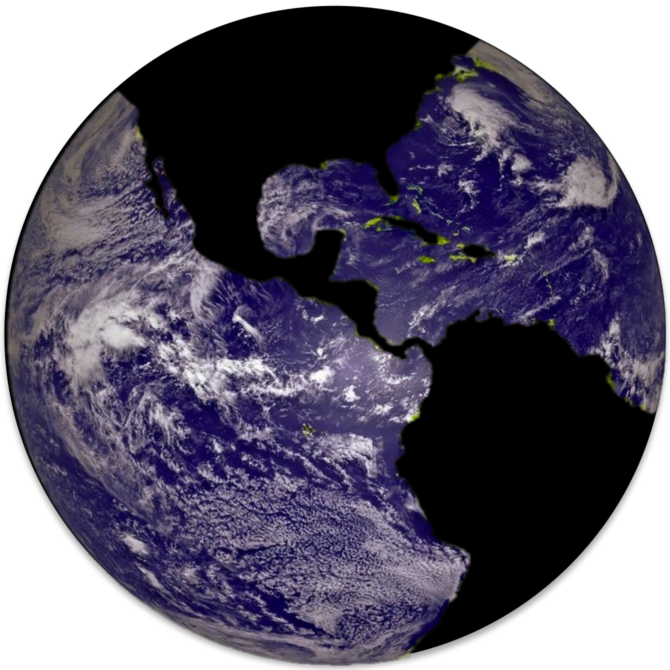
Modeling the terrestrial biosphere in the Earth system: moving beyond the incorrect but useful paradigm

Gordon Bonan
National Center for Atmospheric Research
Boulder, Colorado, USA

Environmental Science and Engineering
Caltech
Pasadena, CA
16 October 2019

NCAR is major facility sponsored by the National Science Foundation under Cooperative Agreement No. 1852977

Terrestrial ecosystems and climate science



(Will Wieder, NCAR)

Geophysical perspective
Atmospheric physics
Fluid dynamics

Terrestrial ecosystems and climate science

(Will Wieder, NCAR)

Biogeoscience perspective

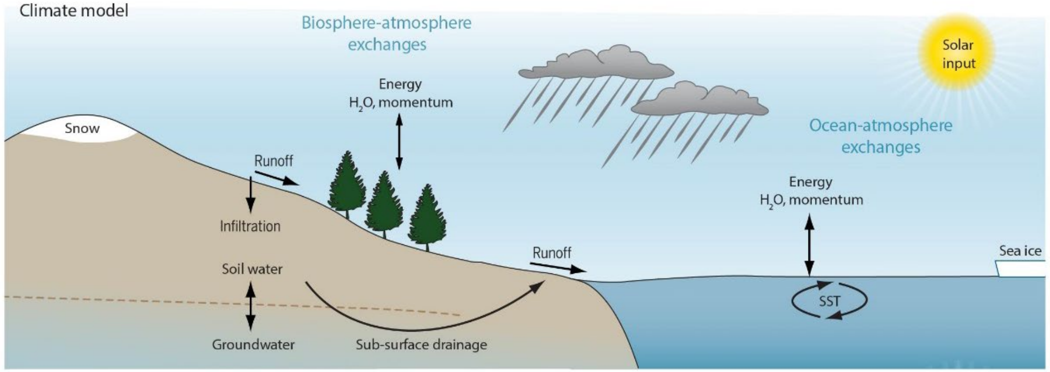
Effects of ecosystems on climate and atmospheric composition through:

- Energy and water
- Carbon cycle
- Reactive nitrogen
- Chemistry-climate (BVOCs, O_3, CH_4, aerosols)
- Biomass burning
- Land use & land-cover change

Ecology is as important to climate science as is geophysical fluid dynamics

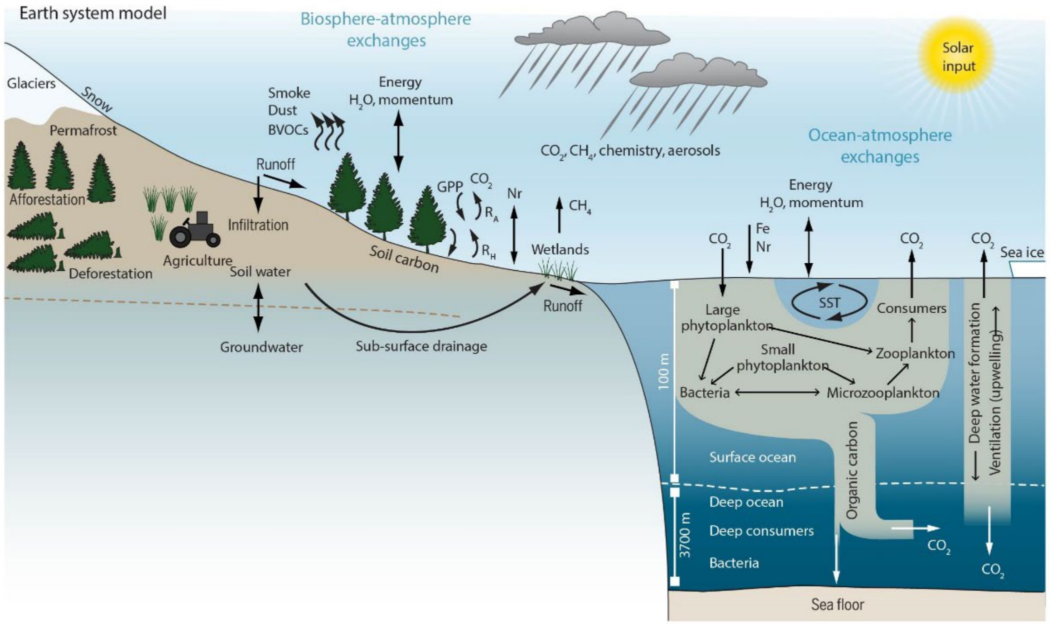
From climate models to Earth system models

Physical representation of climate (circa 1990s)



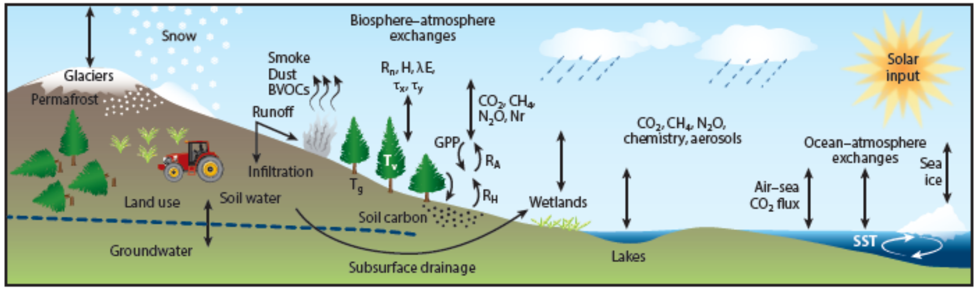
Bonan & Doney (2018) *Science*, 359, eaam8328, doi:10.1126/science.aam8328

Earth system perspective with terrestrial and marine ecosystems and biogeochemical cycles (circa 2010s)



Outline of talk

1. What are Earth system models and how are they used?
   - Deforestation/afforestation
   - Carbon cycle-climate feedbacks

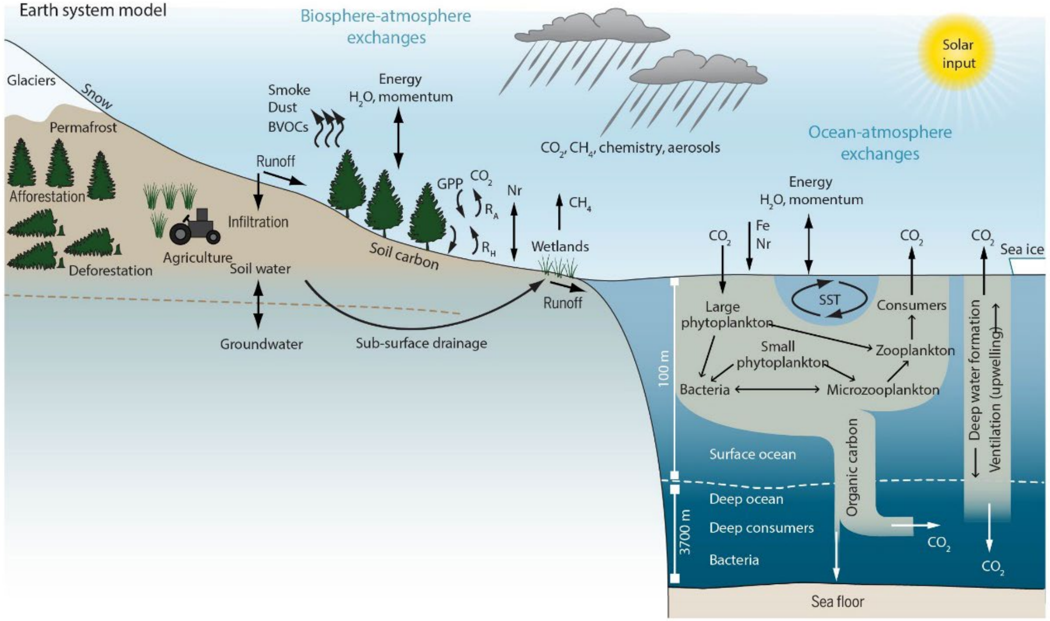


Bonan (2016) *Annu. Rev. Ecol. Evol. Syst.*, 47, 97-121

2. Reducing uncertainty
   - Terrestrial carbon cycle

3. The path forward
   - Model complexity and technical debt
   - Overcoming disciplinary chauvinism

Earth system models



Bonan & Doney (2018) *Science*, 359, eaam8328, doi:10.1126/science.aam8328

Earth system models use mathematical formulas to simulate the **physical**, **chemical**, and **biological** processes that drive Earth's atmosphere, hydrosphere, biosphere, and geosphere

A typical Earth system model consists of coupled models of the **atmosphere**, **ocean**, **sea ice**, **land**, and **glaciers**

Land is represented by its **ecosystems**, **watersheds**, **people**, and **socioeconomic** drivers of environmental change

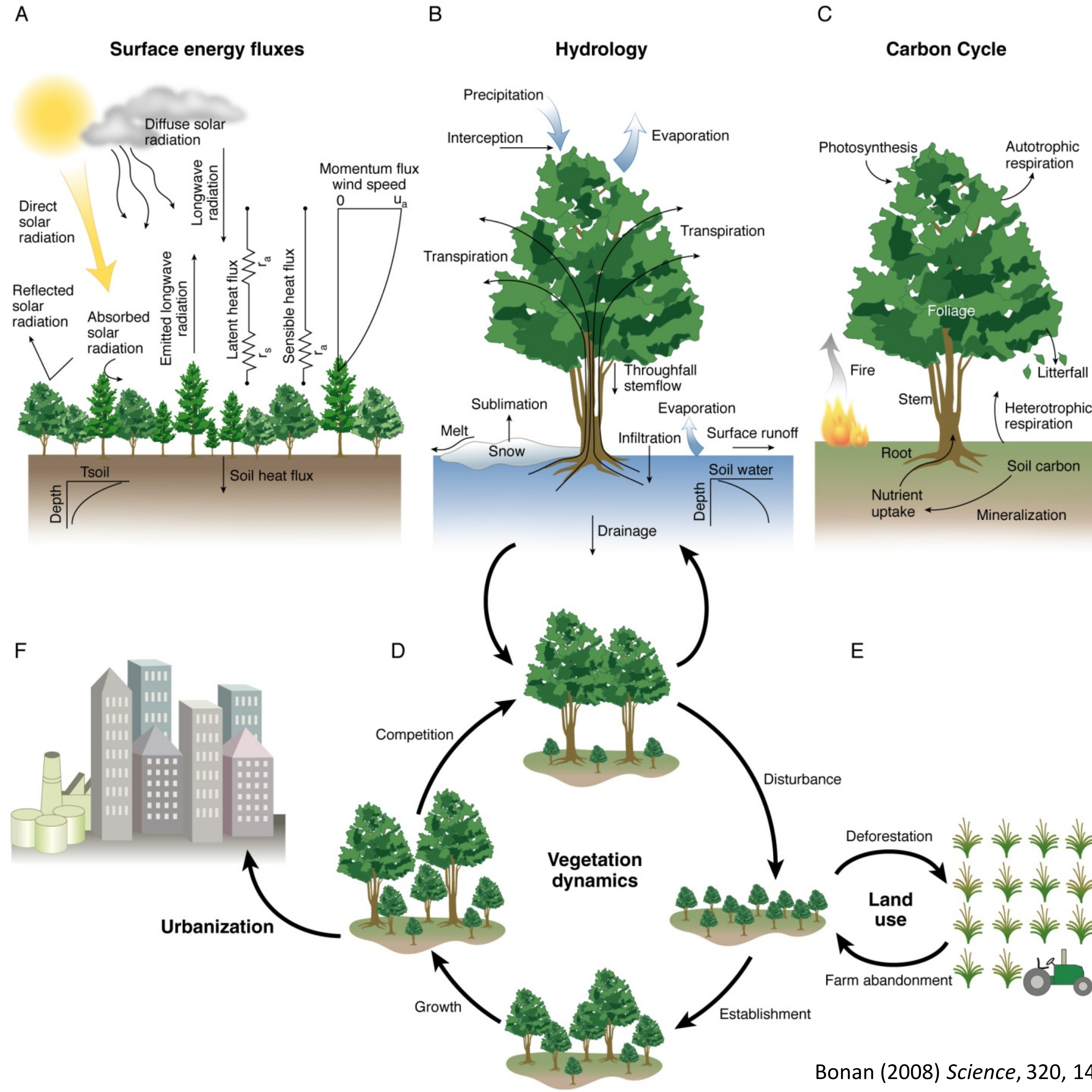
The model provides a comprehensive understanding of the processes by which people and ecosystems **affect**, **adapt to**, and **mitigate** global environmental change

Terrestrial ecosystems in Earth system models

Multiple processes at many timescales

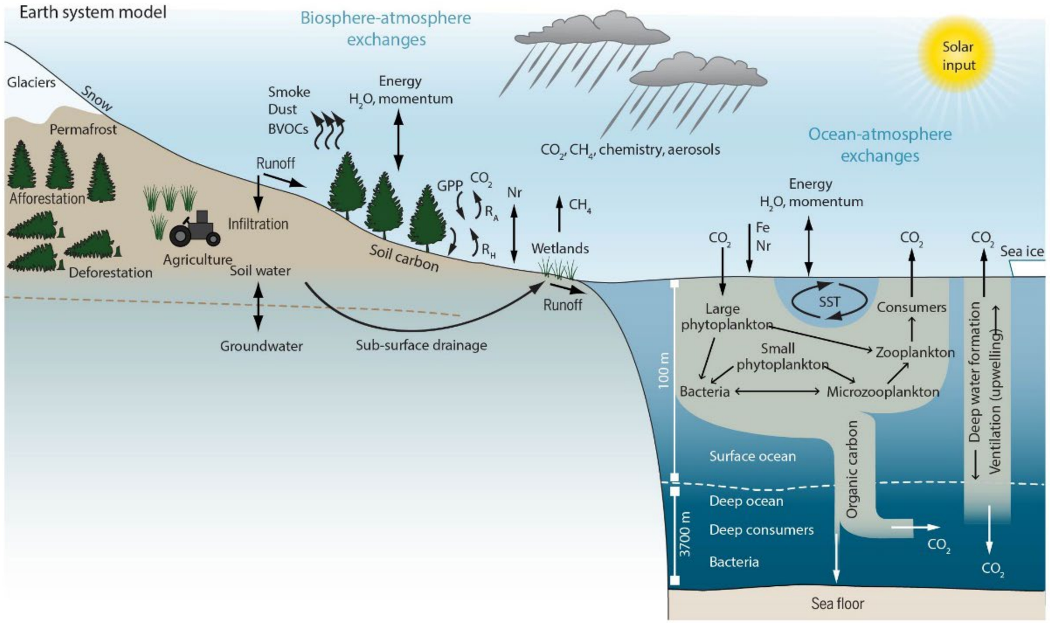
Near-instantaneous (30-min) coupling with atmosphere (energy, water, chemical constituents)

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



Bonan (2008) *Science*, 320, 1444-49

Earth system models as a tool for ecological science



Bonan & Doney (2018) *Science*, 359, eaam8328, doi:10.1126/science.aam8328

Earth system prediction

What are the consequences of alternative socioeconomic pathways?

