE)

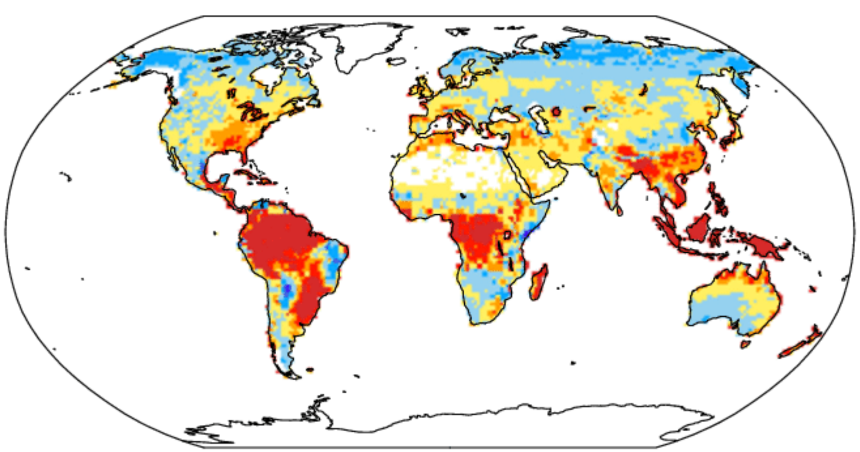
Green: Improved in CLM4.5
Red: Degraded in CLM4.5

CLM4.5BGC



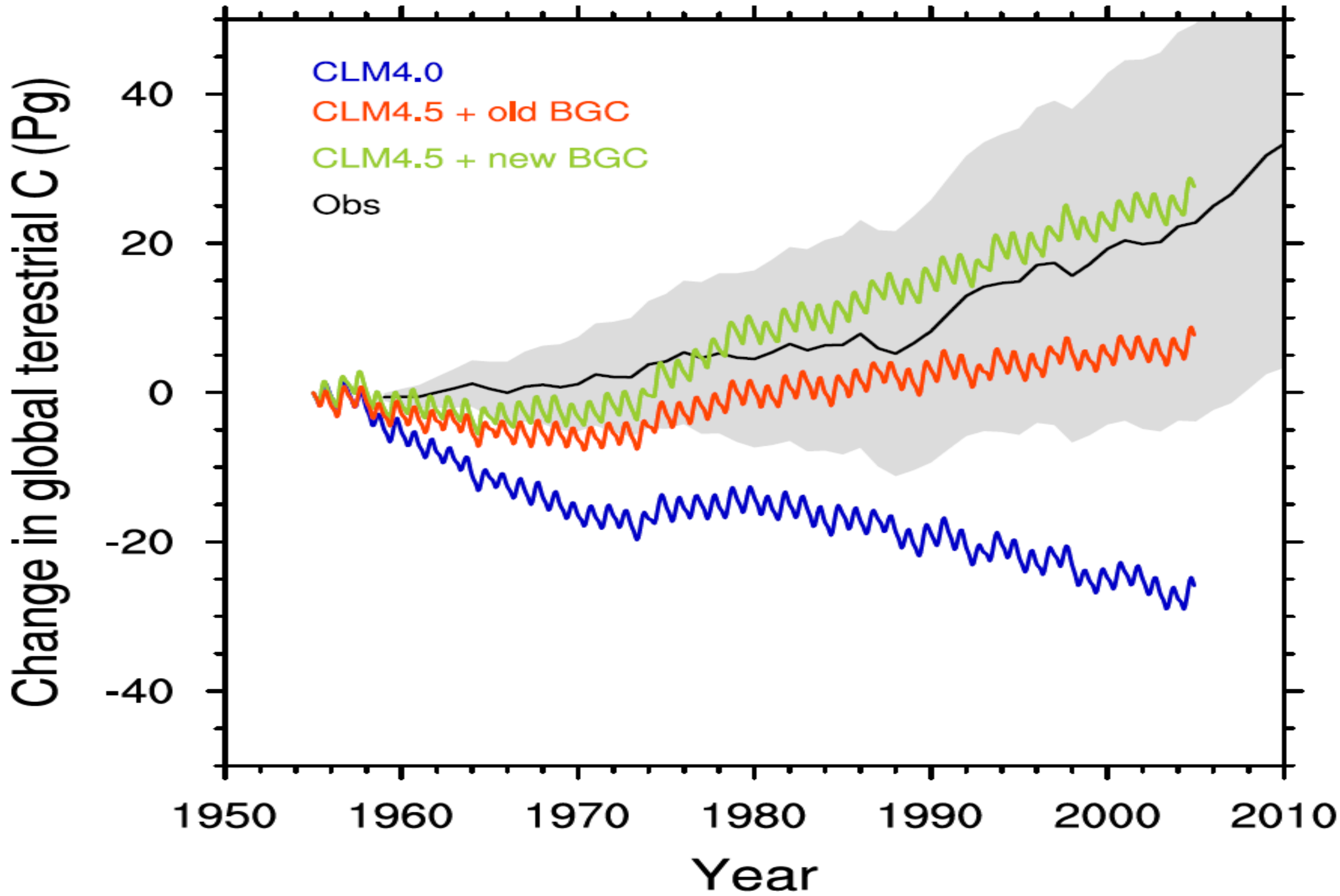


CLM4CN



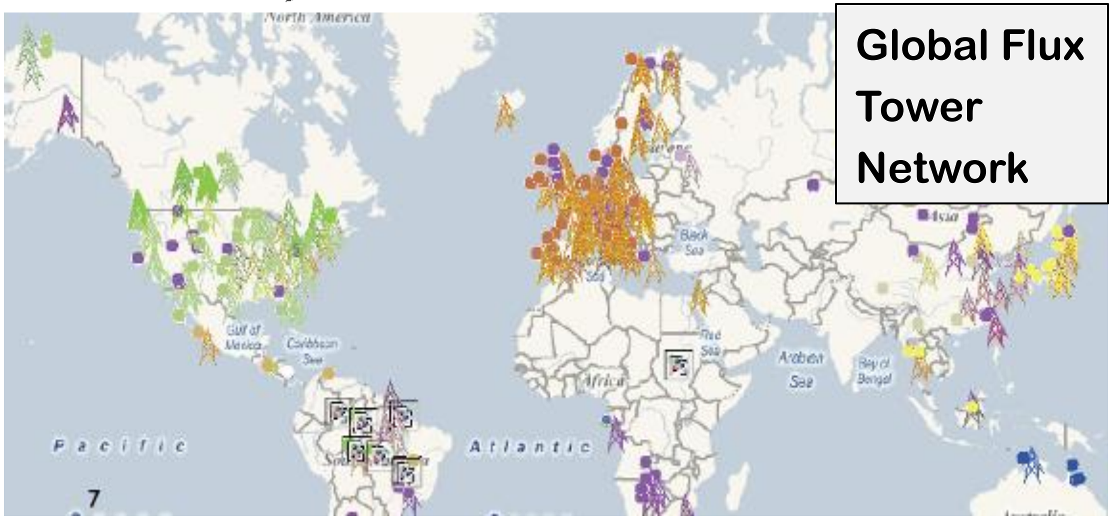
	CLM4	CLM4.5
LH (W m^{-2})	8.9	5.9
GPP (gC m^{-2} d^{-1})	0.41	0.07
Albedo (%)	-0.41	-0.52

Carbon stock trajectory

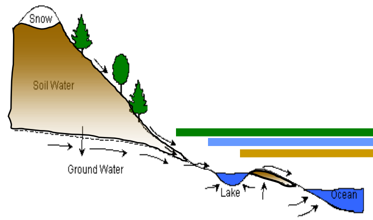


Koven et al. 2013

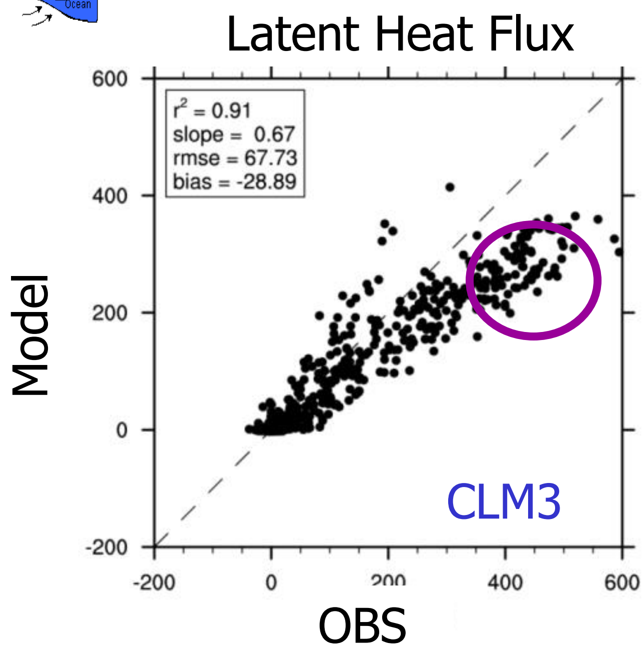
Evaluating and Improving the model with Tower Flux data

