Modeling terrestrial ecosystems: Biogeophysics & canopy processes

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CLM Tutorial 2019

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Role of land surface in Earth system models

- Provides the biogeophysical boundary conditions at the land-atmosphere interface
  - e.g. albedo, longwave radiation, turbulent fluxes (momentum, sensible heat, latent heat, water vapor)
- Partitions available energy (net radiation) at the surface into sensible and latent heat flux, soil heat storage, and snow melt
- Partitions rainfall into runoff, evapotranspiration, and soil moisture
  - Evapotranspiration provides surface-atmosphere moisture flux
  - River runoff provides freshwater input to the oceans
- Provides the carbon fluxes at the surface (photosynthesis, respiration, fire, land use)
- Updates state variables which affect surface fluxes
  - e.g. snow cover, soil moisture, soil temperature, vegetation cover, leaf area index, vegetation and soil carbon and nitrogen pools
- Other chemical fluxes (CH_4, Nr, BVOCs, dust, wildfire, dry deposition)
- Land surface model cost is not that high (~10% of fully coupled model)

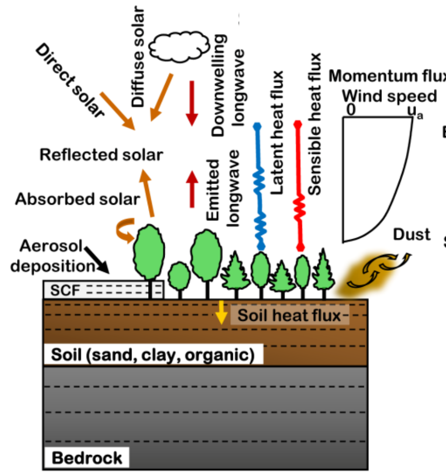
The Community Land Model

Fluxes of energy, water, CO_2, CH_4, BVOCs, and Nr and the processes that control these fluxes in a changing environment

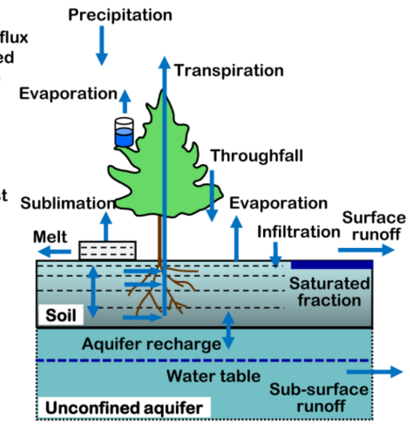
Lawrence et al. (2019) *J. Adv. Mod. Earth Syst.*, submitted

CLM5 documentation: cesm.ucar.edu/models/cesm2/land

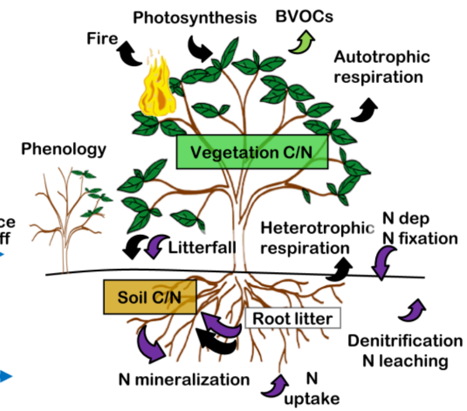
Surface energy fluxes



Hydrology

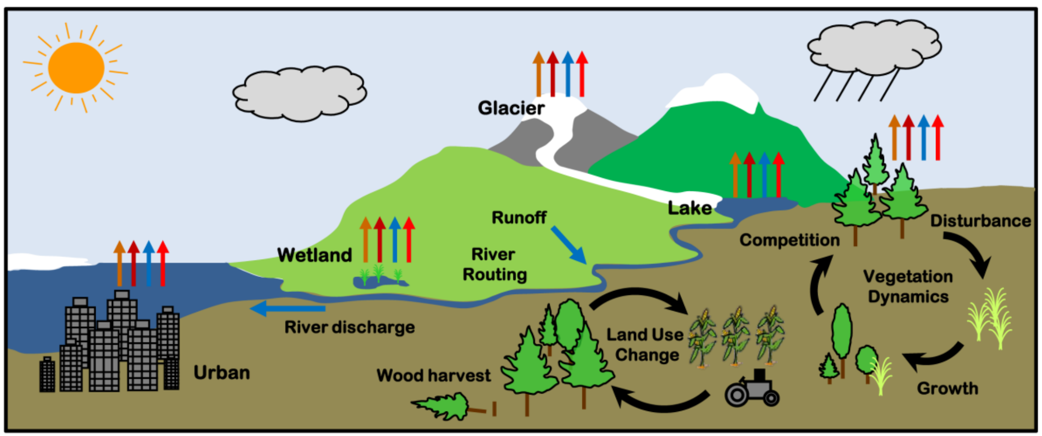


Biogeochemistry



Spatial scale

1.25° longitude × 0.9375° latitude (288 × 192 grid), ~100 km × 100 km



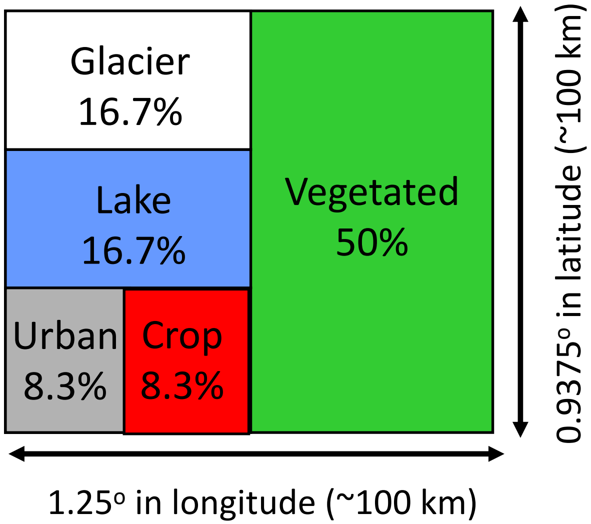
Landscape dynamics

Temporal scale

- 30-minute coupling with atmosphere
- Seasonal-to-interannual (phenology)
- Decadal-to-century (disturbance, land use, succession)
- Paleoclimate (biogeography)

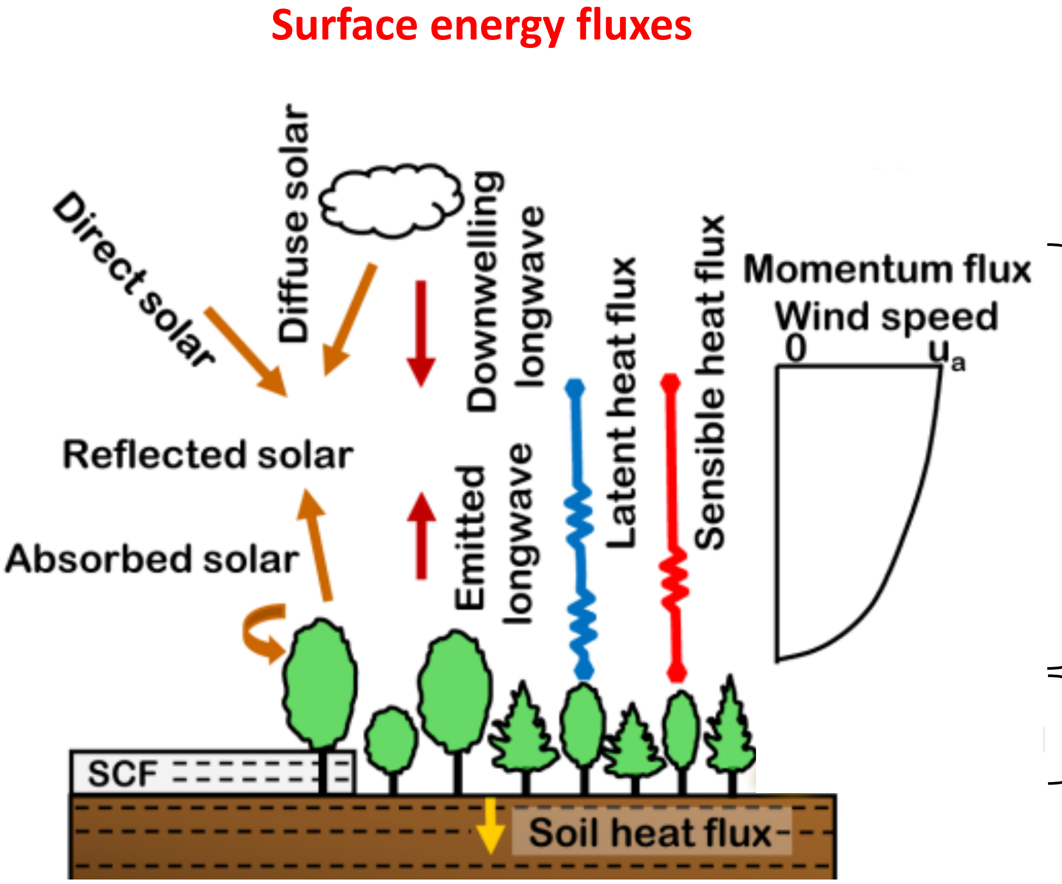
Land surface heterogeneity

Sub-grid land cover and plant functional types



The model simulates a column extending from the soil through the plant canopy to the atmosphere. CLM represents a model grid cell as a mosaic of several primary land units. Each land unit can have multiple columns. Vegetated land is further represented as patches of individual plant functional types

Canopy biogeophysics



Boundary layer meteorology
Micrometeorology

Radiative transfer
Leaf physiology and gas exchange
Scaling from leaf to canopy

CLM5 surface fluxes

CLM5

Many interconnected routines

- CanopyHydrology
- CanopySunShadeFracs
- SurfaceRadiation
- CanopyTemperature
- BareGroundFluxes
- CanopyFluxes
    - FrictionVelocity
    - Photosynthesis
    - PhotosynthesisHydraulicStress
    - Fractionation
    - CalcOzoneStress
    - LUNA
- VOCEmission
- SoilTemperature
- SoilFluxes
- DryDepVelocity
- SurfaceAlbedo

A knot to untangle …

… or the kraken devouring a ship

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

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

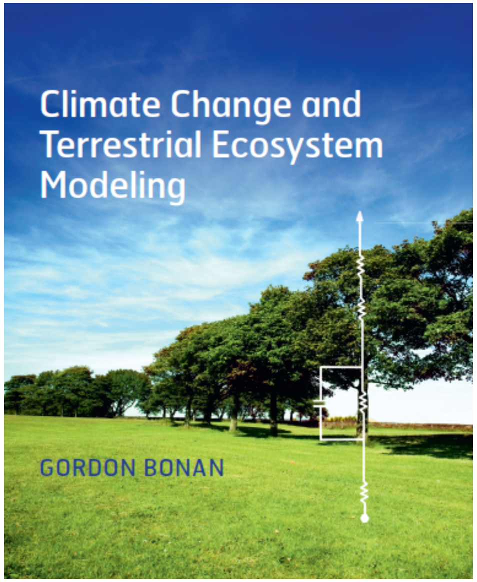
Richards equation $$\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial z}\left[K(\theta)\frac{\partial \psi}{\partial z}\right] + \frac{\partial K}{\partial z}$$

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)