Scientific discovery

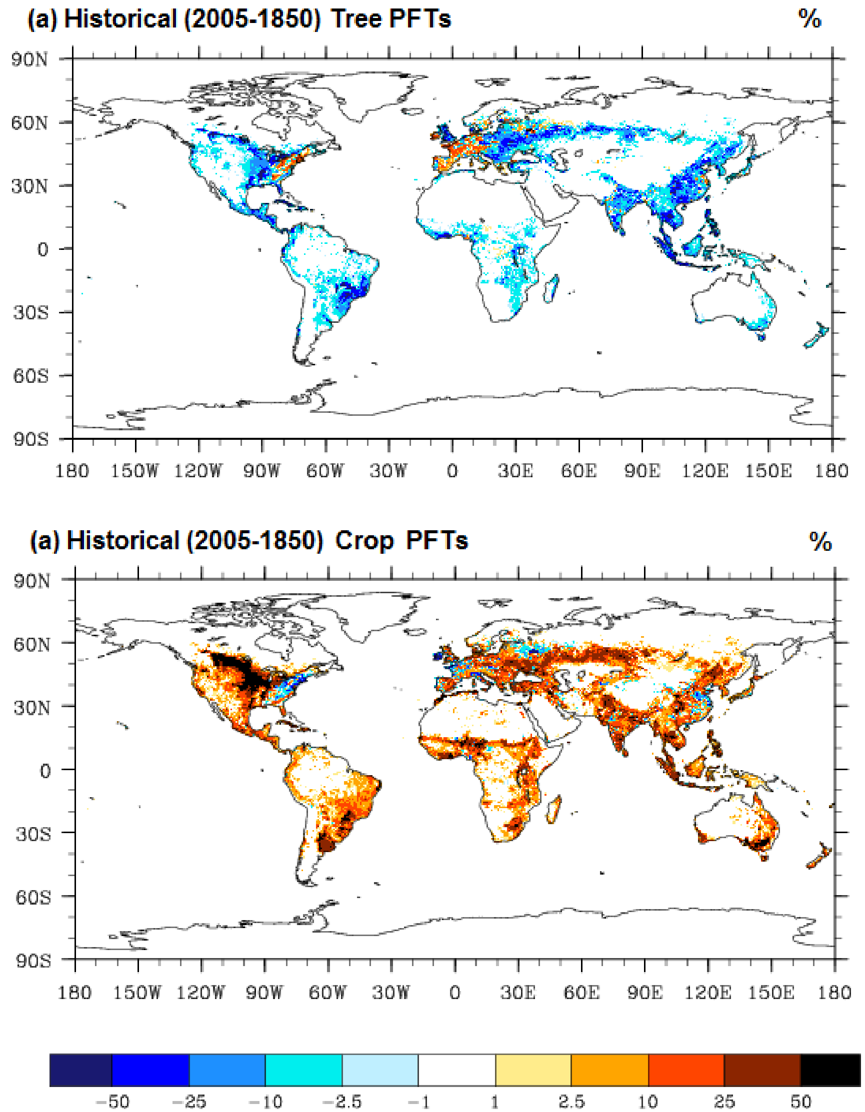
Identify ecological processes that determine climate

Advance theory

Test generality of ecological theories at the macroscale

Historical land cover change (1850-2005)

Change in tree and crop cover (percent of grid cell)



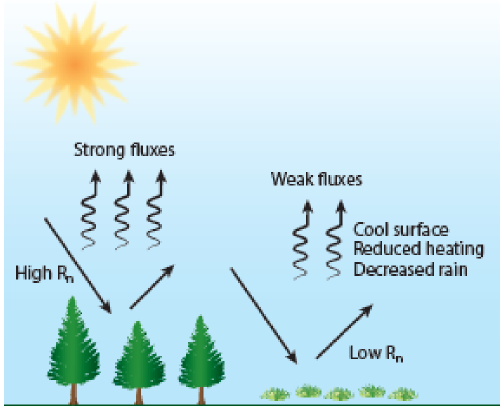
<u>Historical land use & land-cover change</u>

- Loss of tree cover and increase in cropland
- Farm abandonment and reforestation in eastern U.S. and Europe

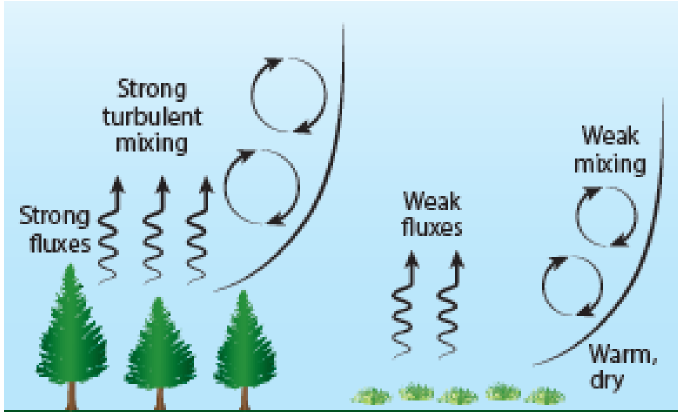
Lawrence et al. (2012) *J. Clim.*, 25, 3071-95

Land-atmosphere interactions

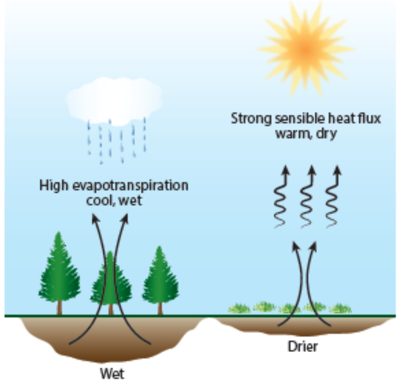
Forest have a low albedo



Forests are tall (aerodynamically rough)

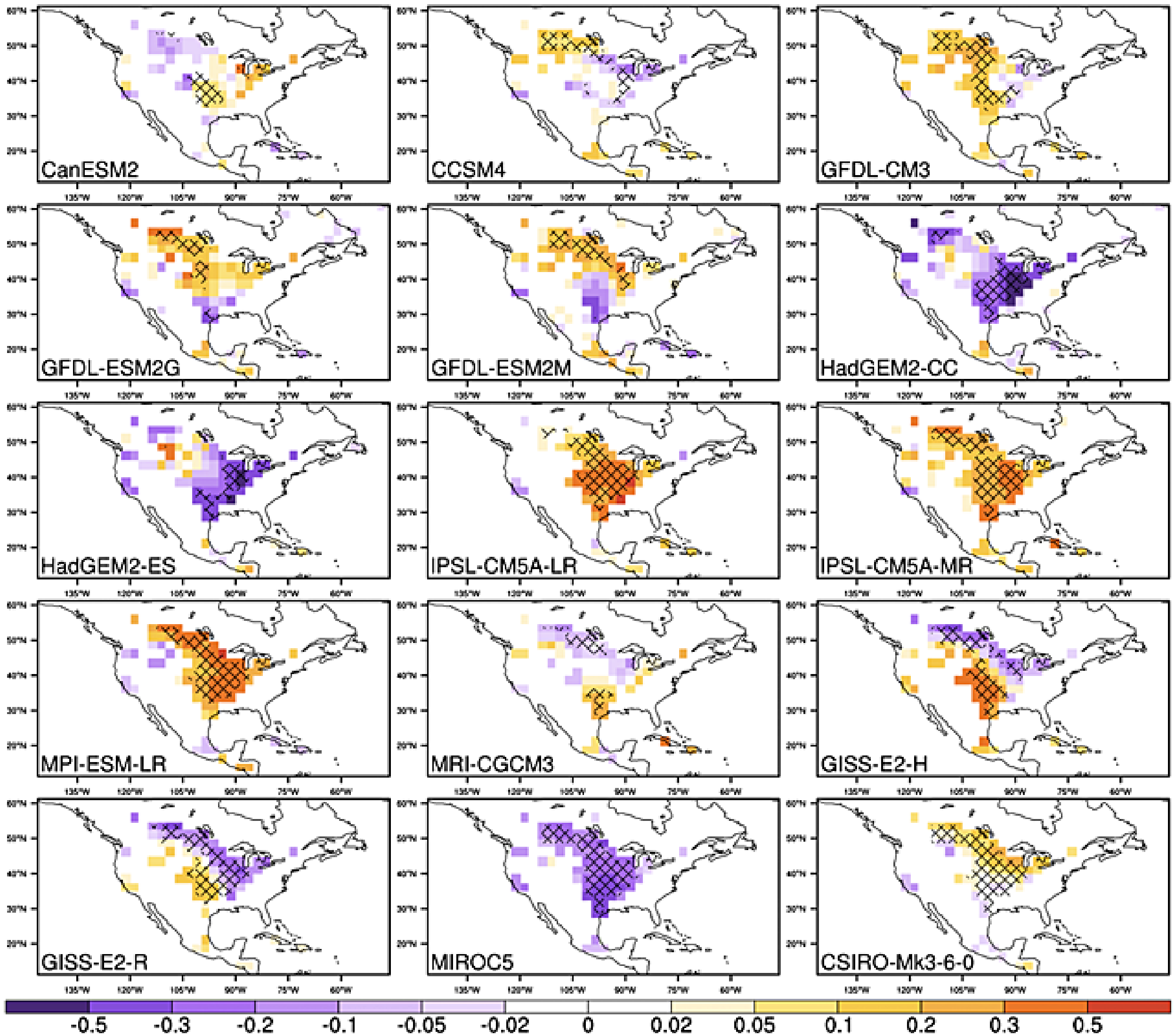


Forests are leafy and have deep roots



Bonan (2016) *Annu. Rev. Ecol. Evol. Syst.*, 47, 97-121

Model variability



15 CMIP5 models: Change in JJA temperature (°C) with 20th century land-cover change

- Atmosphere model
- Land model
- How land cover change is implemented

How do observations constrain models?

T_{rad}, T_s, T_a
Radiative forcing

Bonan (2016) *Annu. Rev. Ecol. Evol. Syst.*, 47, 97-121

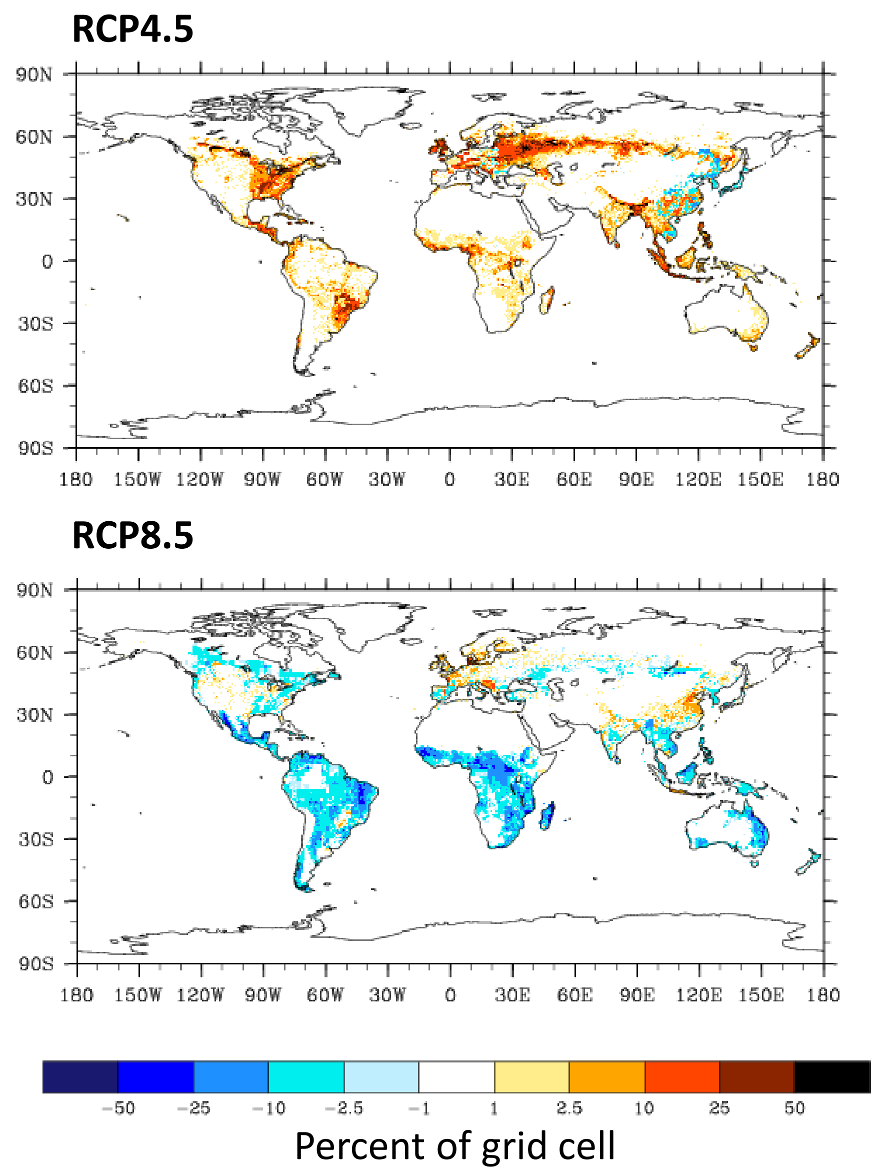
Kumar et al. (2013) *JGR: Atm*, 118, doi:10.1002/jgrd.50463

Twenty-first century land-cover change

Mitigation - afforestation to enhance the terrestrial carbon sink

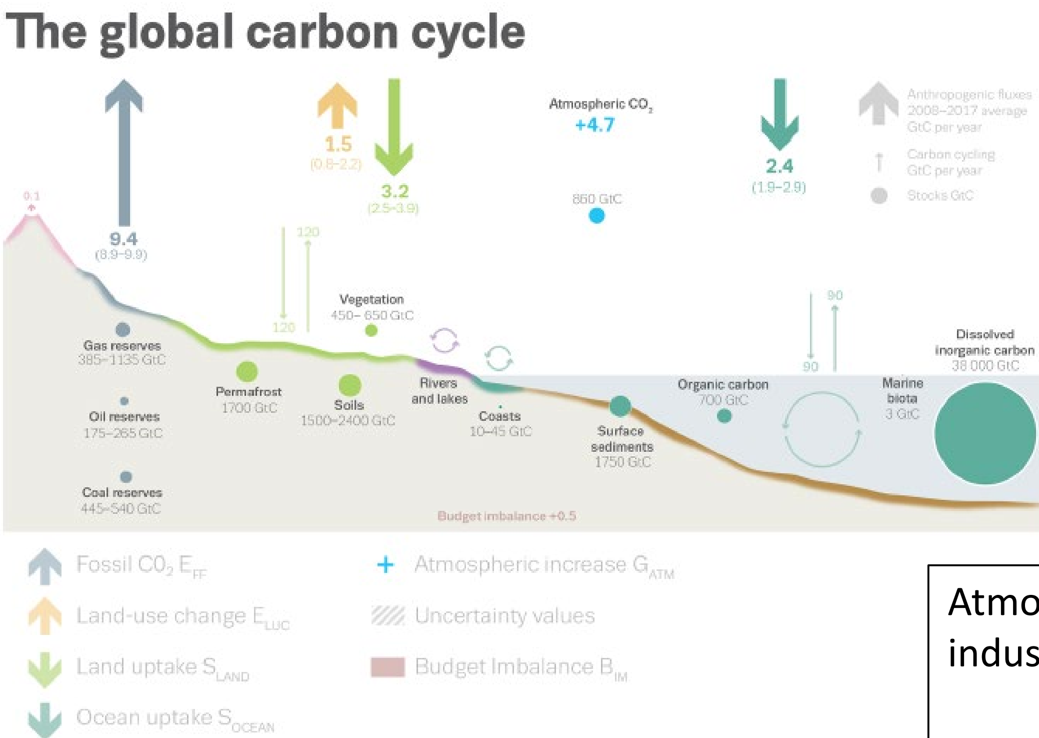
Business as usual - continued deforestation

Change in tree cover (percent of grid cell)



Lawrence et al. (2012) *J. Clim.*, 25, 3071-95

Carbon cycle



Le Quéré et al. (2018) *Earth Syst. Sci. Data*, 10, 2141-94

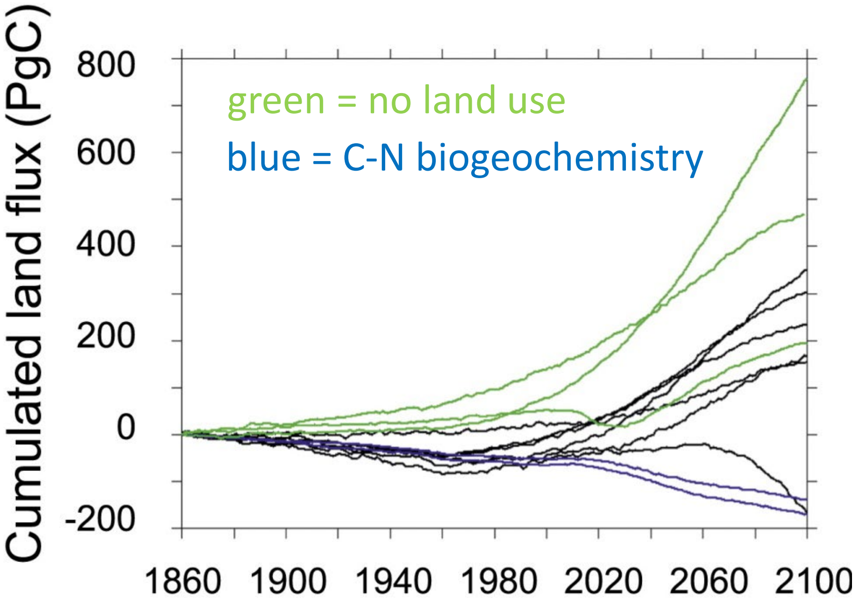
Atmospheric CO_2 has increased over the industrial era as the balance of:

- Fossil fuel emissions
- Land use and land-cover change emissions
- Terrestrial and oceanic sinks

How will the global carbon cycle change in the future?

Will the terrestrial biosphere continue to be a carbon sink?

