The Community Land Model, version 5

Building a community to build a community model

David Lawrence and many, many others

dlawren@ucar.edu

https://github.com/ESCOMP/ctsm

NCAR

NSF

This material is based upon work supported by the National Center for Atmospheric Research, which is a major facility sponsored by the National Science Foundation under Cooperative Agreement No. 1852977.

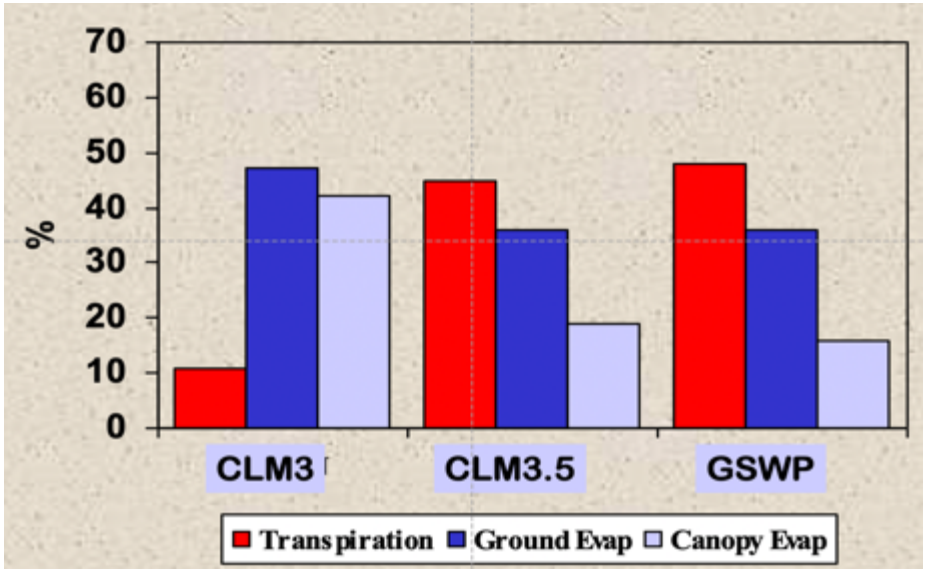
CCSM Distinguished Achievement Award to the Land Model Working Group

"for their cooperative work in producing CLM3.5 which is a considerable improvement over CLM3"

CLM3.5

- Updated surface data sets
- New parameterizations for canopy integration, canopy interception
- Frozen soil
- Soil evaporation
- TOPMODEL-based surface and subsurface runoff
- Simple groundwater model

Partitioning of Evapotranspiration



CLM3.5 (May 2007)

- Updated surface data sets
- New parameterizations for canopy integration, canopy interception
- Frozen soil
- Soil evaporation
- TOPMODEL-based surface and subsurface runoff
- Simple groundwater model

CLM3.5 CLM4 (June 2010)

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

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]

JAMES
JOURNAL OF ADVANCES IN MODELING EARTH SYSTEMS

- Updated surf
- New parame integration, c
- Frozen soil
- Soil evaporat
- TOPMODEL subsurface ru
- Simple groun

- Carbon and nitrogen model
- Prognostic vegetation state / phenology
- Transient land cover change
- Wood harvest
- 'Permafrost-enabled' – organic soil, deep ground
- Aerosol deposition onto snow
- Urban model

CLM4 widely used

> 1000 citations for paper

> 1300 citations for Tech Note

CLM3.5 CLM4 CLM4.5 (June 2013)

- Updated surf
- New parame integration, c
- Frozen soil
- Soil evaporat
- TOPMODEL- subsurface ru
- Simple groun

- Carbon and nitroge
- Prognostic vegetatic phenology
- Transient land cover
- Wood harvest
- 'Permafrost-enabled deep ground
- Aerosol deposition
- 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

CLM3.5 CLM4 CLM4.5 CLM5 (Feb 2018)




- Updatec
- New pa integrat
- Frozen
- Soil eva
- TOPMC subsurfa
- Simple g

- Carbon a
- Prognost phenolog
- Transient
- Wood ha
- 'Permafrc deep grou
- Aerosol
- Urban m

- Vertically-r
- Co-limitati of photosyr
- Variable riv
- Natural CH
- Human trig suppressior
- Cold regior
- Revised lak
- Multiple ur classes

- Flexible leaf stoichiometry
- Leaf N optimize for photosynthesis
- Carbon costs for plant N uptake
- Plant hydraulics w/ hydraulic redistribution
- Spatially explicit soil depth
- Dry surface layer, revised GW
- Revised canopy interception
- MOSART river model (hillslope → tributary → main channel)
- Canopy snow storage and radiation
- Fresh snow density (T, wind)
- Simple firn model

- Global crop model (8 crop types)
- Transient irrigation and fertilization
- Dynamic landunits (nat veg ←→ crop, *glacier* ←→ *nat veg*,)
- Urban heating and AC, heat stress indices
- Deforestation, cropland fire
- New PFT and CFT distributions
- Carbon isotopes
- *Coupled fire trace gas emissions Ecosystem demography (FATES),*
- *Ozone damage to plants*
- *Shifting cultivation*

JAMES | Journal of Advances in Modeling Earth Systems

Research Article | Open Access

The Community Land Model Version 5: Description of New Features, Benchmarking, and Impact of Forcing Uncertainty

David M. Lawrence, Rosie A. Fisher, Charles D. Koven, Keith W. Oleson, Sean C. Swenson, Gordon Bonan, Nathan Collier, Bardan Ghimire, Leo van Kampenhout, Daniel Kennedy, Erik Kluzek, Peter J. Lawrence, Fang Li, Hongyi Li, Danica Lombardozzi, William J. Riley, William J. Sacks, Mingjie Shi, Mariana Vertenstein, William R. Wieder, Chonggang Xu, Ashehad A. Ali, Andrew M. Badger, Gautam Bisht, Michiel van den Broeke, Michael A. Brunke, Sean P. Burns, Jonathan Buzan, Martyn Clark, Anthony Craig, Kyla Dahlin, Beth Drewniak, Joshua B. Fisher, Mark Flanner, Andrew M. Fox, Pierre Gentine, Forrest Hoffman, Gretchen Keppel-Aleks, Ryan Knox, Sanjiv Kumar, Jan Lenaerts, L. Ruby Leung, William H. Lipscomb, Yaqiong Lu, Ashutosh Pandey, Jon D. Pelletier, Justin Perket, James T. Randerson, Daniel M. Ricciuto, Benjamin M. Sanderson, Andrew Slater, Zachary M. Subin, Jinyun Tang, R. Quinn Thomas, Maria Val Martin, Xubin Zeng ... See fewer authors

First published:19 October 2019 | https://doi.org/10.1029/2018MS001583 | Citations: 30

More than 50 researchers from ~30 institutions involved in development and assessment of CLM5

CLM land-only forced with GSWP3

for full CLM results:
www.cesm.ucar.edu/experiments/cesm2.0/land/diagnostics/clm_diag_ILAMB.html

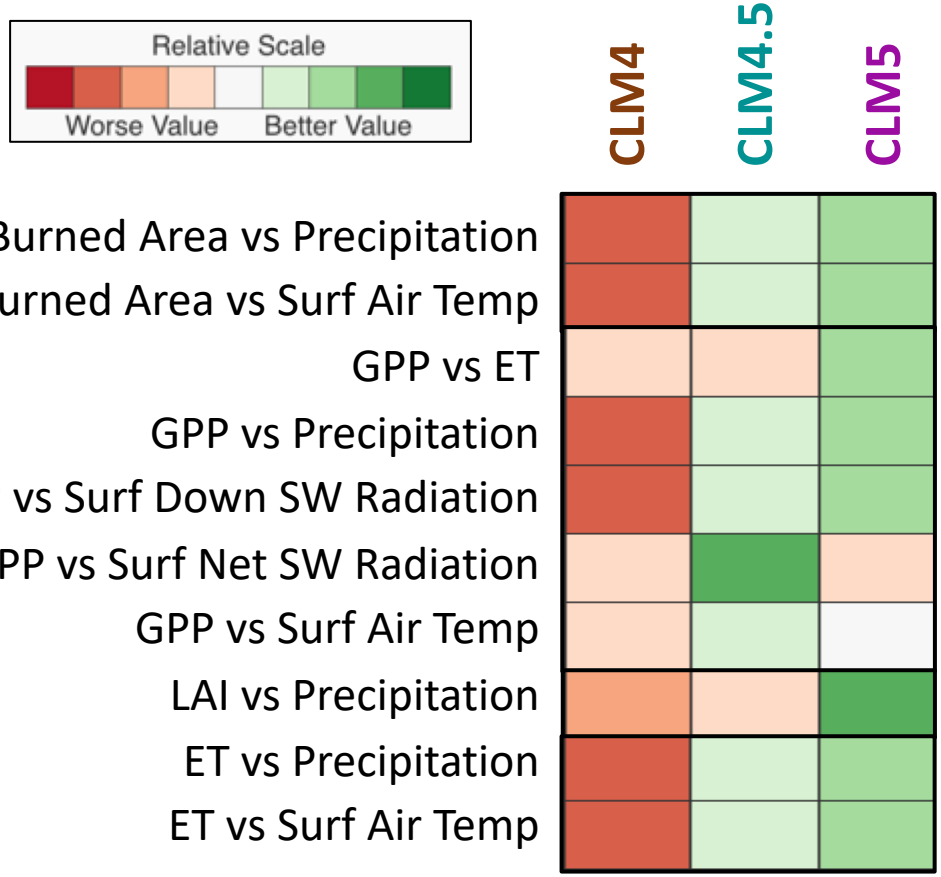
International Land Model Benchmarking (ILAMB) project

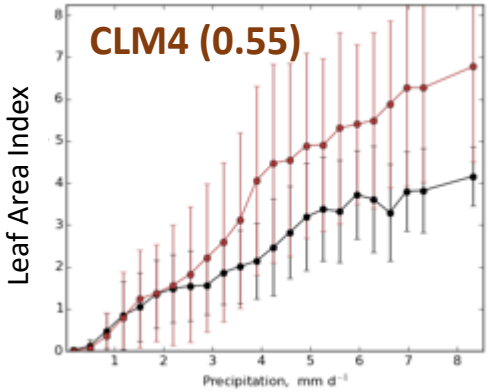
- Integrates analysis of ~30 variables against 70+ global, regional, and site-level observational datasets
- Graphics and scoring system for
  - RMSE
  - bias
  - seasonal cycle phase
  - spatial patterns
  - interannual variability
  - variable-to-variable relationships