Surface energy balance and surface temperature

Surface energy balance:

absorbed longwave, emitted longwave, latent heat

$(1-\rho)\, S\!\downarrow + \varepsilon L\!\downarrow - \varepsilon\, \sigma \theta_s^{\,4} - H[\theta_s] - \lambda E[\theta_s]$ = soil heat storage

absorbed solar, sensible heat

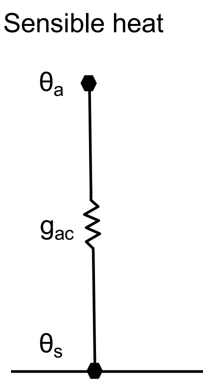
Soil heat storage:

$$c_v \frac{\partial T}{\partial t} = \frac{\partial}{\partial z}\left(\kappa \frac{\partial T}{\partial z} \right)$$

Flux = Δ concentration * conductance

$$H = c_p \left(\theta_s - \theta_a \right) g_{ac}$$

$$E = \frac{q_{sat}(\theta_s) - q_a}{g_{ac}^{-1} + g_c^{-1}}$$



Atmospheric forcing

$S\!\downarrow$ - solar radiation (visible, near-infrared; direct, diffuse)

$L\!\downarrow$ - longwave radiation

θ_a - air temperature

q_a - atmospheric water vapor

u - wind speed

P - surface pressure

Surface properties

ρ - albedo

ε - emissivity

g_{ac} - aerodynamic conductance (roughness length)

g_c - surface conductance (canopy, soil moisture)

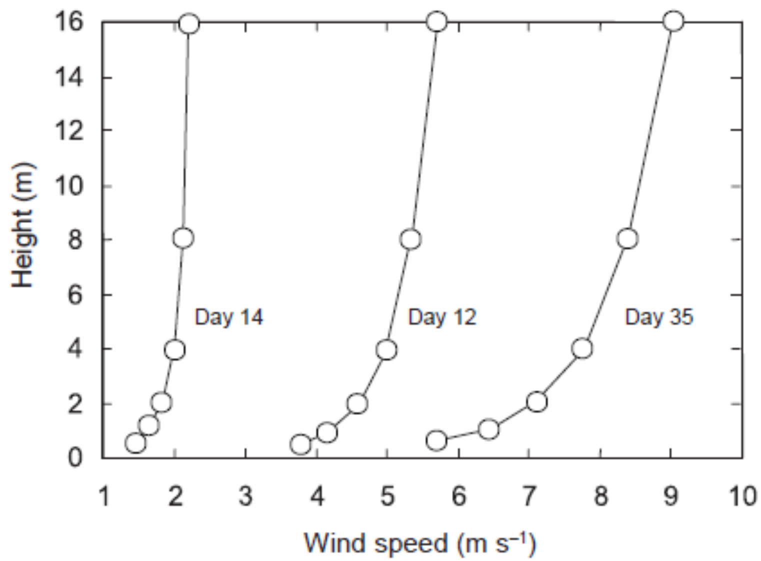
k - thermal conductivity

c_v - soil heat capacity

With atmospheric forcing and surface properties specified, solve for surface temperature θ_s that balances the energy budget

Monin-Obukhov similarity theory

Logarithmic wind profile over grassland (Australia)



Flux-profile equation

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

Integrated profile equation

$$u\left(z\right)=\frac{u_*}{k}\left[\ln\left(\frac{z-d}{z_{0m}}\right)-\psi_m\left(\frac{z-d}{L_{MO}}\right)+\psi_m\left(\frac{z_{0m}}{L_{MO}}\right)\right]$$

Momentum flux (conductance form)

$$\tau=u\left(z\right)g_{am}\left(z\right)$$

$$g_{am}\left(z\right)=\rho_m k^2 u\left(z\right)\left[\ln\left(\frac{z-d}{z_{0m}}\right)-\psi_m\left(\frac{z-d}{L_{MO}}\right)+\psi_m\left(\frac{z_{0m}}{L_{MO}}\right)\right]^{-2}$$

u_*	= friction velocity (m s^{-1})
L_{MO}	= Obukhov length (m)
ϕ_m, ϕ_c	= similarity function
ψ_m, ψ_c	= integrated form of ϕ
d	= displacement height (m)
z_{0m}, z_{0c}	= roughness length (m)
g_{am}, g_{ac}	= conductance (mol m^{-2} s^{-1})

Monin-Obukhov similarity theory

Similar equations for scalars (θ, q)

Flux-profile equation

$$\frac{k(z-d)}{\theta_*}\frac{\partial\theta}{\partial z}=\phi_c\left(\frac{z-d}{L_{MO}}\right) \qquad \theta_* u_* = -\frac{H}{\rho_m c_p}$$

Integrated profile equation

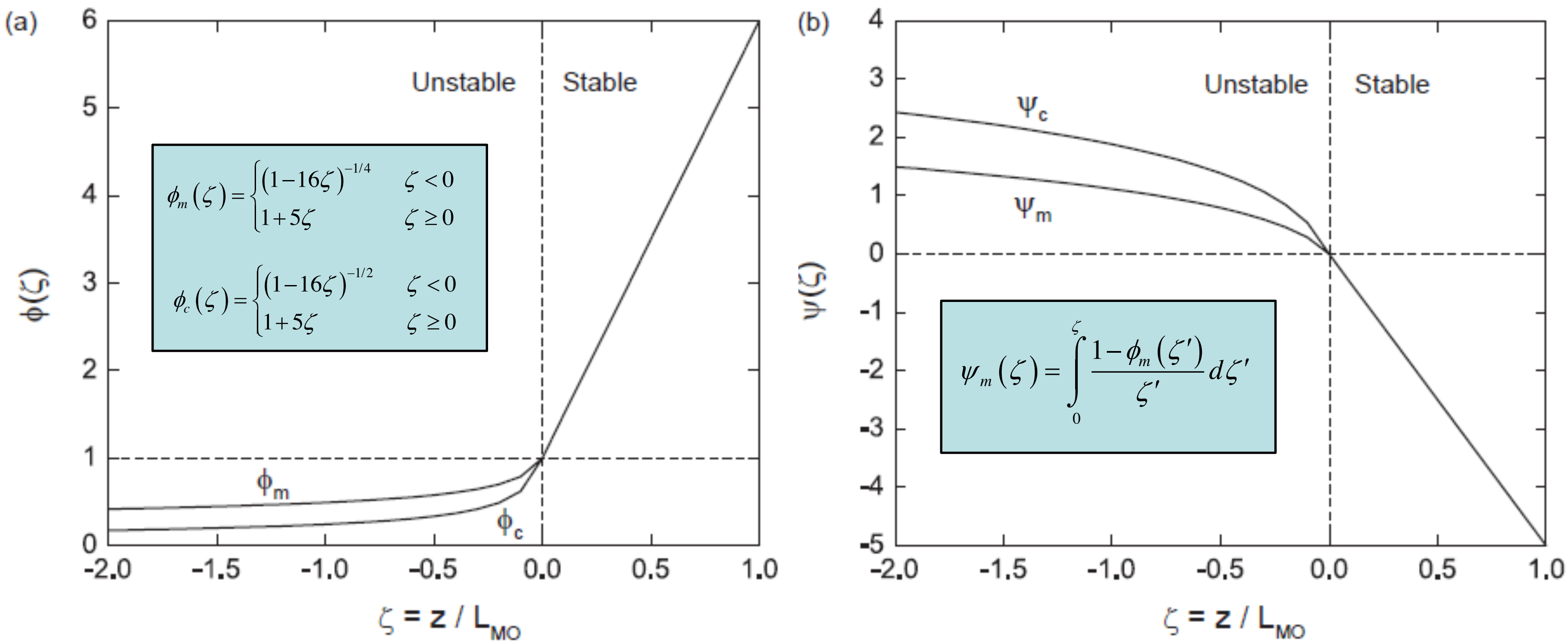
$$\theta(z)-\theta_s=\frac{\theta_*}{k}\left[\ln\left(\frac{z-d}{z_{0c}}\right)-\psi_c\left(\frac{z-d}{L_{MO}}\right)+\psi_c\left(\frac{z_{0c}}{L_{MO}}\right)\right]$$

Sensible heat flux (conductance form)

$$H=-c_p\left[\theta(z)-\theta_s\right]g_{ac}(z)$$

$$g_{ac}(z)=\rho_m k^2 u(z)\left[\ln\left(\frac{z-d}{z_{0m}}\right)-\psi_m\left(\frac{z-d}{L_{MO}}\right)+\psi_m\left(\frac{z_{0m}}{L_{MO}}\right)\right]^{-1}\left[\ln\left(\frac{z-d}{z_{0c}}\right)-\psi_c\left(\frac{z-d}{L_{MO}}\right)+\psi_c\left(\frac{z_{0c}}{L_{MO}}\right)\right]^{-1}$$

Similarity functions (ϕ, ψ)



ϕ_m, ϕ_c are empirical relationships obtained over smooth surfaces (grassland); but differ among models

CLM5 similarity functions (ϕ, ψ)

CLM5

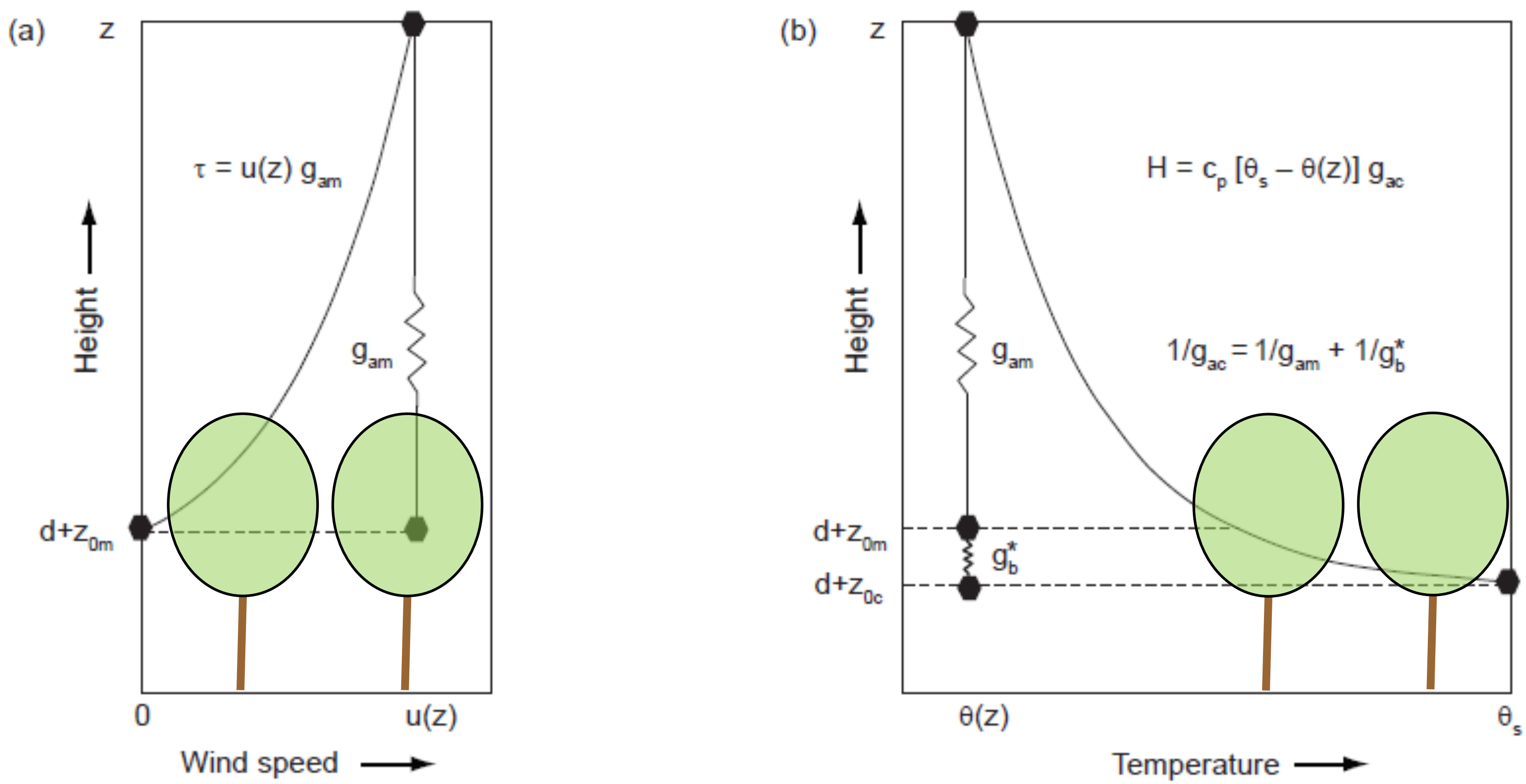
$\phi_m(\zeta) = 0.7k^{2/3}(-\zeta)^{1/3}$	for $\zeta < -1.574$	(very unstable)
$\phi_m(\zeta) = (1-16\zeta)^{-1/4}$	for $-1.574 \le \zeta < 0$	(unstable)
$\phi_m(\zeta) = 1 + 5\zeta$	for $0 \le \zeta \le 1$	(stable)
$\phi_m(\zeta) = 5 + \zeta$	for $\zeta > 1$	(very stable).

