Why we model the land (at an atmospheric research center)

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

2026 CLM Tutorial
NSF National Center for Atmospheric Research
Boulder, Colorado
19 November 2026

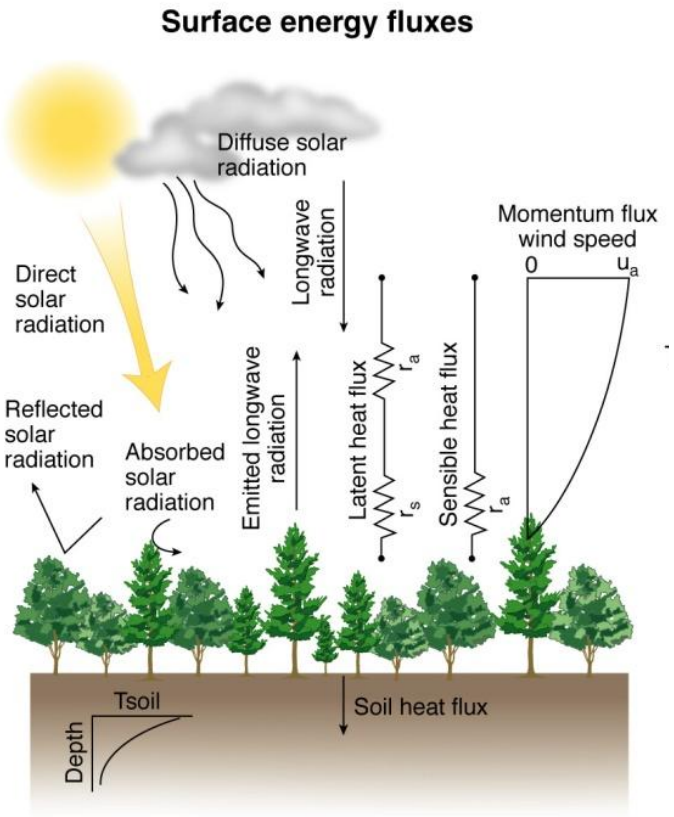

Quanta magazine / Gabriel Popkin

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

Land as a surface boundary condition

1. CLM provides fluxes at the land-atmosphere interface needed to solve the equations of atmospheric physics and motion:
   - Albedo and longwave radiation
   - Turbulent fluxes (momentum, sensible heat, latent heat, water vapor)
   - Constituent fluxes: CO_2, aerosols, BVOCs

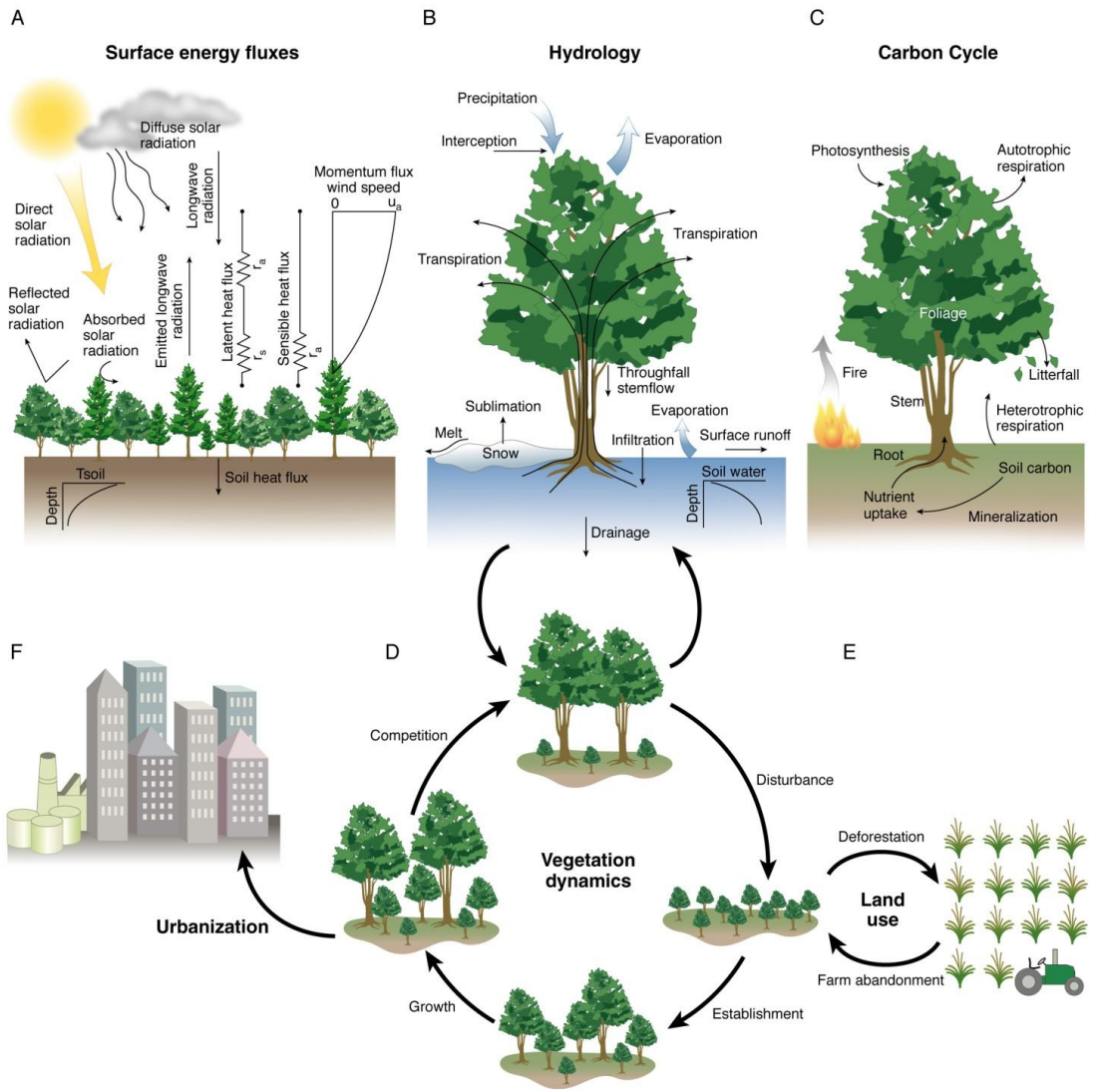
2. CLM provides freshwater runoff to the ocean