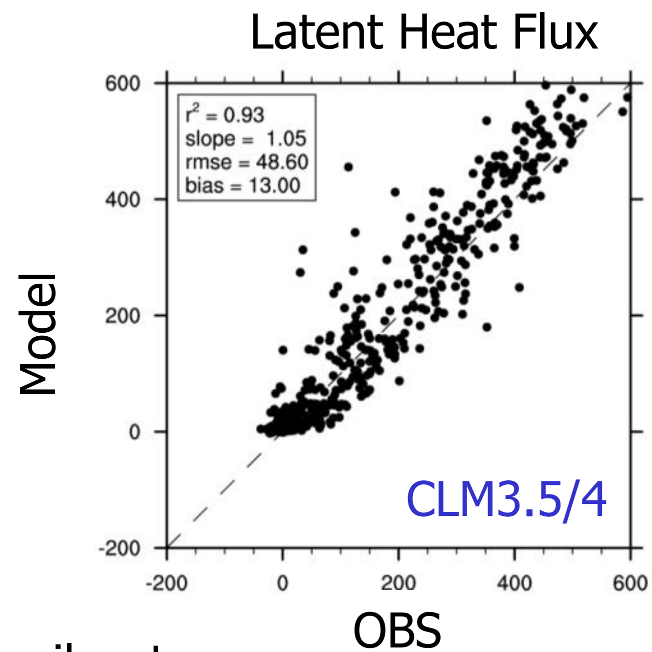


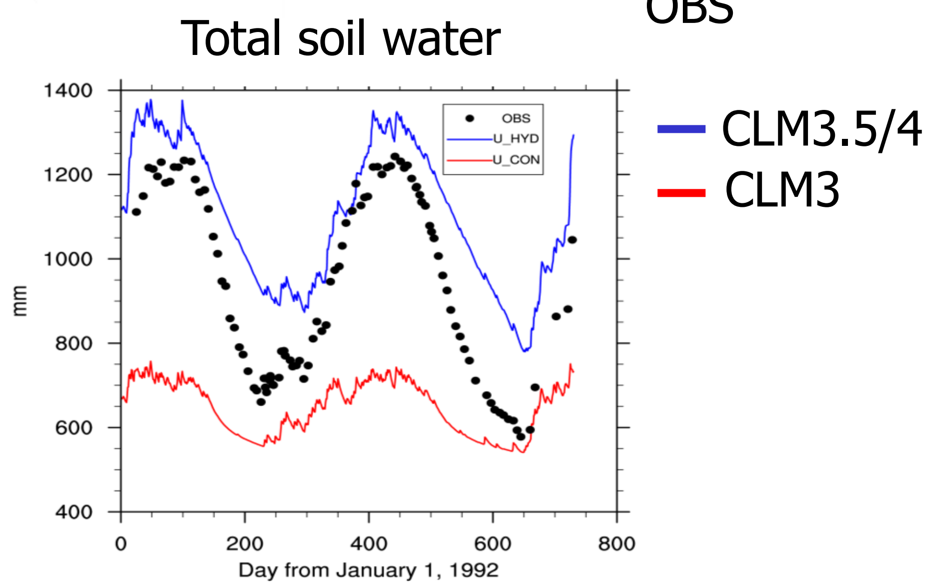
Global Flux Tower Network



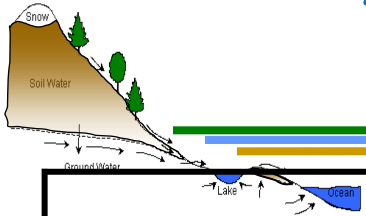
Abracos tower site (Amazon)







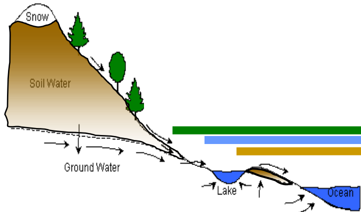
Tower flux statistics (15 sites incl. tropical, boreal, mediterannean, alpine, temperate; hourly)



	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

Standardized benchmarking / metrics

Class	Variable	Obs dataset	W (1-5)	CCSM4	CLM4 CN	CLM4.5 BGC
Global or regional	LH	FLUXNET-MTE	4	0.68	0.63	0.71
	SCF	AVHRR	3	0.68	0.75	0.74
	Albedo	MODIS	4	0.62	0.65	0.66
	Biomass	NBCD (US), Tropical Biomass	3	0.65	0.59	0.63
	Burnt Area	GFED3	3	0.39	0.38	0.43
	P	CMAP	2	0.48	0.93	0.93
	T_{air}	CRU	2	0.91	0.93	0.93
Site level	NEE	FLUXNET	3	0.19	0.23	0.25
	GPP	FLUXNET	3	0.66	0.76	0.80
	SH	FLUXNET	4	0.73	0.80	0.79
Functional relationship	R / P	riv disc, CMAP	5	0.63	0.57	0.59
Total				21.76	22.98	23.86



Potential development targets for CLM5+

Landscape dynamics
- Dynamic landunits
- iESM infrastructure

Hydrology
- MOSART routing model
- Progress on lateral flow processes
- Human management and withdrawals

Agriculture
- Extend crops to global
- Additional crop management processes

Evapotranspiration, partitioning of ET
- Address unrealistic hydrologic response to land cover change
- Soil evap, canopy turbulence, canopy evap
- Water isotopes

Nutrient dynamics
- Plant nitrogen uptake and allocation
- N-gas emissions
- Leaching and riverine transport
- Phosphorous dynamics

Ecosystem disturbance
- Ecosystem Demography model
- Trace gas emissions from fire