$\phi_h(\zeta) = \phi_w(\zeta) = 0.9k^{4/3}(-\zeta)^{-1/3}$	for $\zeta < -0.465$	(very unstable)
$\phi_h(\zeta) = \phi_w(\zeta) = (1-16\zeta)^{-1/2}$	for $-0.465 \le \zeta < 0$	(unstable)
$\phi_h(\zeta) = \phi_w(\zeta) = 1 + 5\zeta$	for $0 \le \zeta \le 1$	(stable)
$\phi_h(\zeta) = \phi_w(\zeta) = 5 + \zeta$	for $\zeta > 1$	(very stable).

Roughness length and displacement height

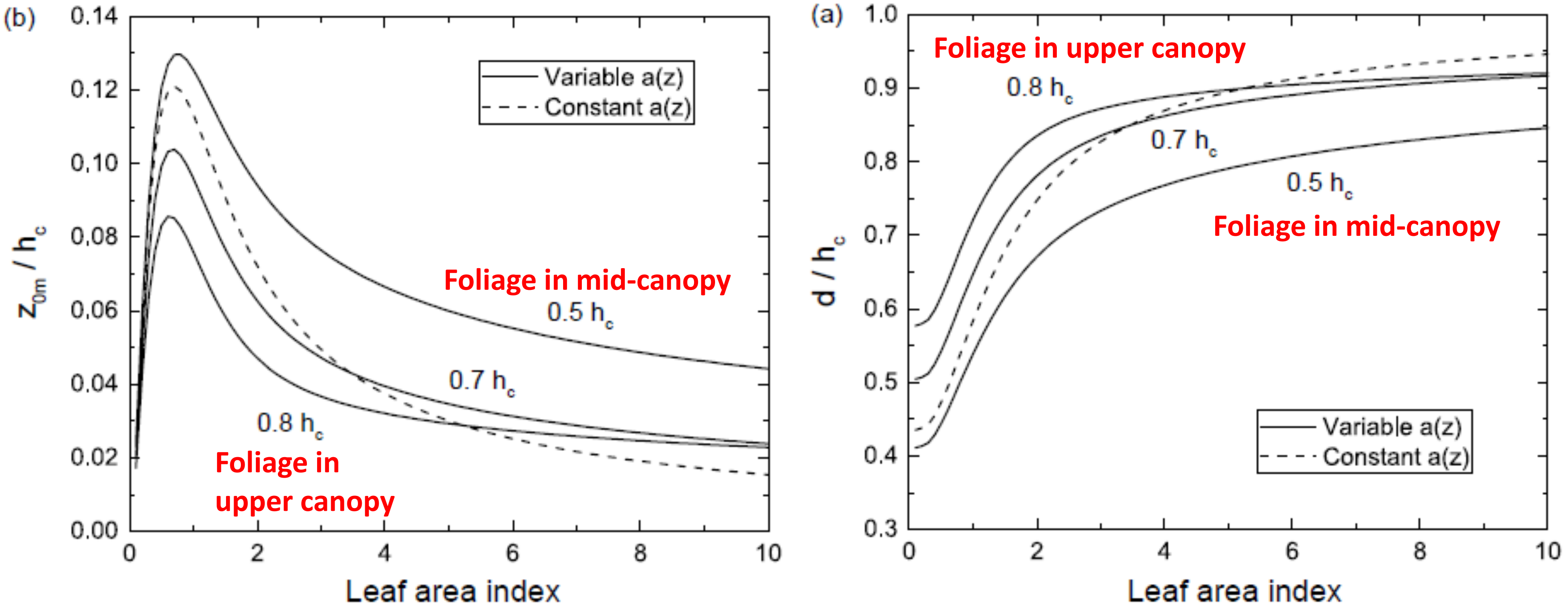
d + z_{0m} is the theoretical height at which u(z) = 0

d + z_{0c} is the theoretical height at which $\theta(z) = \theta_s$



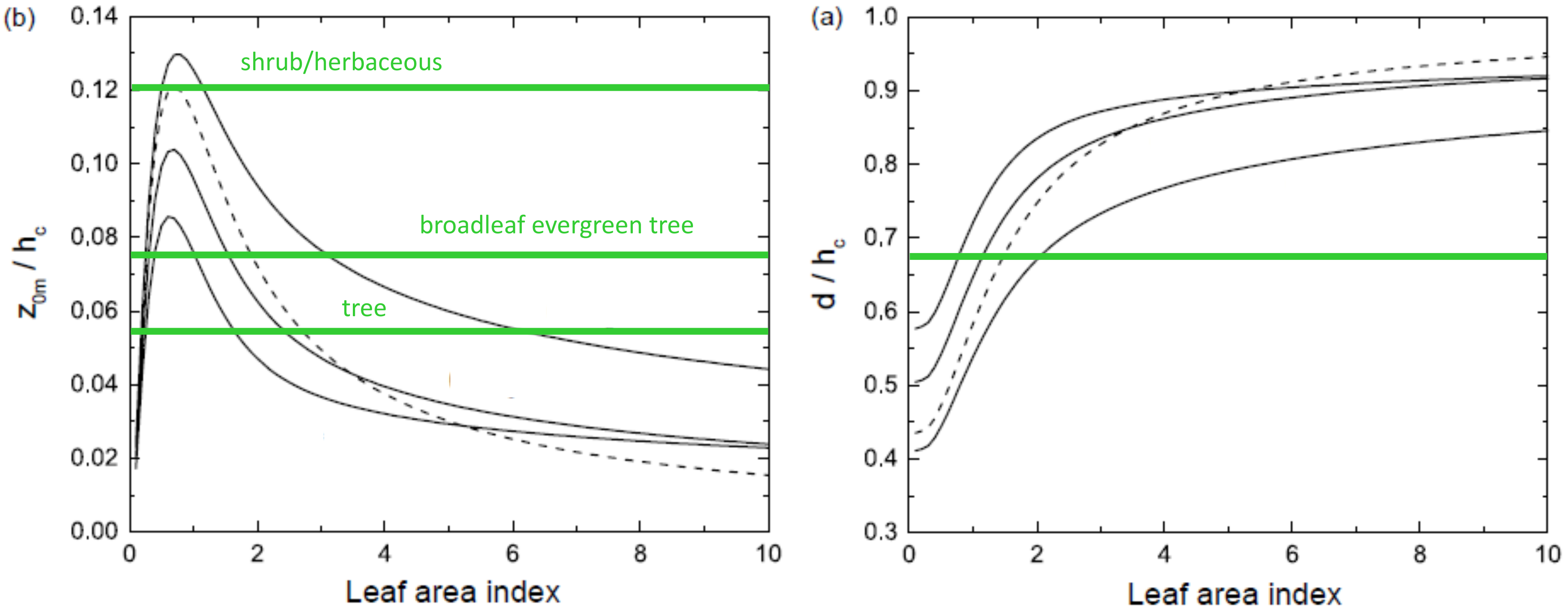
Roughness length and displacement height

z_{0m} and d depend on leaf area and its vertical distribution in the canopy



Roughness length and displacement height

CLM5: z_{0m}/h_c and d/h_c are prescribed by PFT and are a weighted average with ground

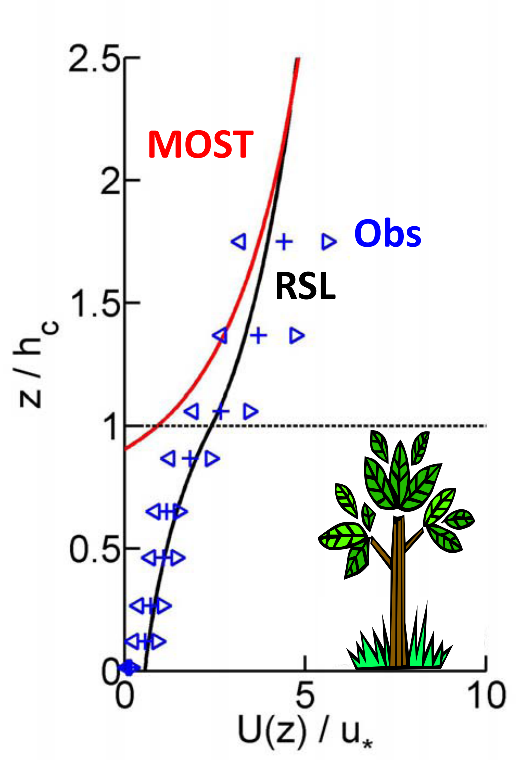


Roughness sublayer

Profiles from the CSIRO flux station near Tumbarumba

Roughness sublayer

CLM (and most other models) use MOST, which fails above and within tall plant canopies