Bonan (2008) *Science*, 320, 1444-1449

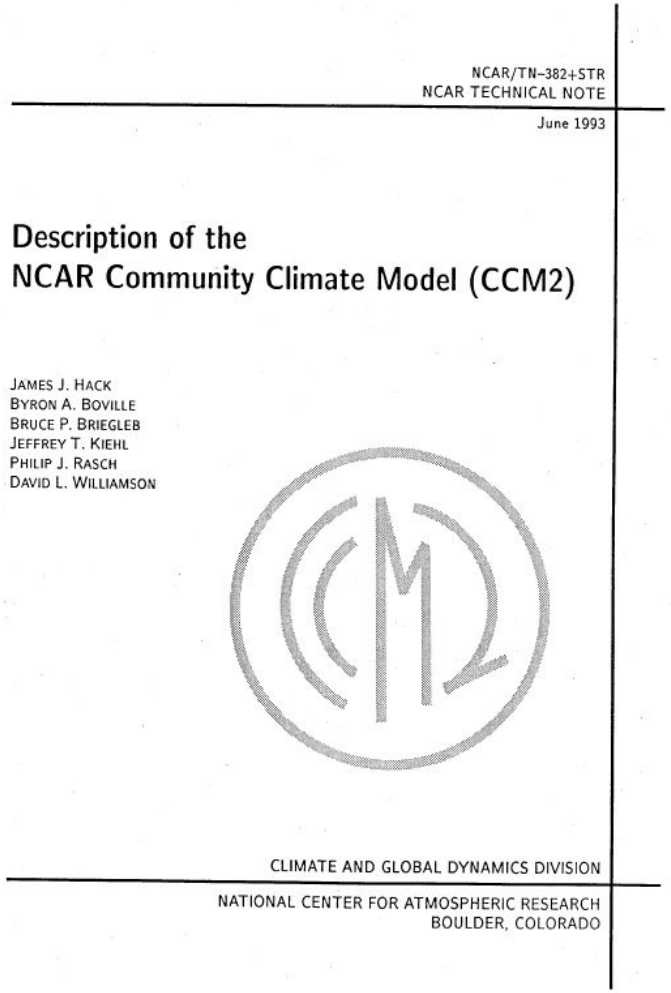
Model design philosophy

1. Coupling with the atmosphere every model timestep is a fundamental constraint (≤ 30 minute timestep)
2. CLM uses the same spatial grid (resolution, shape) as the atmosphere
3. Conservation of energy and mass is required
4. CLM models the global land surface. There is tension between site-specific studies and global implementation
5. We strive to develop a process-level understanding across multiple ecosystems and at multiple timescales (diurnal, seasonal, annual, decadal, centuries)



Bonan (2008) *Science*, 320, 1444-1449

NCAR models circa 1993



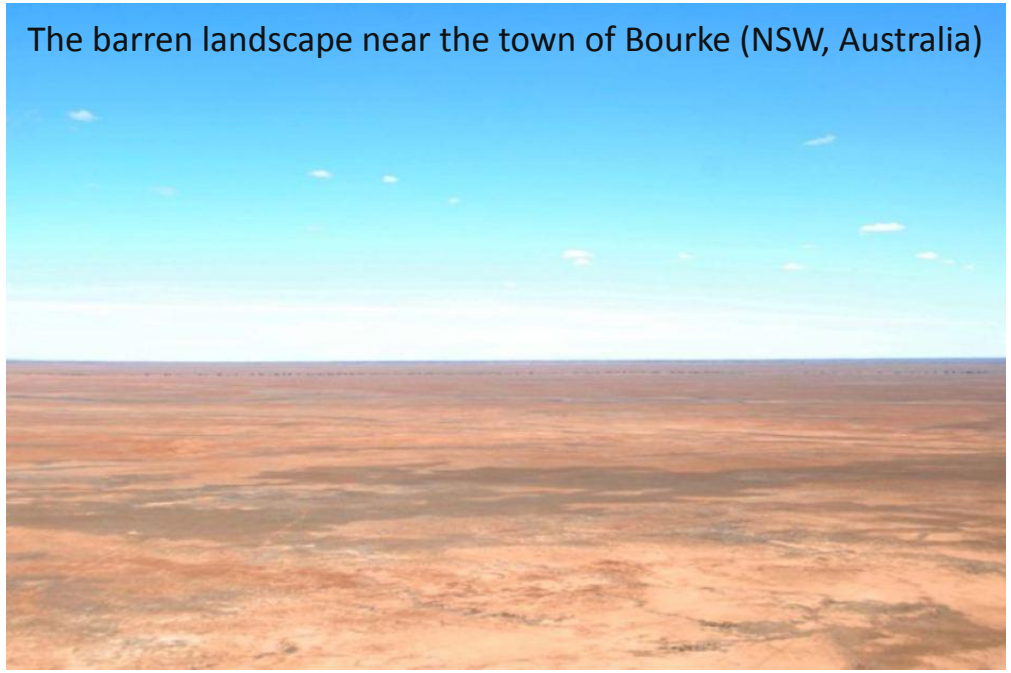
NCAR/TN-382+STR
NCAR TECHNICAL NOTE
June 1993

Description of the
NCAR Community Climate Model (CCM2)

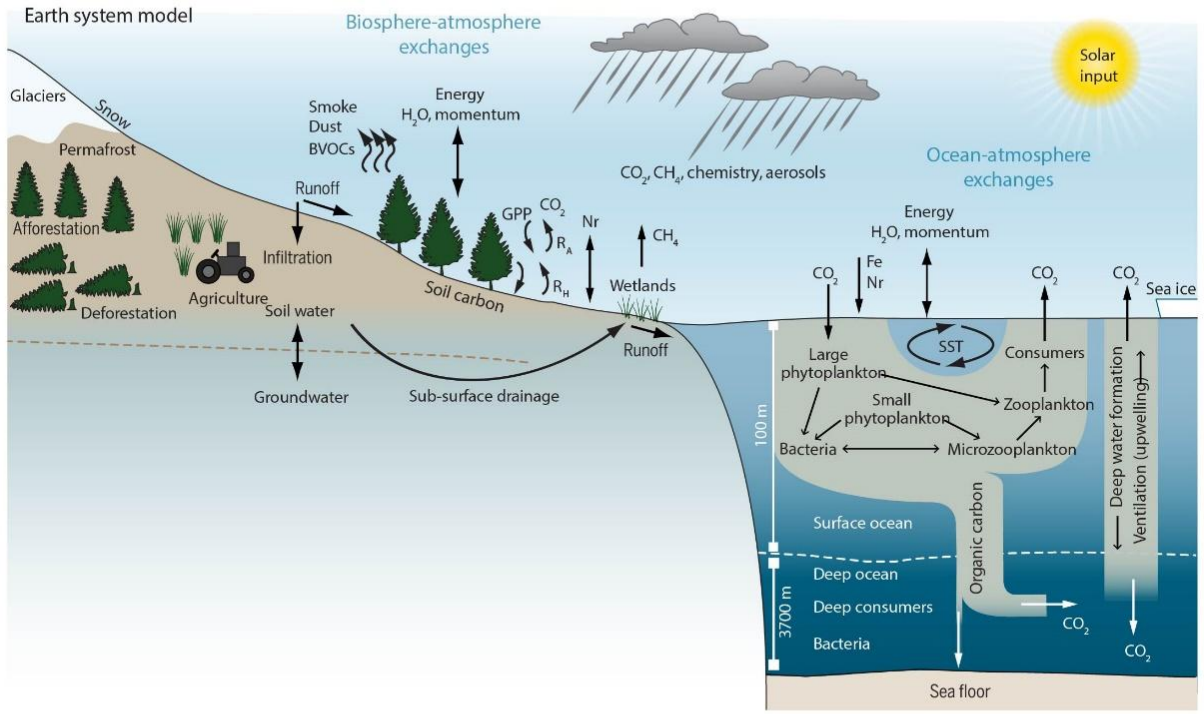
JAMES J. HACK
BYRON A. BOVILLE
BRUCE P. BRIEGLEB
JEFFREY T. KIEHL
PHILIP J. RASCH
DAVID L. WILLIAMSON