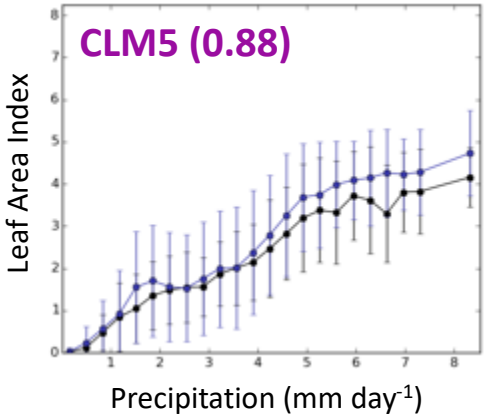
Lawrence et al., 2019

RUBISCO

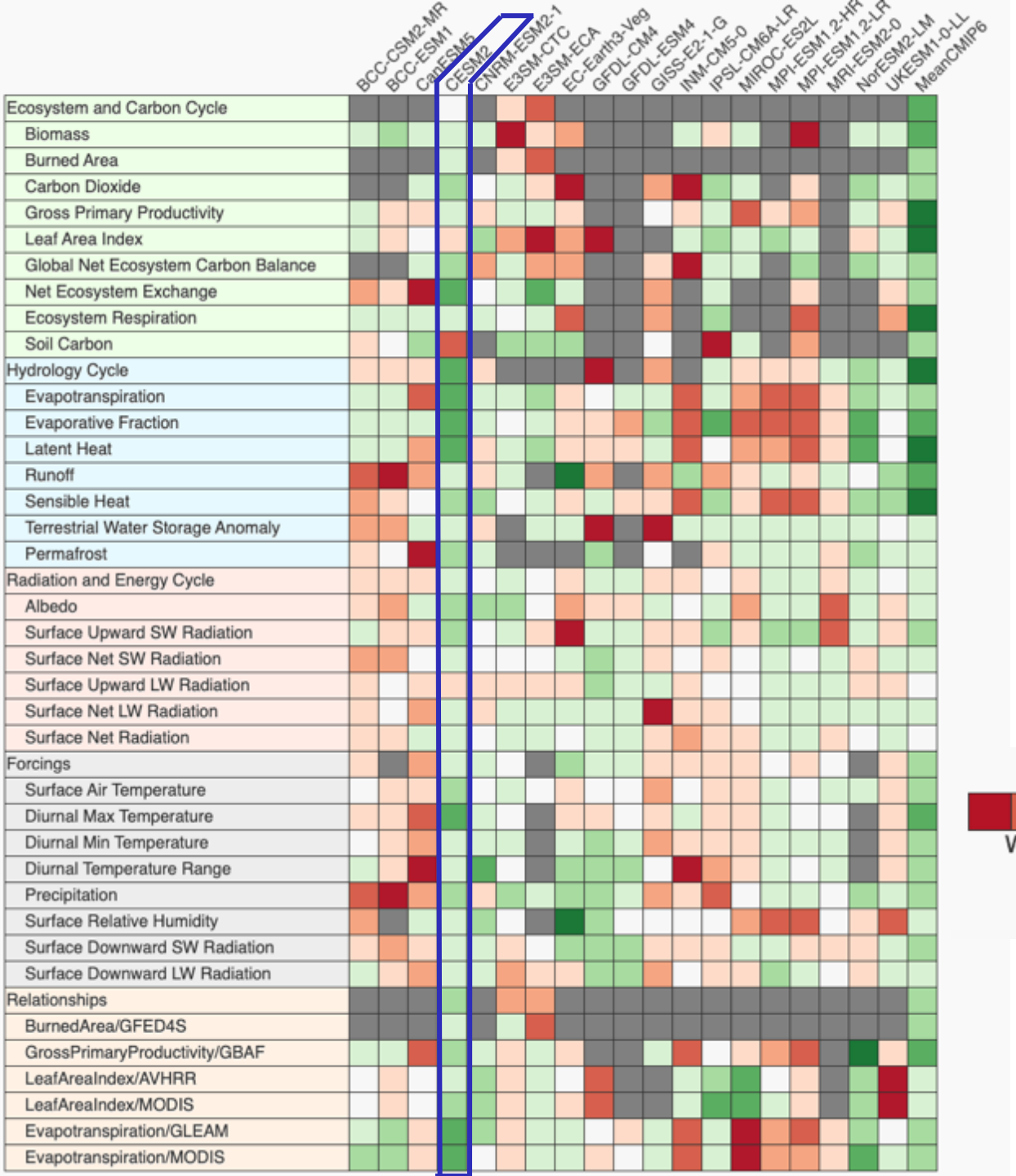
Variable-to-variable comparisons







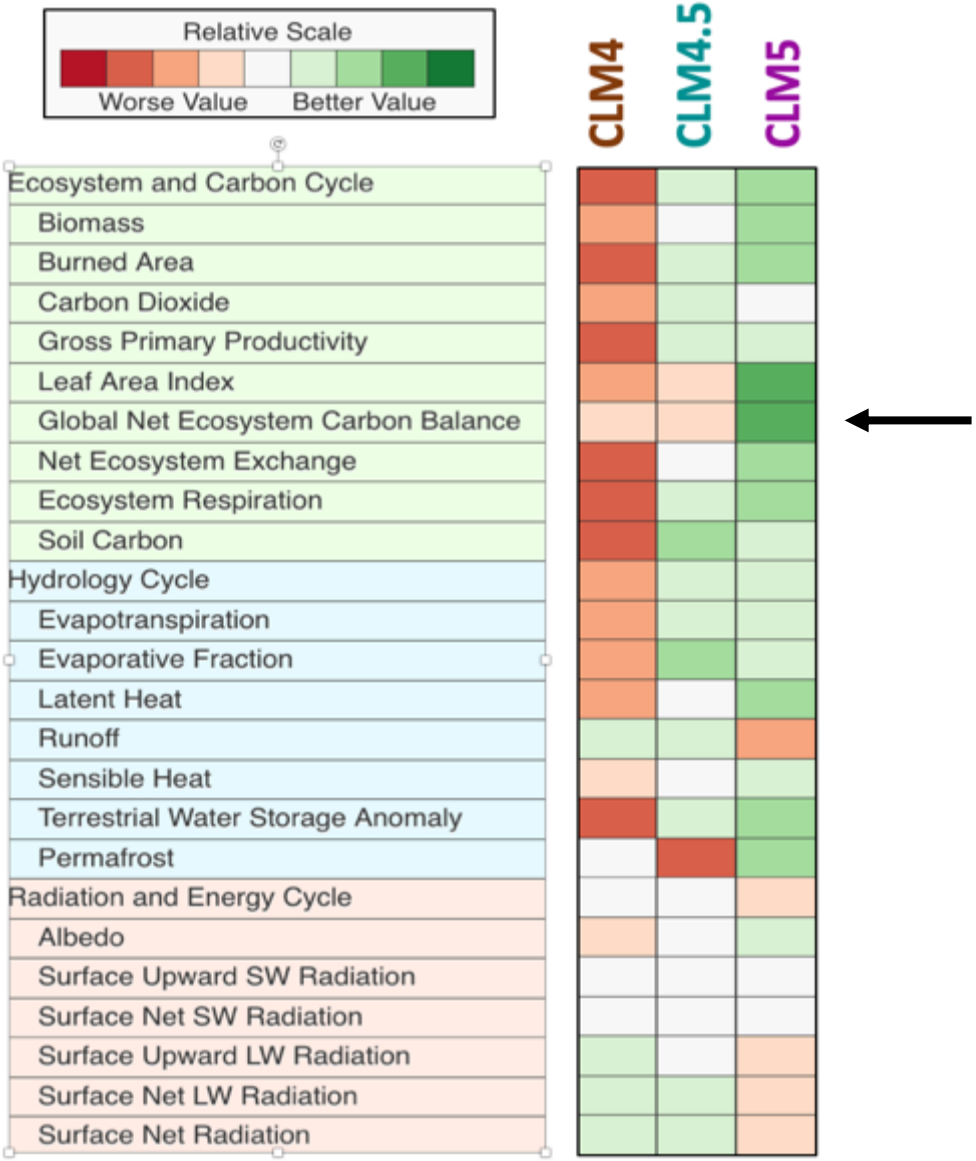
ILAMB assessment of CMIP6 models



Hoffman et al, in prep

RUBISCO

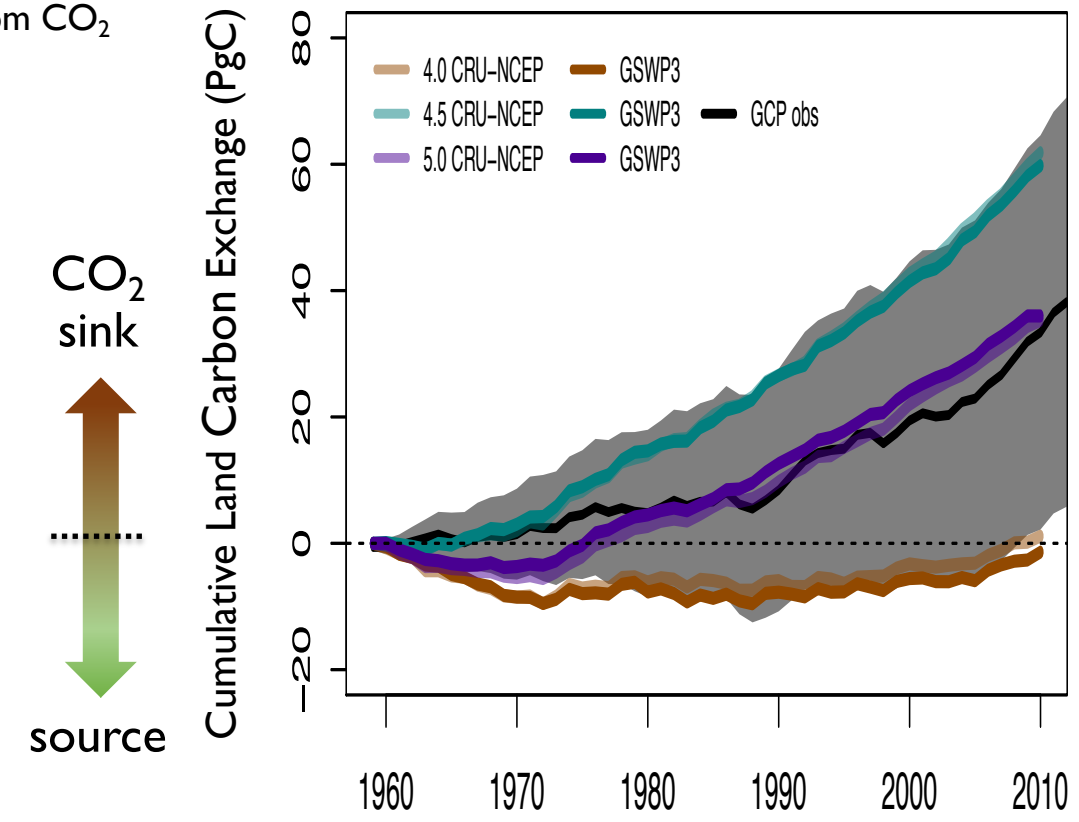
CLM land-only forced with GSWP3



RUBISCO

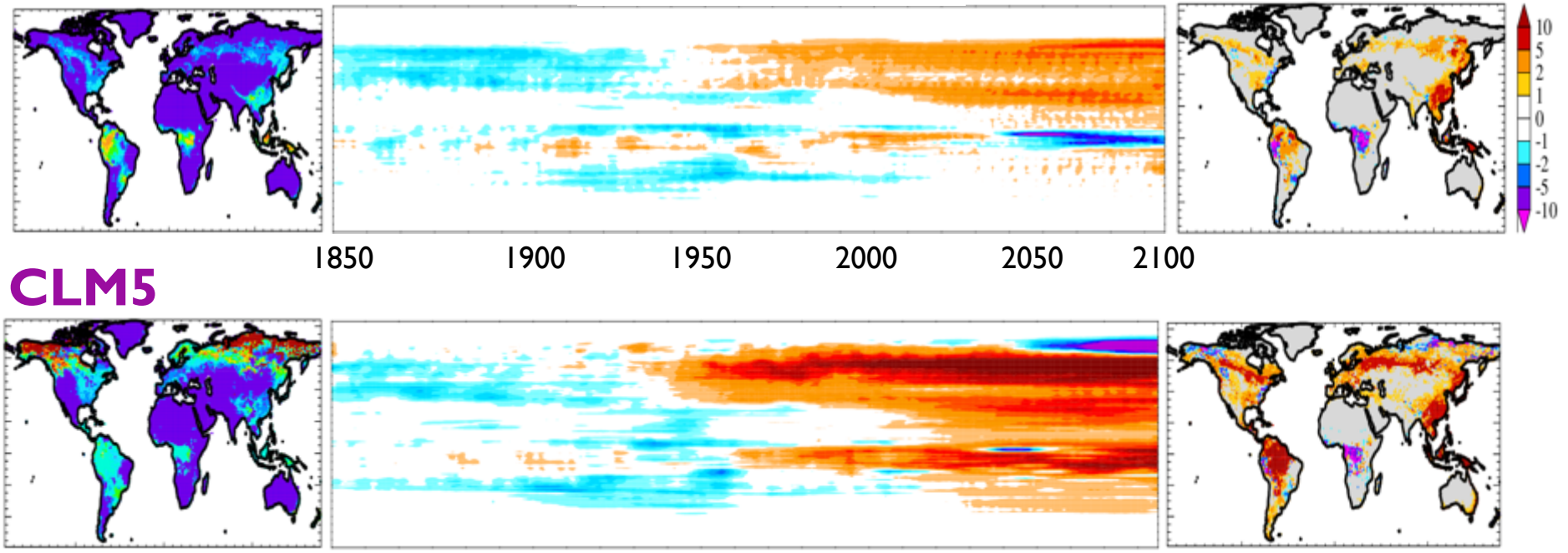
Cumulative historical land carbon fluxes

1 PgC ≅ 0.5 ppm CO_2



- Improved response to CO_2 and N-addition (Wieder et al., 2019)
- On longer timescales, uncertainty associated with historical climate uncertainty is high (Bonan et al., 2019)