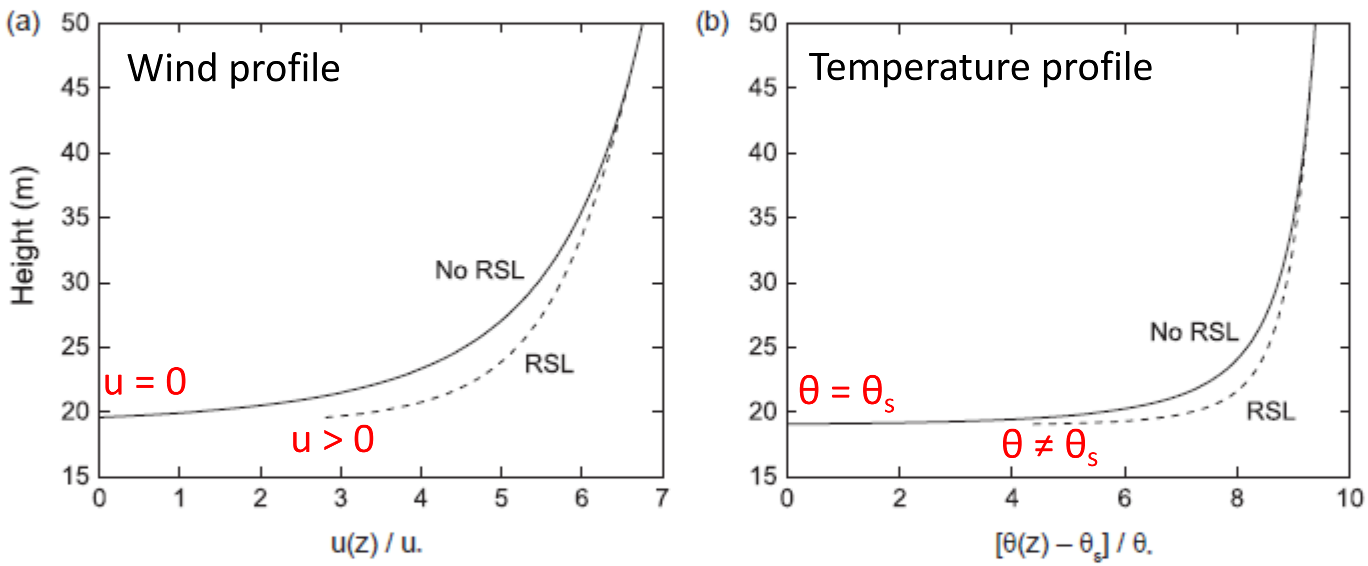


Harman & Finnigan (2007) *Boundary-Layer Meteorol.*, 123, 339-63
Harman & Finnigan (2008) *Boundary-Layer Meteorol.*, 129, 323-51

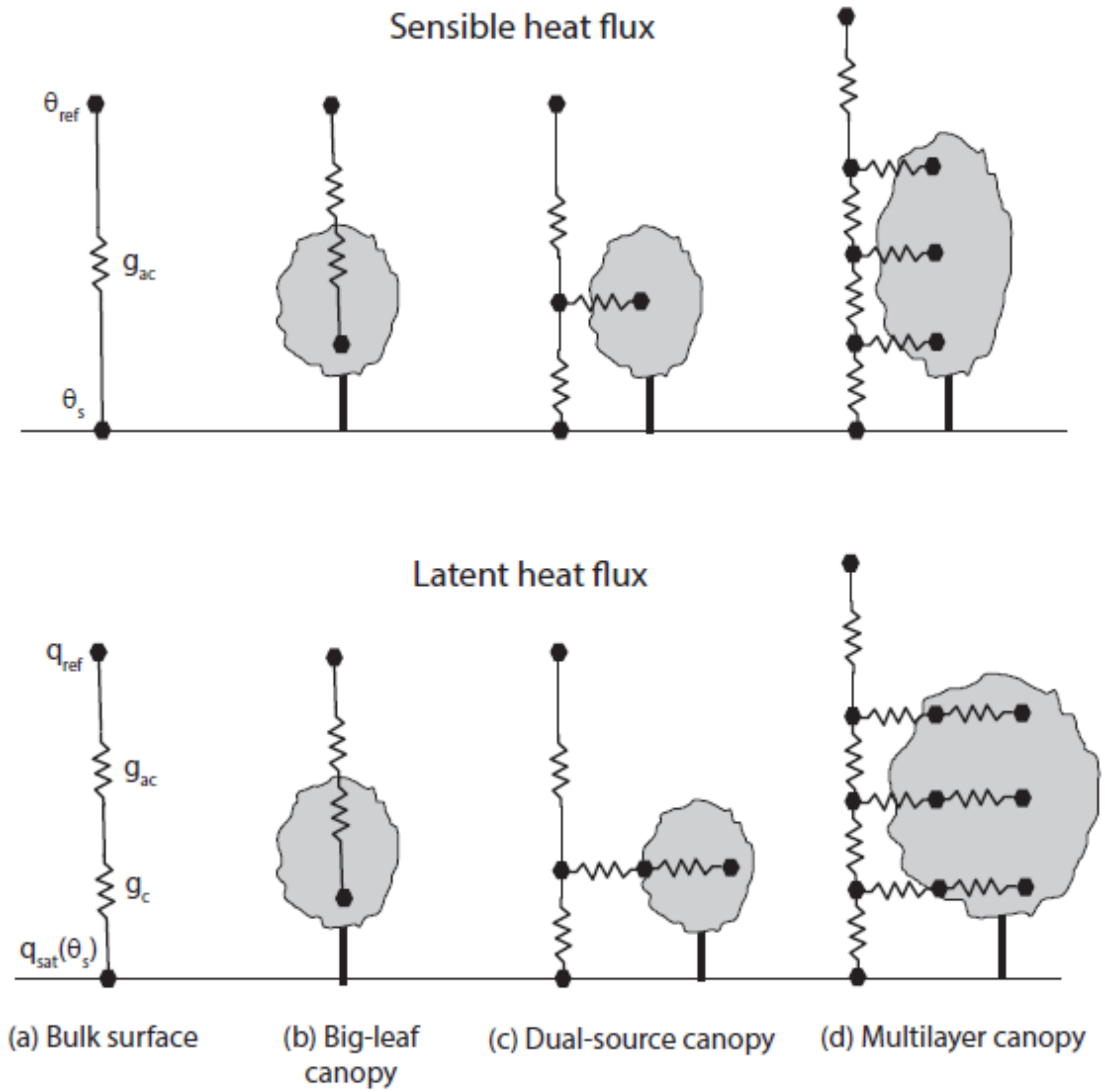
Roughness sublayer

$$\frac{k(z-d)}{u_*}\frac{\partial u}{\partial z} = \phi_m\left(\frac{z-d}{L_{MO}}\right)\hat{\phi}_m\left(\frac{z-d}{L'}\right) \qquad u(z)=\frac{u_*}{k}\left[\ln\left(\frac{z-d}{z_{0m}}\right)-\psi_m\left(\frac{z-d}{L_{MO}}\right)+\psi_m\left(\frac{z_{0m}}{L_{MO}}\right)+\hat{\psi}_m(z)\right]$$

Physick & Garratt (1995) *Boundary-Layer Meteorology*, 74, 55-71



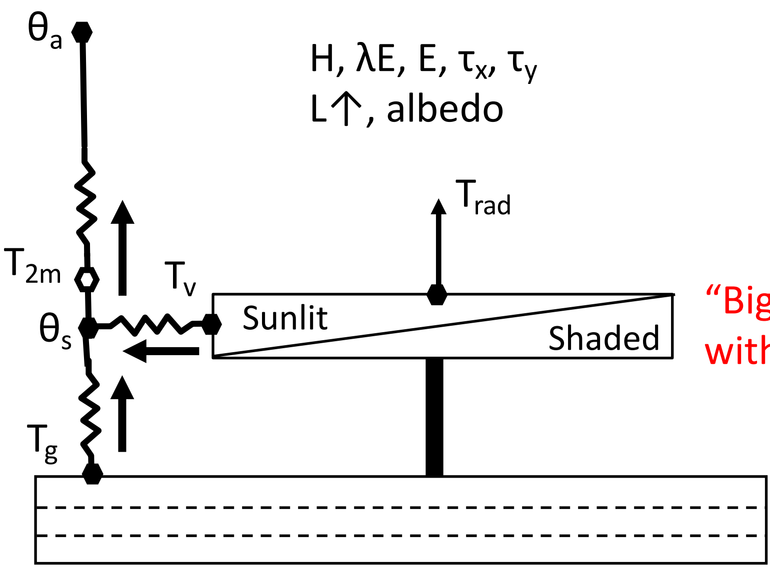
Plant canopies



Plant canopies in CLM5

Flux to atmosphere uses MOST

“Surface” is an imaginary height (where wind speed extrapolates to zero)



“Big-leaf” canopy without vertical structure

Deardorff (1978) *JGR*, 83C, 1889-1903
Dickinson et al. (1986) NCAR/TN-275+STR
Dickinson et al. (1993) NCAR/TN-387+STR

What is needed?

- Radiation absorption by canopy and ground
- Leaf fluxes scaled to canopy
- Separate fluxes of transpiration and evaporation of intercepted water
- Soil fluxes

Some key approximations

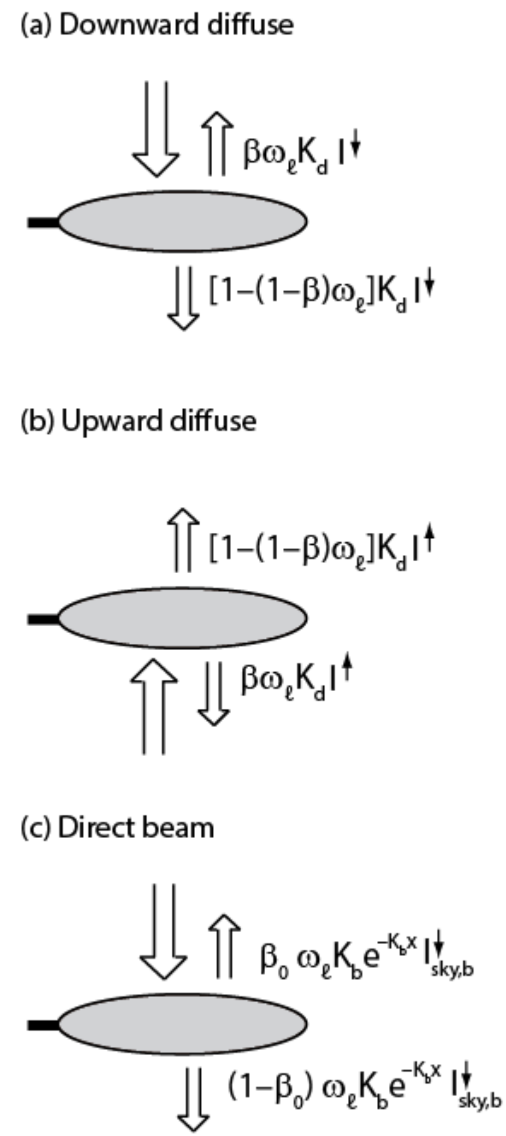
- Leaf fluxes: wind speed in canopy = u_*
- Soil fluxes: within canopy aerodynamic conductance is proportional to wind speed
- 2m is defined above d + z_{0m}

Radiative transfer

CLM5 uses the two-stream approximation (Dickinson, Sellers)

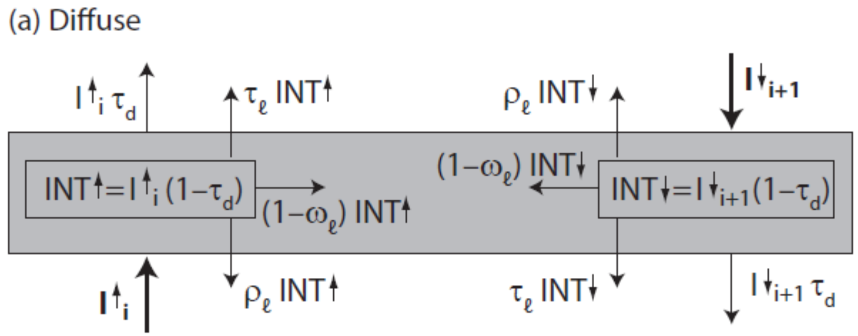
$$\frac{dI^{\uparrow}}{dx} = \left[1-(1-\beta)\,\omega_\ell\right]K_d I^{\uparrow} - \beta\omega_\ell K_d I^{\downarrow} - \beta_0\omega_\ell K_b I^{\downarrow}_{sky,b} e^{-K_b x}$$