CLIMATE AND GLOBAL DYNAMICS DIVISION
NATIONAL CENTER FOR ATMOSPHERIC RESEARCH
BOULDER, COLORADO

- No hydrologic cycle on land
- No plant canopies (no leaves or stomata)
- Prescribed surface albedos
- Bulk aerodynamic formulation of surface fluxes and land surface temperature with prescribed soil wetness



Earth system models



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

Scientific discovery

Identify ecological processes that determine climate

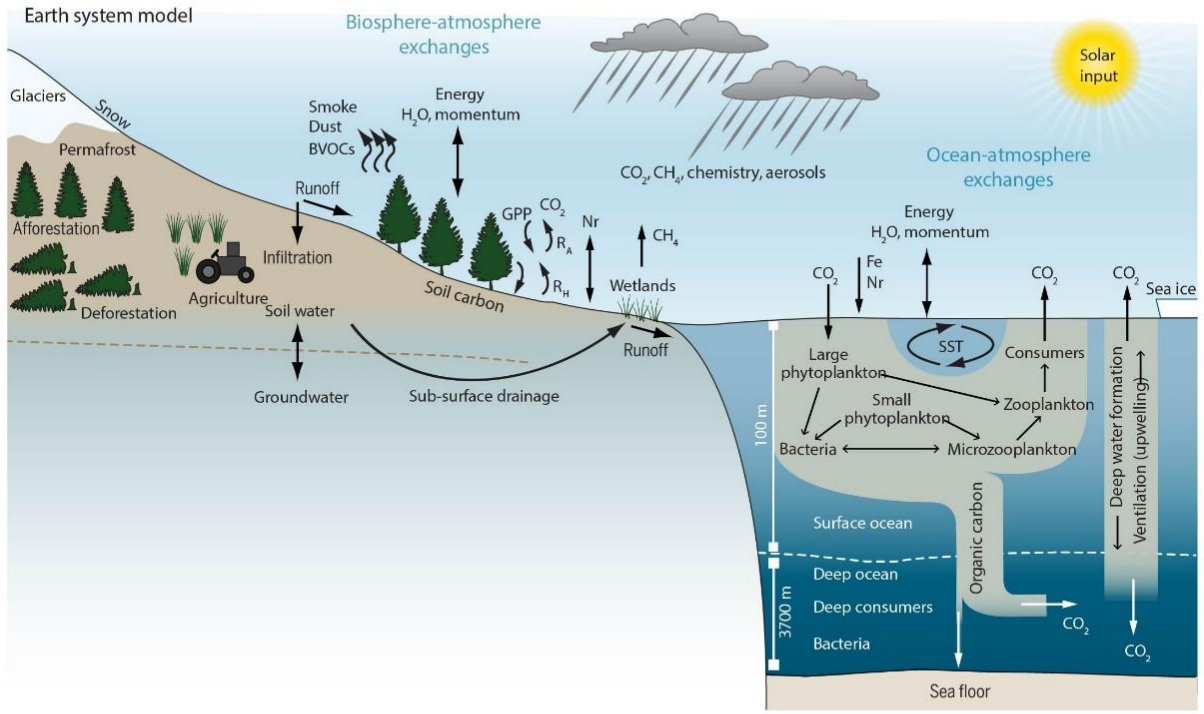
Advance theory

Test generality of ecological theories at the macroscale

Earth's past and future

What are the consequences of alternative socioeconomic pathways?