Canopy processes
- Multi-layer, turbulence, optimization

Where to find information about CLM and CESM

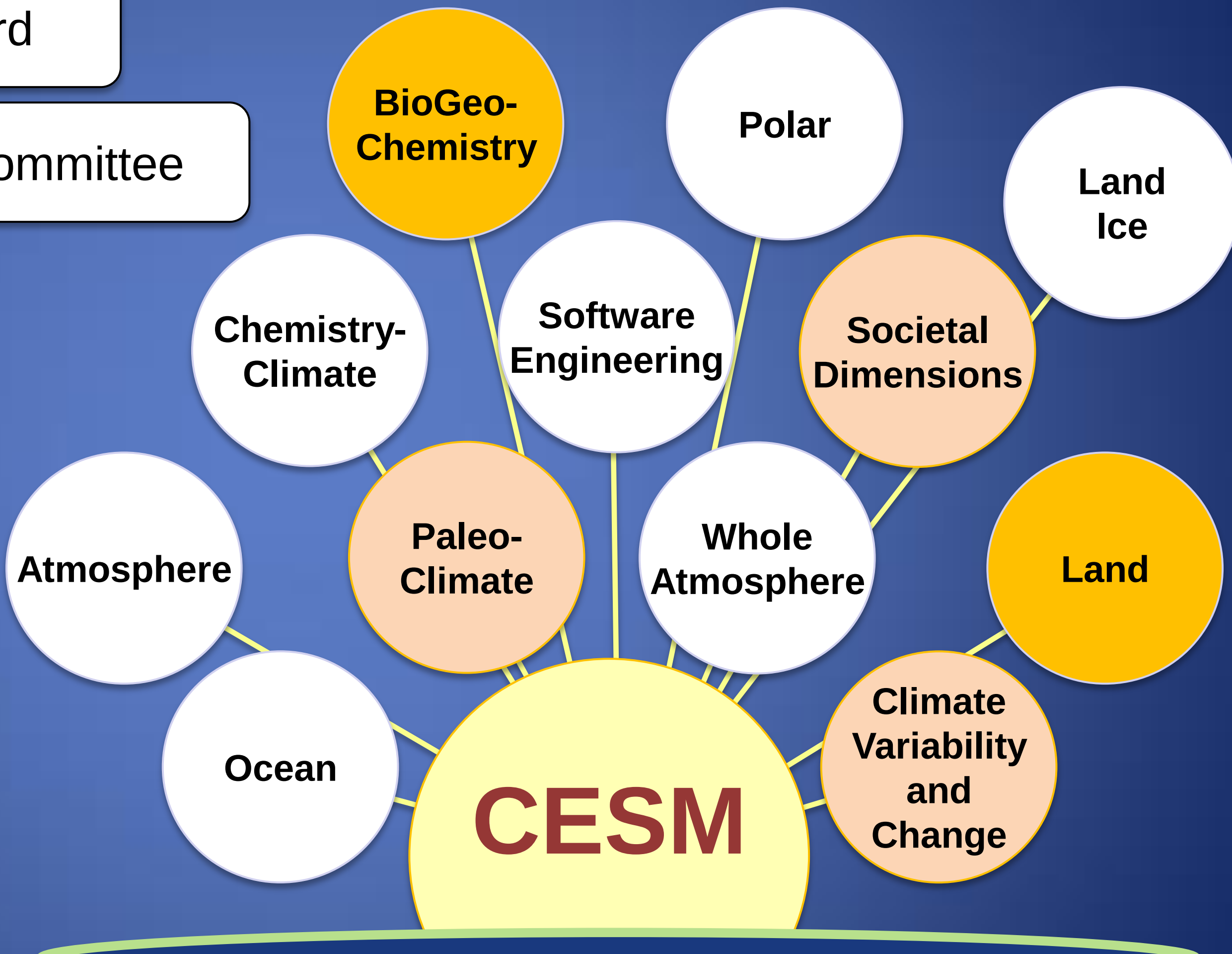
CESM Management Structure

12 working groups – encompass both model development and applications

CESM Advisory Board

CESM Scientific Steering Committee

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



http://www.cesm.ucar.edu/management

CESM1.2: CLM DOCUMENTATION

INTRODUCTION

The Community Land Model versions 4.0 and 4.5 in CESM1.2.0 are 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.

www.cesm.ucar.edu/models/cesm1.2/clm

DOCUMENTATION

- User's Guide for CLM4.5 and CLM4.0 in CESM1.2.0 [html] [pdf] (Last update: [an error occurred while processing this directive])
- Technical Description for CLM4.5 (Last update: Aug/ 1/2013)
- Technical Description for CLM4.0, CLM4.0 Urban Model, CLM4.0 Crop and Irrigation Model
- Explanation of supported configurations in CLM4.5 and CLM4 in CESM1.2
- What's new in CLM in CESM1.2 (CLM4.5 release) Science, CESM1.2 (CLM4.5 release) Software, CESM1.1.1, CESM1.1.0, CESM1.0.5, CESM1.0.4, CESM1.0.3, CESM1.0.2, CESM1.0.1, CESM1.0, CCSM4.0 (CLM4.0 release).
- Known bugs in CLM in CESM1.2.0, CESM1.1.0, CESM1.0.4, CESM1.0.3, CESM1.0.2, CESM1.0.1, CESM1.0.
- Known limitations in CLM in CESM1.2.0, CESM1.1.0.

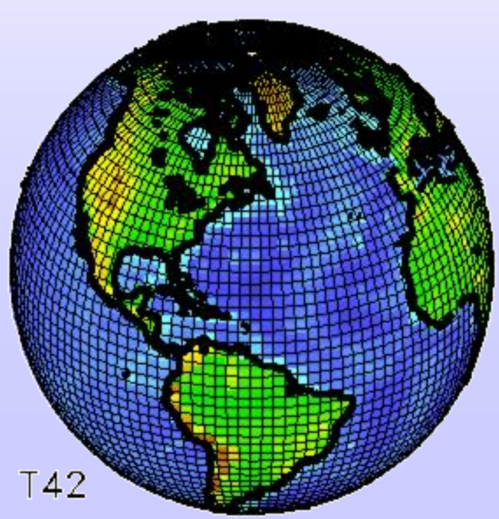
MODEL OUTPUT AND OFFLINE FORCING DATA AND DIAGNOSTIC PLOTS

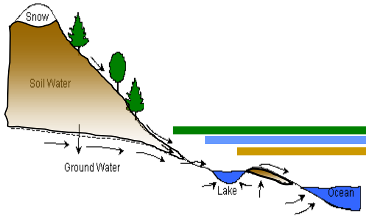
- CLM4.0 and CLM4.5 offline control simulations: Diagnostic plots
- CLM4.0 and CLM4.5 offline control simulations (links need to be updated and data posted to ESG)): Model output data
- CLM4.0 and CLM4.5 offline control simulations (links need to be updated and data posted to ESG): Model forcing data
- CLM4.0 and CLM4.5 offline historical and RCP simulations: CCSM4 coupler history forcing data

CLM configurations in CESM1.2

- **CLM4.5SP** Prescribed Satellite Phenology
- **CLM4.5BGC** Prognostic vegetation state / biogeochemistry
- **CLM4.5BGCDV** Prognostic BGC with dynamic vegetation

Options: Prescribed land use change
Crops and irrigation,
VIC hydrology





Documentation
http://www.cesm.ucar.edu/models/cesm1.2/clm

NCAR/TN-503+STR
NCAR Technical Note

July 2013

Technical Description of version 4.5 of the
Community Land Model (CLM)

Coordinating Lead Authors
Keith W. Oleson, David M. Lawrence

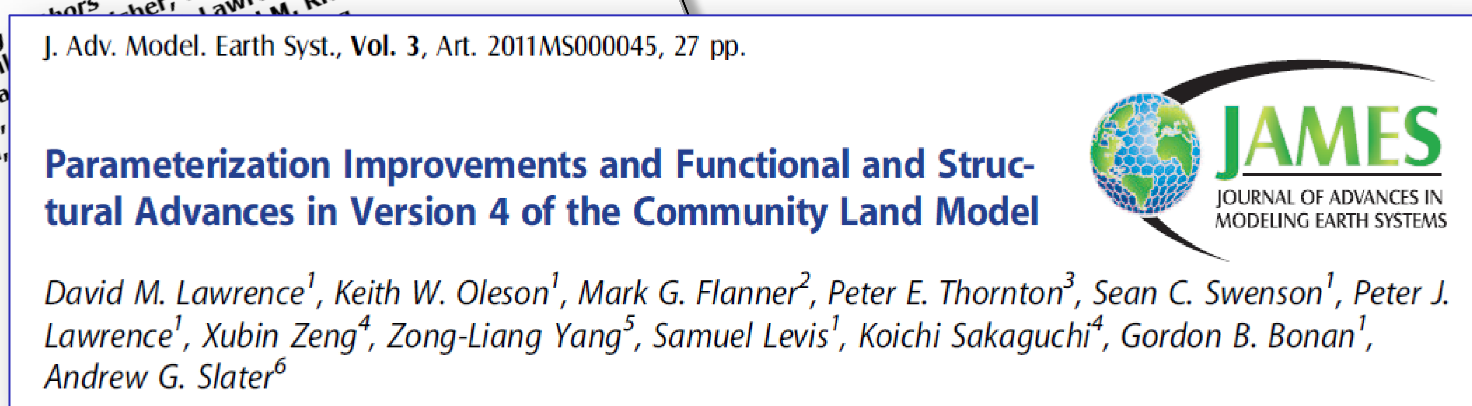
Lead Authors
Gordon B. Bonan, Beth Drewniak, Maoyi Huang, Charles D.
Koven, Samuel Levis, Fang Li, William J. Riley, Zachary M.
Subin, Sean C. Swenson, Peter E. Thornton