- Strong parametric dependence (Fisher et al., 2019)

Land carbon stock trends

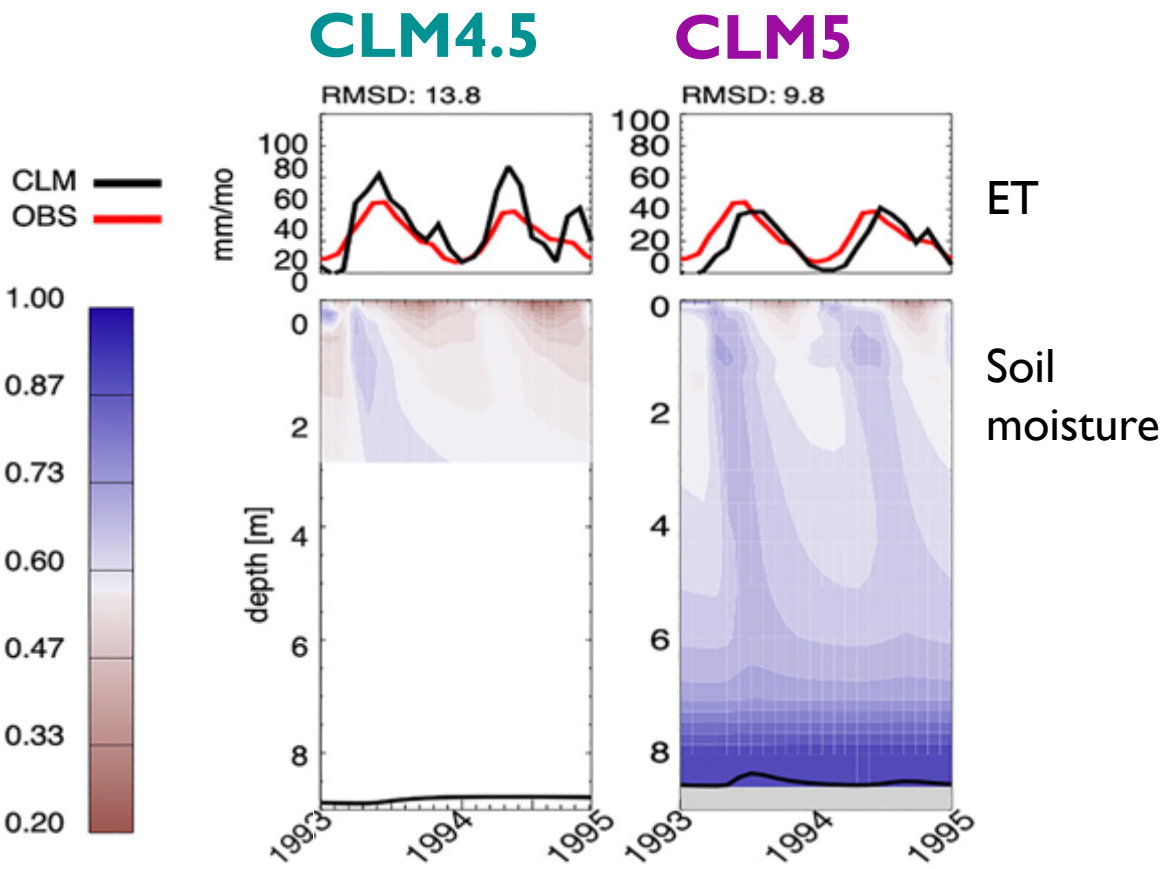


Zonal mean year-on-year changes in land ecosystem carbon

Blues are losses of carbon
Reds are gains of carbon

Soil hydrology (variable soil depth)

Grid cell in southwest US

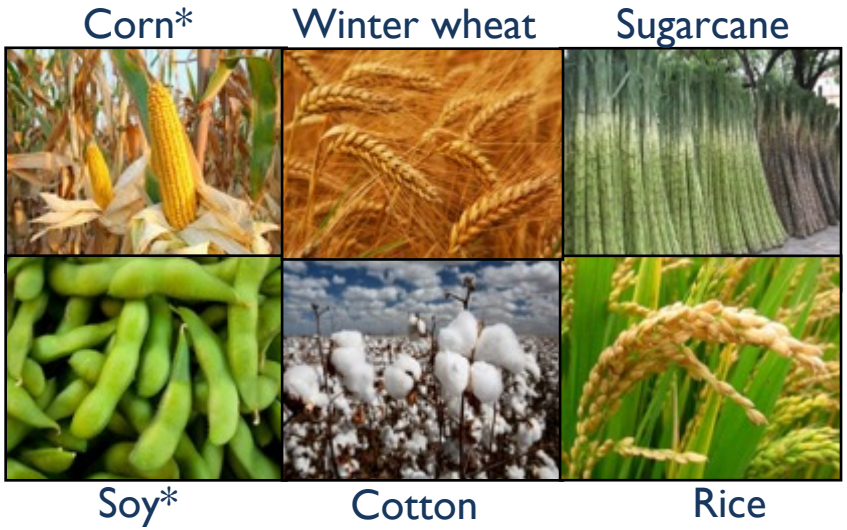


Land management in CLM5

Exploring tradeoffs and co-benefits of various forms of land management

Included in default CLM5/CESM2

- Global crop model; planting, grain fill, harvest
- Crop irrigation
- Crop industrial fertilization
- Wood harvest
- Urban environments
- Anthropogenic fire ignition and suppression, degradation fires