Earth system models

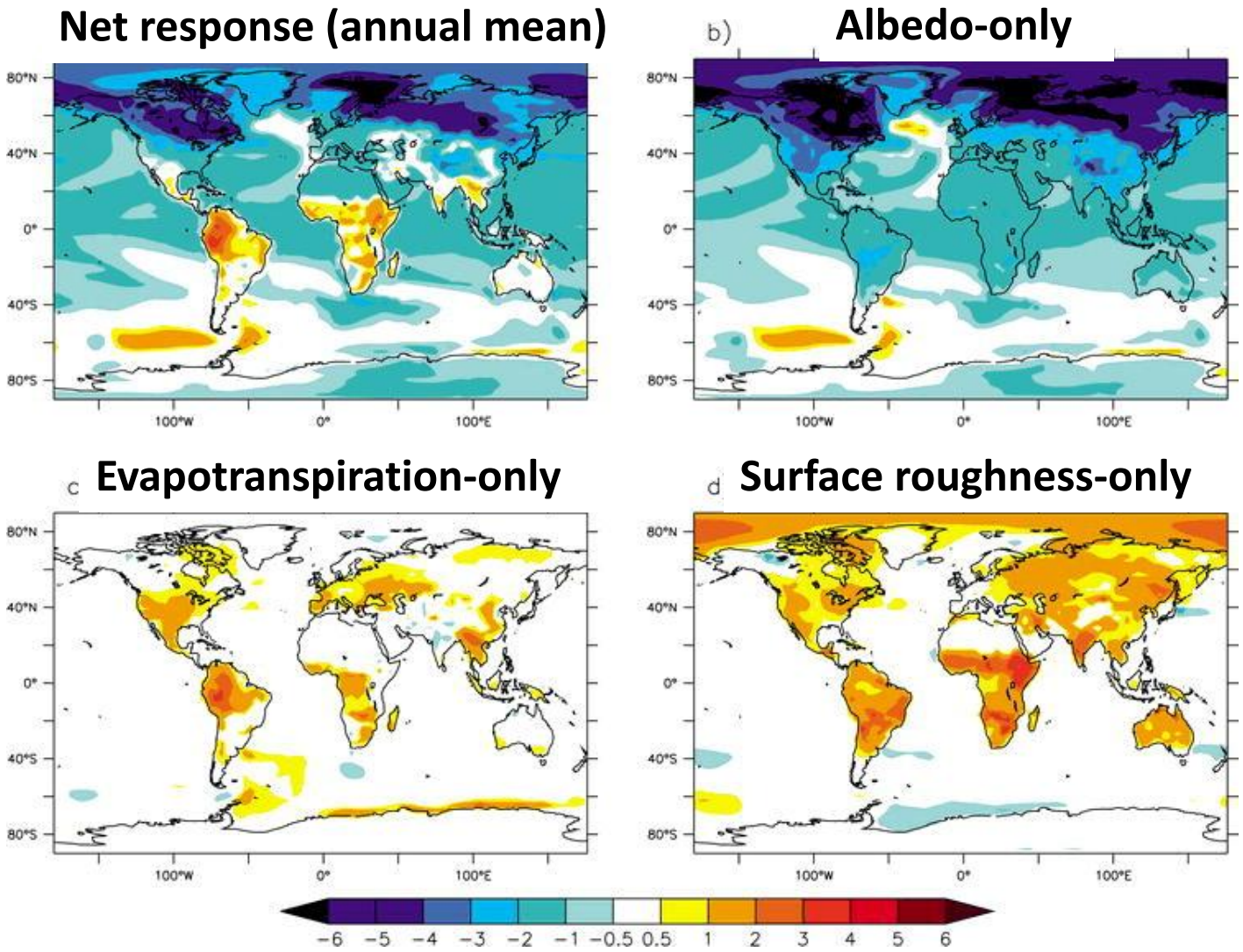


Bonan & Doney (2018) *Science*, 359, eaam8328, doi:10.1126/science.aam8328

Prominent terrestrial feedbacks

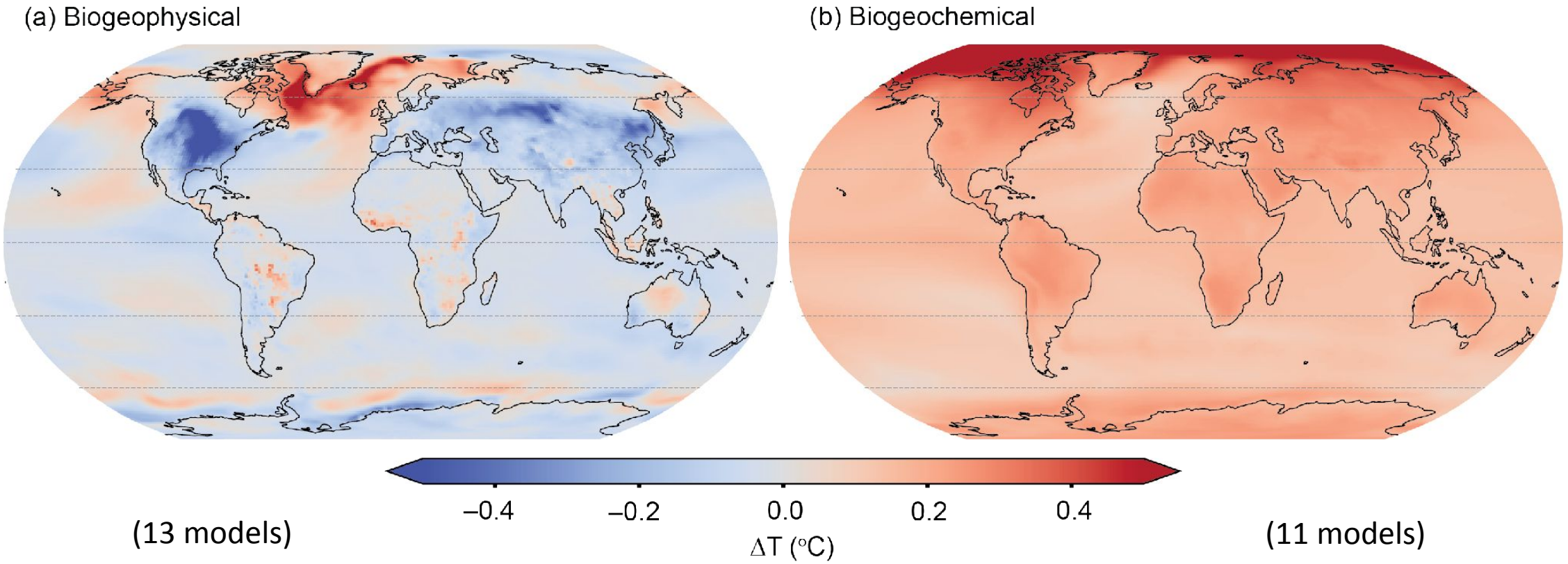
- Snow cover
- Soil moisture-evapotranspiration-precipitation
- Land use & land cover change
- Carbon cycle
- Physiological forcing (stomata)
- Reactive nitrogen
- Chemistry-climate (BVOCs, O_3, CH_4, aerosols)
- Biomass burning, mineral dust