CMIP5 carbon cycle projections



Friedlingstein et al. (2014) *J. Clim.*, 27, 511-526

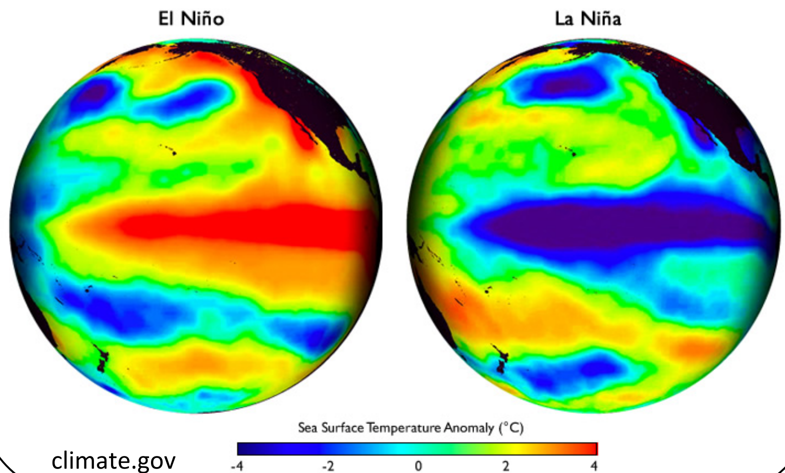
11 Earth system models with RCP8.5

Large uncertainty in cumulative land uptake

Much interest in how to reduce uncertainty

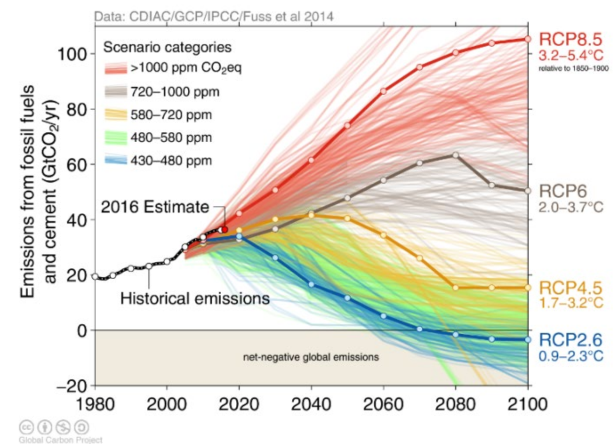
Sources of uncertainty

Internal variability



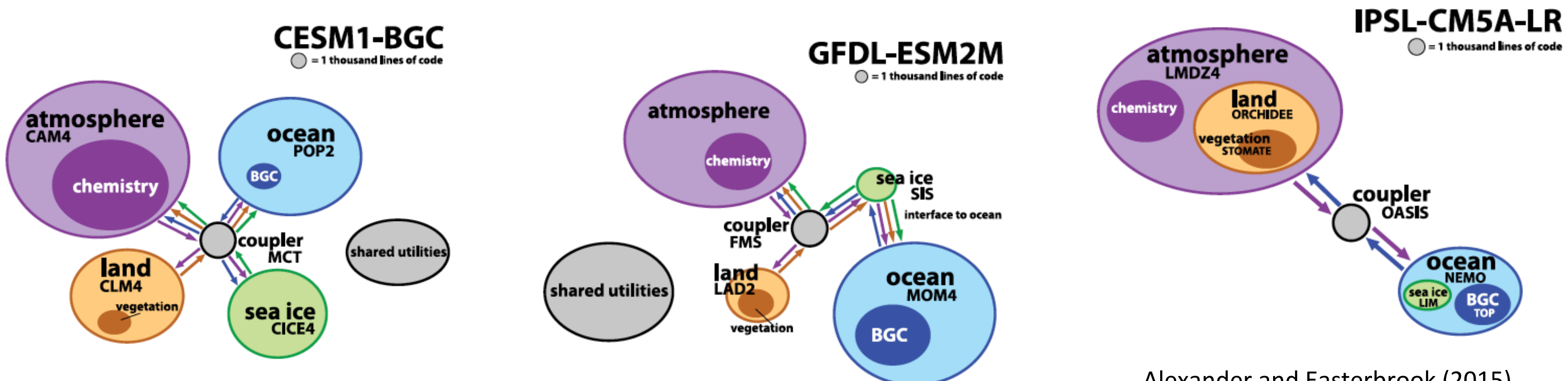
climate.gov

Emission scenario



Global Carbon Project

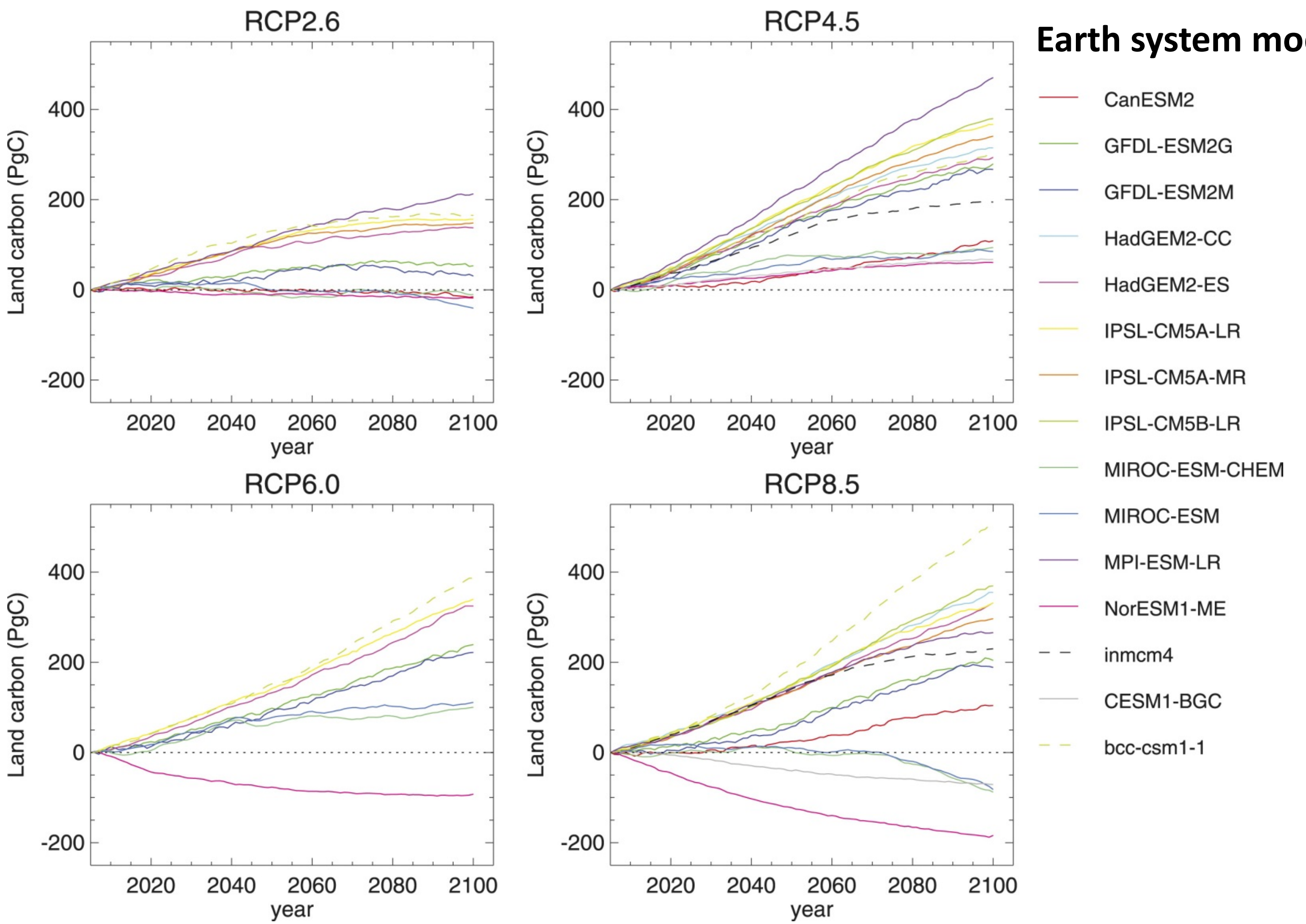
Model structure



Alexander and Easterbrook (2015)

(Nikki Lovenduski, CU-Boulder)

CMIP5 carbon cycle projections



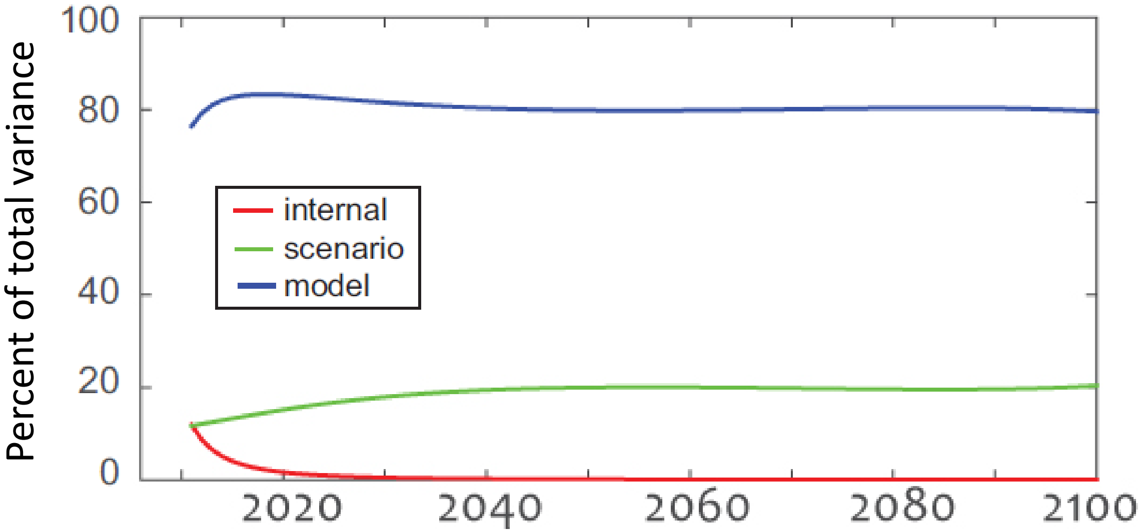
Uncertainty in land carbon uptake due to differences among models is considerably larger than the spread across scenarios

Jones et al. (2013) *J. Clim.*, 26, 4398-4413

CMIP5 carbon cycle uncertainty

Sources of uncertainty
- Internal variability
- Model structure
- Scenarios

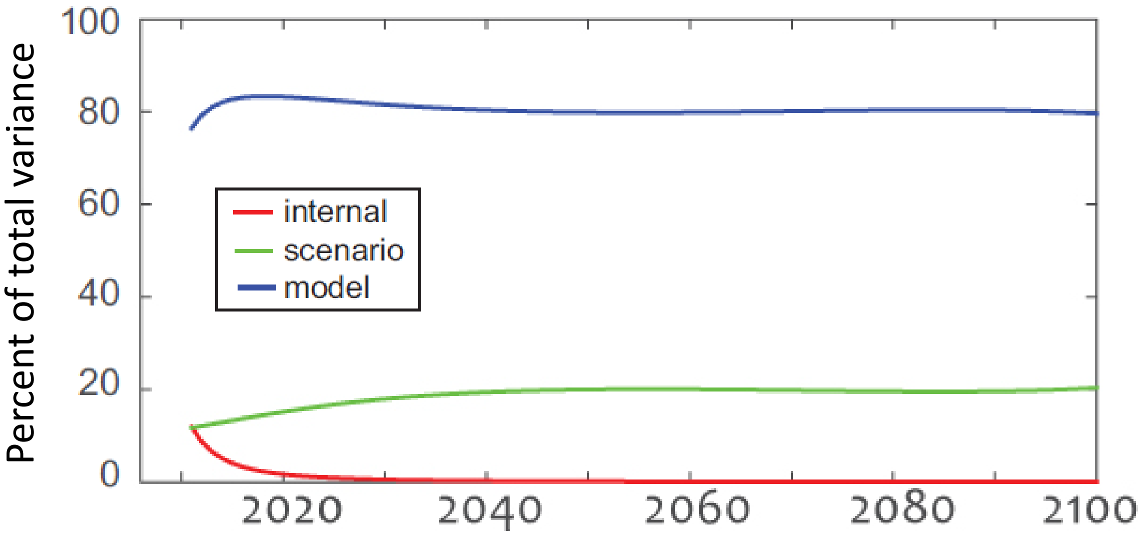
Hawkins & Sutton (2009) *BAMS*, 90, 1095-1107



Lovenduski & Bonan (2017) *Environ. Res. Lett.*, 12, 044020

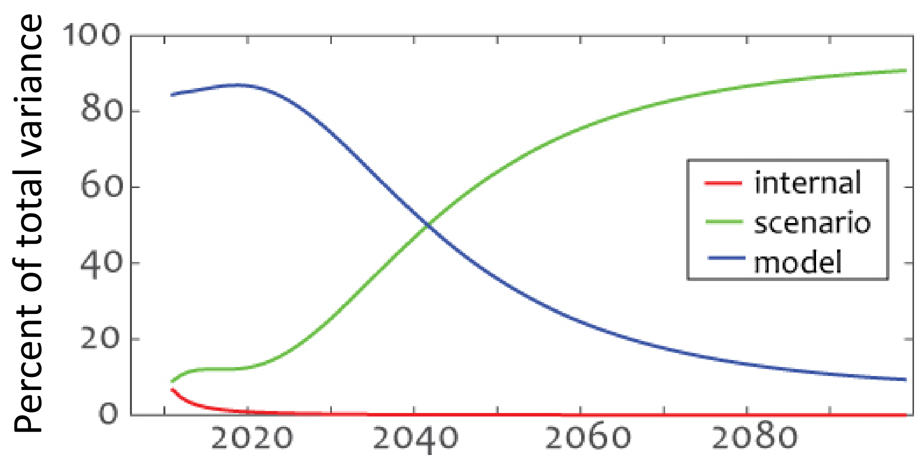
CMIP5 carbon cycle uncertainty

Land carbon uptake

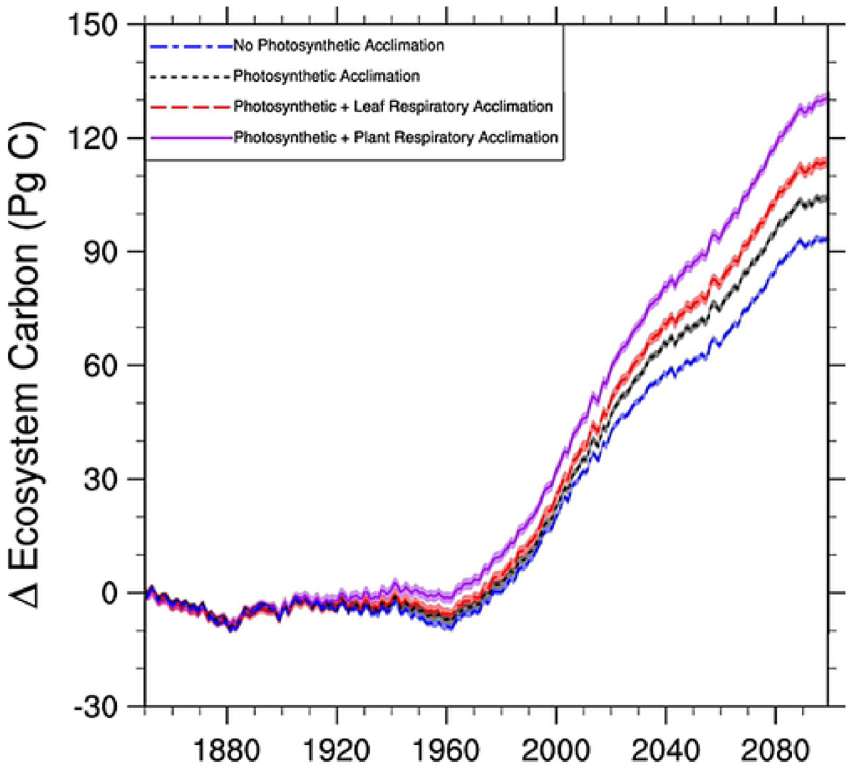


Lovenduski & Bonan (2017) *Environ. Res. Lett.*, 12, 044020

Ocean carbon uptake



Process uncertainty



Lombardozzi et al. (2015) *Geophys. Res. Lett.*, 42, 8624-31, doi:10.1002/2015GL065934

Temperature acclimation

Plants adjust their enzymatic photosynthetic or respiratory response to temperature as a result of acclimation to a new growth temperature over periods of days to weeks. Acclimation changes the shape and/or basal rate of the temperature response.

<u>Many other processes</u>

- Triose phosphate limitation
- Ozone damage
- Biological nitrogen fixation
- Soil carbon dynamics
- N & P limitations
- Many, many more …

The rules of life

Leaf → canopy → global

What are the rules that govern biological systems across a hierarchy from biomolecules to organisms to ecosystems to biomes?