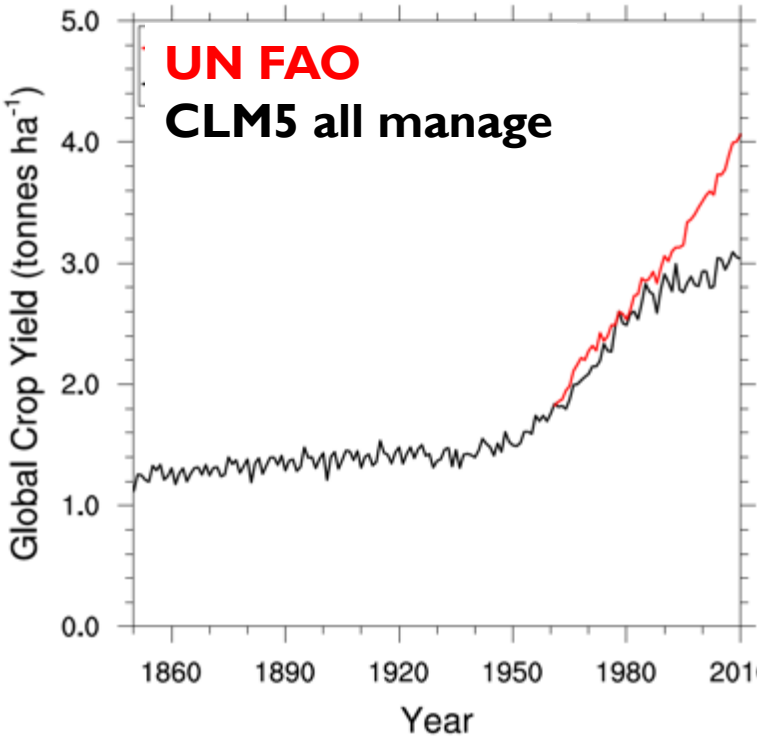


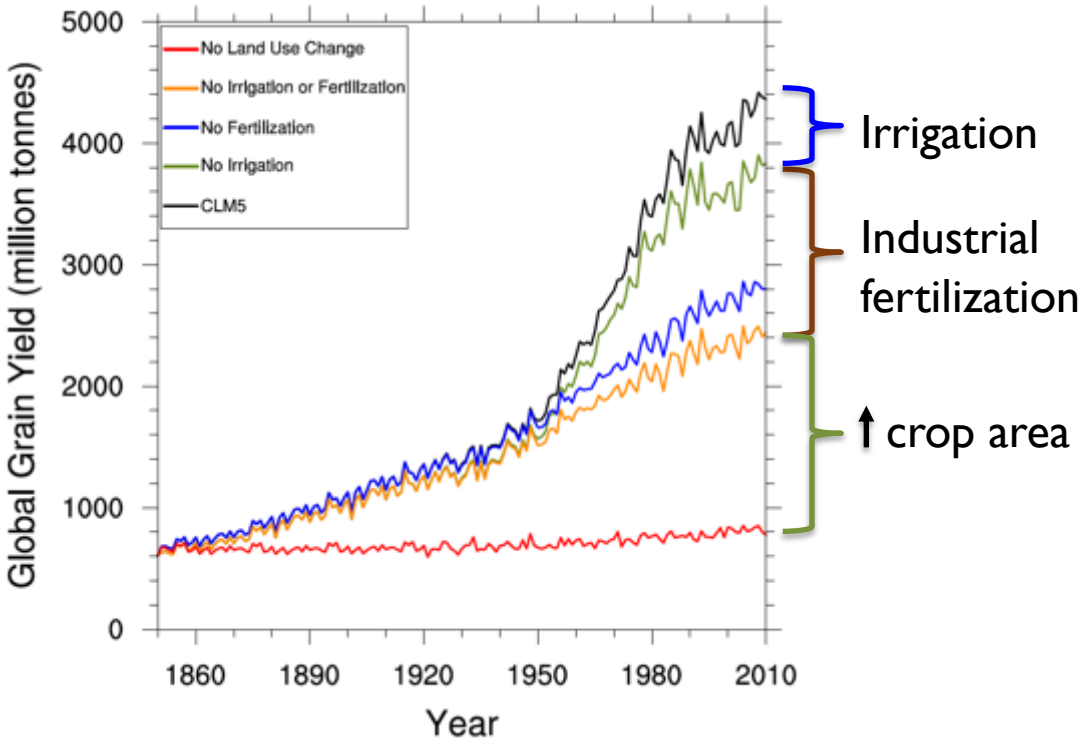
* *Temperate and tropical varieties*

Land-only land management experiments with CLM5

Embedded impacts model

Crop Yield





Lombardozzi et al., 2020

Terrestrial Processes in CMIP6

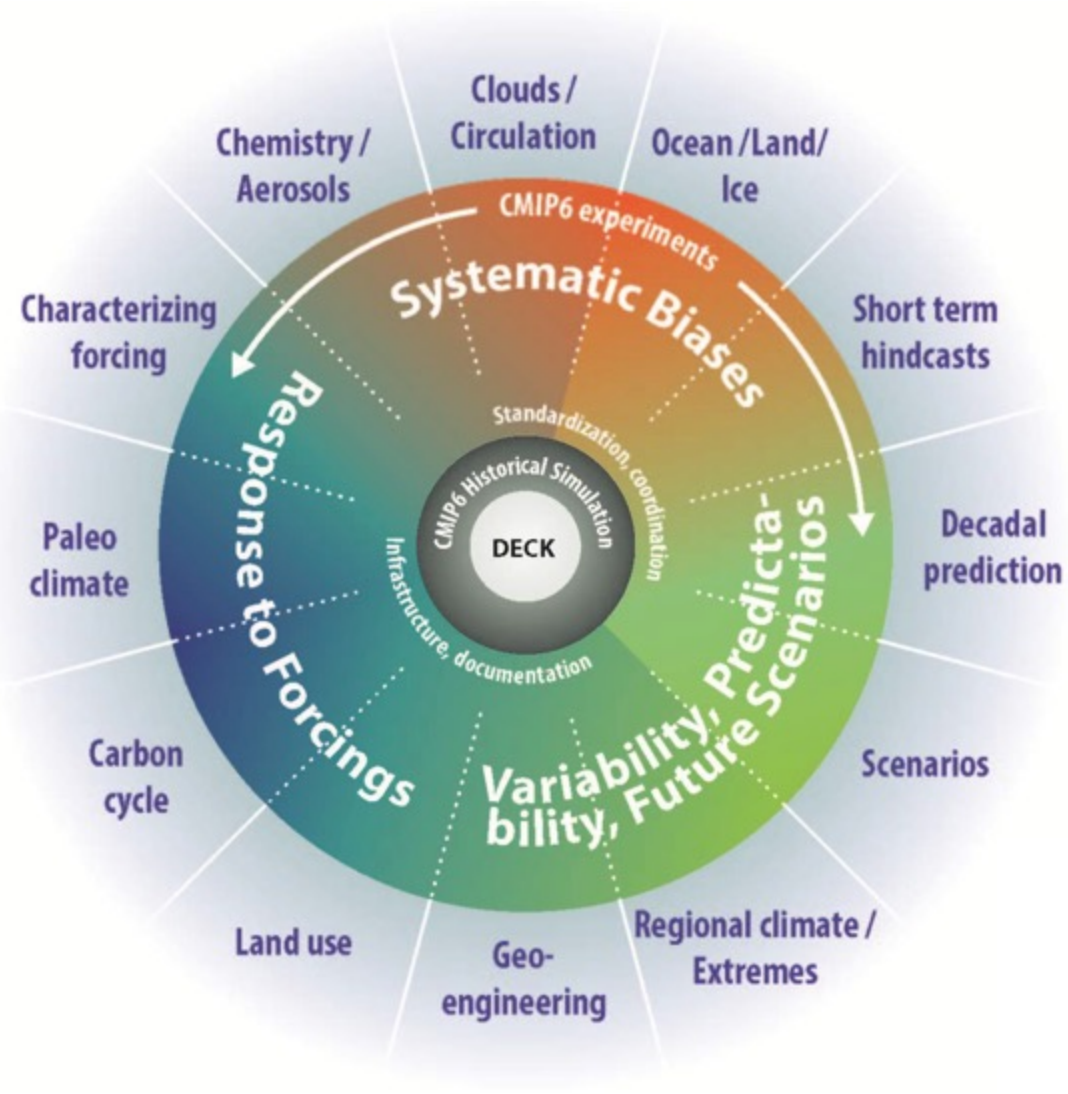
Coordinated activities to assess land role and response to climate and climate change

- **Land-only** simulations forced with obs historical climate, land systematic biases

- **Land Use (LUMIP)**
  land use forcing on climate and carbon, impacts of land management, land management as mitigation

- **Water, Land-atmos (LS3MIP)**
  biogeophys feedbacks including soil moisture and snow feedbacks

- **Carbon (C4MIP)**
  land biogeochemical feedbacks on climate, permissible emissions

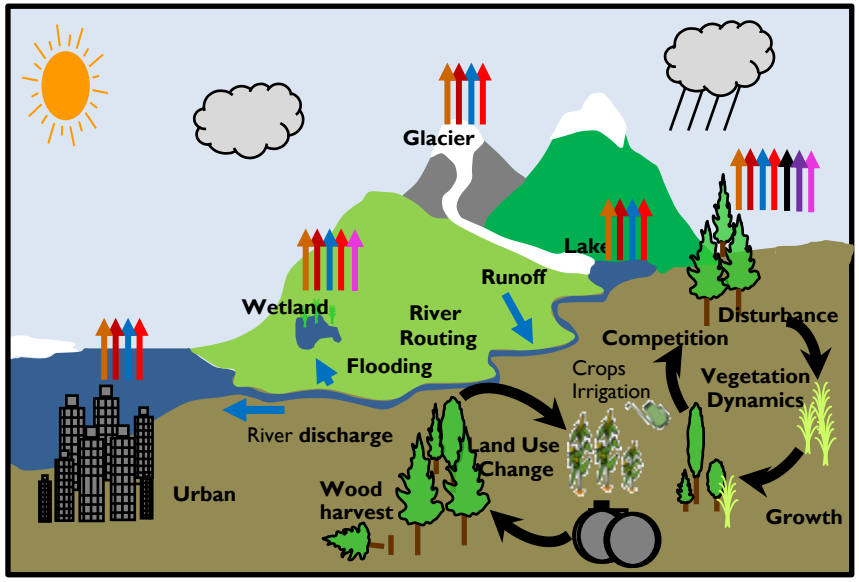


The CLM5 Development Process

Scientific priorities driving CLM development

Understanding and predicting …

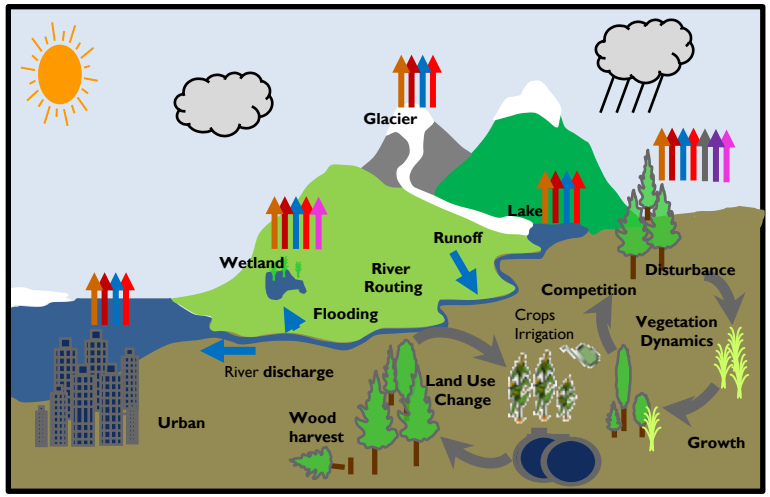
- land processes in weather, climate variability, and climate change
- ecosystem vulnerability/resilience and impacts on carbon cycle and ecosystem services
- sources of predictability from land; ecological prediction
- land management for climate change and GHG mitigation; tradeoffs and co-benefits
- water and food security