Contributing
Anil Bozbiyi
Francois La
Lipscomb,
Ying Sun,

CLM4.5 Technical Description

- ~420 pages
- 27 chapters

Papers – Over 300 papers in CLM Bibliography



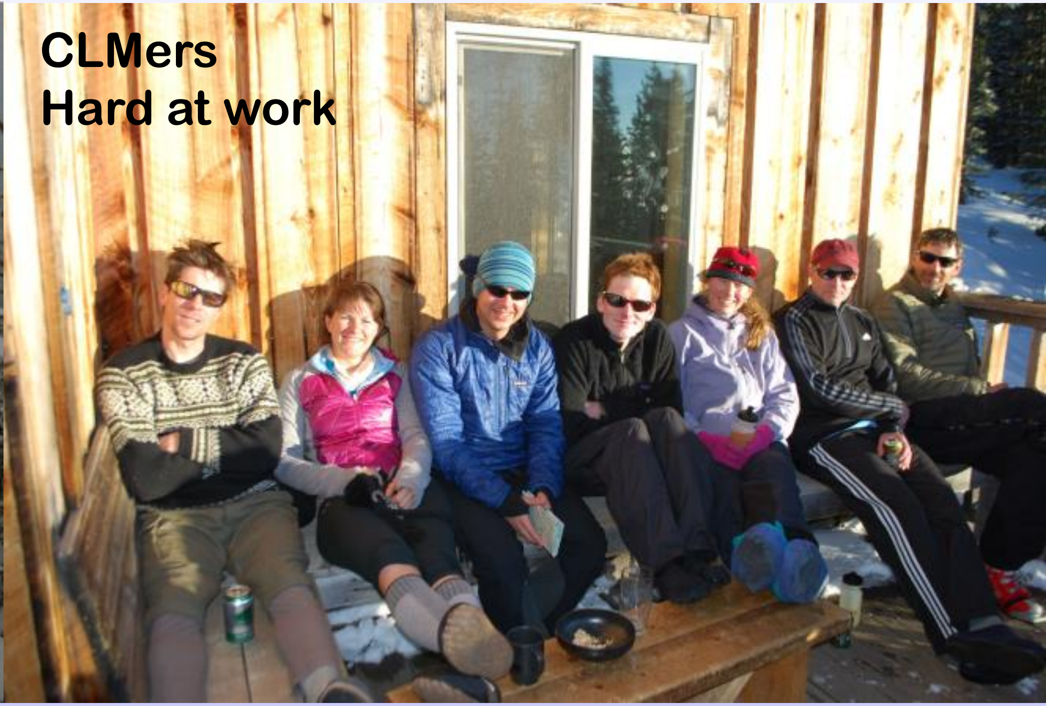
J. Adv. Model. Earth Syst., **Vol. 3**, Art. 2011MS000045, 27 pp.

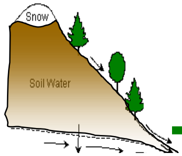
JAMES
JOURNAL OF ADVANCES IN MODELING EARTH SYSTEMS

Parameterization Improvements and Functional and Structural Advances in Version 4 of the Community Land Model

David M. Lawrence[1], Keith W. Oleson[1], Mark G. Flanner[2], Peter E. Thornton[3], Sean C. Swenson[1], Peter J. Lawrence[1], Xubin Zeng[4], Zong-Liang Yang[5], Samuel Levis[1], Koichi Sakaguchi[4], Gordon B. Bonan[1], Andrew G. Slater[6]

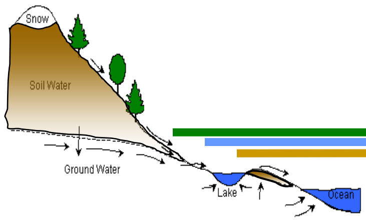
Thanks and welcome to the CESM/CLM research community!





Potential metrics for inclusion in a comprehensive land benchmarking system

- **Large-scale state and flux estimates**
  - LH, SH, total water storage, albedo, river discharge, SCF, LAI, soil and veg C stocks, GPP, NEE, ER, burnt area, permafrost distribution, T_{2m}, P, …
  - RMSE, annual cycle phase, spatial pattern corr, interannual variability
- **Functional relationships and emergent properties**
  - soil moisture – ET, soil moisture – runoff, stomatal response to VPD transient carbon storage trajectory, runoff ratio, land cover change
- **Experimental manipulation (testing model functional responses)**
  - N additions, FACE, artificial warming, rainfall exclusion

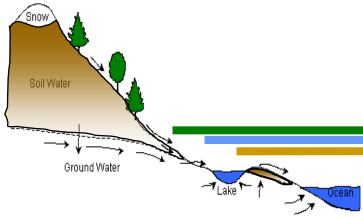


The role of CLM in CESM: Land to Atmosphere

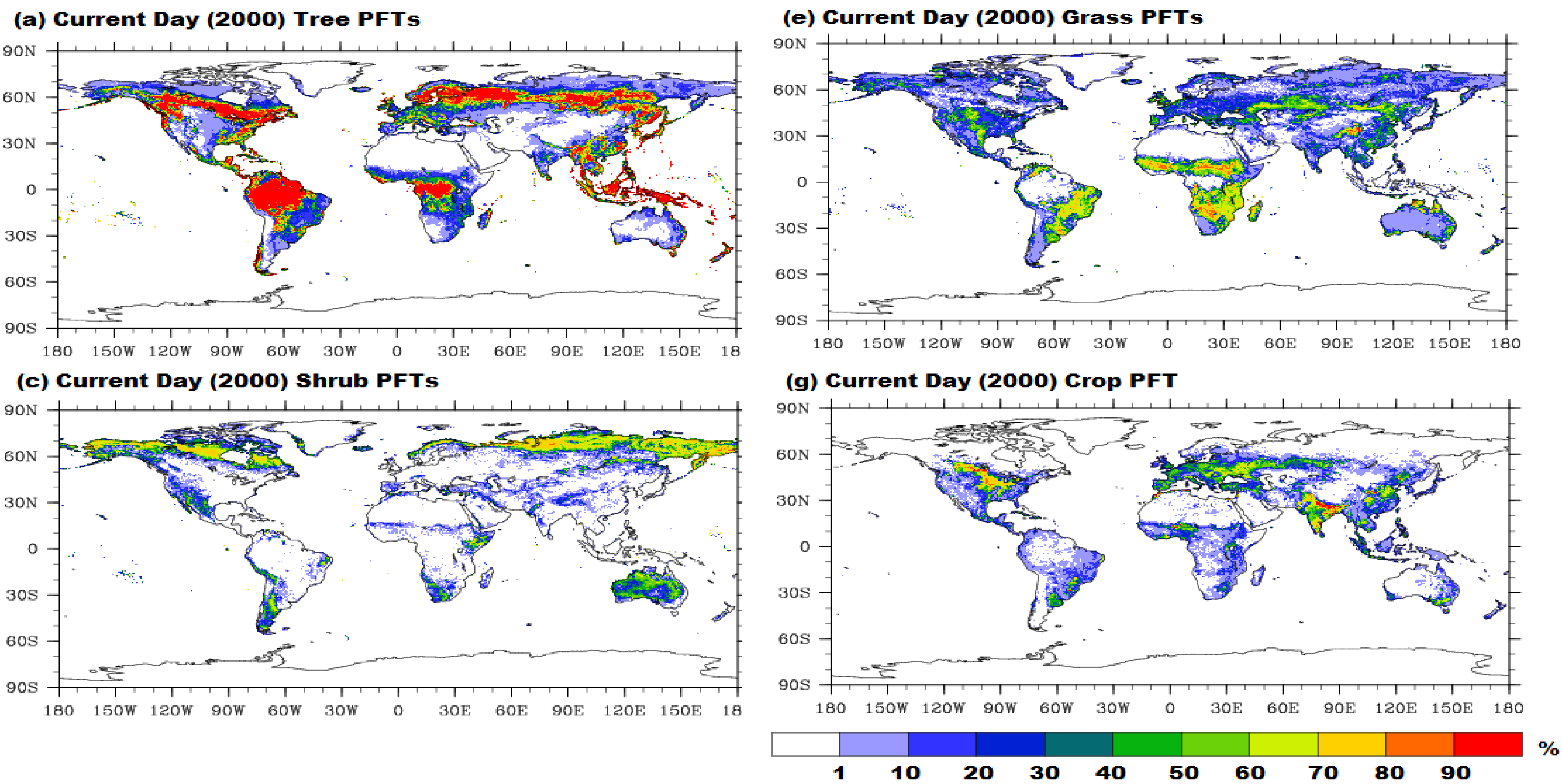
[1]Latent heat flux	$\lambda_{vap}E_v + \lambda E_g$	W m^{-2}
Sensible heat flux	$H_v + H_g$	W m^{-2}
Water vapor flux	$E_v + E_g$	mm s^{-1}
Zonal momentum flux	τ_x	kg m^{-1} s^{-2}
Meridional momentum flux	τ_y	kg m^{-1} s^{-2}
Emitted longwave radiation	$L\uparrow$	W m^{-2}
Direct beam visible albedo	$I\uparrow_{vis}^{\mu}$	-
Direct beam near-infrared albedo	$I\uparrow_{nir}^{\mu}$	-
Diffuse visible albedo	$I\uparrow_{vis}$	-
Diffuse near-infrared albedo	$I\uparrow_{nir}$	-
Absorbed solar radiation	$\vec{S}$	W m^{-2}
Radiative temperature	T_{rad}	K
Temperature at 2 meter height	T_{2m}	K
Specific humidity at 2 meter height	q_{2m}	kg kg^{-1}
Snow water equivalent	W_{sno}	m
Aerodynamic resistance	r_{am}	s m^{-1}
Friction velocity	u_*	m s^{-1}
[2]Dust flux	F_j	kg m^{-2} s^{-1}
Net ecosystem exchange	NEE	kgCO_2 m^{-2} s^{-1}