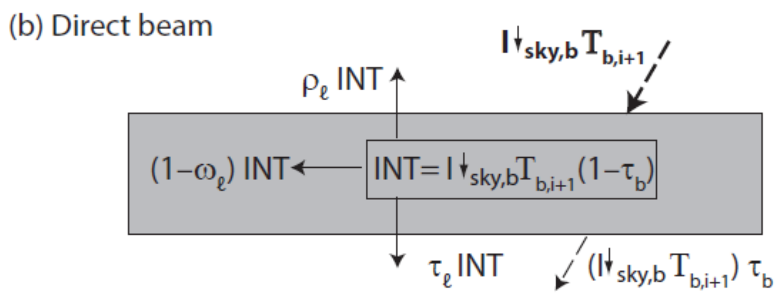
$$\frac{dI^{\downarrow}}{dx} = -\left[1-(1-\beta)\,\omega_\ell\right]K_d I^{\downarrow} + \beta\omega_\ell K_d I^{\uparrow} + (1-\beta_0)\,\omega_\ell K_b I^{\downarrow}_{sky,b} e^{-K_b x}$$



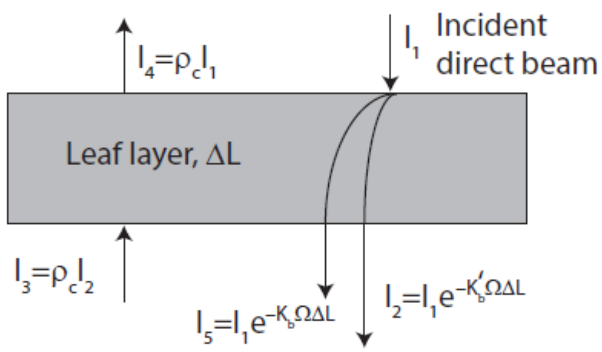
Other models

Norman (1979)



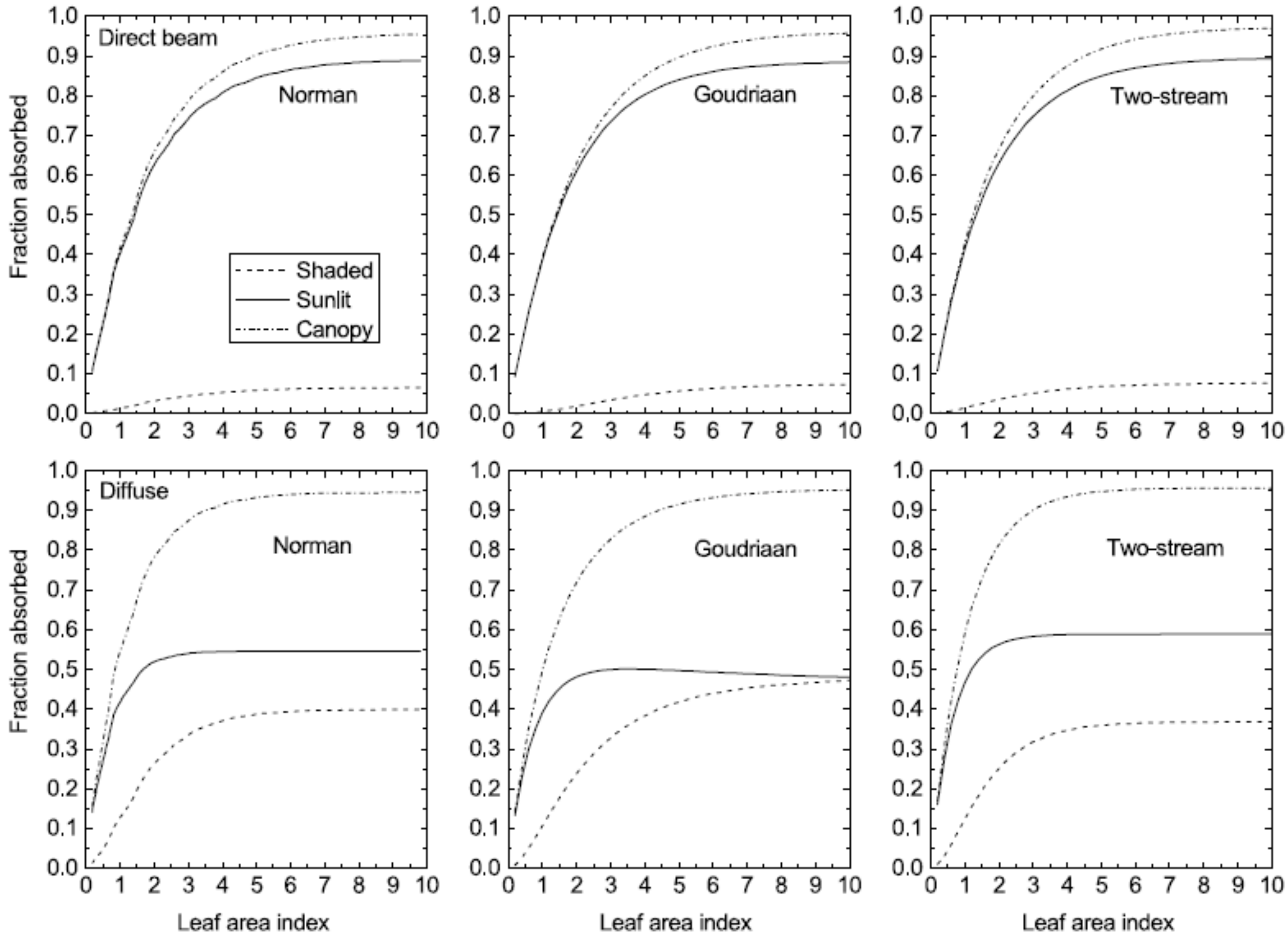


Goudriaan (1977)



Absorption of radiation

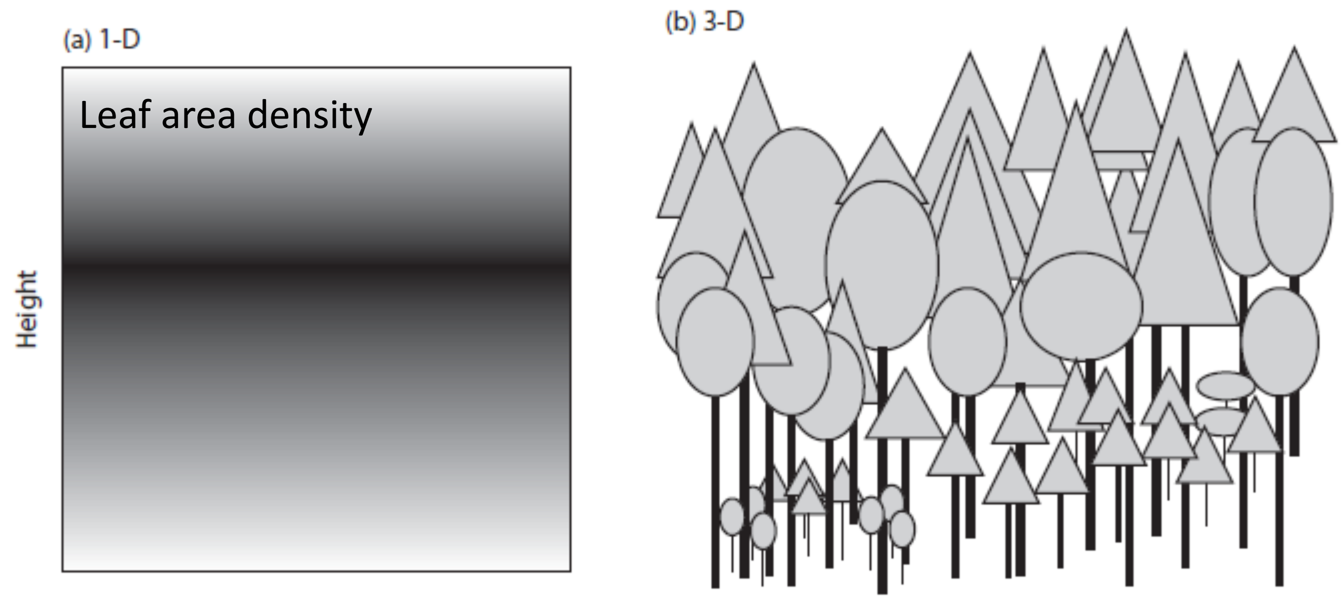
Different models give different results, especially for diffuse radiation



Radiative transfer

Plane-parallel canopy
(vertical profile of leaf area)

3-dimensional canopy
structure



Does not account for canopy gaps or separate absorption by leaves and stems

Leaf temperature and fluxes

Leaf energy balance:

$$c_L \frac{\partial T_\ell}{\partial t} = Q_a - 2\varepsilon_\ell \sigma T_\ell^4 + 2c_p \left(T_\ell - T_a\right) g_{bh} + \lambda \left[q_{sat}\left(T_\ell\right) - q_a \right] g_\ell$$

CLM5 ignores this term

Atmospheric forcing

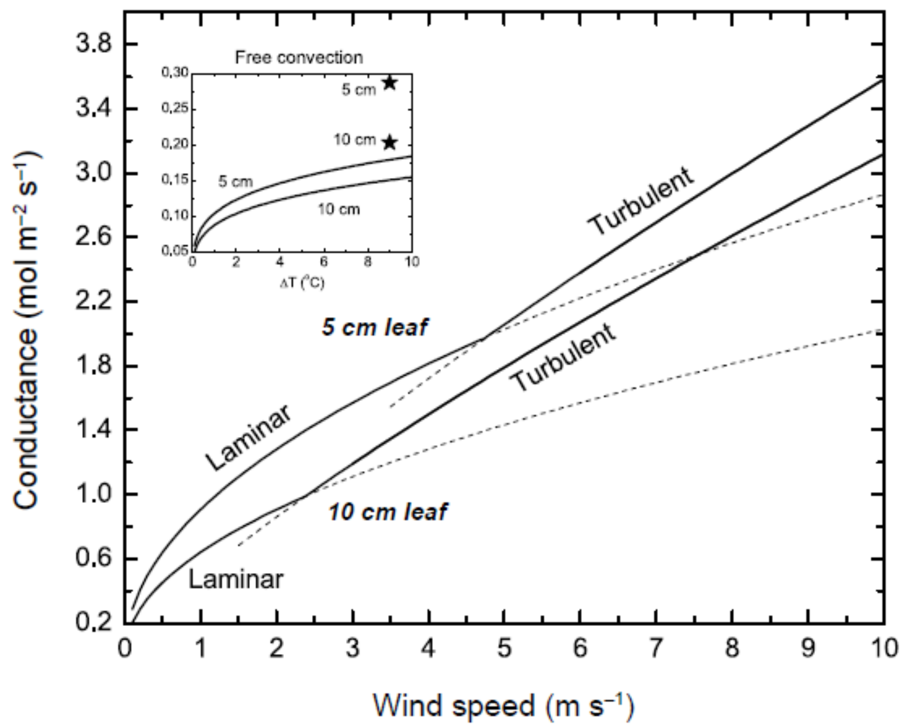
Q_a - radiative forcing (solar and longwave)
T_a - air temperature
q_a - water vapor (mole fraction)
u - wind speed
P - surface pressure