Forests influences on global climate



Davin & de Noblet-Ducoudré (2010) *J. Clim.*, 23, 97-112

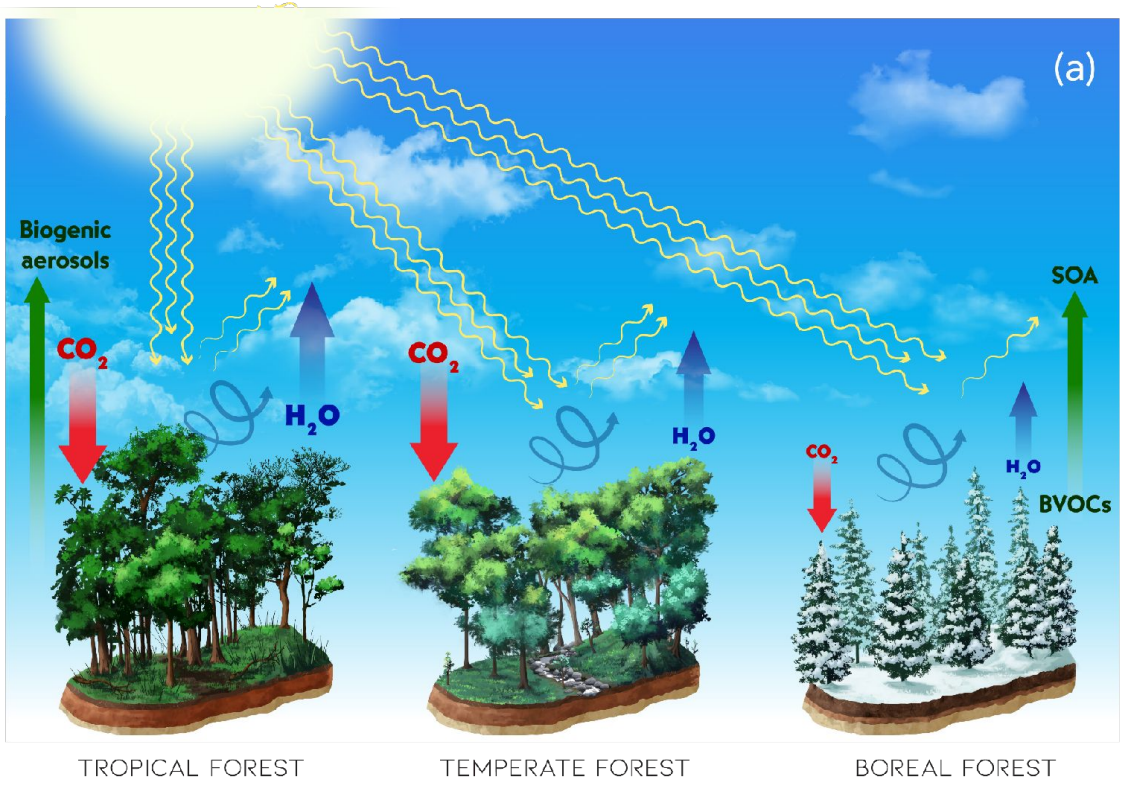
Historical LULCC



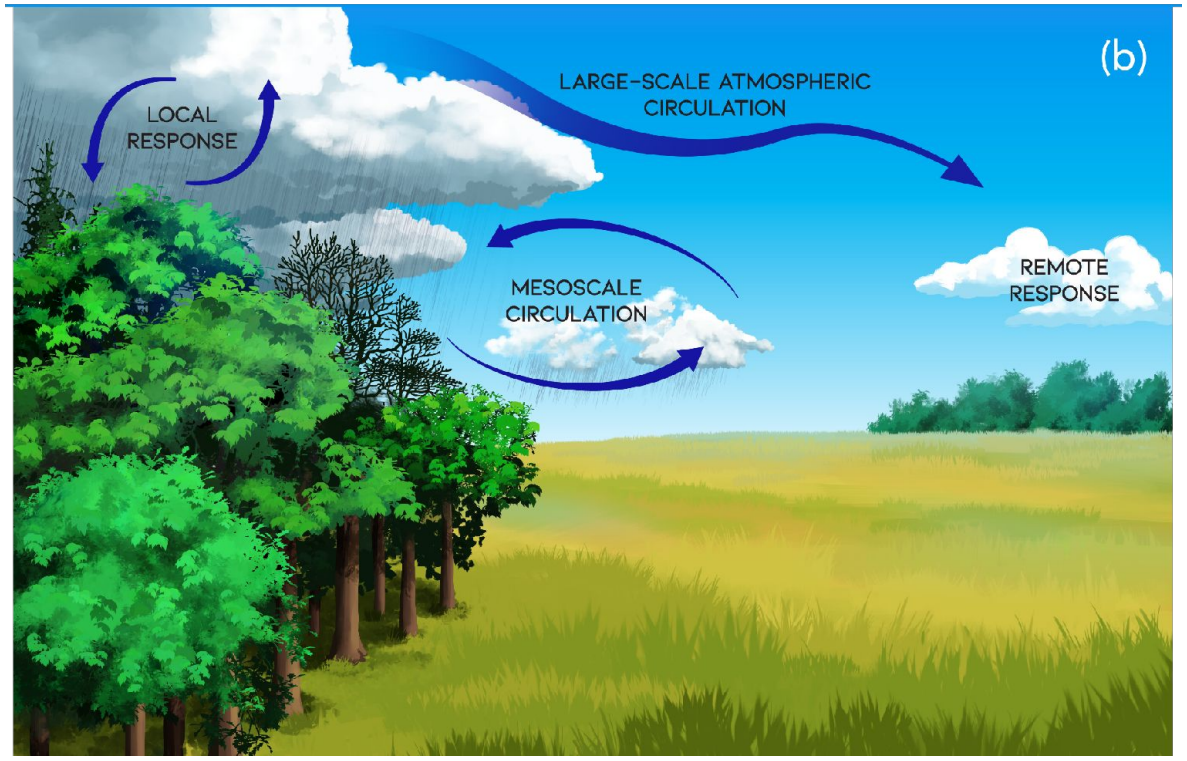
Amali et al. (2025) *Earth Syst. Dyn.*, 16, 803–840