The role of CLM in CESM: Atmosphere to Land

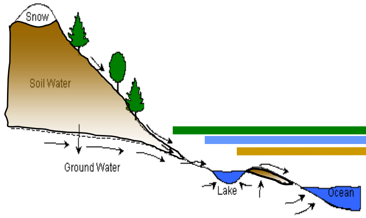
[1]Reference height	z'_{atm}	m
Zonal wind at z_{atm}	u_{atm}	m s^{-1}
Meridional wind at z_{atm}	v_{atm}	m s^{-1}
Potential temperature	$\overline{\theta_{atm}}$	K
Specific humidity at z_{atm}	q_{atm}	kg kg^{-1}
Pressure at z_{atm}	P_{atm}	Pa
Temperature at z_{atm}	T_{atm}	K
Incident longwave radiation	$L_{atm}\downarrow$	W m^{-2}
[2]Liquid precipitation	q_{rain}	mm s^{-1}
[2]Solid precipitation	q_{sno}	mm s^{-1}
Incident direct beam visible solar radiation	$S_{atm}\downarrow^{\mu}_{vis}$	W m^{-2}
Incident direct beam near-infrared solar radiation	$S_{atm}\downarrow^{\mu}_{nir}$	W m^{-2}
Incident diffuse visible solar radiation	$S_{atm}\downarrow_{vis}$	W m^{-2}
Incident diffuse near-infrared solar radiation	$S_{atm}\downarrow_{nir}$	W m^{-2}
Carbon dioxide (CO_2) concentration	c_a	ppmv
[3]Aerosol deposition rate	D_{sp}	kg m^{-2} s^{-1}
[4]Nitrogen deposition rate	NF_{ndep_sminn}	g (N) m^{-2} yr^{-1}



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



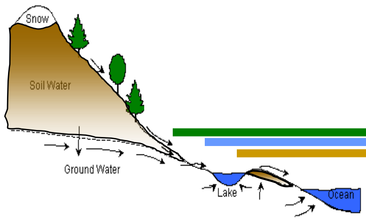
Lawrence and Chase, 2007



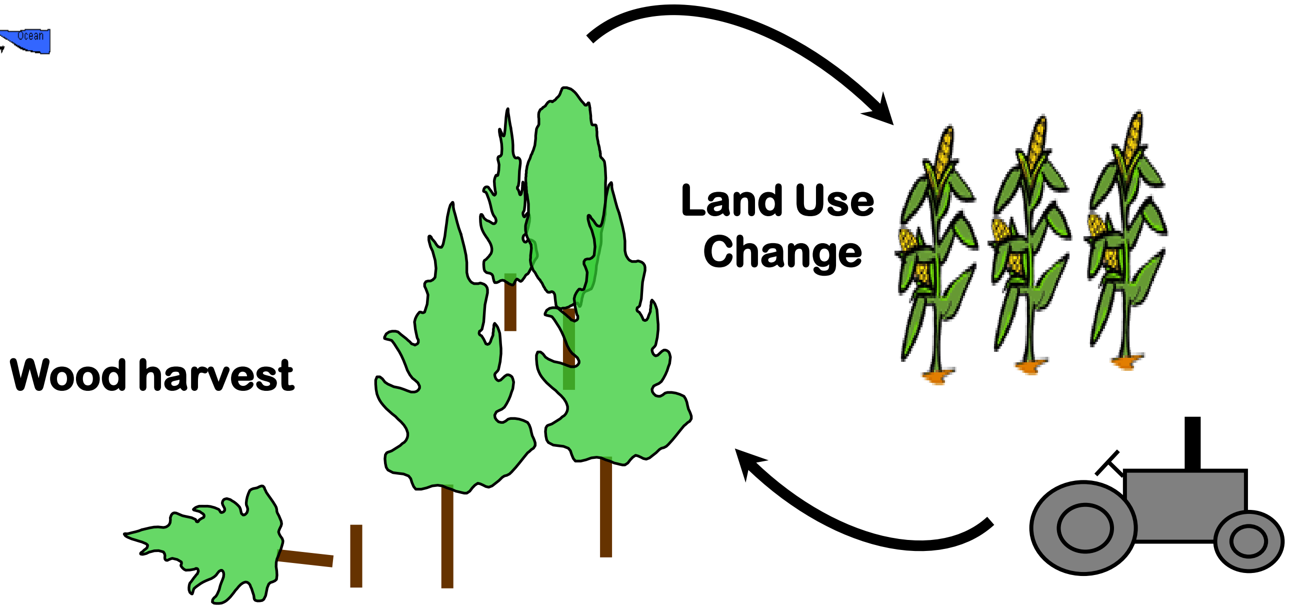
Plant Functional Type Parameters

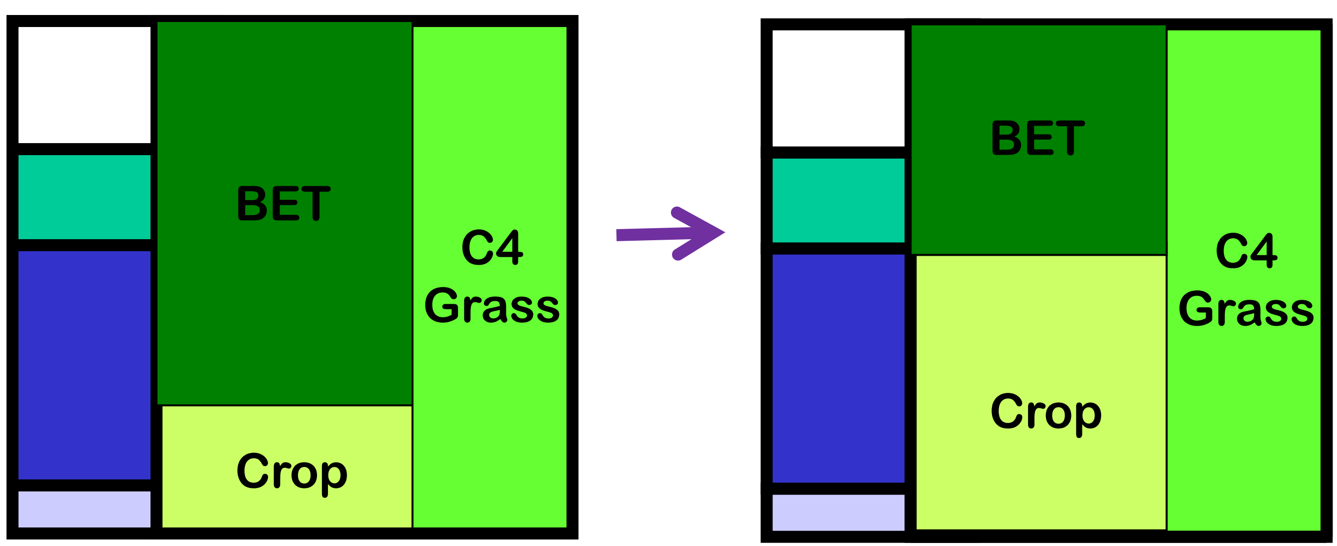
- Optical properties (visible and near-infrared):
  - Leaf angle
  - Leaf reflectance
  - Stem reflectance
  - Leaf transmittance
  - Stem transmittance
- Land-surface models are parameter heavy!!!