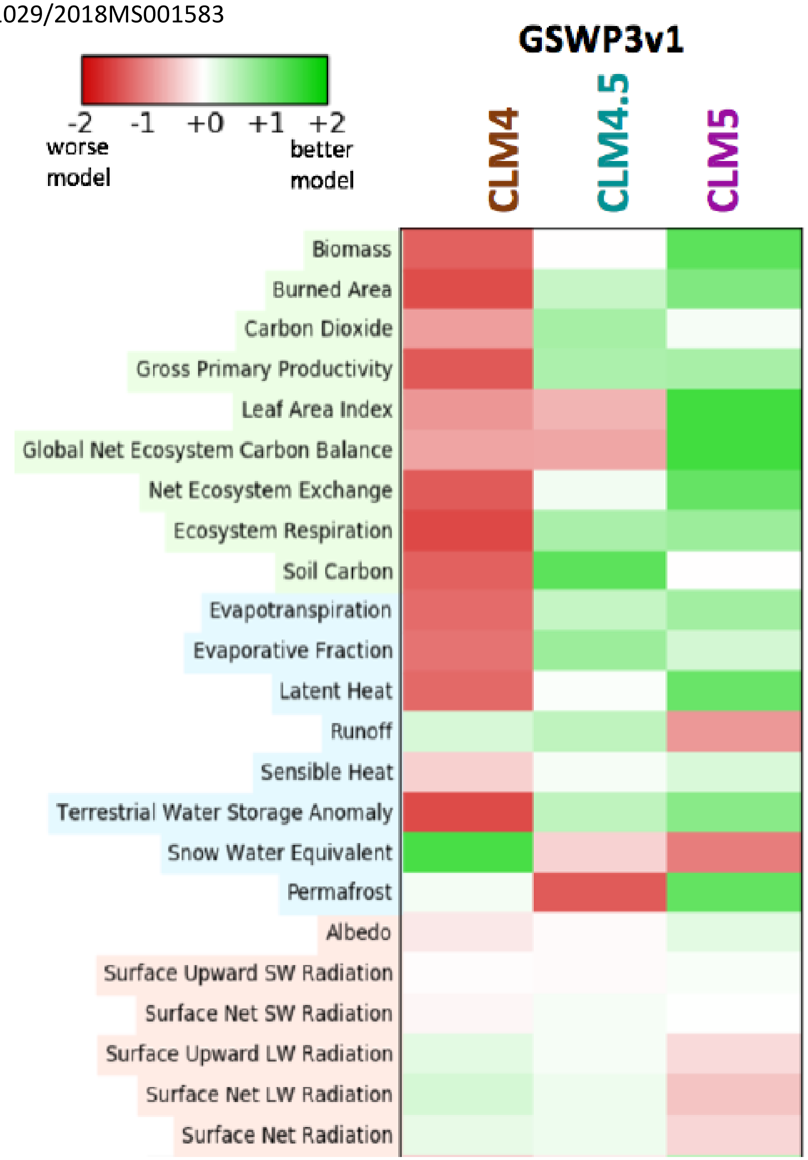
What are the mathematical equations to describe those rules?

How do we know if our models are getting better?

Data will solve the problem

ILAMB benchmarking

Lawrence et al. (2019) *J. Adv. Mod. Earth Syst.*, doi:10.1029/2018MS001583



- Progressive improvement from CLM4 to CLM4.5 and CLM5, but are we getting the right answer for the right reason?
- Reducing uncertainty is more insidious than minimizing differences with observations

Ensemble of land-only CLM historical simulations

3 models × 2 climates

Model	
CLM4	Strong N downregulation of GPP; low soil C
CLM4.5	Improved GPP and vertically-resolved soil C
CLM5	Flexible plant C:N; optimal canopy N; cost of N uptake

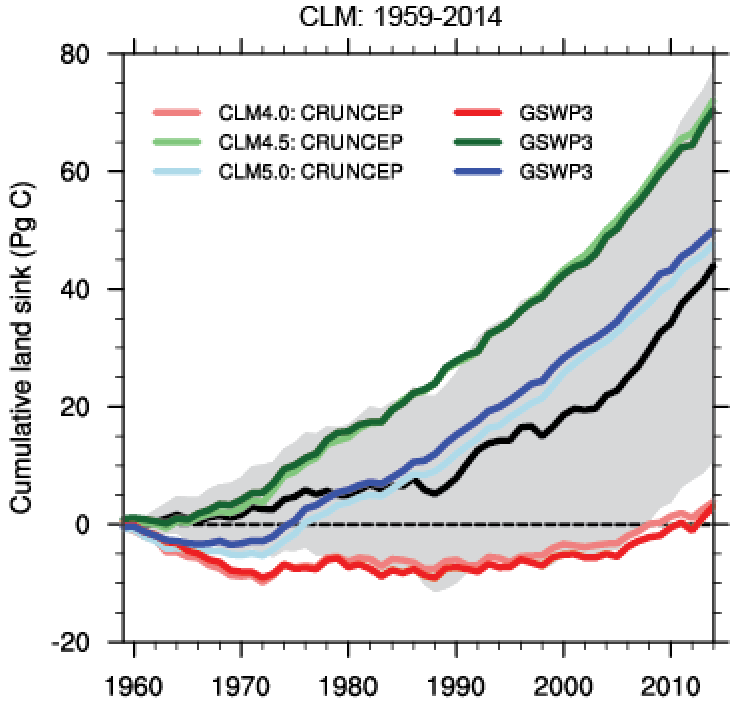
Poleward shift in C
Less sensitive to N addition
Higher CO_2 fertilization

Climate	
CRUNCEP	GCP, Trendy
GSWP3	CMIP6: LUMIP, LS3MIP

Use analysis of variance to examine the contribution of model structure and climate forcing to carbon cycle uncertainty

Bonan et al. (2019) *Global Biogeochem. Cycles*, doi:10.1029/2019GB006175

Which model is best?

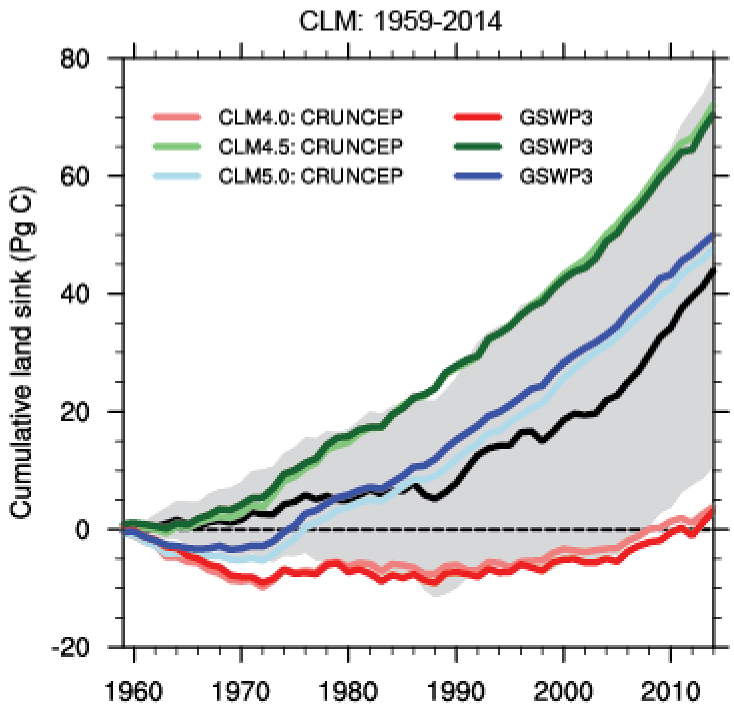


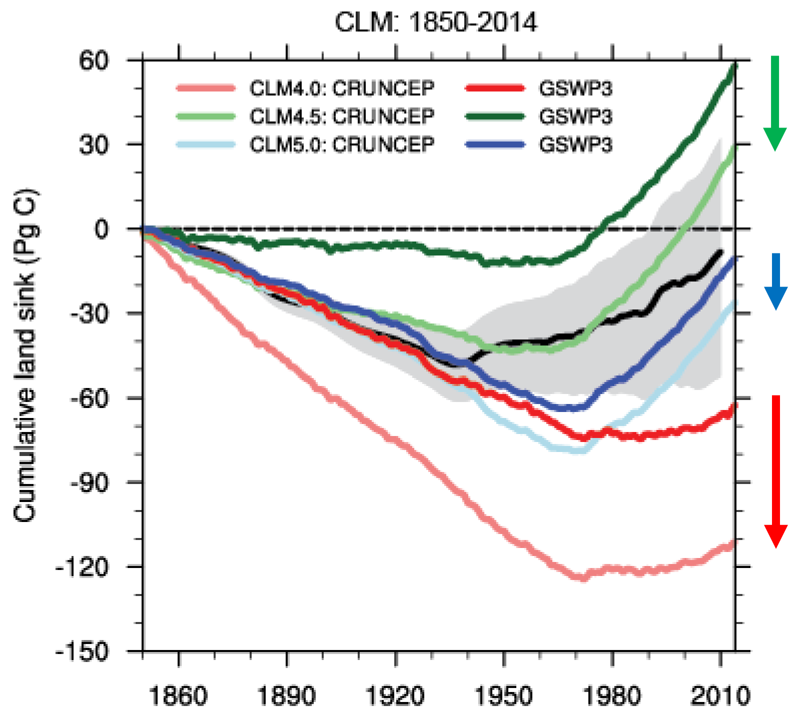
CLM5 is improved compared with other models

Climate is less important than model differences

Bonan et al. (2019) *Global Biogeochem. Cycles*, doi:10.1029/2019GB006175

Which model is best?





CLM5 is improved compared with other models

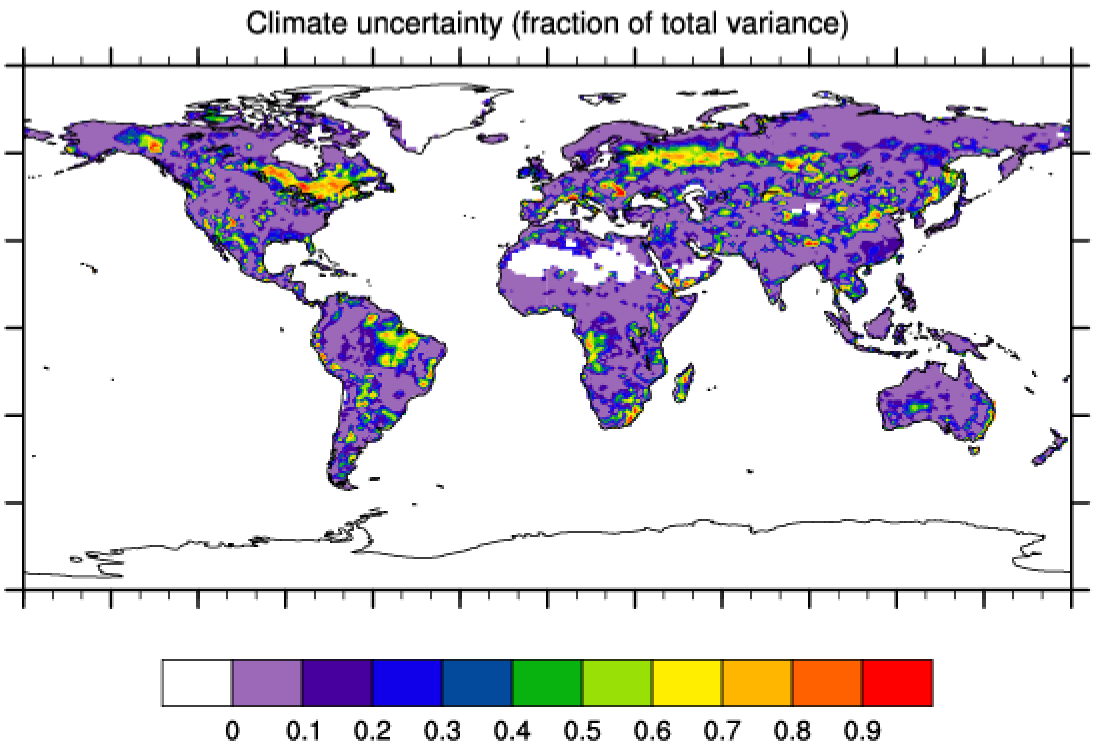
Climate is less important than model differences

CRUNCEP reduces land sink compared with GSWP3

CLM4.5 (CRUNCEP) and CLM5 (GSWP3) are equally “good” and within uncertainty

Bonan et al. (2019) *Global Biogeochem. Cycles*, doi:10.1029/2019GB006175

GPP uncertainty (2000-2009)



The current study highlights the importance of climate forcing in generating carbon cycle uncertainty, *even when the models are forced with best-estimate climate reconstructions over the industrial era*

Bonan et al. (2019) *Global Biogeochem. Cycles*, doi:10.1029/2019GB006175

Earth system prediction

REVIEW SUMMARY

EARTH SYSTEMS

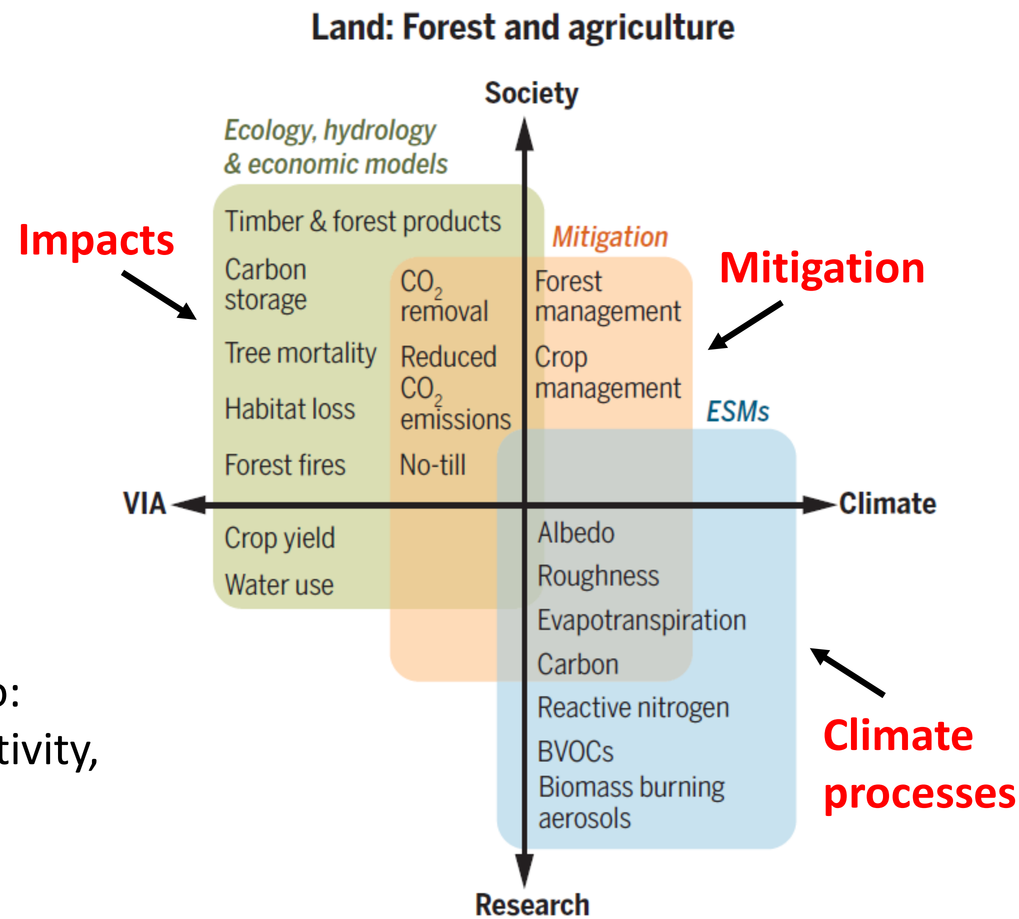
Climate, ecosystems, and planetary futures: The challenge to predict life in Earth system models

Gordon B. Bonan* and Scott C. Doney*

Bonan & Doney (2018) *Science*, 359, eaam8328,
doi:10.1126/science.aam8328

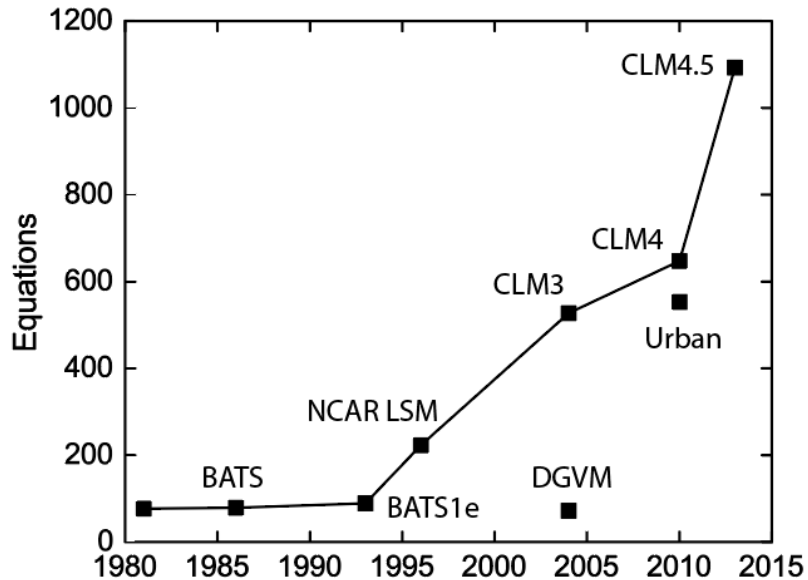
The various models used for climate projections, mitigation, and impacts (VIA) overlap in scope and would benefit from a broad perspective of Earth system prediction

Not just weather and climate, but also:
Wildfires, forest dieback, crop productivity, habitat loss, …



Increasing model complexity

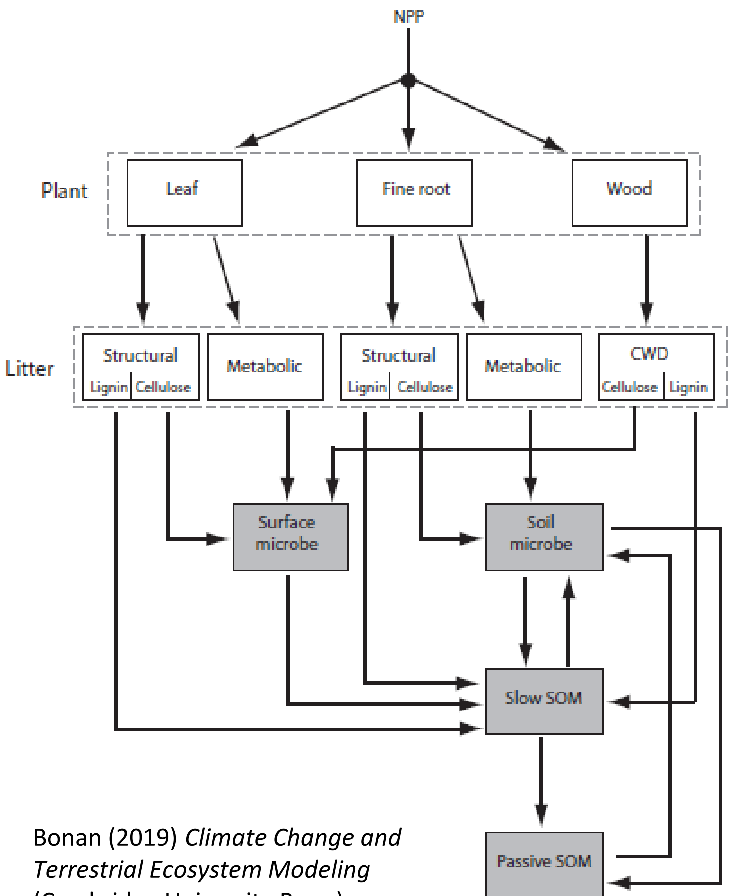
Breadth and complexity of land surface models as documented by NCAR technical notes



Bonan (2019) *Climate Change and Terrestrial Ecosystem Modeling* (Cambridge University Press)

Do more complexity and more authentic process parameterizations provide a better model?