Climate services of forests

Local land-atmosphere coupling

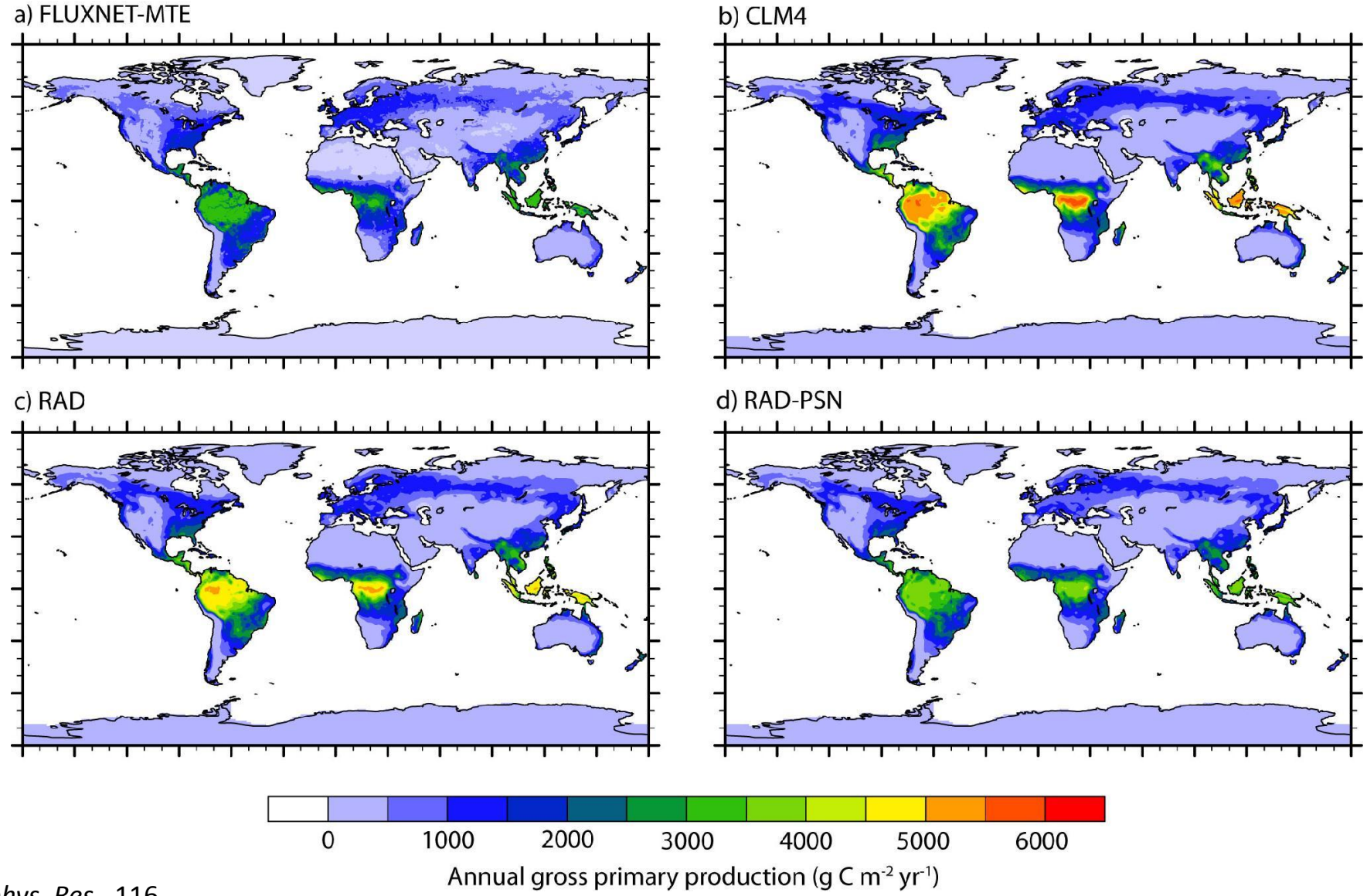


Atmospheric dynamics



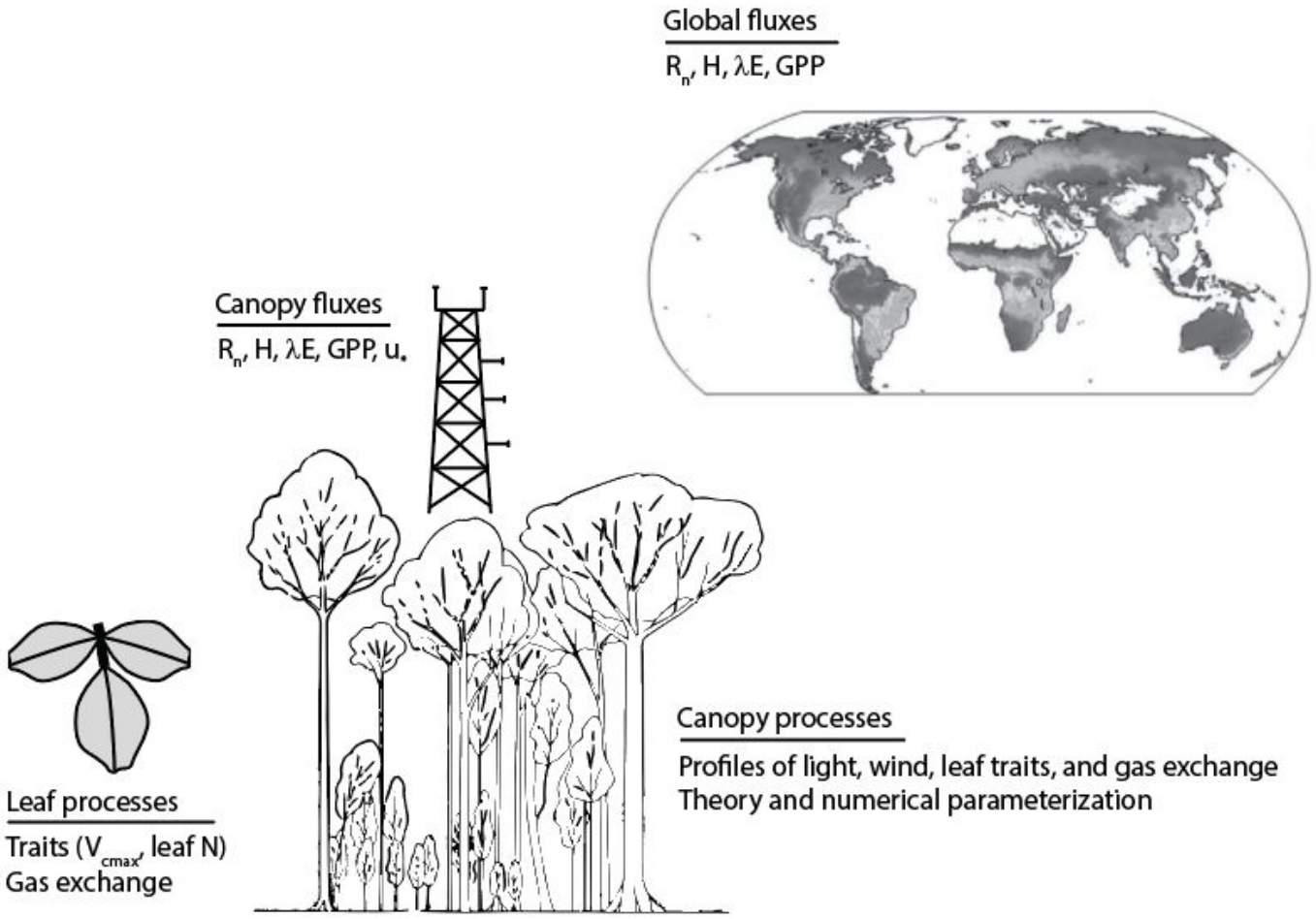
Bonan et al. (2024) *J. Adv. Model. Earth Syst.*, doi:10.1029/2023MS004017; Bonan (2008) *Science*, 320, 1444-49
See also Bonan (2027) *Ecological Climatology*, 4th ed. (Cambridge Univ. Press)

Process studies: GPP



Bonan et al. (2011) *J. Geophys. Res.*, 116, G02014, doi:10.1029/2010JG001593

Multi-scale model evaluation



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

Consistency among parameters, theory, processes, and observations across multiple scales, from leaf to canopy to global

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

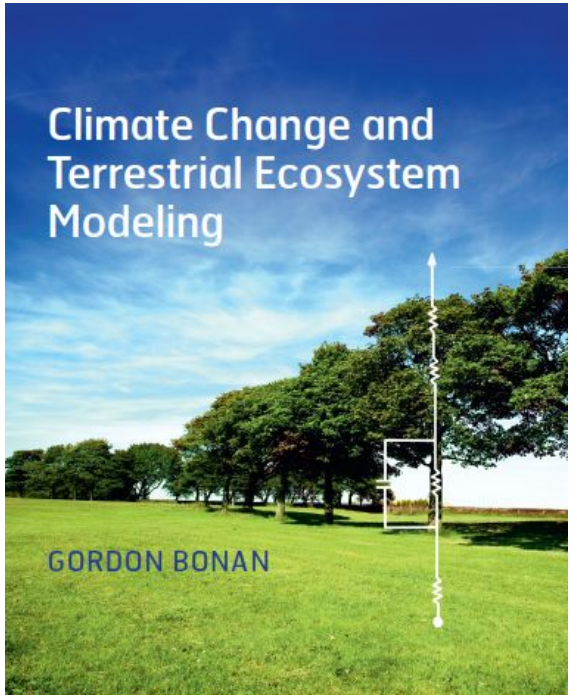
Richards equation $$\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial z}\left[K(\theta)\frac{\partial \psi}{\partial z}\right] + \frac{\partial K}{\partial z}$$