Leaf properties

ε_ℓ - emissivity
g_{bh} - leaf boundary layer conductance
g_ℓ - leaf conductance to water vapor
c_L - heat capacity

With atmospheric forcing and leaf properties specified, solve for temperature T_ℓ that balances the energy budget

Leaf boundary layer



Boundary layer conductance depends on:

- Leaf size
- Wind speed
- Forced or free convection
- Laminar or turbulent flow
- Diffusivity (heat, H_2O, CO_2, etc.)
- Derived from flat plates, with a correction factor (~1.5 for plant canopies)

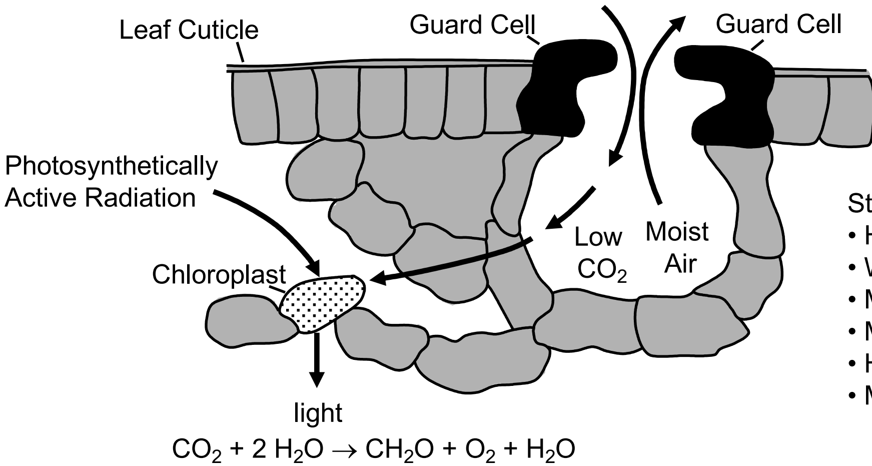
C_v = parameter

CLM5

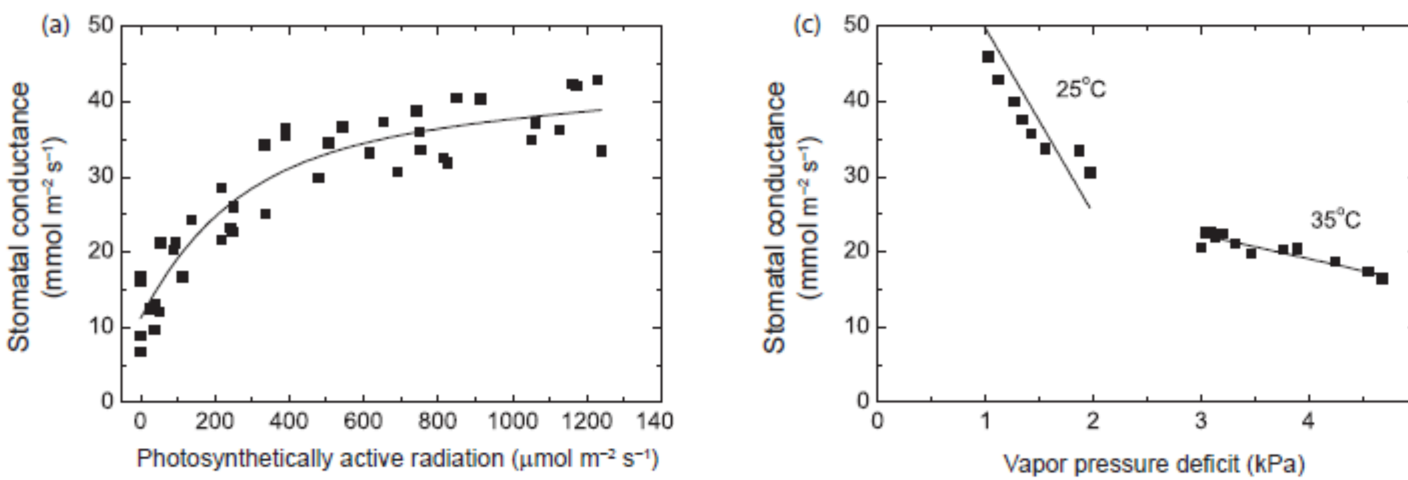
Forced, laminar regime

$$g_b = C_v (u / d_\ell)^{1/2}$$

Stomatal gas exchange

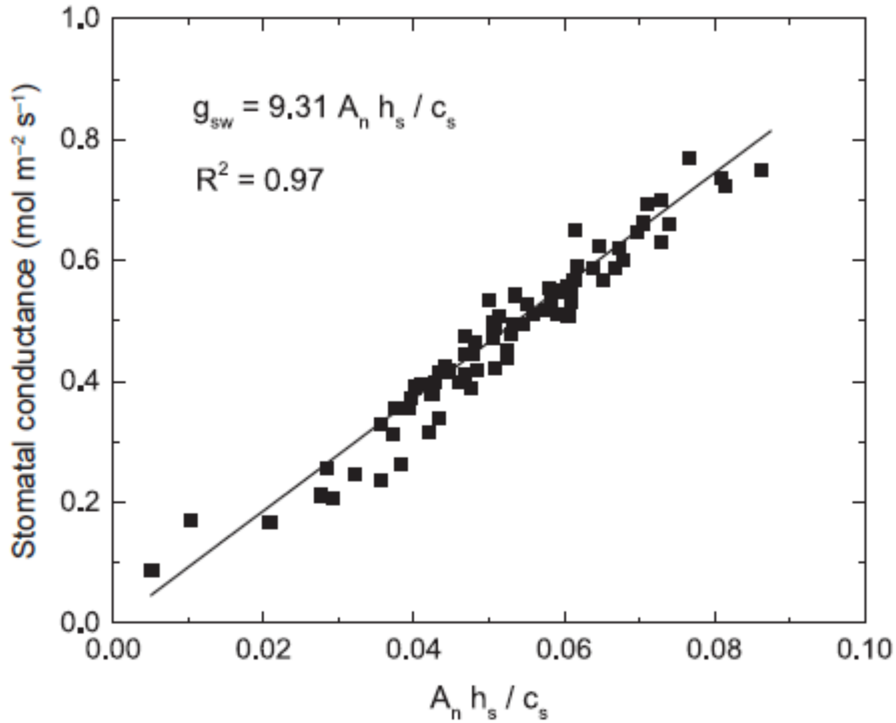


Stomata open:
- High light
- Warm temperature
- Moist air
- Moderate CO_2
- High leaf nitrogen
- Moist leaf



Stomatal gas exchange

Stomatal conductance scales linearly with photosynthesis



Ball et al. (1987) In *Progress in Photosynthesis Research,* vol. 4, pp. 221–224

Leaf photosynthesis

Farquhar, von Caemmerer & Berry photosynthesis model

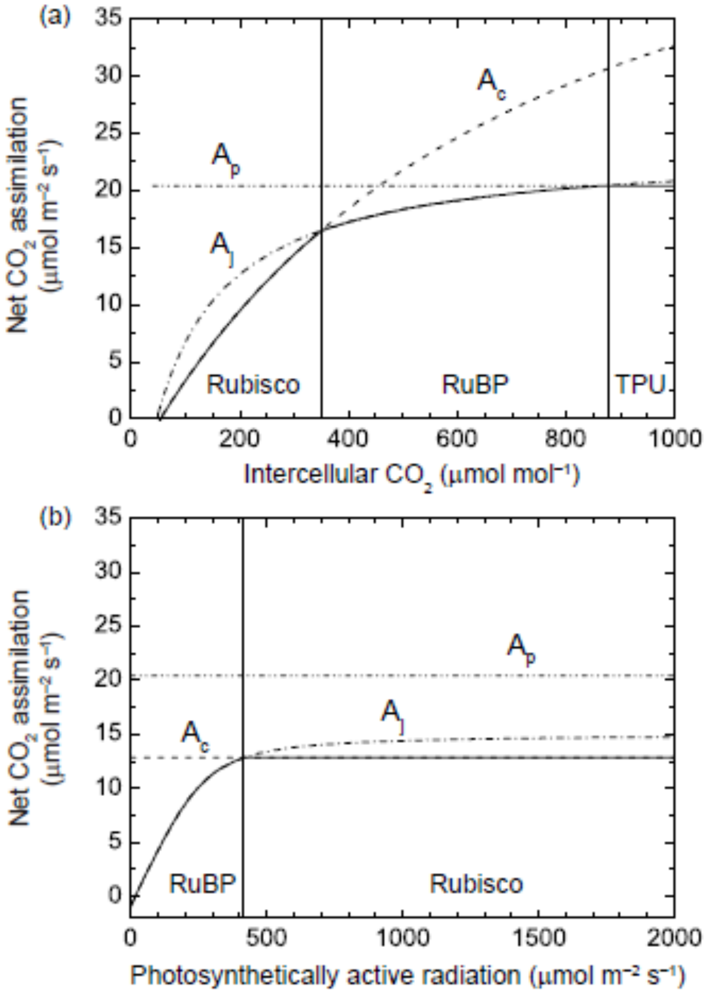
$$A_n = \min(A_c, A_j) - R_d$$

Rubisco-limited rate is

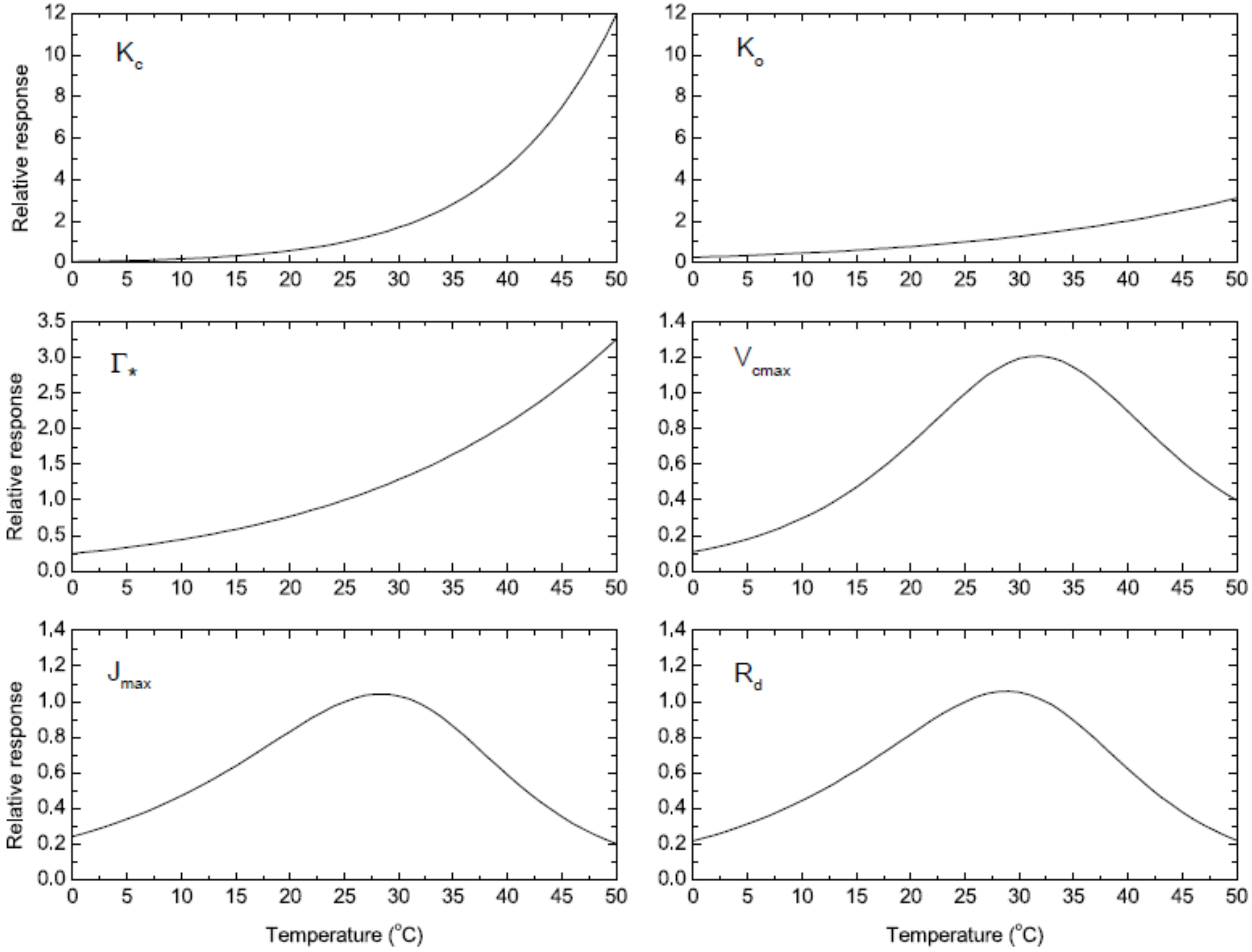
$$A_c = \frac{V_{c\max}\left(c_i - \Gamma_*\right)}{c_i + K_c\left(1 + o_i / K_o\right)}$$