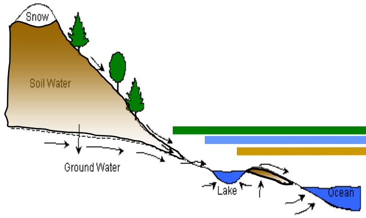
- Morphological properties:
  - Leaf area index (annual cycle)
  - Stem area index (annual cycle)
  - Leaf dimension
  - Roughness length/displacement height
  - Canopy height
  - Root distribution
- Photosynthetic parameters:
  - specific leaf area (m^2 leaf area g^{-1} C)
  - m (slope of conductance-photosynthesis relationship)



Land cover / land use change (prescribed)



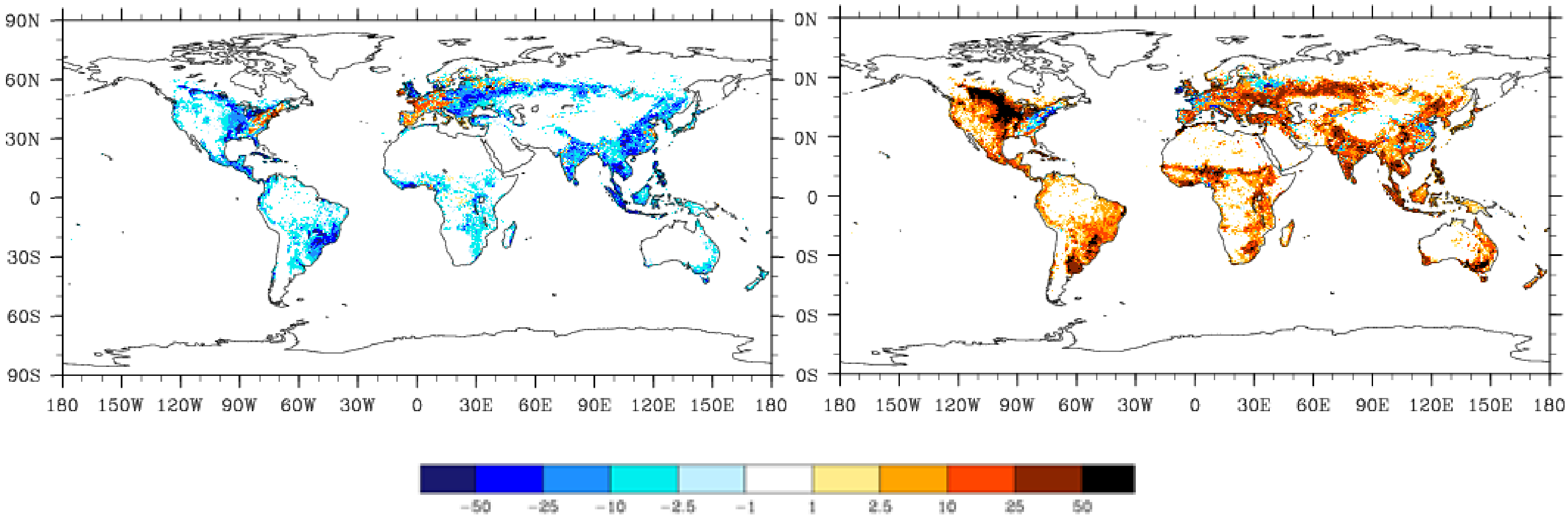




Land cover change (prescribed)

2005 – 1850

Trees **Crops**

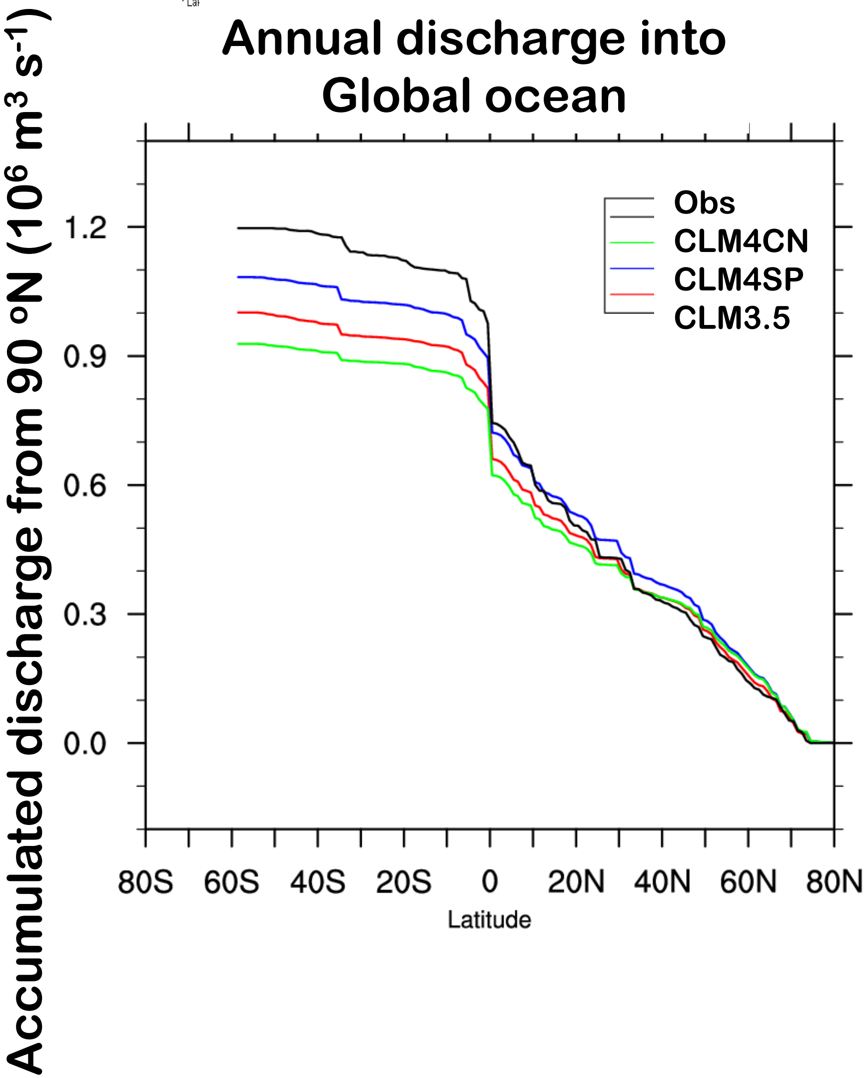


Deforestation across Eastern North America, Eastern Europe, India, China, Indonesia, SE South America for Crops