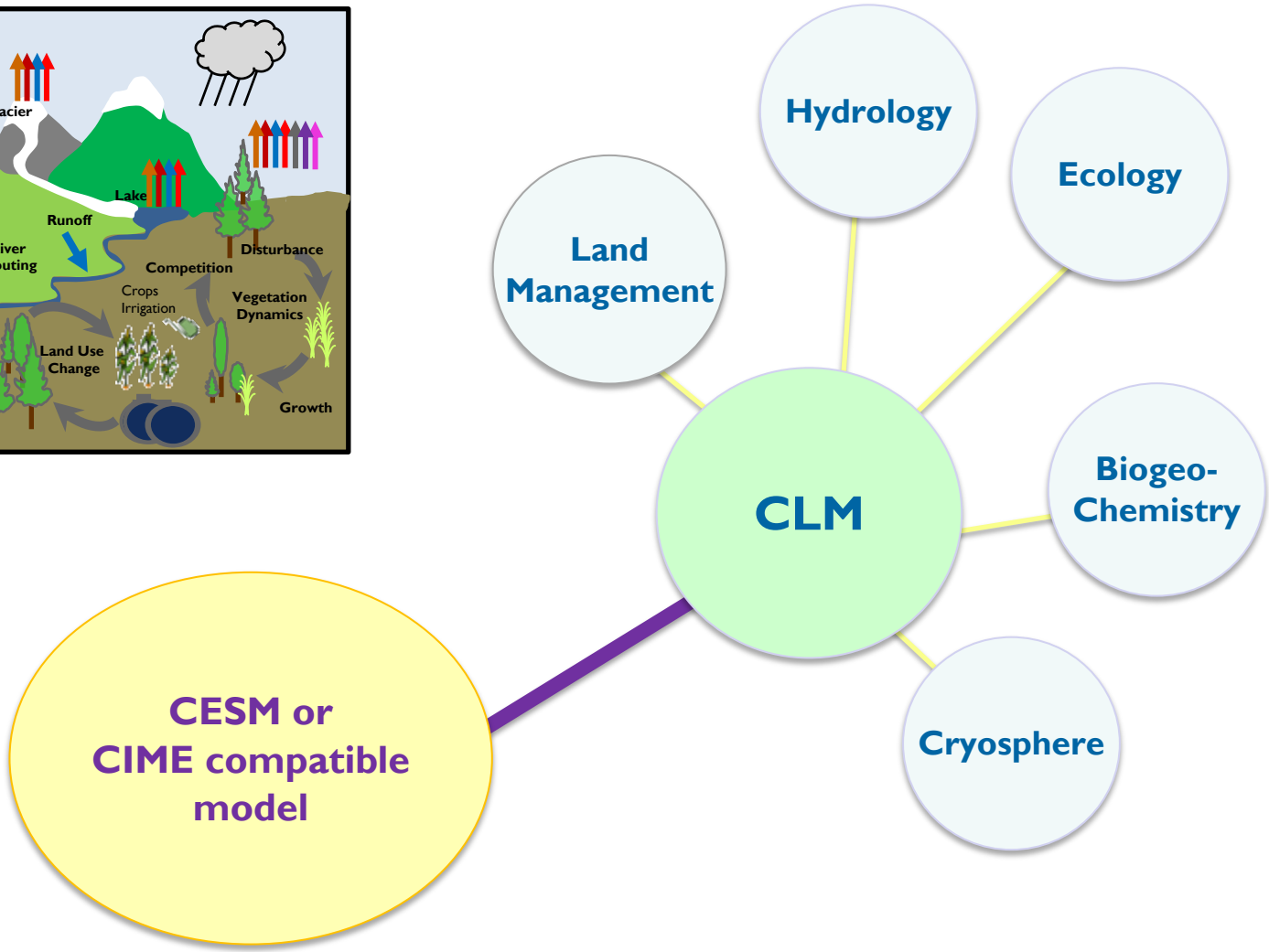


For CLM5, parallel focus on mechanistic improvements and expansion of capabilities

- hydrology more consistent with state-of-art understanding
- more ecologically-relevant plant carbon, nutrient, and water dynamics
- expansion of representation of land management

The community that built CLM5





The community that built CLM5

Contributions rolling in from 2012-2016

A big pile of things, will they work together?

- Flexible leaf stoichiometry
- Leaf N optimize for photosynthesis
- Carbon costs for plant N uptake
- Plant hydraulics w/ hydraulic redistribution
- Spatially explicit soil depth
- Dry surface layer, revised GW
- Revised Canopy interception
- MOSART river model (hillslope → tributary → main channel)
- Canopy snow storage and radiation
- Fresh snow density (T, wind)
- Simple firn model
- Global crop model (8 crop types)
- Transient irrigation and fertilization
- Dynamic landunits (nat veg ←→ crop, *glacier ←→ nat veg*,)
- Urban heating and AC, heat stress indices
- Deforestation, cropland fire
- New PFT and CFT distributions
- Carbon isotopes
- *Coupled fire trace gas emissions*
  Ecosystem demography (FATES),
- *Ozone damage to plants*
- *Shifting cultivation*

A big pile of things, will they work together?

Software integration



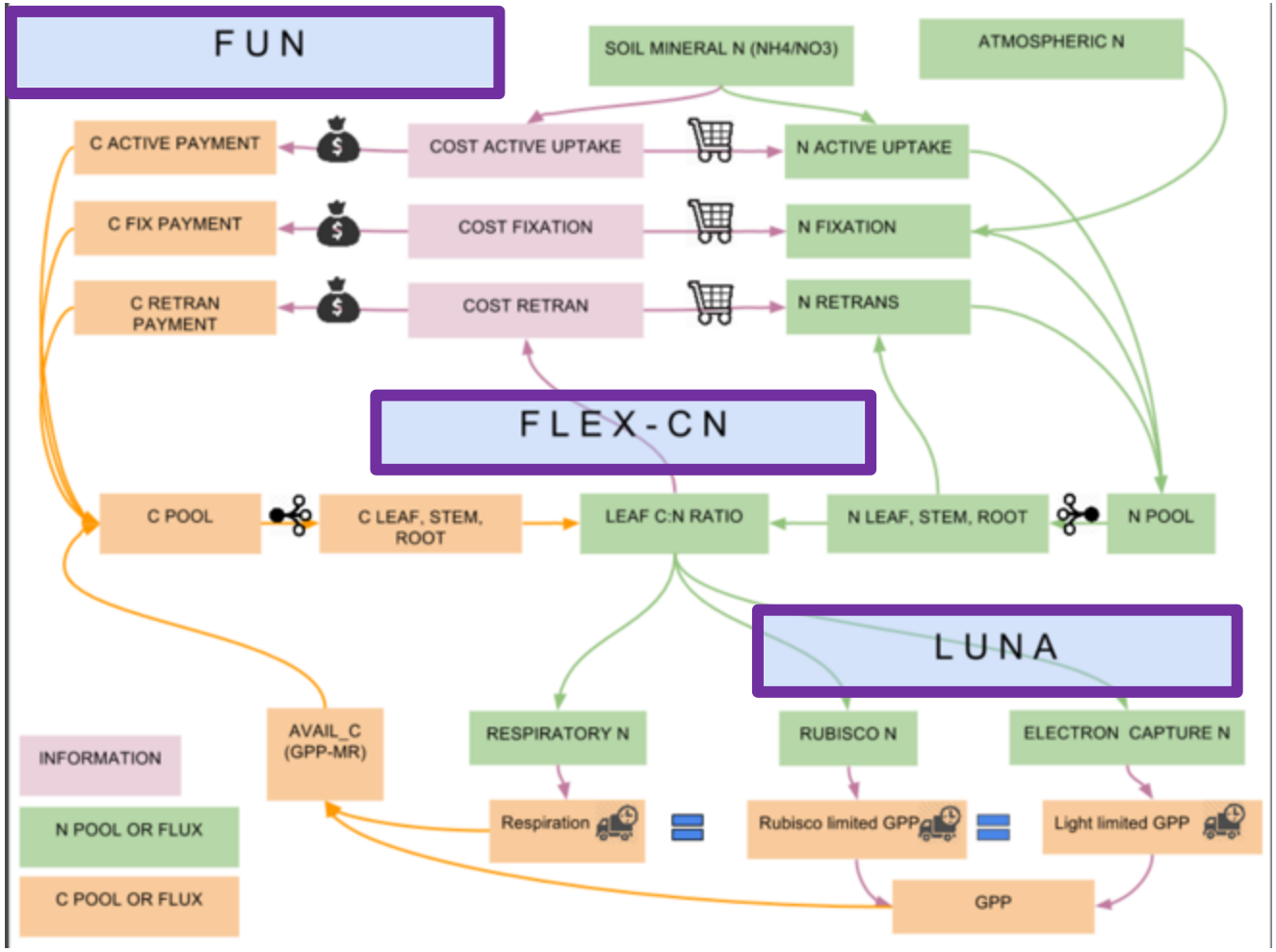
… and science integration



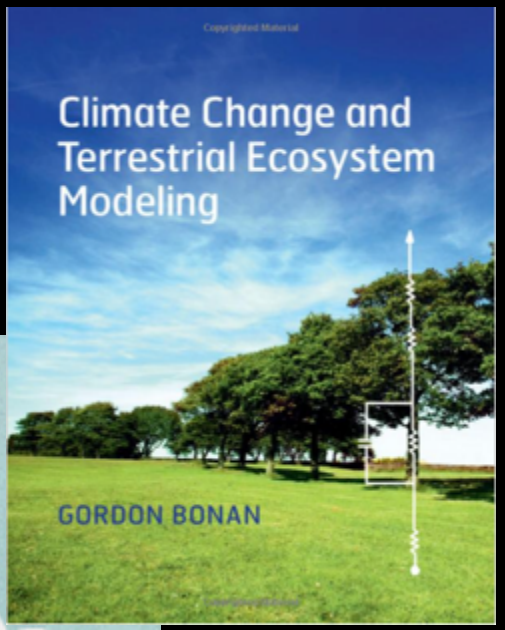


A big pile of things, will they work together?

Merging 3 branches of nitrogen-cycle development



Integration of contributions



Integration of contributions into CLM

Finally, a model configuration that runs with everything we wanted

software integration



… and science integration



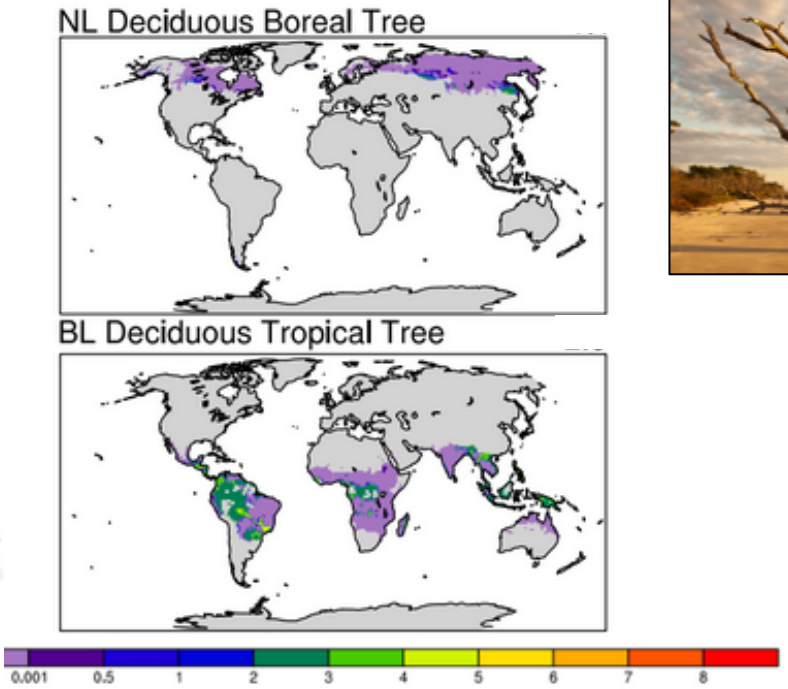


Integration of contributions into CLM

Finally, a model configuration that runs with everything we wanted

… but many new uncertain parameters and a growing realization that in some parts of the parameter space, plants do not survive through spinup

"The Dead Plant Problem"

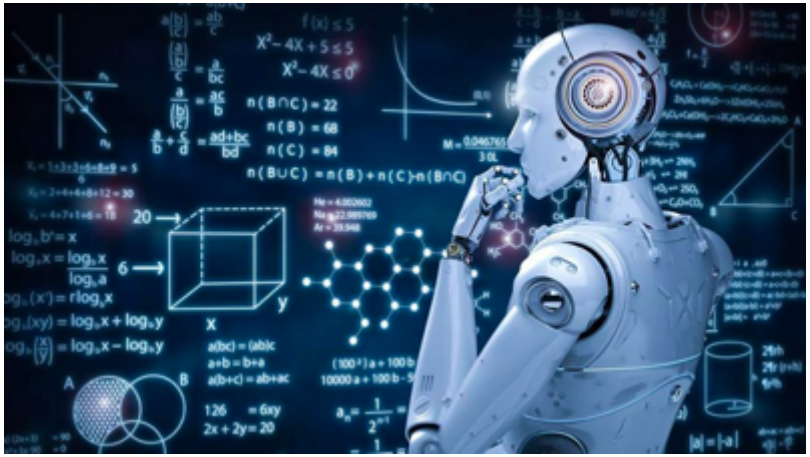


Leaf Area Index

Solving the Dead Plant Problem

many attempts, mostly dead

Global parameter optimization
via machine learning!