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

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

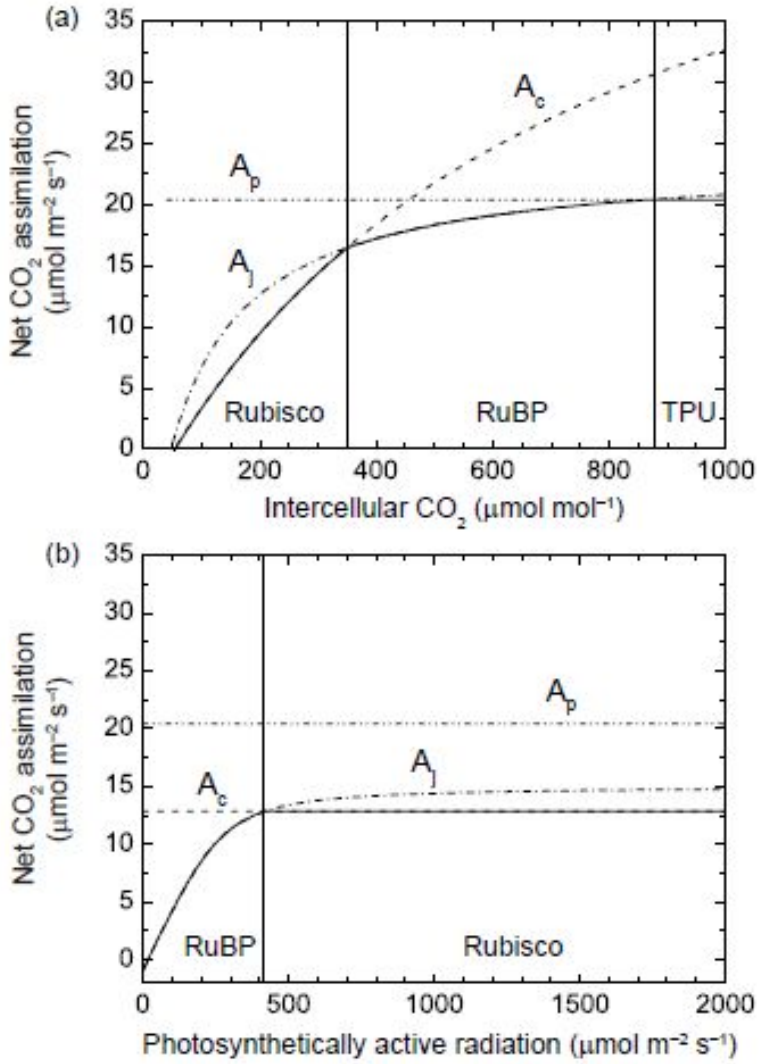
Rubisco-limited rate is

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

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 APAR

Parameters and temperature dependencies:

- K_c, K_o, Γ_*
- V_{cmax}, J_{max}, R_d
- Θ_J, Φ_{PSII}, α

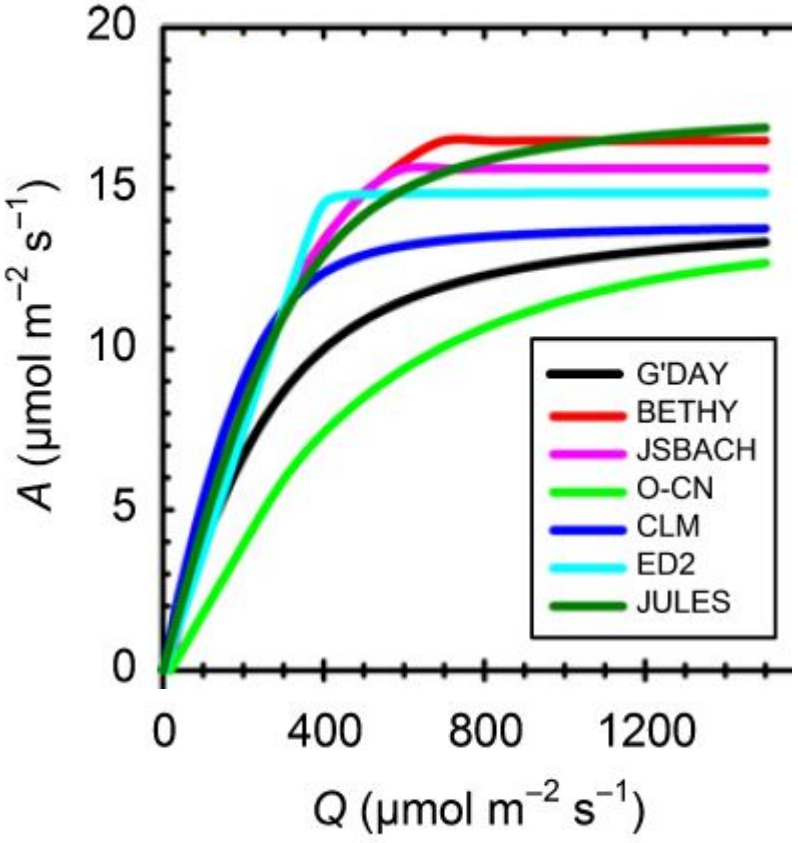
Temperature acclimation



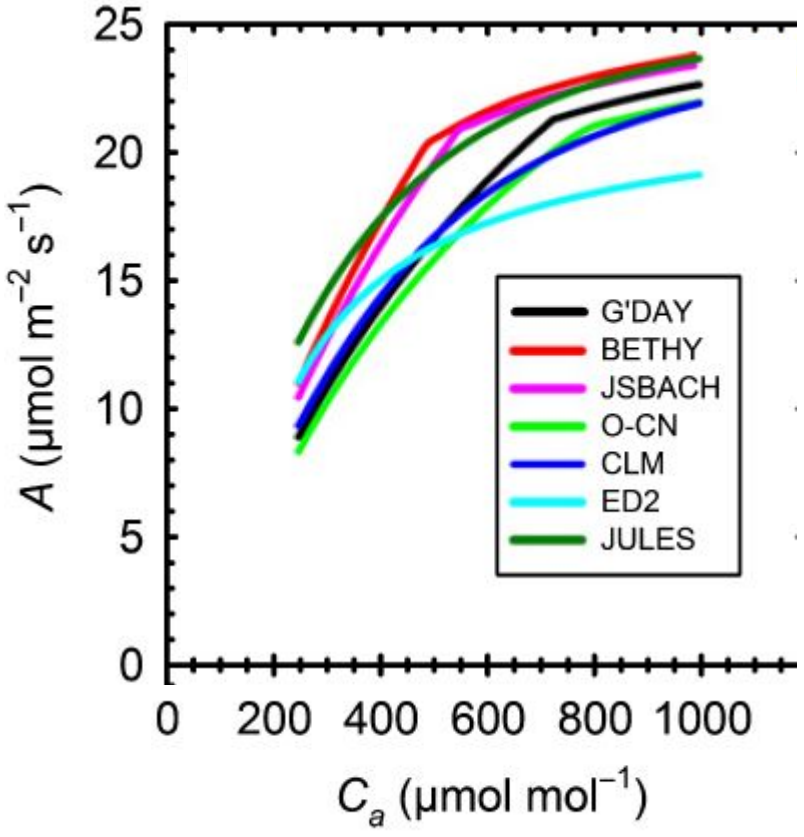
Are we modeling the same thing?