A simple carbon cycle model



Bonan (2019) *Climate Change and Terrestrial Ecosystem Modeling* (Cambridge University Press)

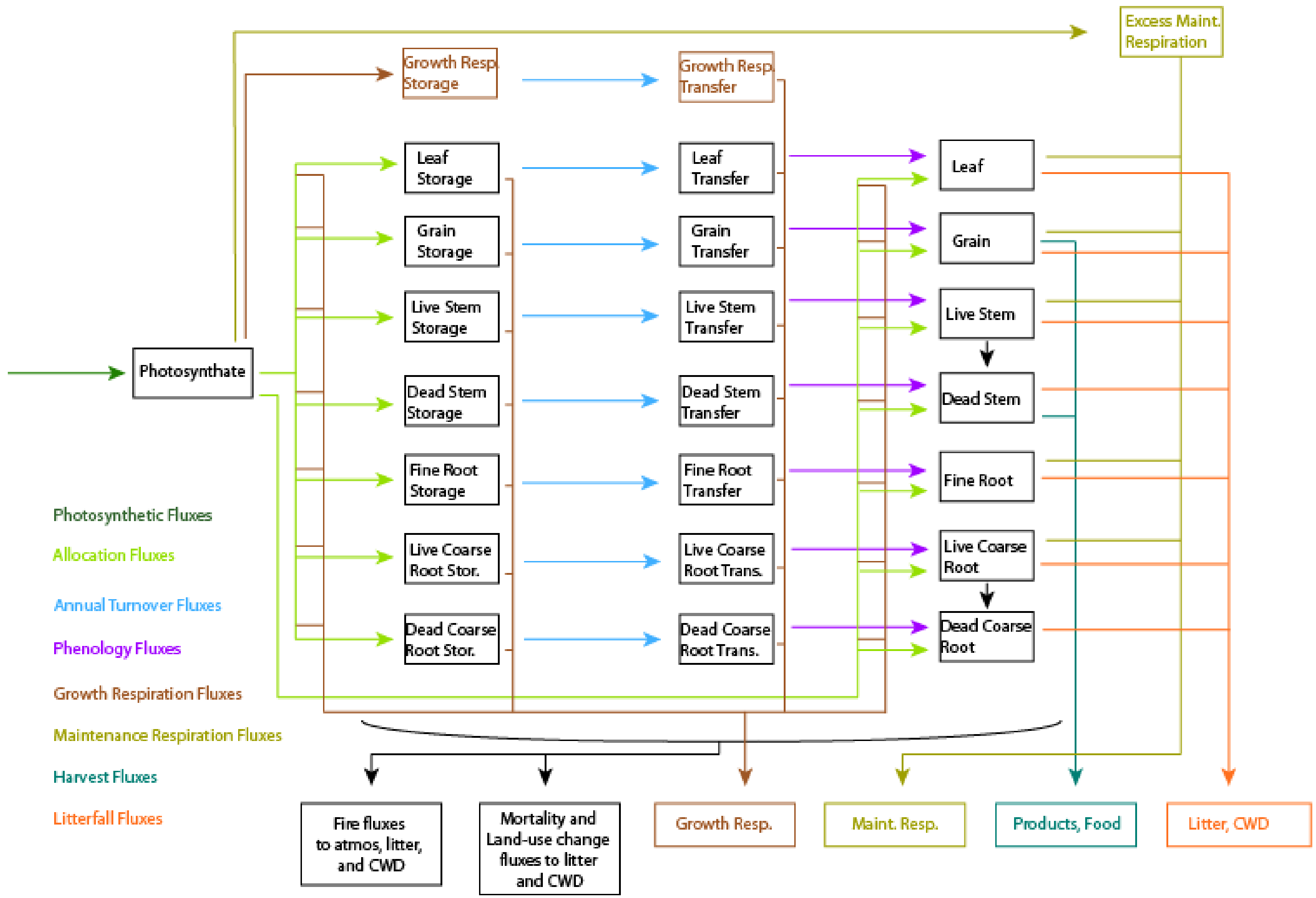
First coupled carbon cycle-climate model at NCAR using CASA' adaptation of CASA biogeochemical model

- Simple 12-pool model

Fung et al. (2005) *PNAS*, 102, 11201-11206

Increasing model complexity

Vegetation carbon pools and fluxes in the Community Land Model



CLM4.5: 70 carbon balance equations (including vertically resolved soil carbon in 10 soil layers)

CLM5.0 Technical Description:
cesm.ucar.edu/models/cesm2/land

The model development process

- Faulty understanding of processes leads to poor comparison of model with observations
- Add another process to reduce the bias, commonly with at least one poorly known parameter
- Tune the model until a better simulation is obtained
- Publish assuming the moral high ground
- Insist that future models must include the new process (my model is better than yours)
- Repeat

Adapted from Colin Prentice
9th New Phytologist Workshop
"Improving representation of photosynthesis in Earth System Models"
Montauk, New York, USA, April 2014

Deconstructing models

deconstruct: to take apart or examine (something) in order to reveal the basis or composition often with the intention of exposing biases, flaws, or inconsistencies (Merriam-Webster)

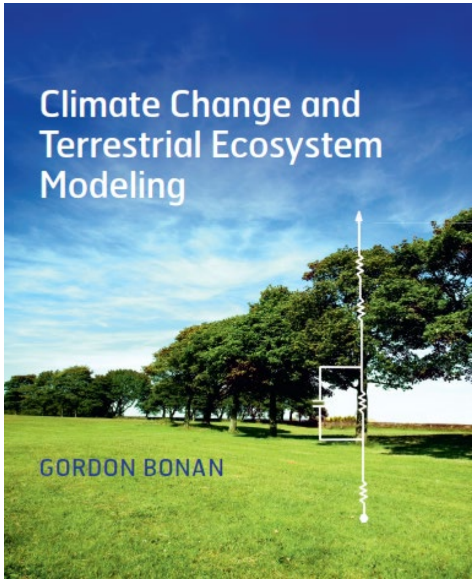
Monin-Obukhov similarity theory
$$\frac{k(z-d)}{u_*}\frac{\partial u}{\partial z} = \phi_m\left(\frac{z-d}{L_{MO}}\right)$$

Richards equation
$$\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial z}\left[K(\theta)\frac{\partial \psi}{\partial z}\right] + \frac{\partial K}{\partial z}$$

FvCB photosynthesis
$$A_c = \frac{V_{c\max}(c_i - \Gamma_*)}{c_i + K_c(1 + o_i/K_o)} - R_d$$
$$A_j = \frac{J}{4}\left(\frac{c_i - \Gamma_*}{c_i + 2\Gamma_*}\right) - R_d$$

Ball-Berry stomatal conductance
$$g_{sw} = g_0 + g_1\frac{A_n}{c_s}h_s$$

Bonan (2019) *Climate Change and Terrestrial Ecosystem Modeling* (Cambridge University Press)



Modeling leaf photosynthesis

Farquhar, von Caemmerer & Berry photosynthesis model

$$A_n = \min(A_c, A_j) - R_d$$

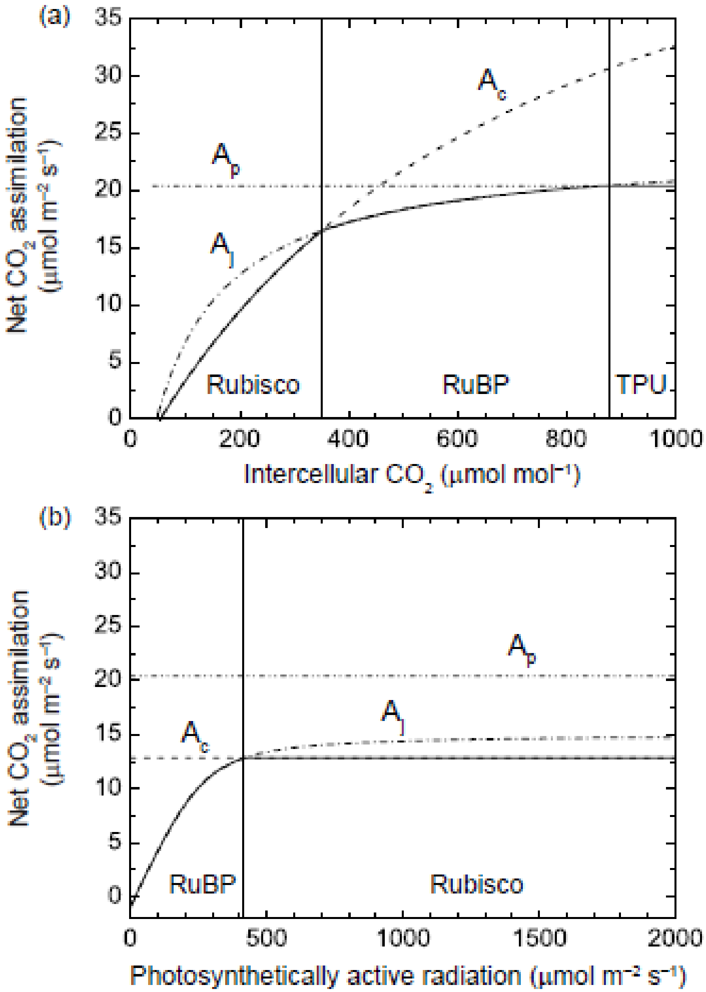
Rubisco-limited rate is

$$A_c = \frac{V_{c\max}\left(c_i - \Gamma_*\right)}{c_i + K_c\left(1 + o_i / K_o\right)}$$

RuBP regeneration-limited rate is

$$A_j = \frac{J}{4}\left(\frac{c_i - \Gamma_*}{c_i + 2\Gamma_*}\right)$$

Farquhar et al. (1980) *Planta*, 149, 78–90



Microdecisions

Farquhar et al. (1980) model of C_3 photosynthesis

What rates:
- Rubisco-limited (V_{cmax}), RuBP regeneration-limited (J_{max}), product-limited (TPU)
- co-limited or minimum rate

RuBP regeneration:
- NADPH requirements or ATP requirements
- Rate of electron transport in relation to PAR

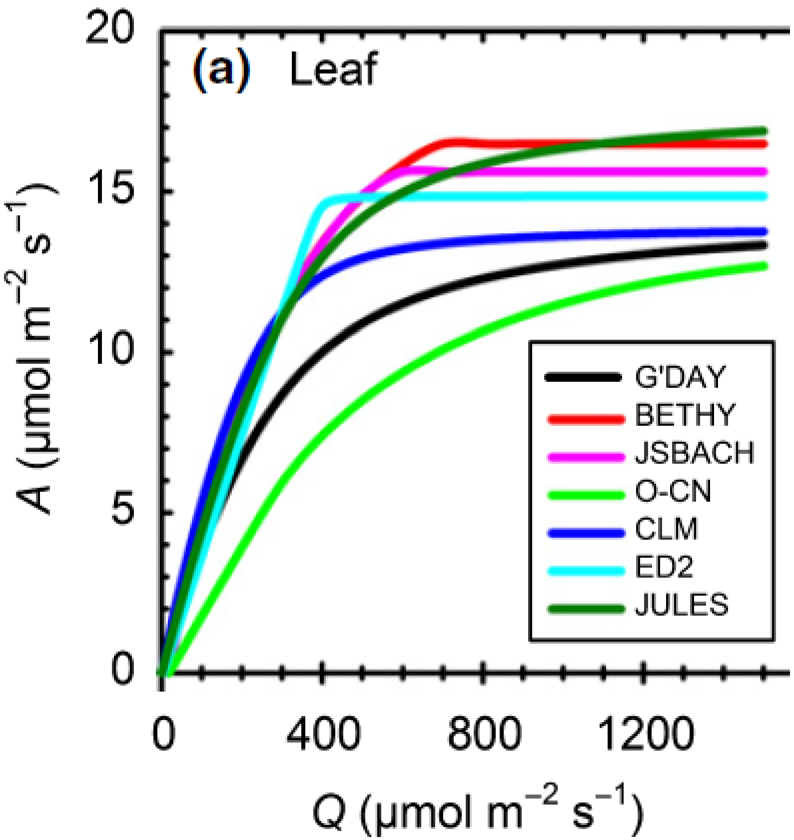
Parameters and temperature dependencies:
- K_c, K_o, Γ_*
- V_{cmax}, J_{max}, R_d
- Θ_J, Φ_{PSII}, α

How to account for leaf nitrogen:
- Carboxylation (V_{cmax}), electron transport (J_{max}), light harvesting (chlorophyll)

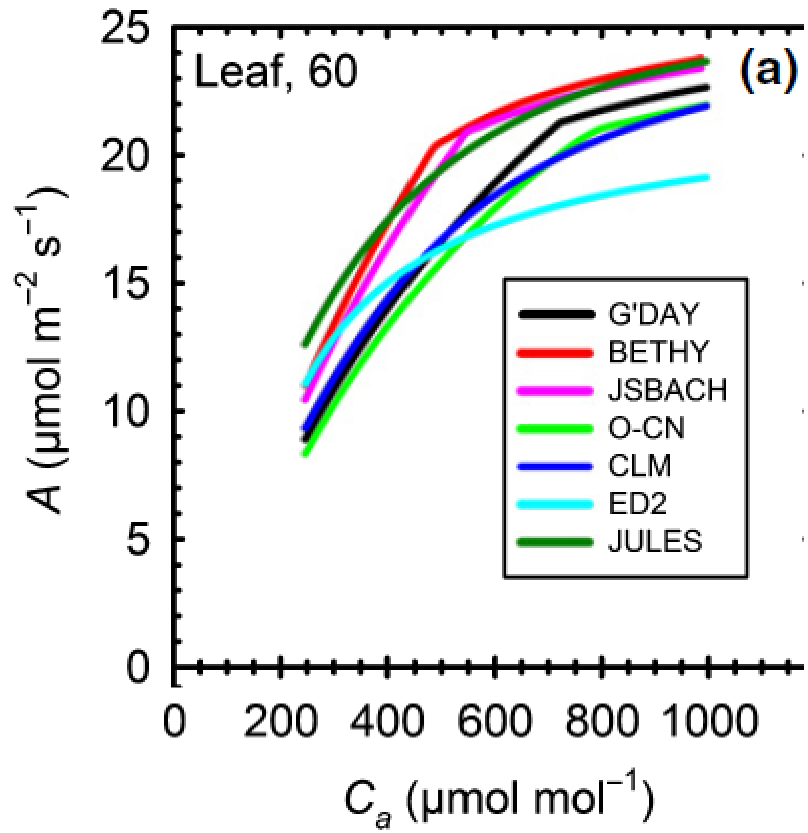
Temperature acclimation

Are we modeling the same thing?

Light response



CO_2 response



Rogers et al. (2017) *New Phytol.*, 213, 22-42

Two viewpoints

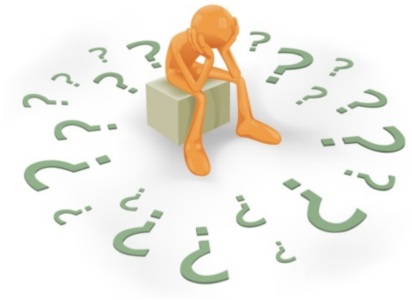
Data will solve the problem

Earth system models disagree wildly about the magnitude and frequency of carbon-climate feedback events, and data to this point have been astonishingly ineffective at reducing this uncertainty.