… meanwhile, the rest of the team focused on painstaking 'hand-tuning' of parameters

... while I ran interference with Jean-Francois

January 25, 2017 (a reenactment)

The scene: We were desperately trying to finalize CESM2 so that we could take advantage of the Cheyenne / Yellowstone overlap to run CMIP simulations. After multiple extensions, Jean-Francois gave us one last weekend to sort out our parameter problems or revert to CLM4.5. On Friday, Keith Oleson set off two CLM spinups, one with a new machine-learning calibrated parameter set and one with our best hand-tuned parameters.

6:45am Monday morning: Keith comes into my office and shows me the calibrated parameter results – mainly dead plants. Dave – "ok, that's expected, check the other parameter set."

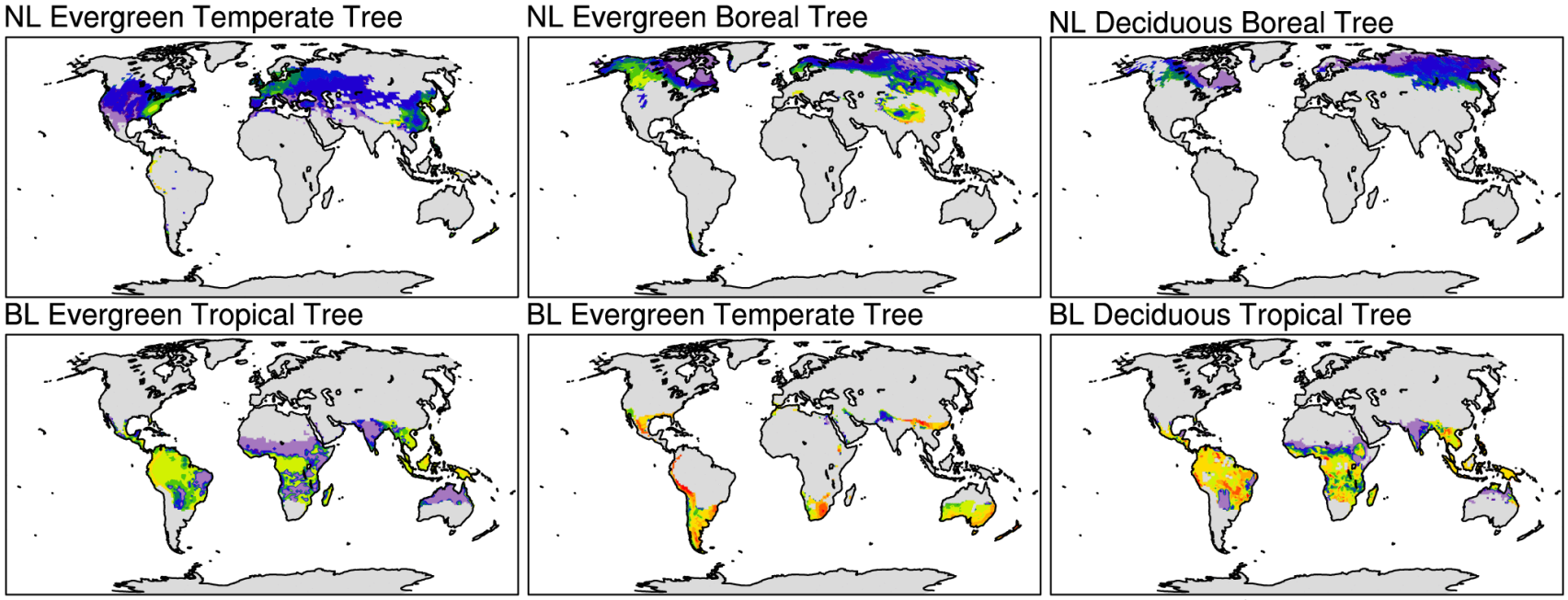
10 minutes later: email from Keith – "Plants in backup parameter set are not surviving either. Uh-oh."

20 minutes later: another email from Keith – "Scratch that. Bug in my code. Backup parameter set results looks great!"

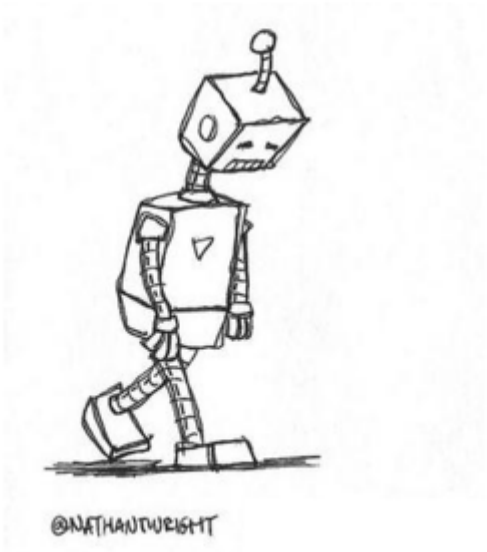
Solving the Dead Plant Problem

Finally, most plants were living and many other metrics looked good

b.e20.BHIST.f09_g17.20thC.215_01_1888: ANN Max TLAI (m^2 m^{-2})



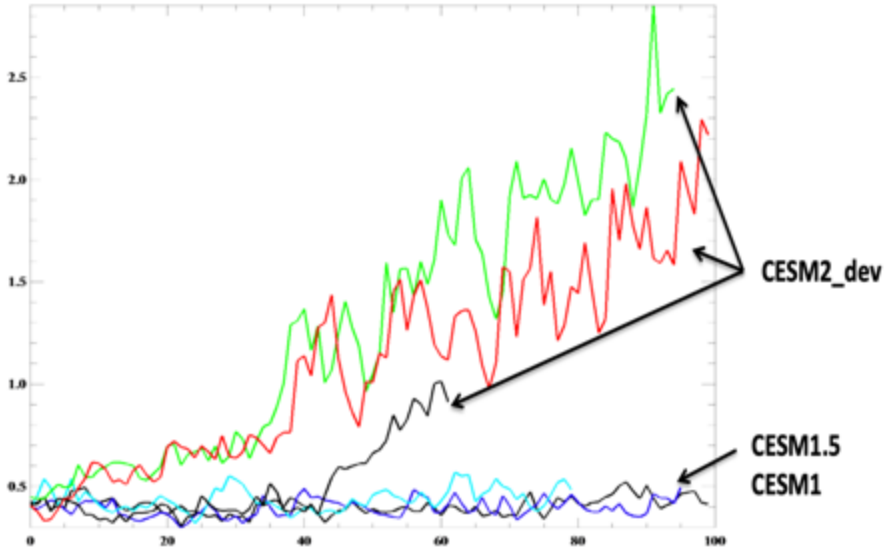
Misadventures in parameterization and why the robots haven't won (yet)



Ben Sanderson, Rosie Fisher, David Lawrence, Keith Oleson and Will Weider

(YET)
see intro to CLM5 Large Parameter Perturbation Experiments Community Project in Will Wieder's LMWG presentation this afternoon

Timeseries of sea ice thickness in Labrador sea



Chimera-like parameter file

Solving the Dead Plant Problem

The giant crop problem

The irrigation problem

The glacier runoff problem

The C4 grass productivity problem

The hydraulic redistribution problem

The energy conservation problem

…

February 2018 CLM5 Release!

Perspectives on community driven model development

- Earth System model development is hard
- Research priorities can be used to guide decisions
- A robust and diverse development and user community is essential (and fun)
- Build and maintain that community
  - Be responsive to contributing collaborators
  - Encourage contributors to take ownership
  - Provide clear software development and decision-making guidance
  - Acknowledge and reward model development

LMWG Andrew Slater Award

Annual award, sponsored by Drew's family, for the "best student or postdoc performance" at winter LMWG meeting

The Land Model Working Group

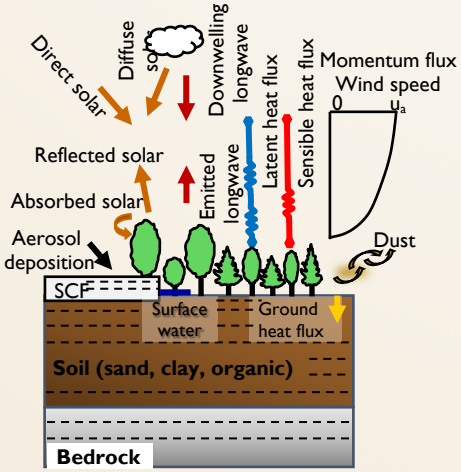
Andrew Slater Award

Is hereby granted to:

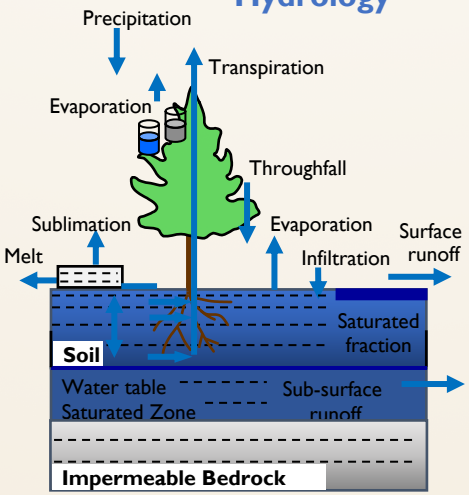
???