V_{cmax} = 60 µmol m^{-2} s^{-1}

Leaf light response



Leaf CO_2 response

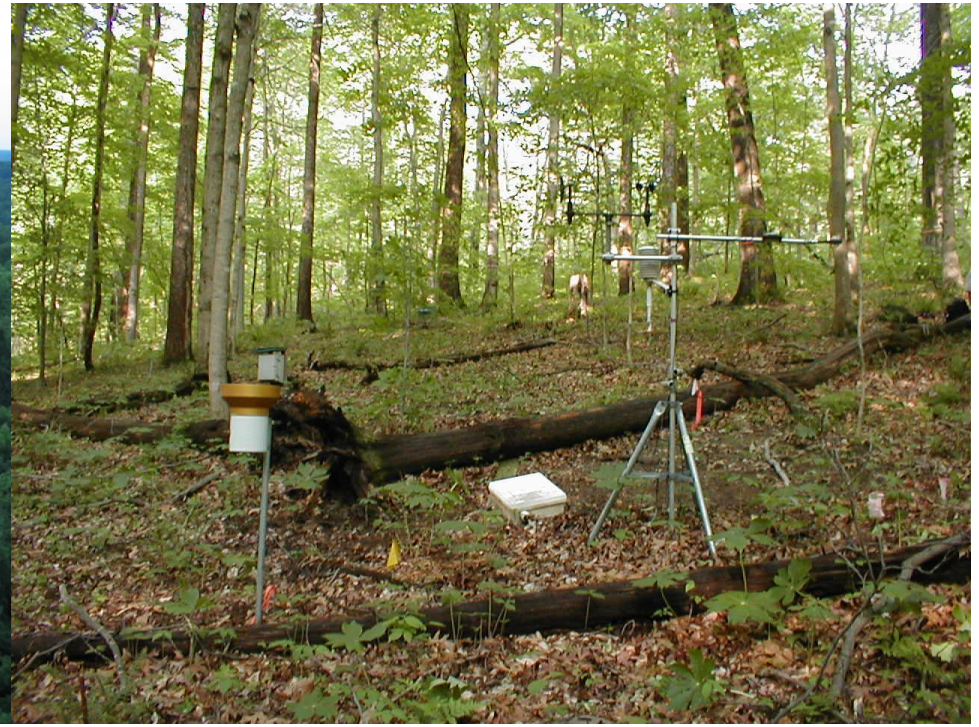


Rogers et al. (2017) *New Phytol.,* 213, 22-42

Reconstructing the Community Land Model

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



Multilayer canopy

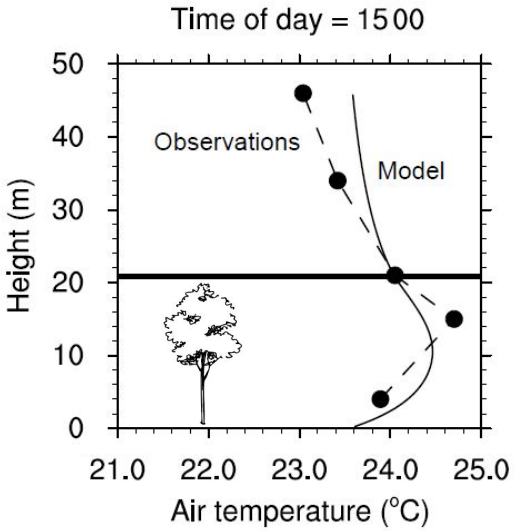
The physics and physiology of the multilayer canopy are simpler and more consistent with theory (and directly observable) than is the CLM6 big-leaf canopy (with many ad-hoc parameterizations and much technical debt), *and it also enables new science*

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

Bonan, Patton, Harman, et al. (2018) *Geosci. Model Dev.*, 11, 1467-1496

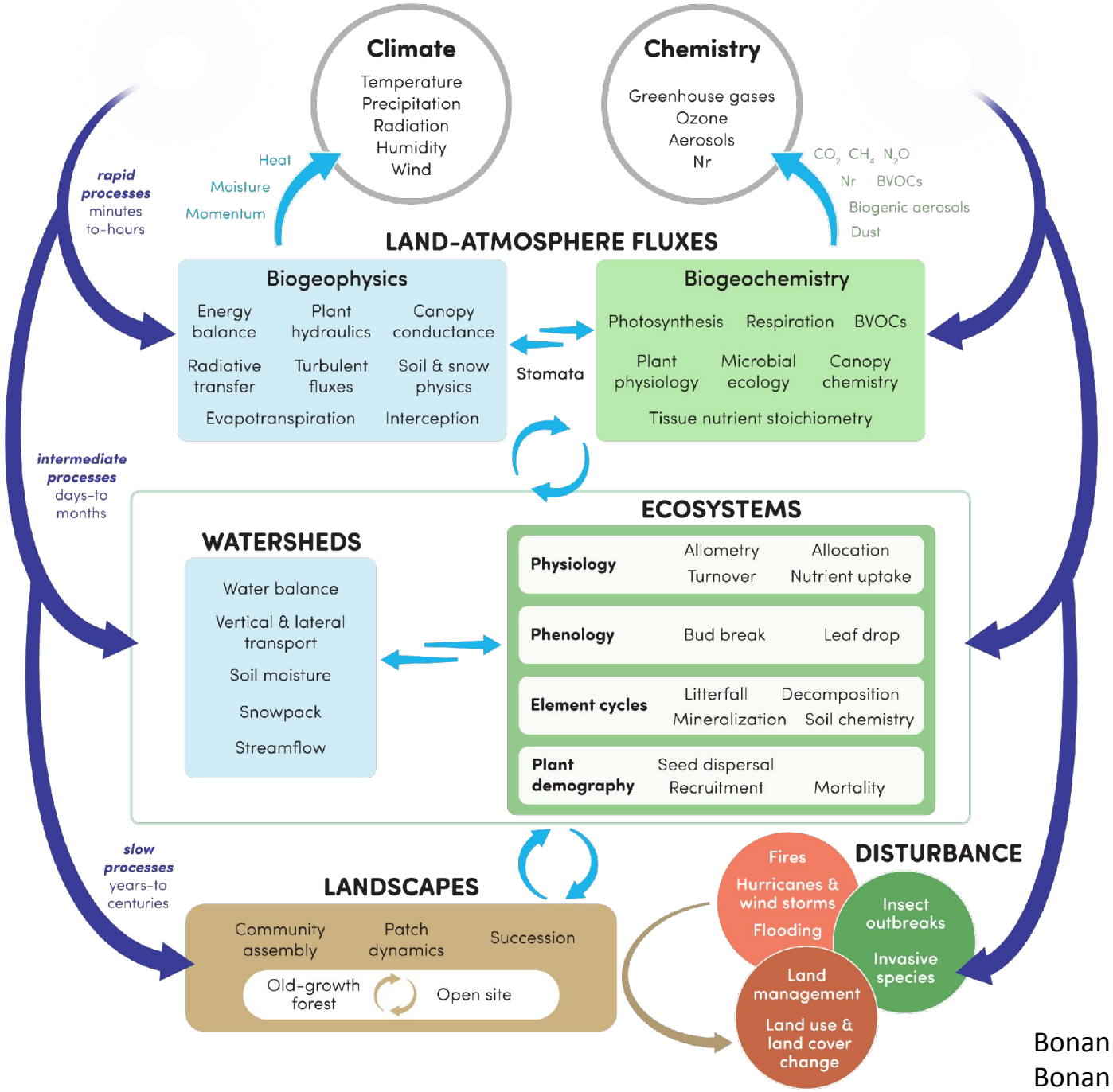
Bonan, Patton, Finnigan, et al. (2021) *Agric. For. Meteorol.*, 306, 108435

Bonan, Burns & Patton (2026) *Agric. For. Meteorol.*, 378, 110960



University of Michigan Biological Station

CLM as an integrator across disciplines



Bonan et al. (2024) *J. Adv. Model. Earth Syst.*, doi:10.1029/2023MS004017
Bonan (2027) *Ecological Climatology*, 4th ed. (Cambridge Univ. Press)

Modeling caveats

CLM is just a starting point for the science. It is not the science itself

- Easy to run the model and get an answer
- Much harder to understand why you got that answer
- Just because a process is in the model does not mean it is correct
- CLM is a very complex, multidisciplinary model that requires a broad perspective of the Earth system