Sellers, Schimel, et al. (2018) *PNAS*, 115, 7860-68

The equifinality thesis

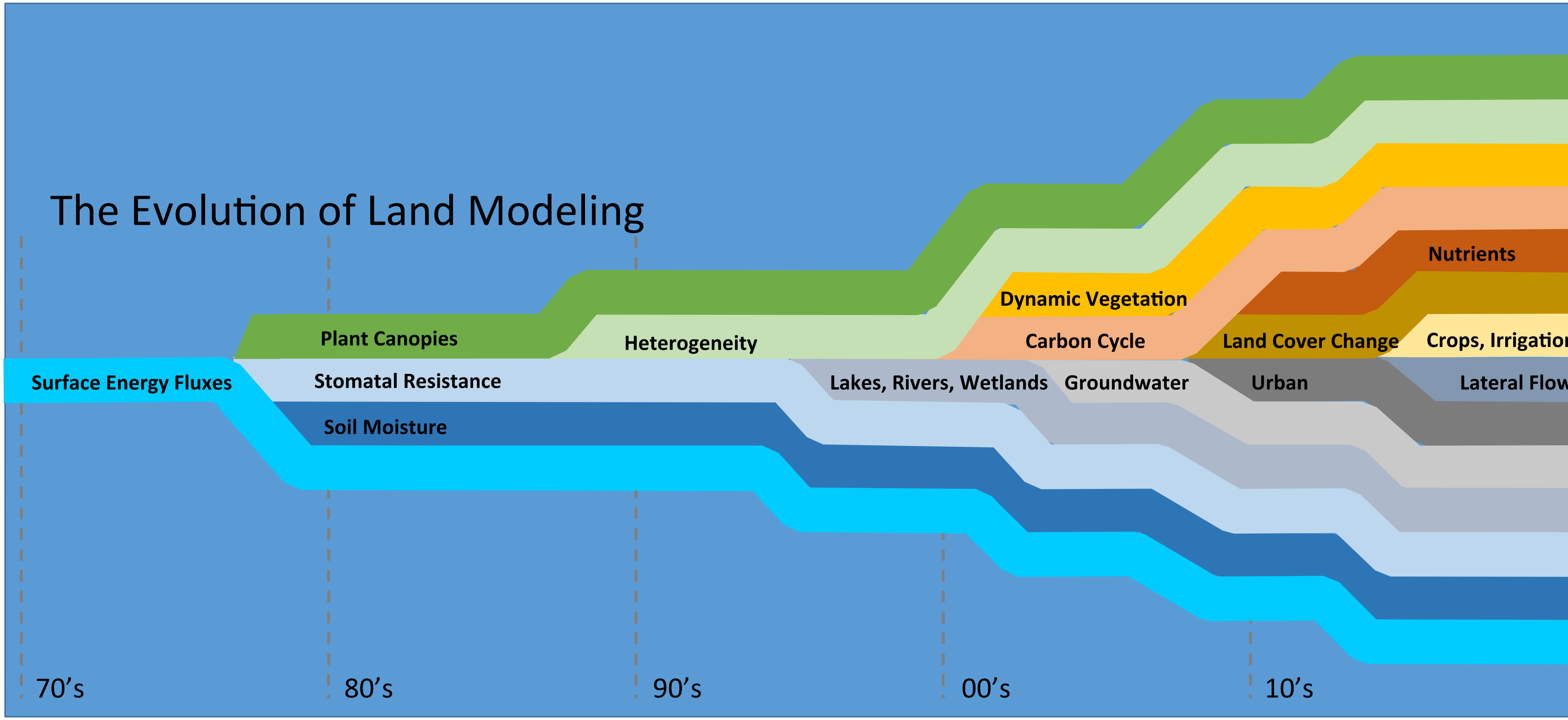
Science … is supposed to be an attempt to work towards a single correct description of reality. It is not supposed to conclude that there must be multiple feasible descriptions of reality. The users of research also do not (yet) expect such a conclusion and might then interpret the resulting ambiguity of predictions as a failure (or at least an undermining) of the science.



Beven (2006) *J. Hydrology*, 320, 18-36

Complexity itself is not the problem

Land as lower boundary condition to atmosphere → Land as integral component of the Earth system



Rosie Fisher (NCAR)

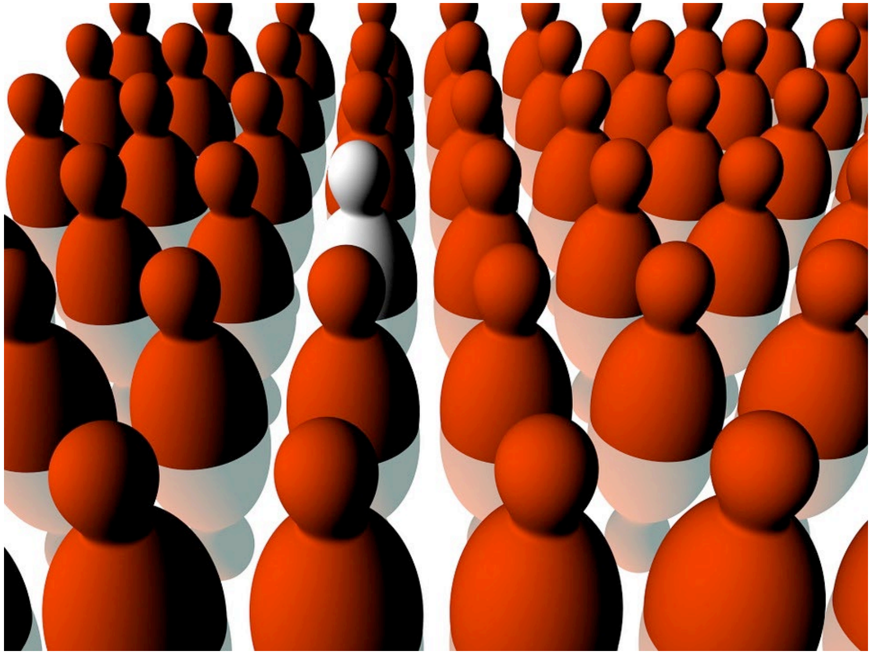
What is the problem?

Model proliferation: Many models, with each group making different decisions at different points in the model development process

Model sprawl: Ad-hoc approach to model development without adequate infrastructure, support, documentation, or testing

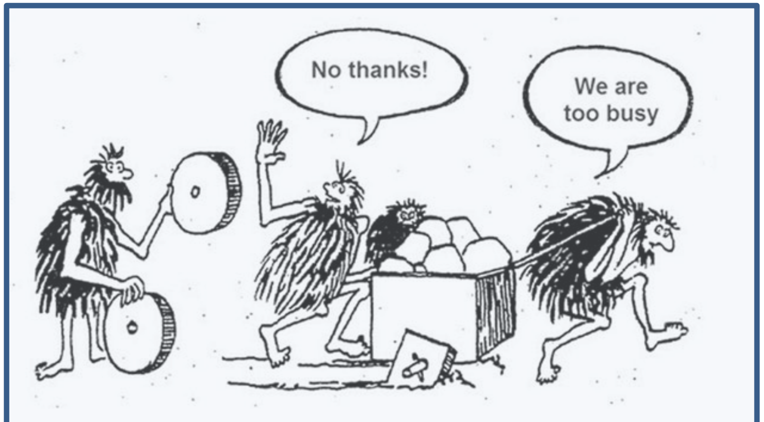
Model proliferation and model sprawl make it difficult to test underlying hypotheses and identify a clear path to model improvement

Adapted from Martyn Clark (NCAR)



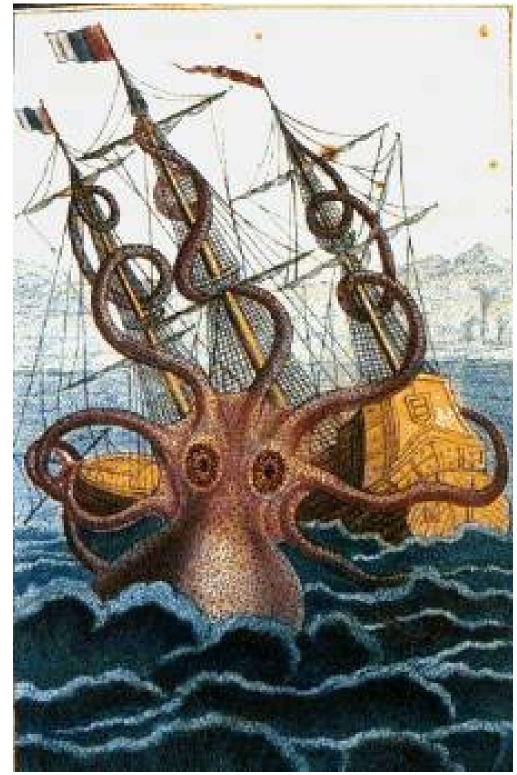
Reconstructing the Community Land Model (CLM)

Technical debt is a software engineering concept that reflects the implied cost of additional rework caused by choosing an easy solution now instead of using a better approach that would take longer
(Wikipedia)



(www.pentalog.com)

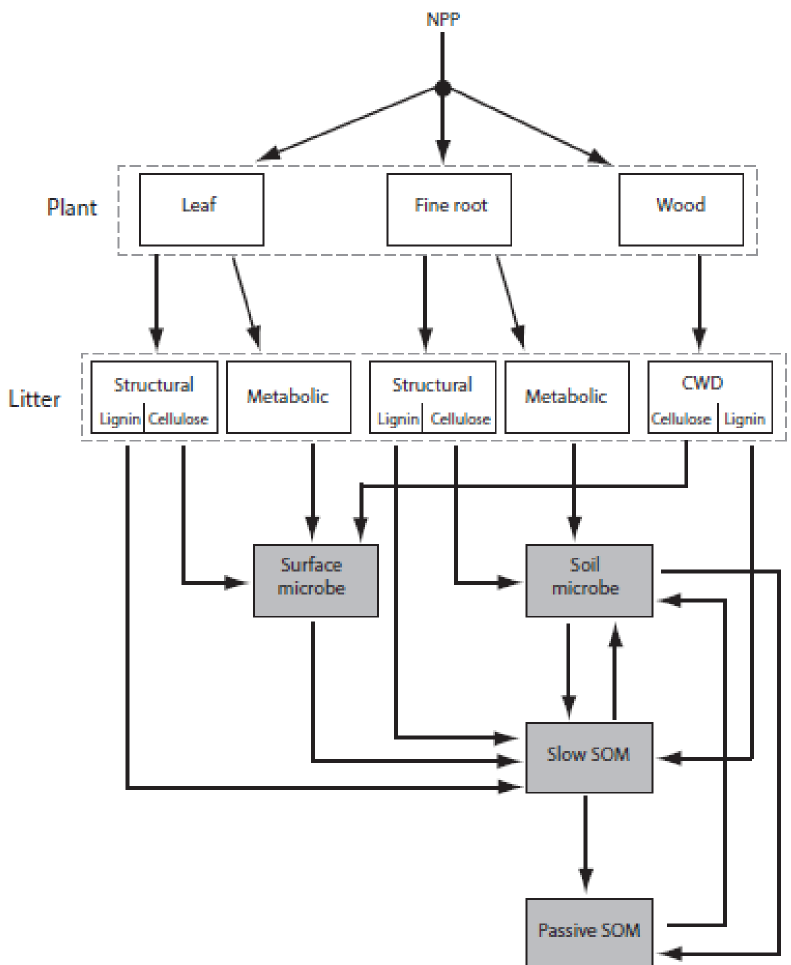
… or the kraken devouring a ship



Colossal octopus attacking a ship (Pierre Denys de Montfort, 1801)

A knot to untangle …

Contrasting views of ecosystems



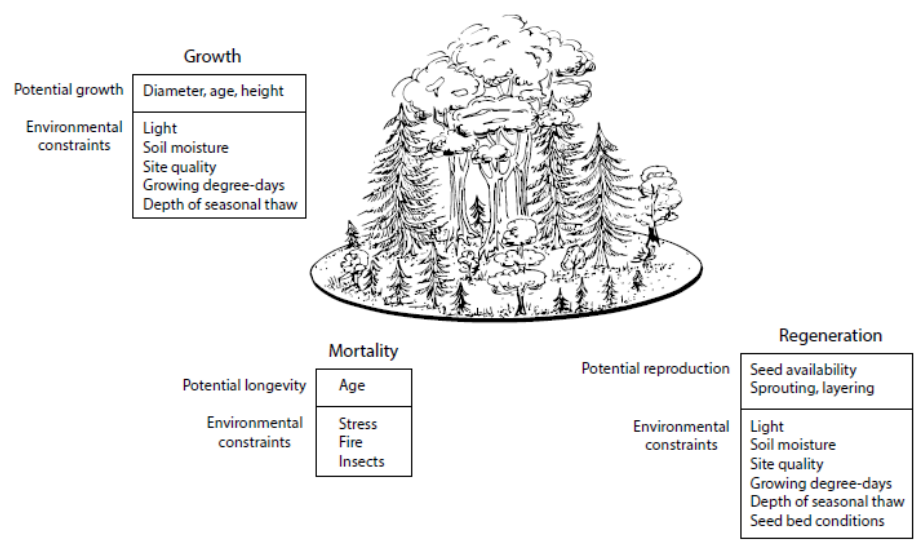
Individual based model

Ecosystem as individual trees

Demography

Life history characteristics

Functional traits



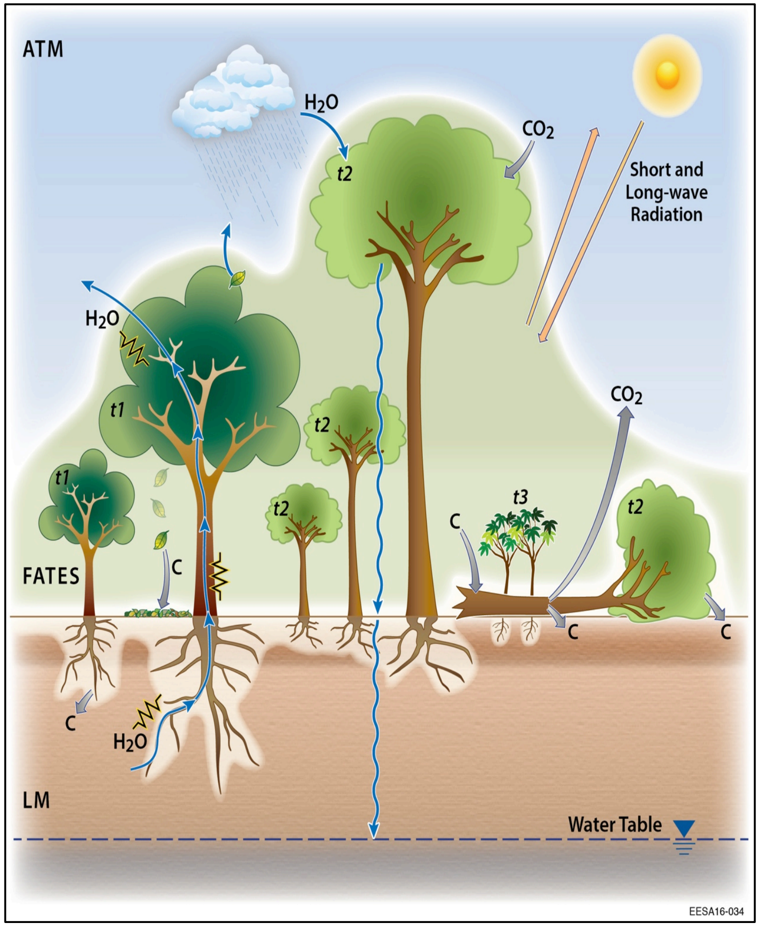
Biogeochemical model

Ecosystem as system of interconnected pools

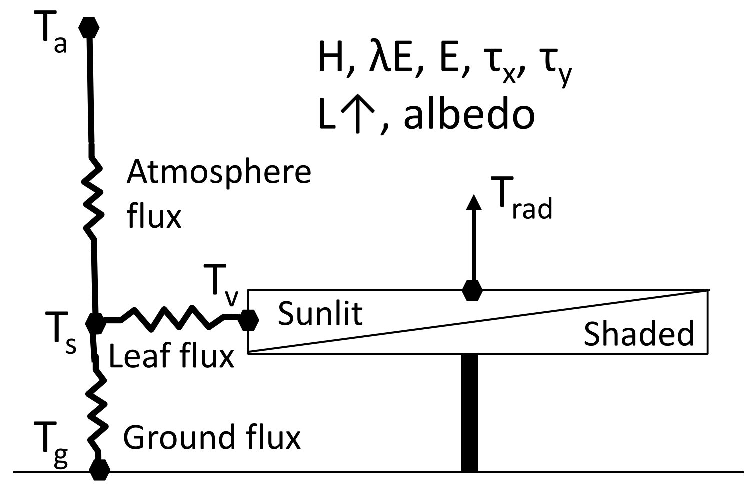
Bonan (2019) *Climate Change and Terrestrial Ecosystem Modeling* (Cambridge University Press)

Coupling FATES and CLM

FATES is a cohort-based model of vertically-structured canopy with vegetation demography