for best student or postdoc performance at LMWG Workshop

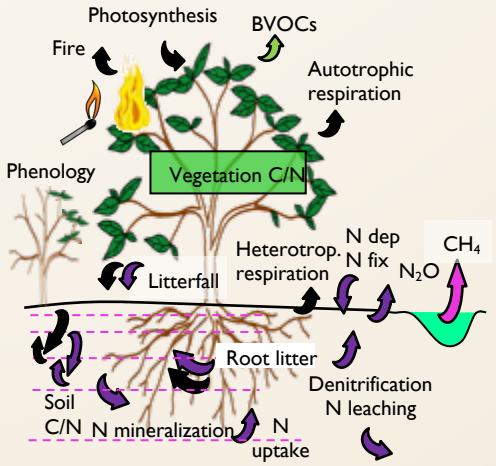
Surface energy fluxes



Hydrology



Biogeochemical cycles



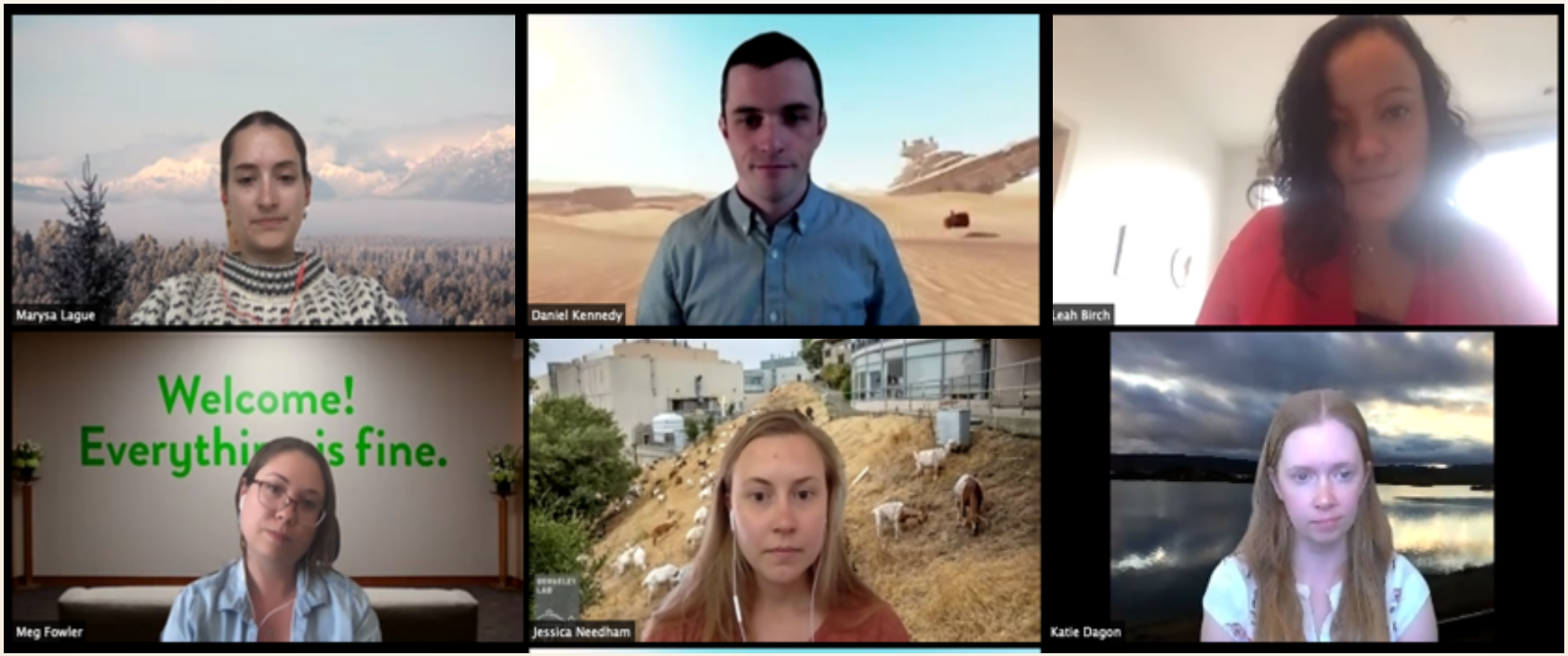
The Land Model Working Group

Andrew Slater Award

Marysa Laguë
U. Washington

Daniel Kennedy
Columbia University

Leah Birch
Woods Hole Inst



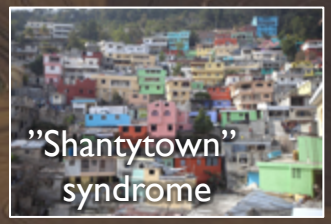
Megan Fowler
UC Irvine

Jesse Needham
LBNL

Katie Dagon
NCAR

Perspectives on community driven model development

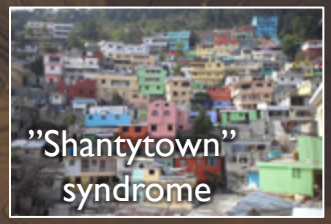
- Earth System model development is hard
- Research priorities can be used to guide decisions
- A robust and diverse development and user community is essential (and fun)
- Build and maintain that community
- Clean, well-structured, and well-documented code is worth its weight in gold
- Full integration requires in-house experts
- Set realistic timelines and try hard to meet them



- Not: "I love deadlines. I like the whooshing sound they make as they fly by." – Douglas Adams

Perspectives on community driven model development

- Earth System model development is hard
- Research priorities can be used to guide decisions
- A robust and diverse development and user community is essential (and fun)
- Build and maintain that community
- Clean, well-structured, and well-documented code is worth its weight in gold
- Full integration requires in-house experts
- Set realistic timelines and try hard to meet them
- Don't panic!
- Keep it fun!



Keep it fun!

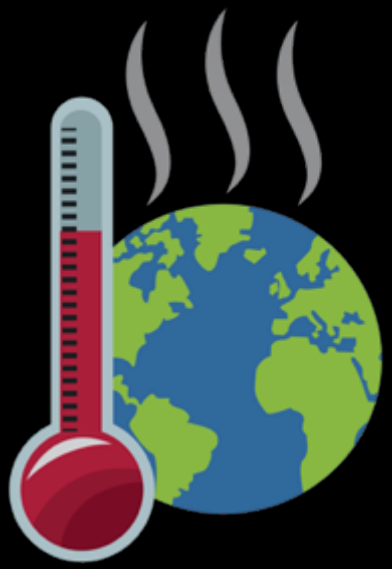
Keep it fun!

"Some people think football (soccer)
is a matter of life and death

… I assure you, it's much more serious than that"

Keep it fun!

"Some people think climate / land modeling is a matter of life and death



… I assure you, it's much more serious than that"

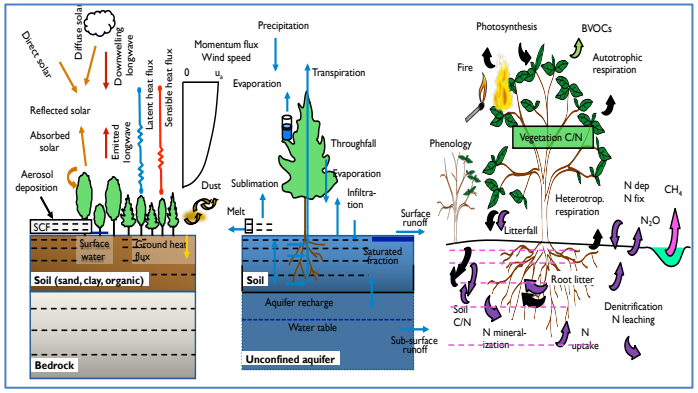
Thanks again!

The "situation"

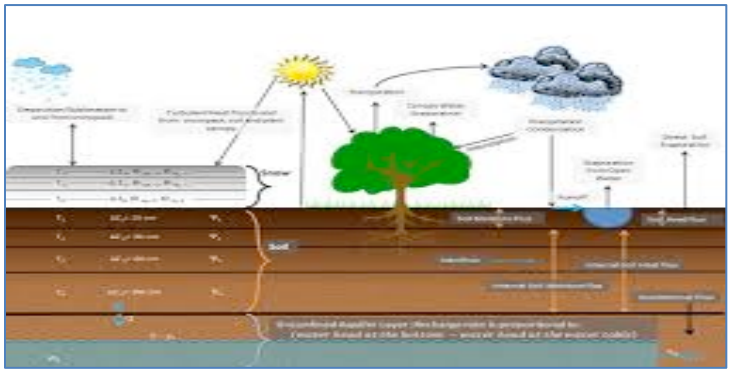
1. Model proliferation

Increasing number of land models, including 2 major models at NCAR

CLM (CGD)



Noah-MP, WRF-Hydro (RAL)



2. "Shantytown" syndrome

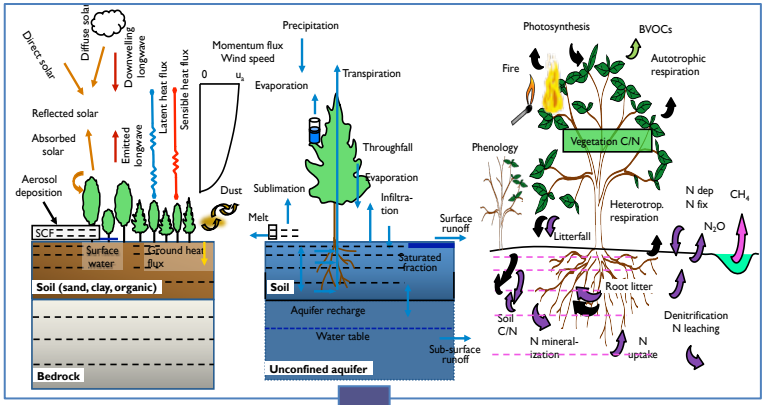
Ad-hoc approach to model development

The Community Terrestrial Systems Model

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

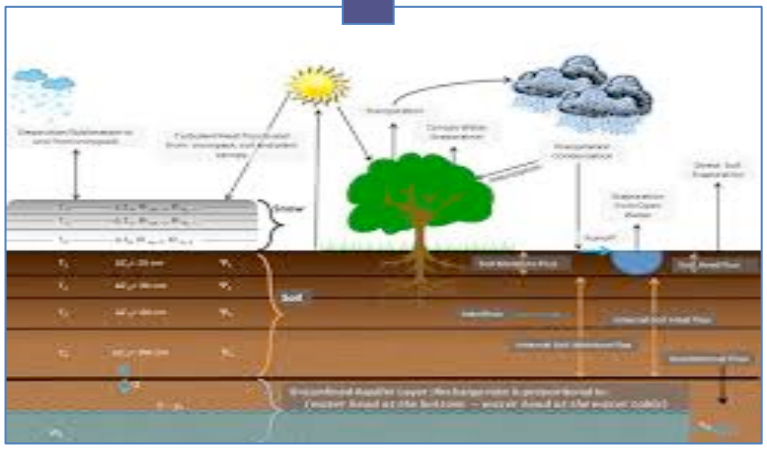
NCAR UCAR

CLM (CGD)