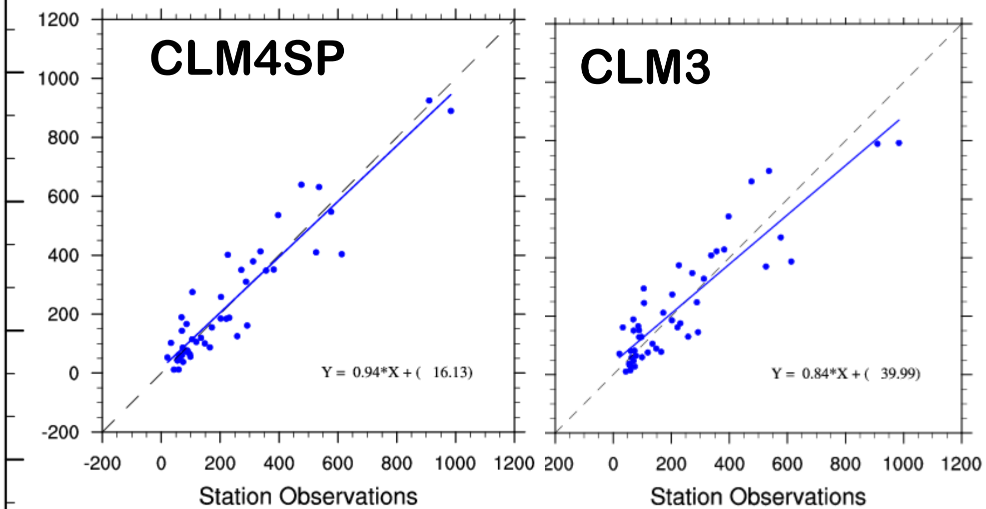
Lawrence, P et al. J. Climate, 2012

River Discharge

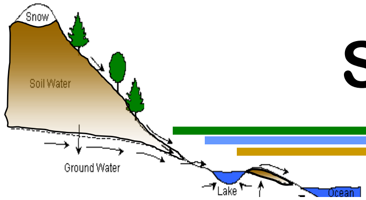
Annual discharge into Global ocean



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

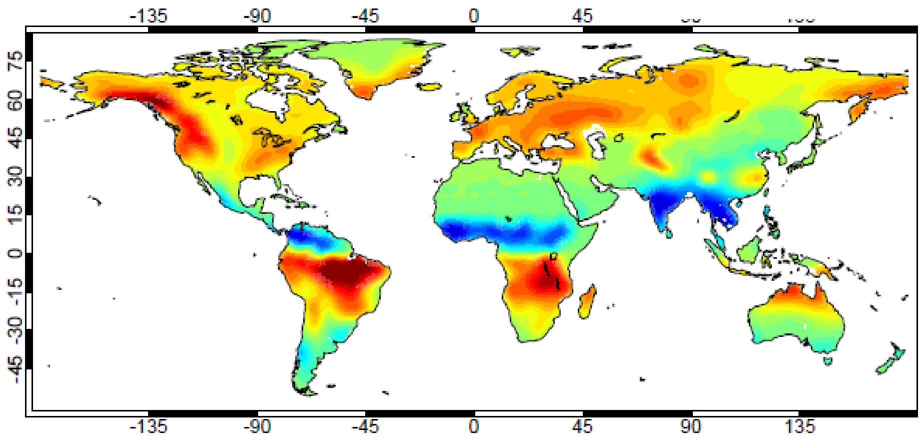


CLM3: r = 0.86
CLM3.5: r = 0.87
CLM4SP: r = 0.94
CLM4CN: r = 0.77

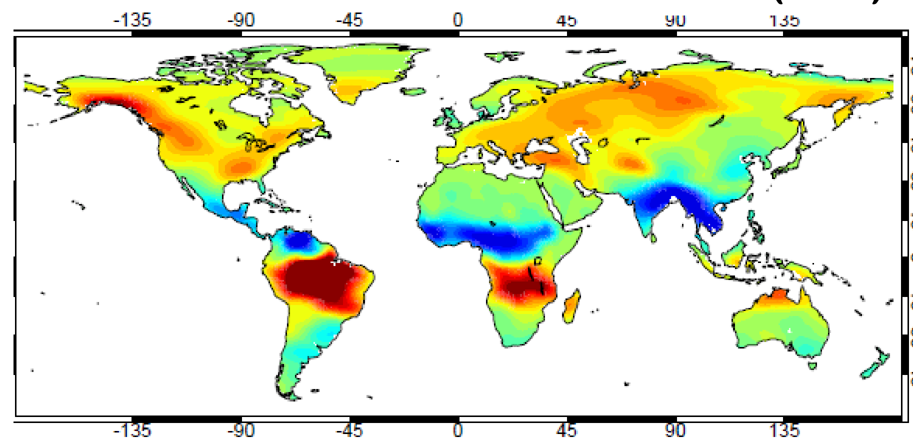


Soil (and snow) water storage (MAM – SON)

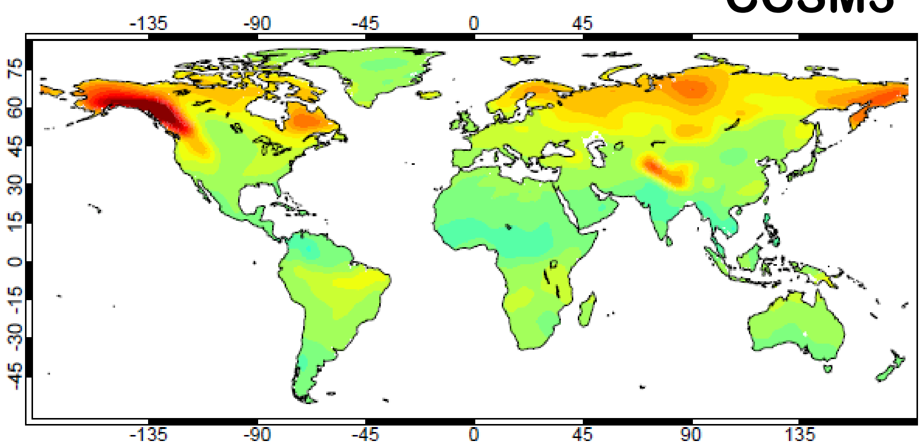
CCSM4

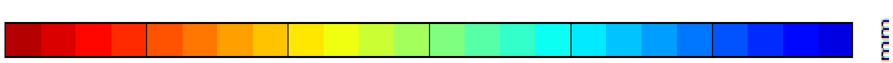


GRACE (obs)



CCSM3



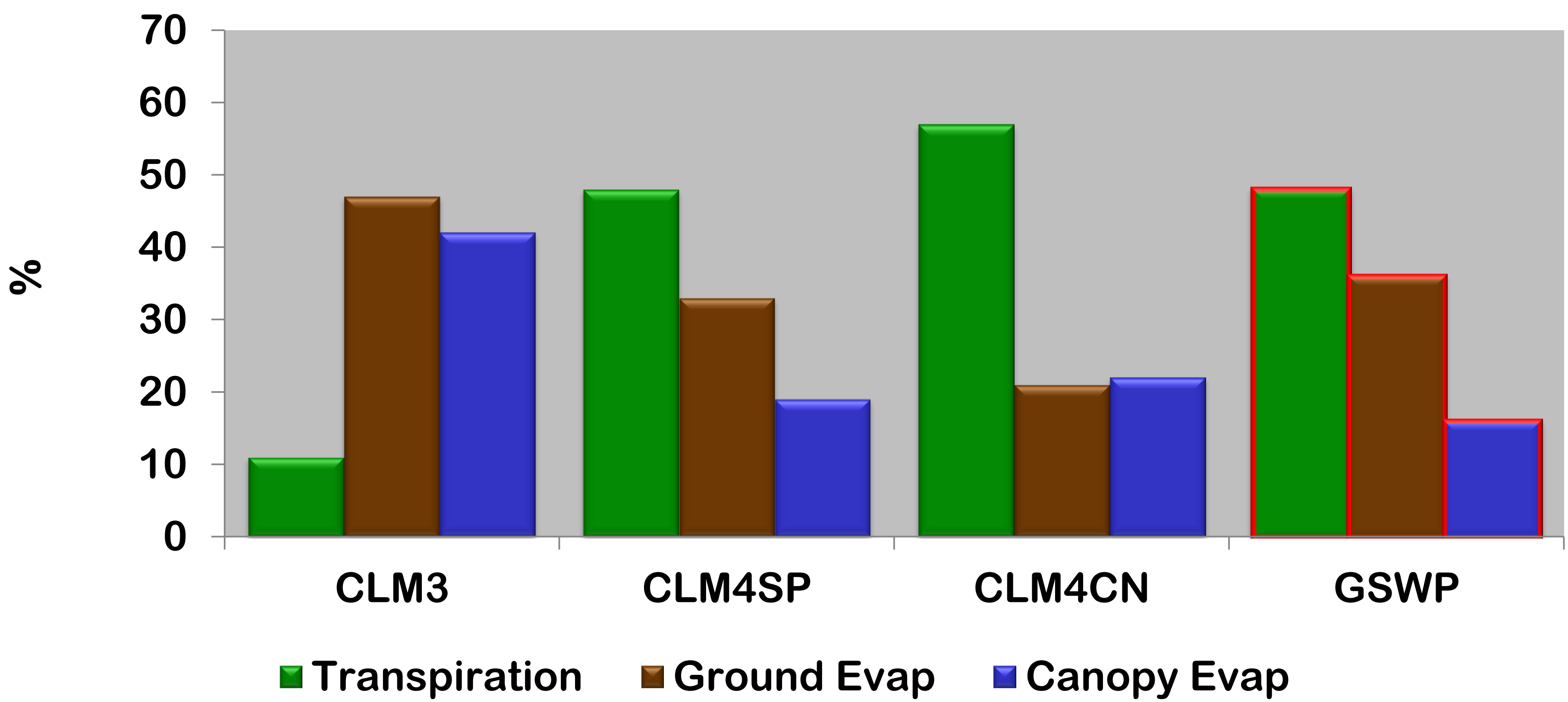


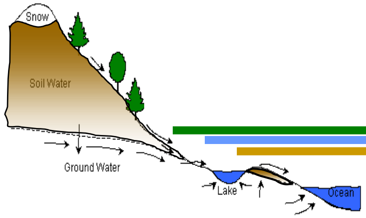
300 200 100 0 -100 -200 -300 (mm)