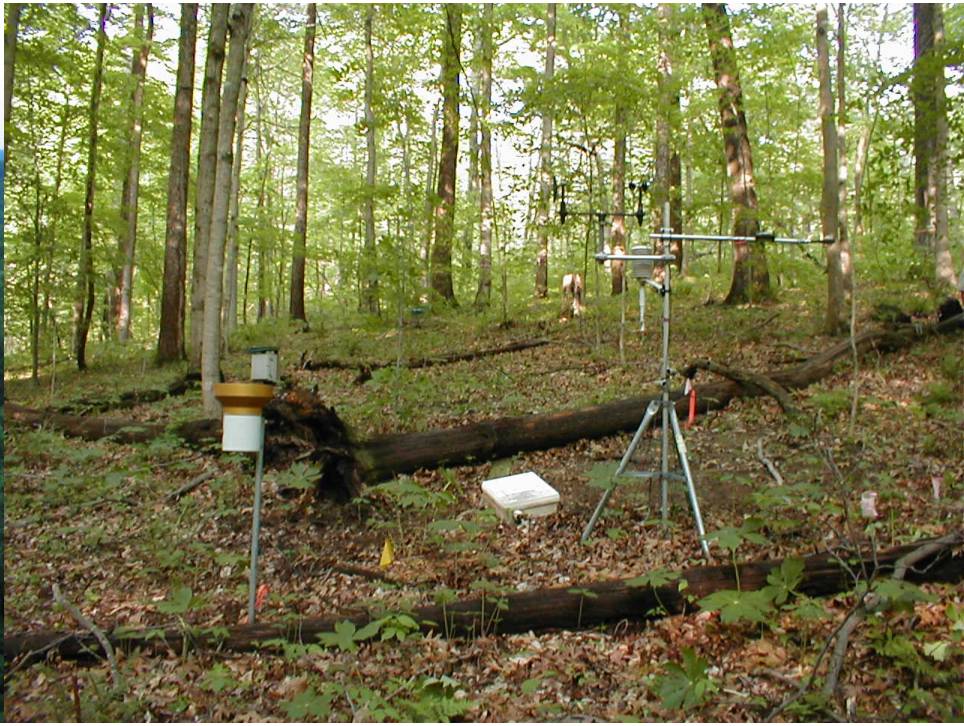
CLM5 = Big-leaf canopy without vertical structure



Enhances technical debt and perpetuates expedient coding practices

Two ways to model plant canopies

Photographs of Morgan Monroe State Forest tower site illustrate two different representations of a plant canopy: as a "big leaf" (below) or with vertical structure (right)



A carpet of leaves

"incorrect but useful"

A vertically-structured canopy

"correct but useless"

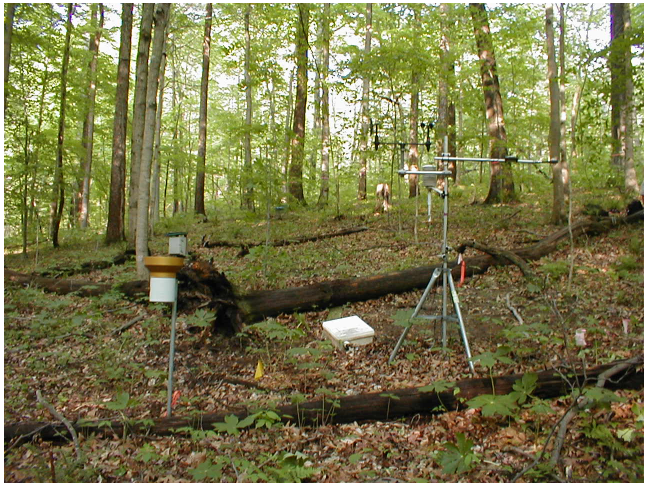
Raupach & Finnigan (1988) *Aust. J. Plant Physiol.*, 15, 705-716

Debate "settled" decades ago

A ONE-DIMENSIONAL THEORETICAL DESCRIPTION OF THE VEGETATION-ATMOSPHERE INTERACTION

W. JAMES SHUTTLEWORTH
Institute of Hydrology, Wallingford, Oxon, England

Boundary-Layer Meteorology **10** (1976) 273–302. *All Rights Reserved*
Copyright © 1976 by D. Reidel Publishing Company, Dordrecht-Holland



Viewpoint

Aust. J. Plant Physiol., 1988, **15**, 705–16

'Single-layer Models of Evaporation from Plant Canopies are Incorrect but Useful, Whereas Multilayer Models are Correct but Useless': Discuss

M. R. Raupach and J. J. Finnigan
Centre for Environmental Mechanics, CSIRO, G.P.O. Box 821, Canberra, A.C.T. 2601, Australia.

Plant, Cell and Environment (1997) **20**, 537–557

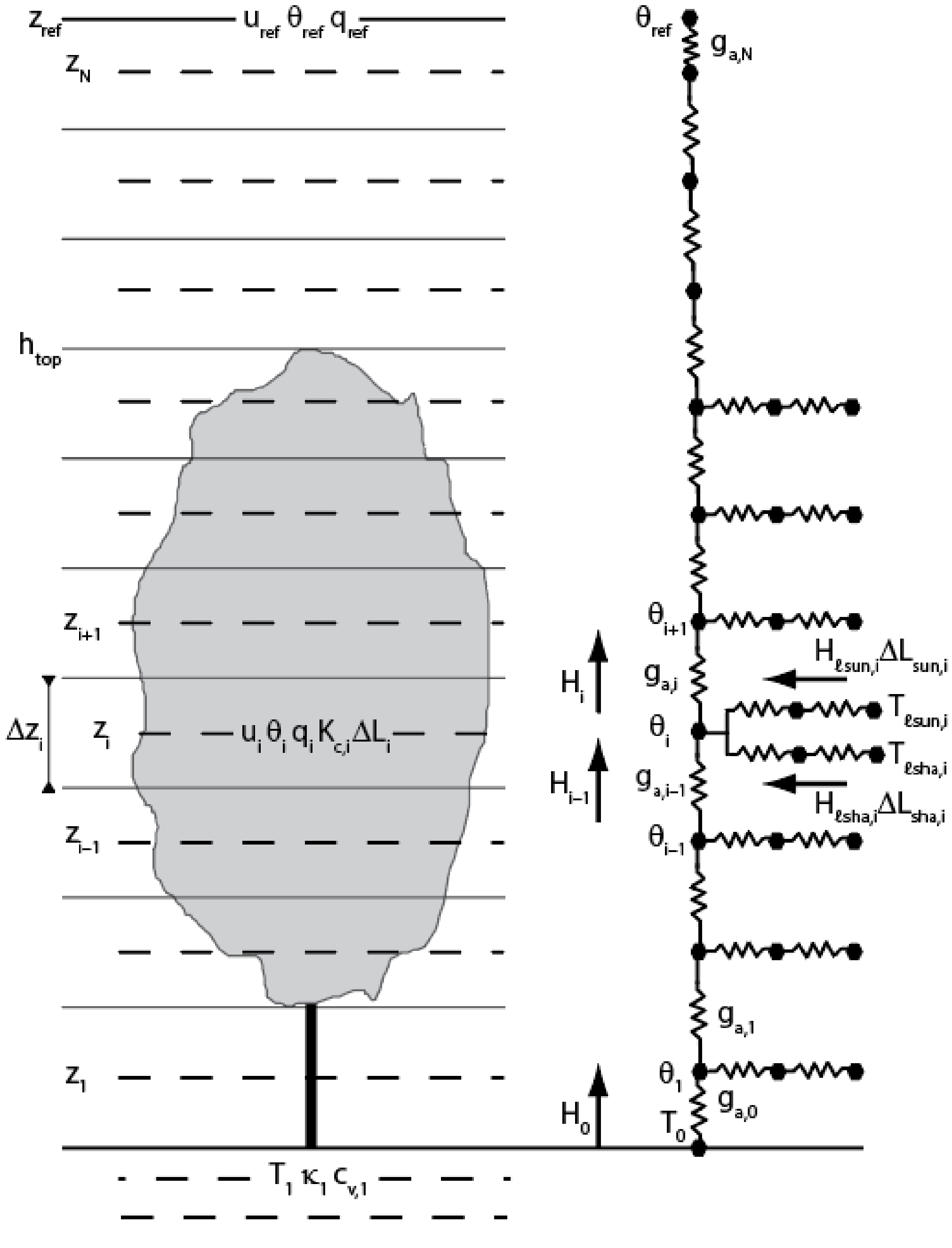
Simple scaling of photosynthesis from leaves to canopies without the errors of big-leaf models

D. G. G. DE PURY & G. D. FARQUHAR
Environmental Biology, Research School of Biological Sciences, Institute of Advanced Studies, The Australian National University, Canberra, ACT, Australia

Agricultural and Forest Meteorology 91 (1998) 89–111

A two-leaf model for canopy conductance, photosynthesis and partitioning of available energy I:
Model description and comparison with a multi-layered model

Y.-P. Wang[a,*], R. Leuning[b]
[a] *CSIRO Division of Atmospheric Research, PMB # 1, Aspendale, Vic 3195, Australia*
[b] *CSIRO Land and Water, FC Pye Laboratory, Canberra, ACT 2601, Australia*



Multilayer canopy

Leaf gas exchange based on water-use efficiency optimization while preventing leaf desiccation (plant hydraulics); sunlit and shaded leaves

Williams et al. (1996) *Plant Cell Environ.*, 19, 911-27

Bonan et al. (2014) *Geosci. Model Dev.*, 7, 2193-2222

Canopy turbulence and roughness sublayer

Harman & Finnigan (2007, 2008) *Boundary-Layer Meteorol.*, 123, 339-63; 129, 323-51

Bonan et al. (2018) *Geosci. Model Dev.*, 11, 1467-96

Solve a system of linear equations for θ, q, $T_{\ell sun}$, $T_{\ell sha}$

Ryder et al. (2016) *Geosci. Model Dev.*, 9, 223-45

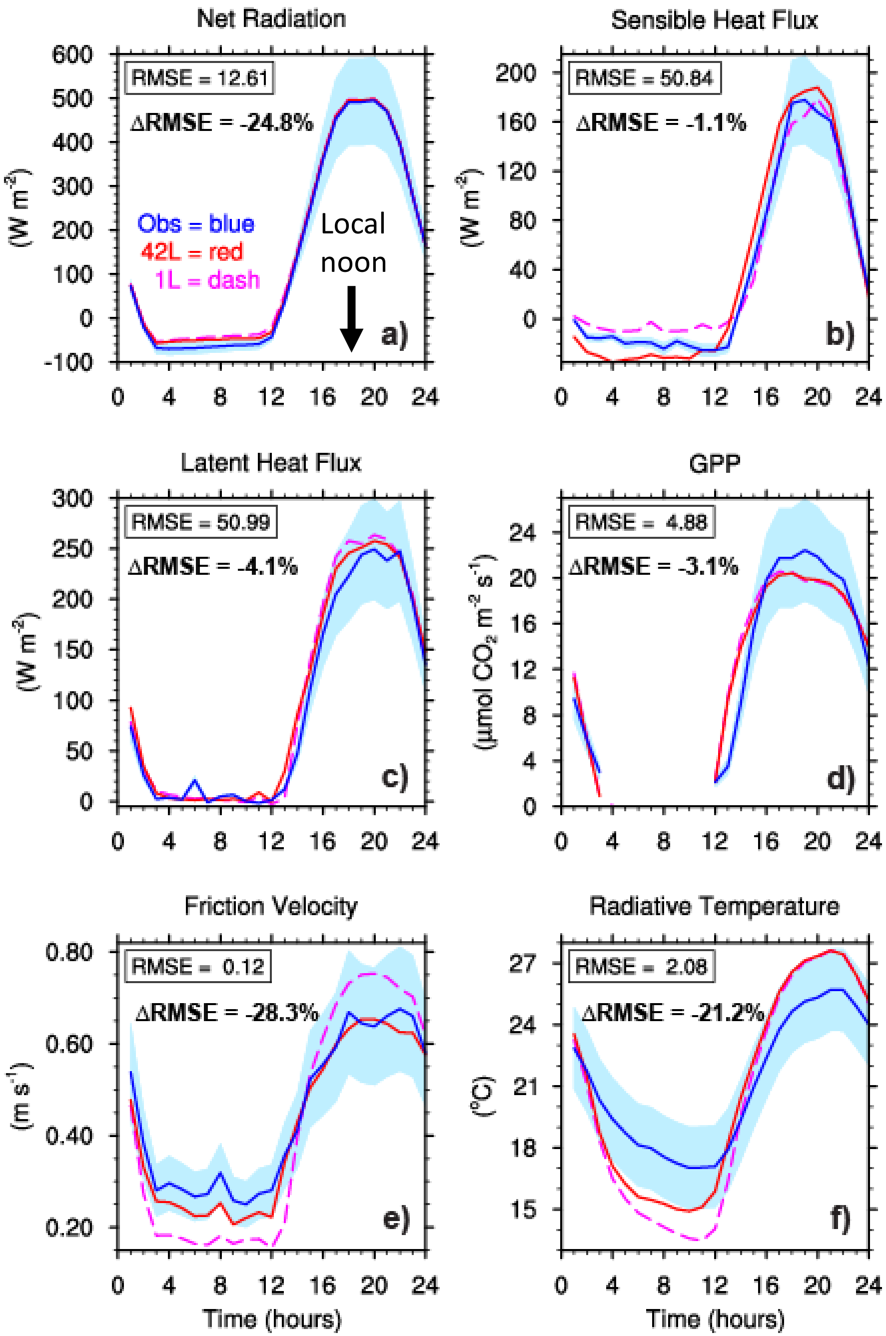
Bonan et al. (2018) *Geosci. Model Dev.*, 11, 1467-96

The physics and physiology of the multilayer canopy are simpler and more consistent with theory than is the CLM5 big-leaf canopy (with many ad-hoc parameterizations and much technical debt)

Above-canopy fluxes

US-UMB, July 2006 (deciduous broadleaf forest)

The 42-layer canopy (**red**) better reproduces the observations (blue) with reduced RMSE compared to the 1-layer canopy (**magenta**)



Bonan, Patton, Finnigan, et al. (unpublished)

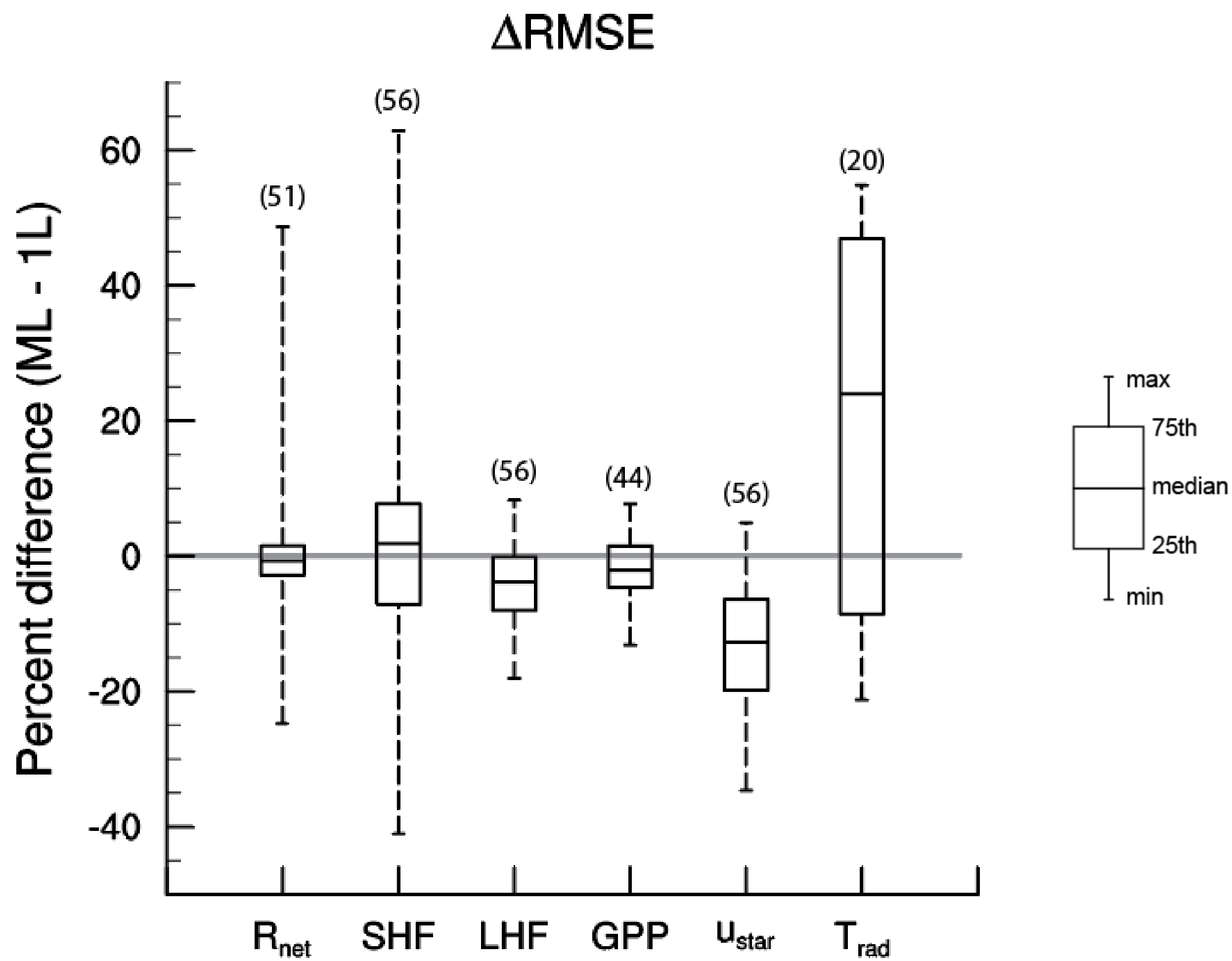
How good is a big-leaf model?