SUMMA concepts

CTSM

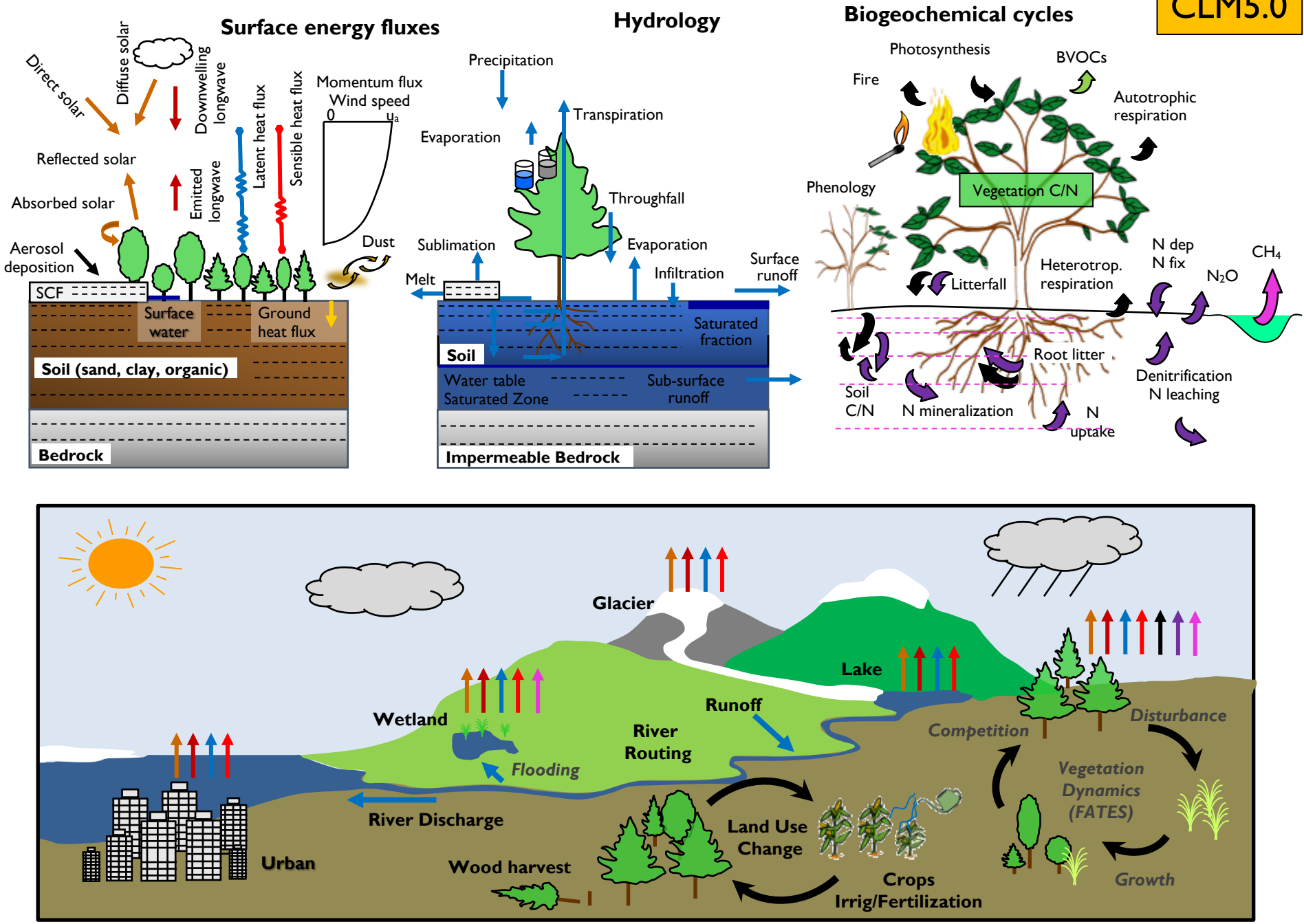


Noah-MP, WRF-Hydro (RAL)

Unify land modeling across NCAR

- More efficient use of NCAR and community resources
- Consistent with NCAR emphasis on unified modeling
- Extend NCAR leadership in community modeling
- Accelerate advances
- Increase flexibility and robustness of process representation, spatial disaggregation, and numerical solution (SUMMA concepts, modularization)
- Enable more hypothesis-driven science
- Integrate and expand land modeling research and development community
- Expand funding opportunities?

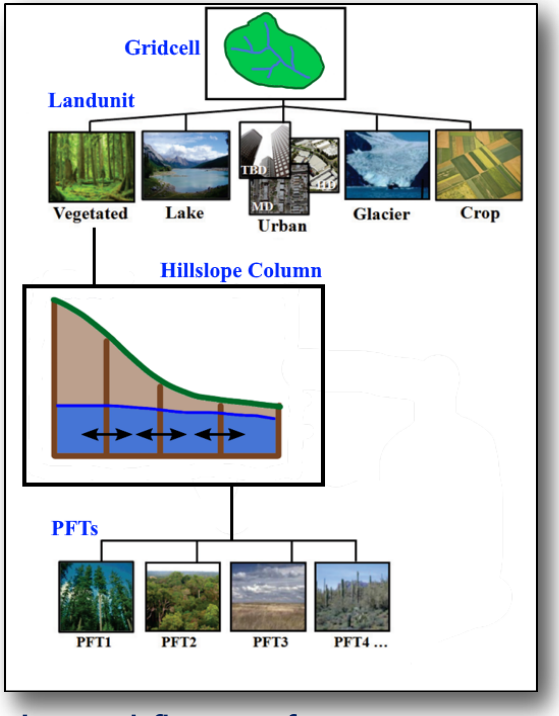
CLM5.0



Lawrence et al., 2019

CLM continually evolving in response to research needs of next generation science questions

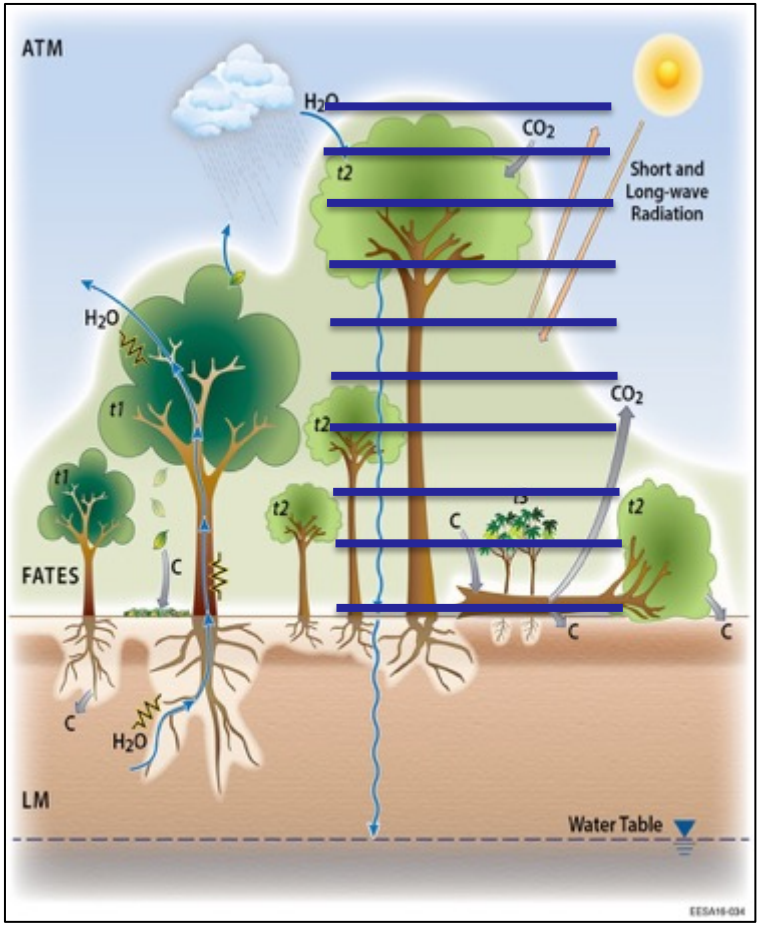
- Ecosystem vulnerability and impacts on carbon cycle and ecosystem services
- Sources of predictability from land processes; Ecological prediction
- Impacts of land use and land-use change on climate, carbon, water, and extremes
- Water and food security in context of climate change, climate variability,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



Lateral fluxes of water

Water and land management

Ecosystem Demography / Multi-layer canopy



THE CHRONICLE OF HIGHER EDUCATION

The Scientific Paper Is Outdated

For the sake of research, their careers, and their mental health, scientists should spend more time developing software

By Ryan Abernathey | FEBRUARY 16, 2020

Martin Leon Barreto for The Chronicle

www.chronicle.com/article/The-Scientific-Paper-Is/248045

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**

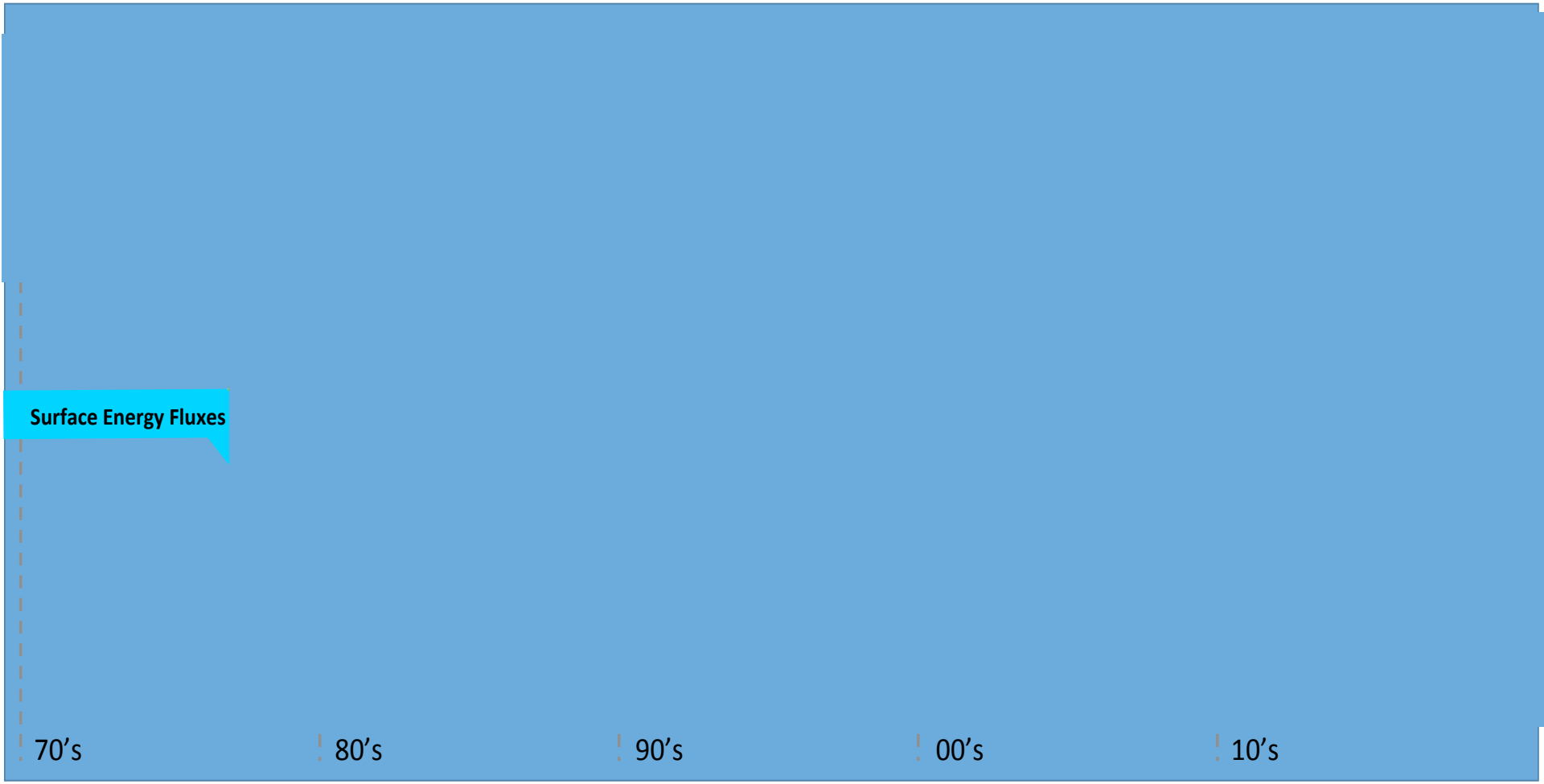


Figure: Fisher, Lawrence, Bonan, Clark, unpublished