RuBP regeneration-limited rate is

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



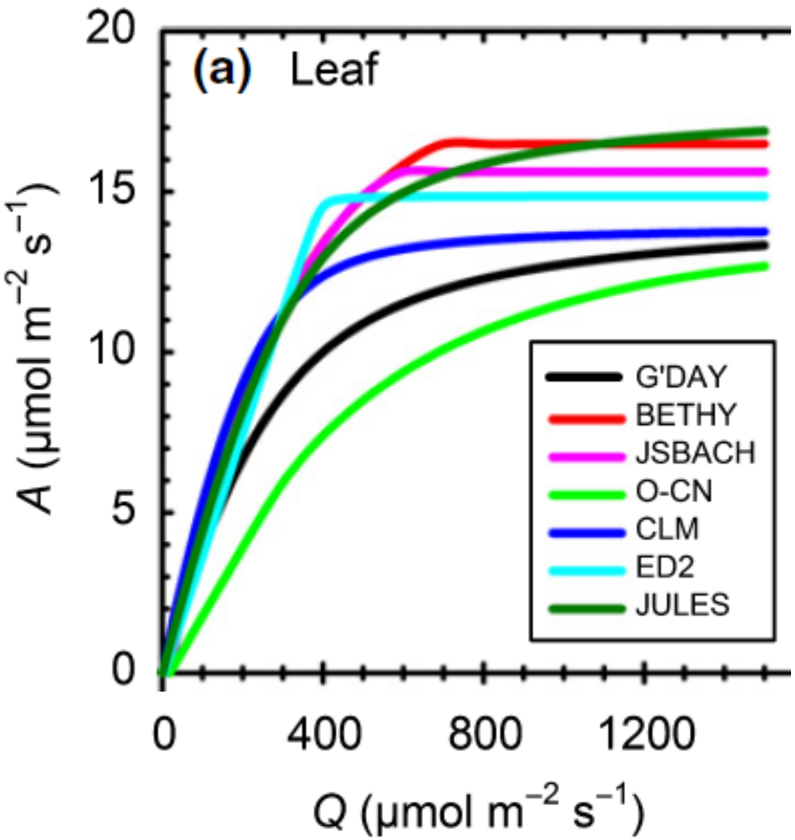
Leaf physiological parameters



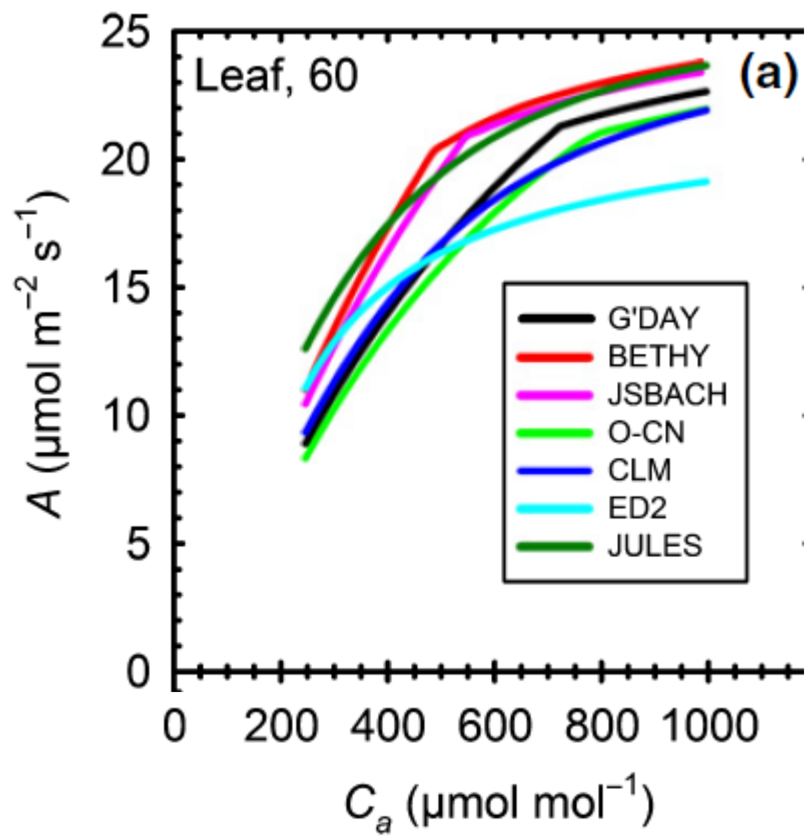
No consensus on temperature responses. And plants grown at warm temperatures have a warmer thermal optimum for photosynthesis. How to account for temperature acclimation?

Are we modeling the same thing?

Light response

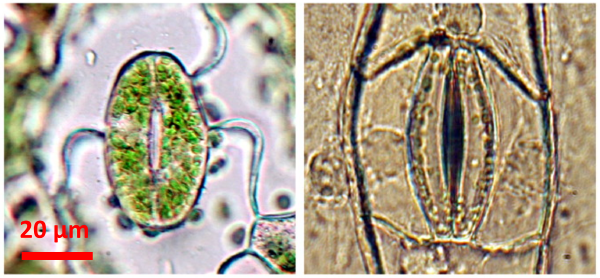


CO_2 response



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

Stomatal conductance



Franks & Farquhar (2007) *Plant Physiol.* ,143, 78-87

Ball, Woodrow & Berry (1987)

$g_{sw} = g_0 + g_{1B} A_n h_s / c_s$

Empirical parameters (g_0, g_{1B})

Empirical relationship between stomatal conductance and photosynthesis. Parameters obtained from leaf gas exchange data.

(CLM4.5)

Medlyn et al. (2011)

$g_{sw} = g_0 + 1.6\ (1 + g_{1M} / D_s^{1/2})\ A_n/c_s$

Derived from optimality theory after many simplifying assumptions

(CLM5)

Optimization theory (Cowan & Farquhar 1977)

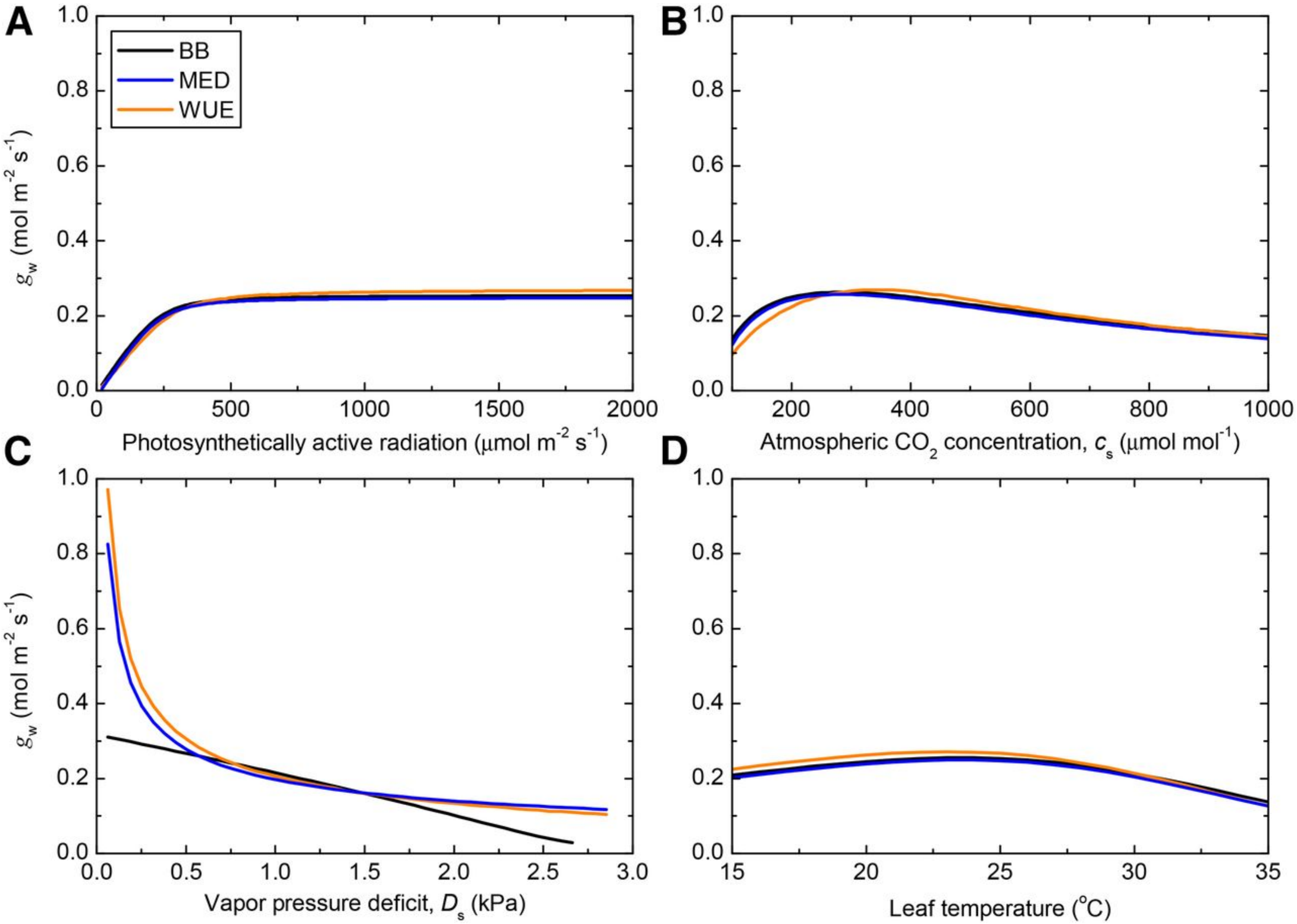
Stomata optimize photosynthetic carbon gain per unit transpiration water loss:

$\partial A_n/\partial E = \iota$

Need to specify ι (marginal water-use efficiency)

Similar model behavior

Using comparable g_{1B}, g_{1M}, and ι values gives similar results



Franks et al. (2017) *Plant Physiol.*, 174, 583-602

Soil moisture stress

How to reduce stomatal conductance for soil moisture stress?