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

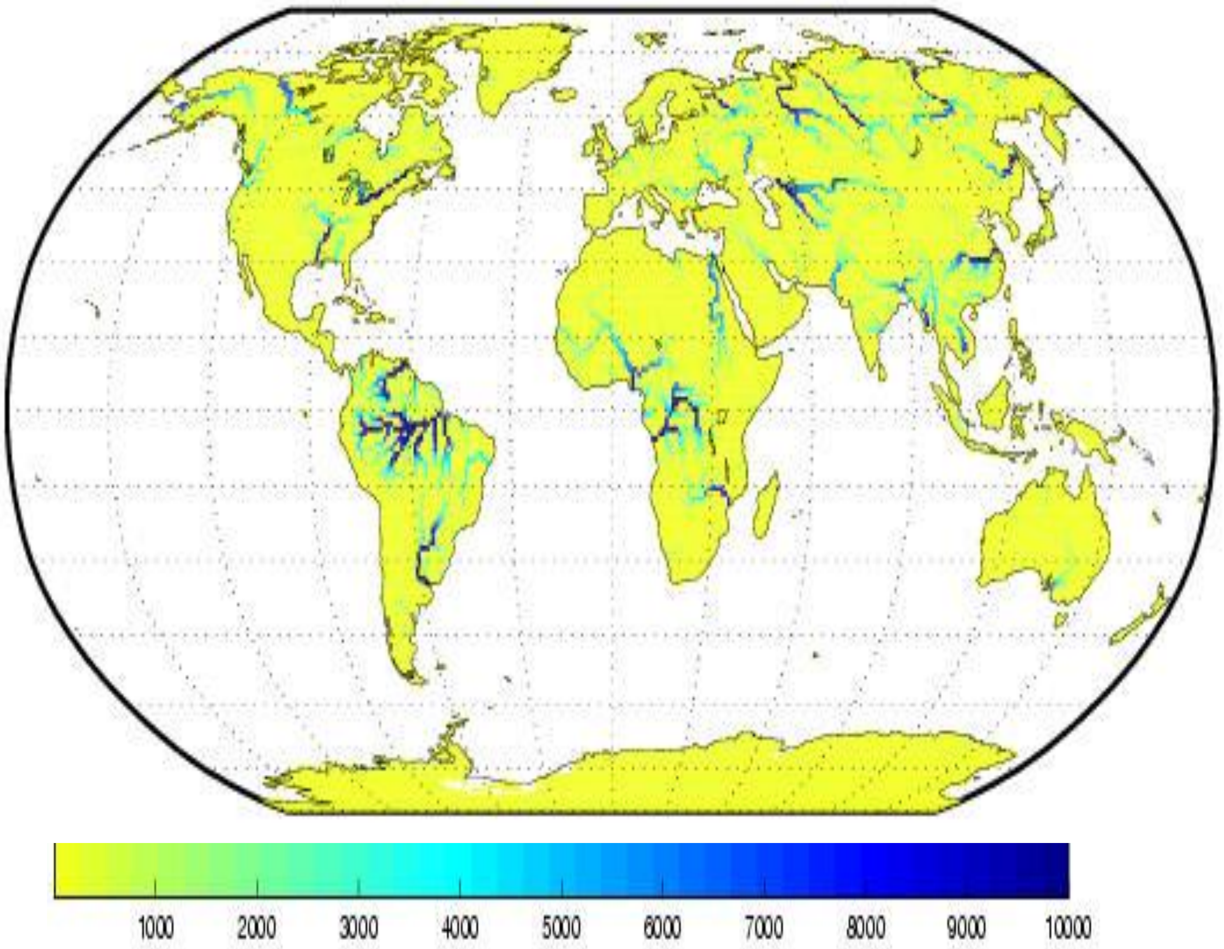
Global Partitioning of Evapotranspiration

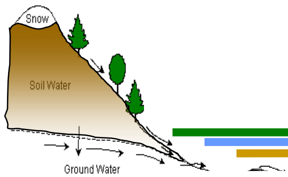




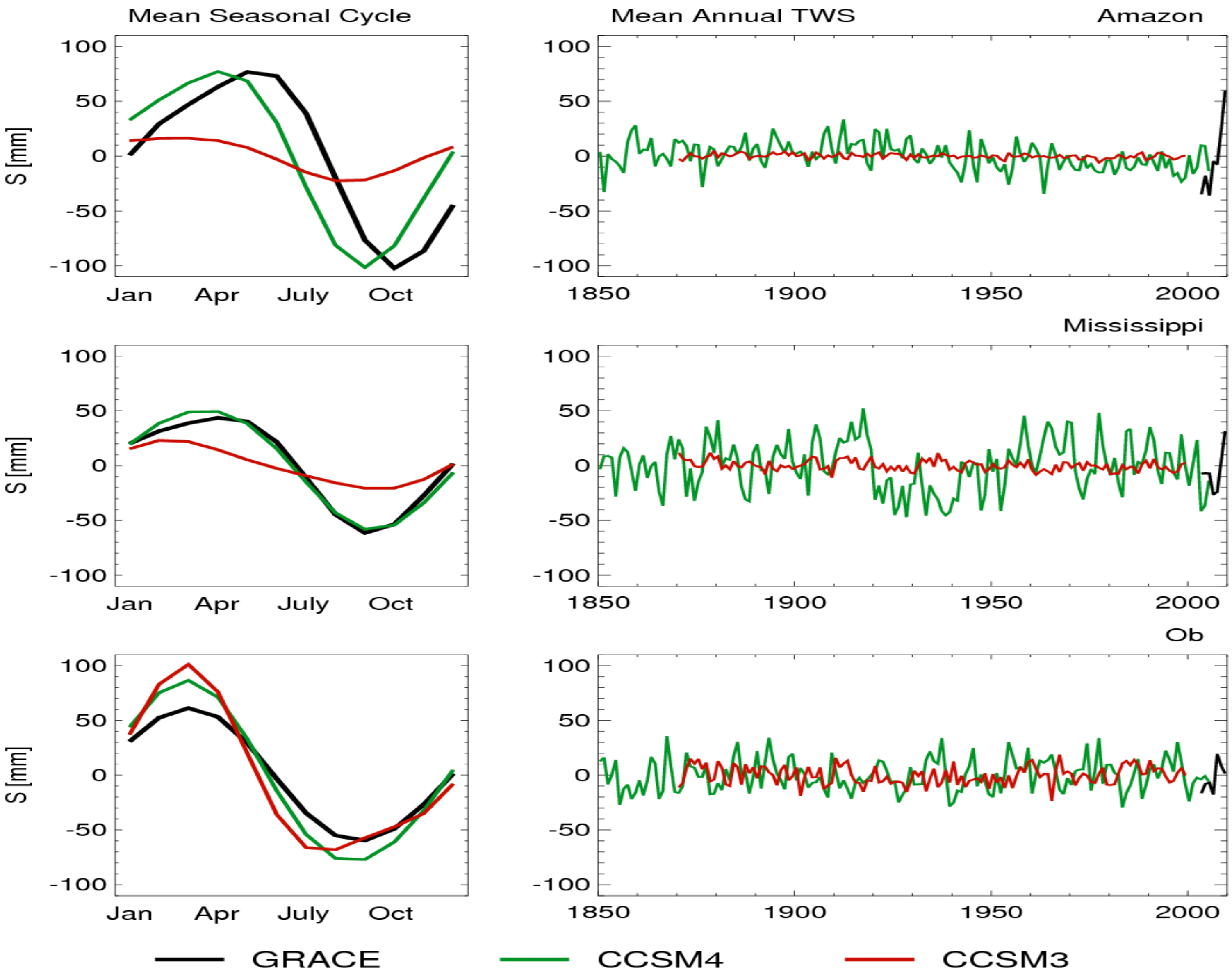
River Transport Model (RTM)

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





Total Land Water Storage (CCSM vs GRACE)



The roles of the land model in an Earth System Model

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