Cross-site synthesis

7 forest eddy covariance sites (Ameriflux)

56 site-years of data

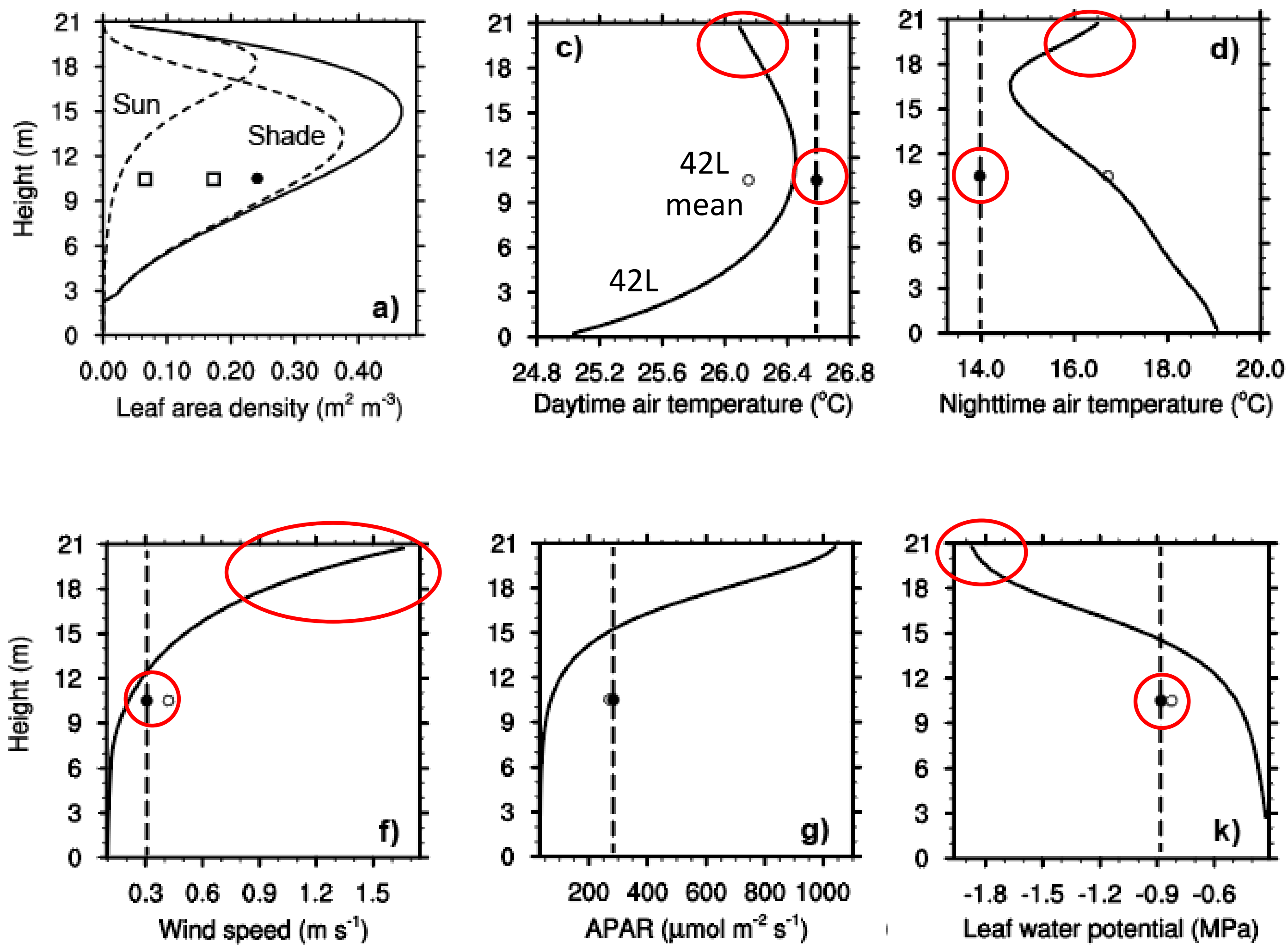
The multilayer canopy better reproduces the observations (reduced RMSE), particularly for latent heat flux, GPP, and friction velocity



Bonan, Patton, Finnigan, et al. (unpublished)

Canopy profiles

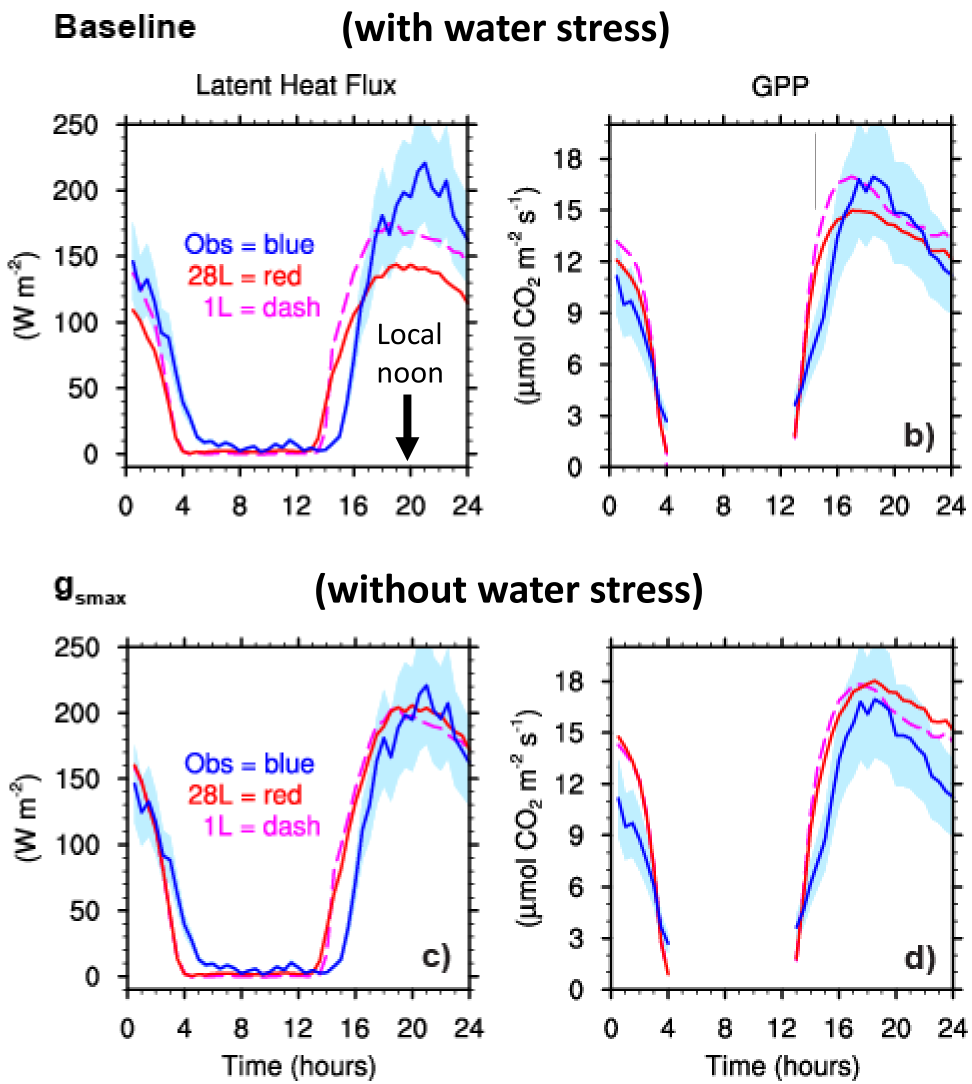
Vertical profiles within the canopy are important



Bonan, Patton, Finnigan, et al. (unpublished)

How does LWP affect scaling error?

US-Me2 (July 2004)

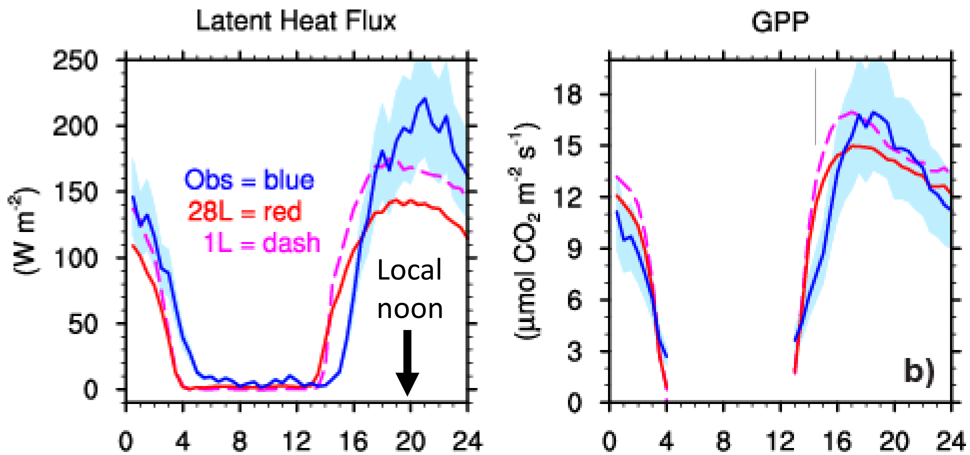


Bonan, Patton, Finnigan, et al. (unpublished)

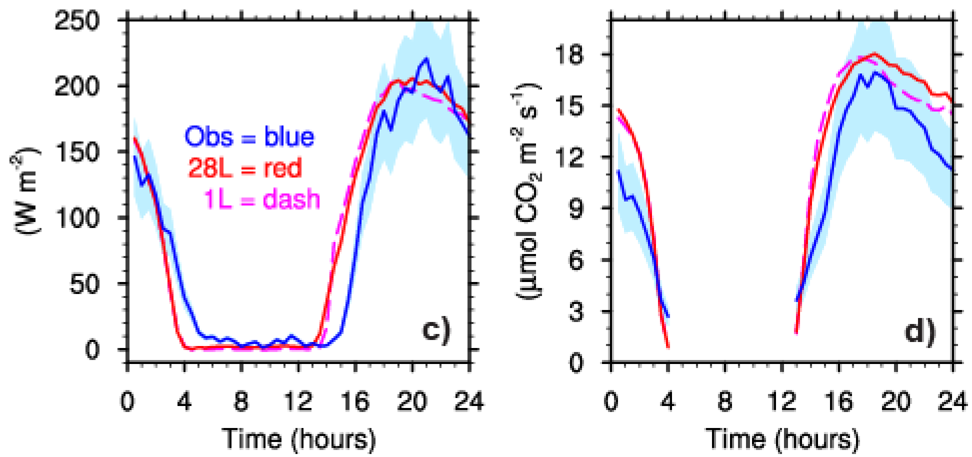
How does LWP affect scaling error?

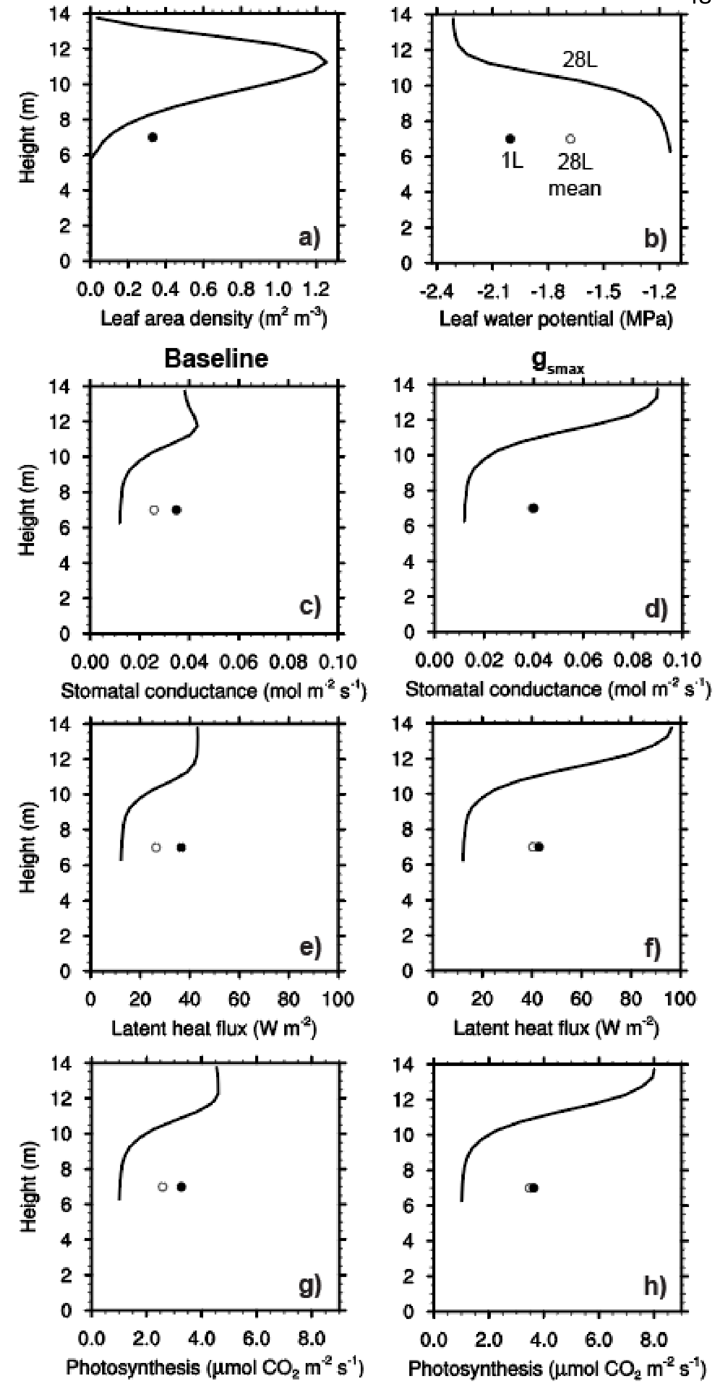
US-Me2 (July 2004)

Baseline **(with water stress)**



g_{smax} **(without water stress)**

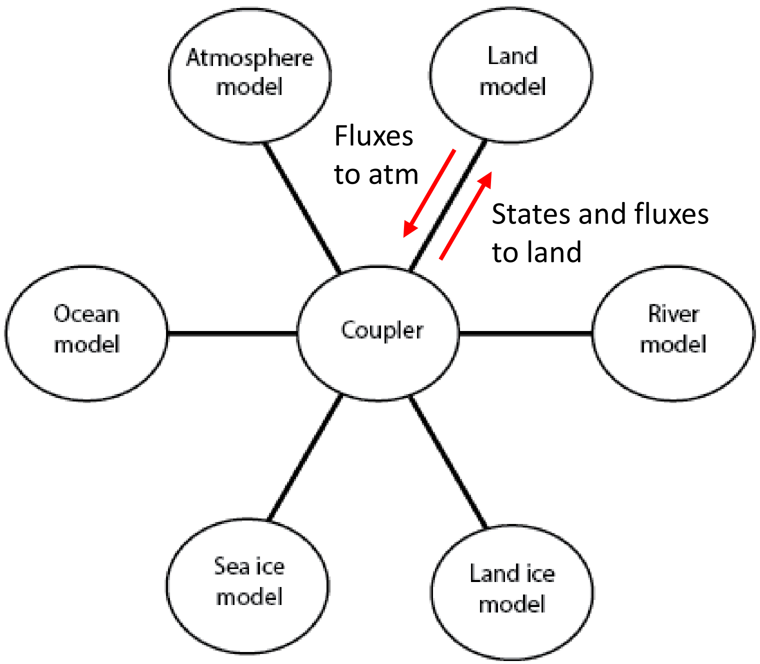




Bonan, Patton, Finnigan, et al. (unpublished)

Land in Earth system models

The CESM perspective …



Bonan (2019) *Climate Change and Terrestrial Ecosystem Modeling* (Cambridge University Press)

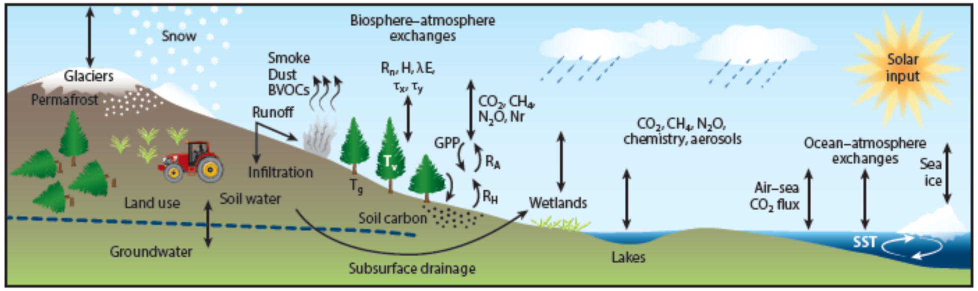
… models as boundary conditions to other models

But where does the atmosphere stop and the land begin? Or, what is the "surface" in a land surface model?

www.datnature.com

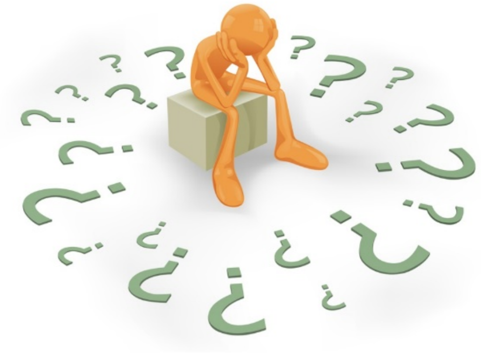
Take home points

1. Earth system models are an important science tool
   - ○ Alternative socioeconomic pathways
   - ○ Identify ecological processes that determine climate
   - ○ Test generality of ecological theories at the macroscale



Bonan (2016) *Annu. Rev. Ecol. Evol. Syst.*, 47, 97-121

2. There is much uncertainty in the models
   - ○ **Modelers** need to do better at characterizing uncertainty
     - ❖ Why is a particular answer attained?
     - ❖ What is the underlying theory?
   - ○ **Observationalists** need to understand uncertainty
     - ❖ Easy to criticize models for lacking a process
     - ❖ More authentic process representations may not reduce uncertainty
     - ❖ More data may not be able to solve the problem



3. The path forward requires a new generation of interdisciplinary Earth system scientists who combine theory, numerical modeling, observations, and data analysis
   - ○ Overcoming disciplinary chauvinism