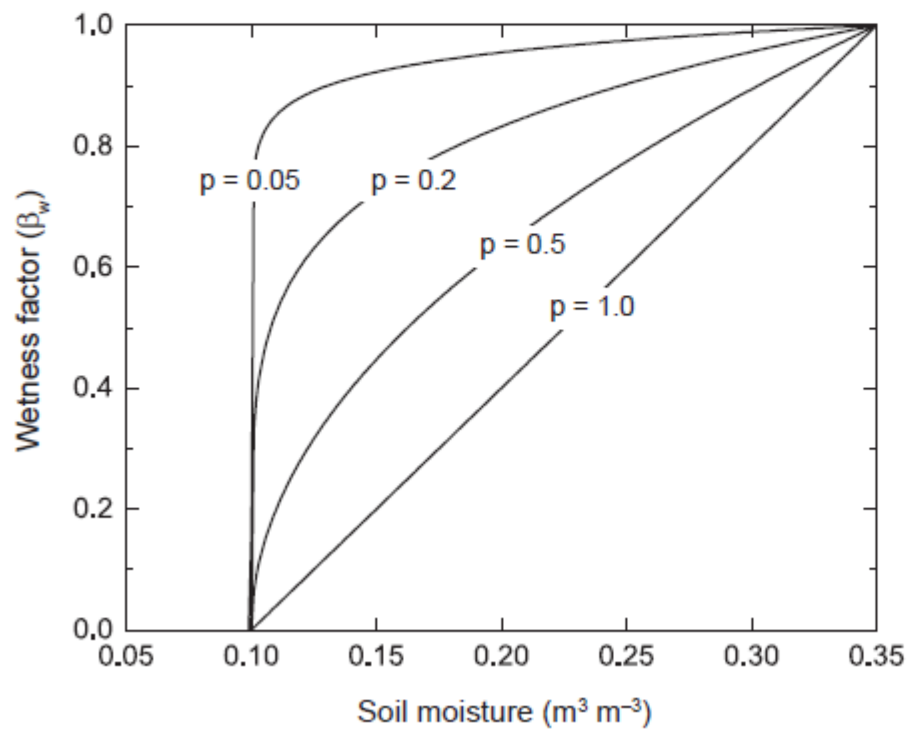
Use an empirical soil wetness factor

Diffusive limitation
$g_1 * \beta_w$

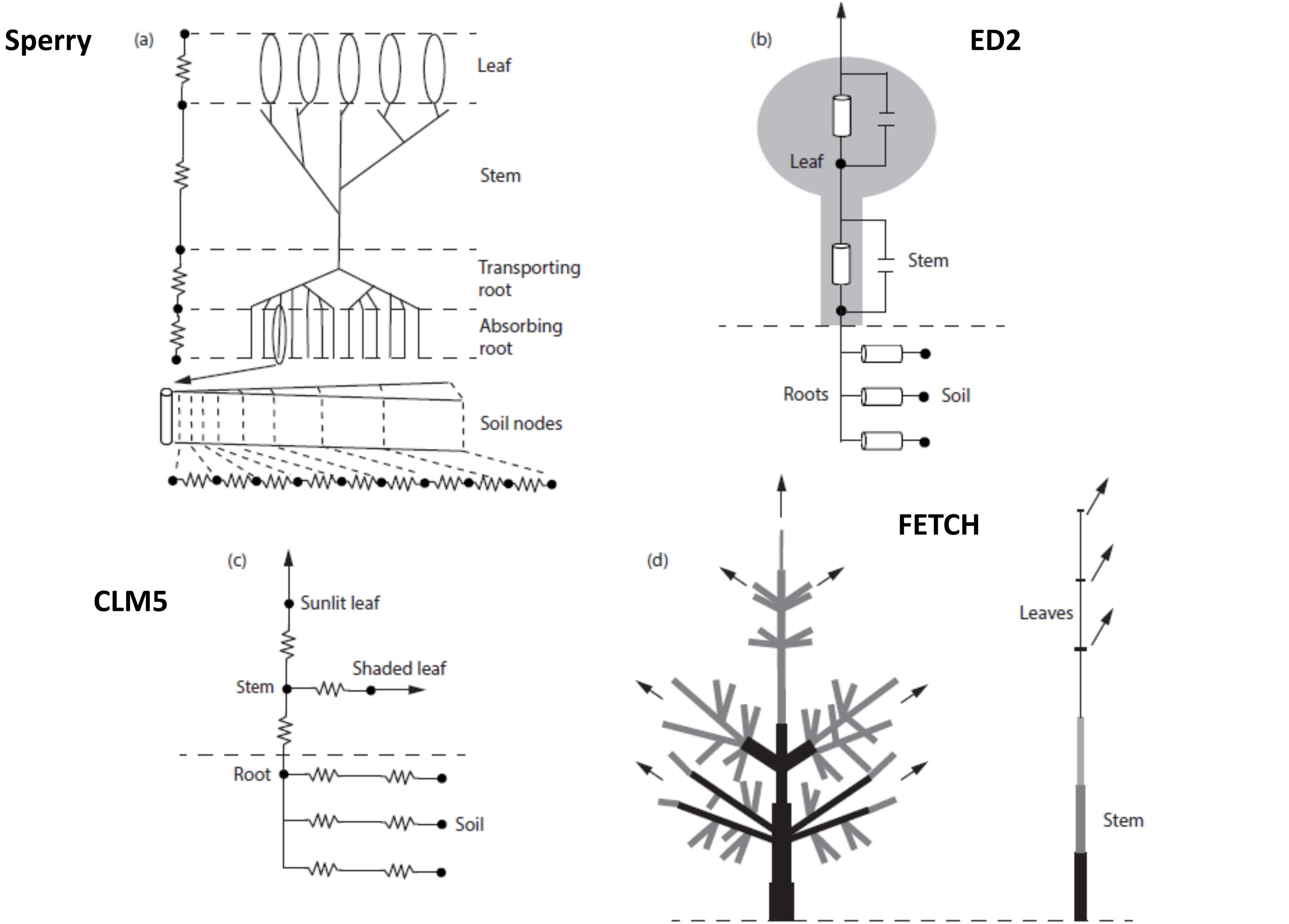
Biochemical limitation
$V_{cmax} * \beta_w$
$J_{max} * \beta_w$

CLM5
$g_0 * \beta_w$
$V_{cmax} * \beta_w$
$R_d * \beta_w$

Key unknowns
Form of β_w
How to apply β_w

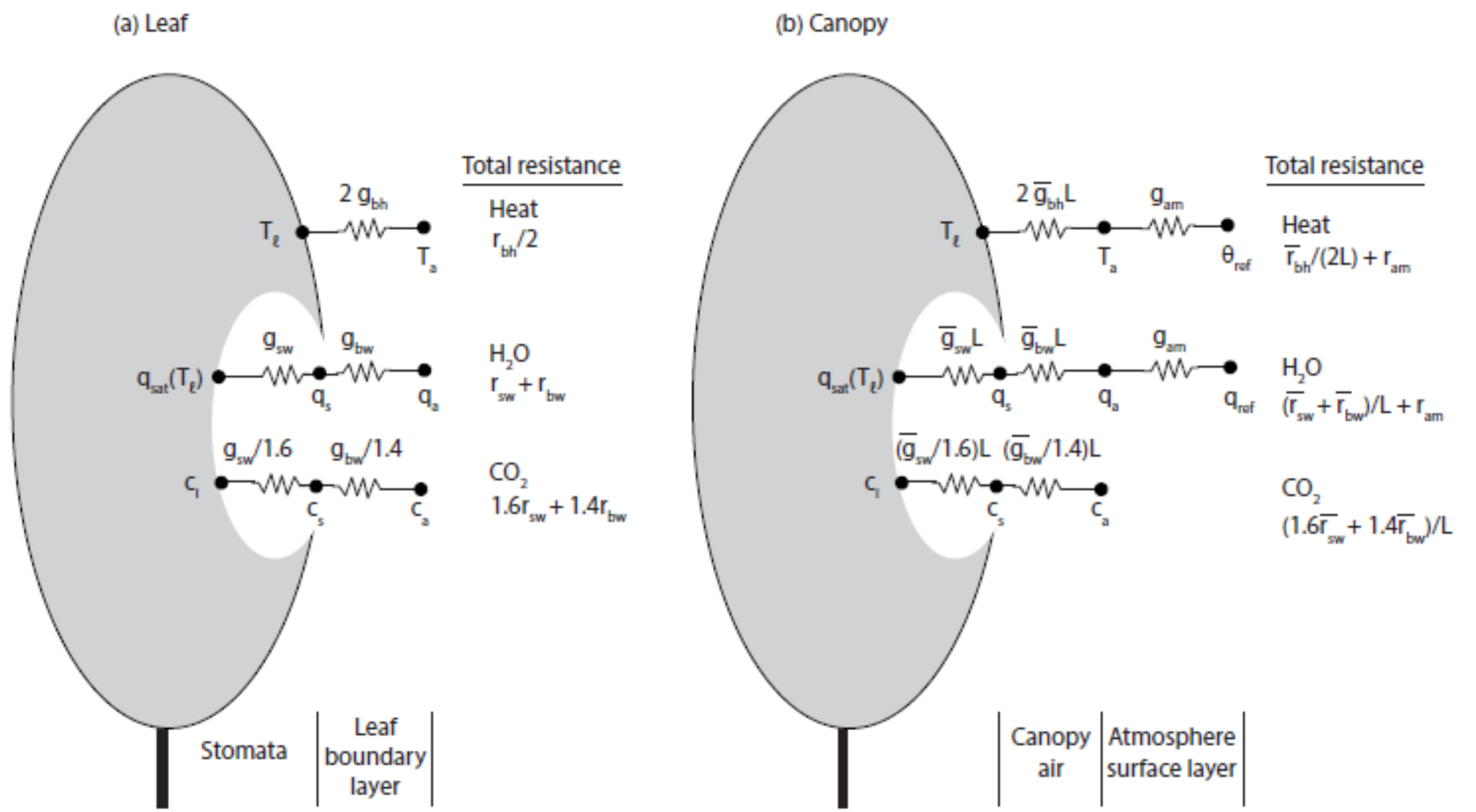


Many different plant hydraulic models



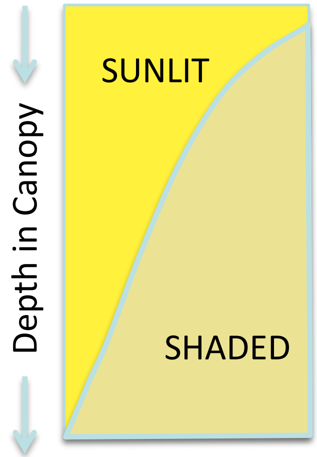
How do we scale from leaf to canopy?

Plant canopy as a "big leaf"



Most models use two-leaves
(sunlit and shaded)

Sunlit and shaded canopy



Sunlit leaves are near the top of the canopy and receive more radiation than shaded leaves

Divide canopy into sunlit and shaded portions

Calculate radiation absorbed by sunlit and shaded leaves

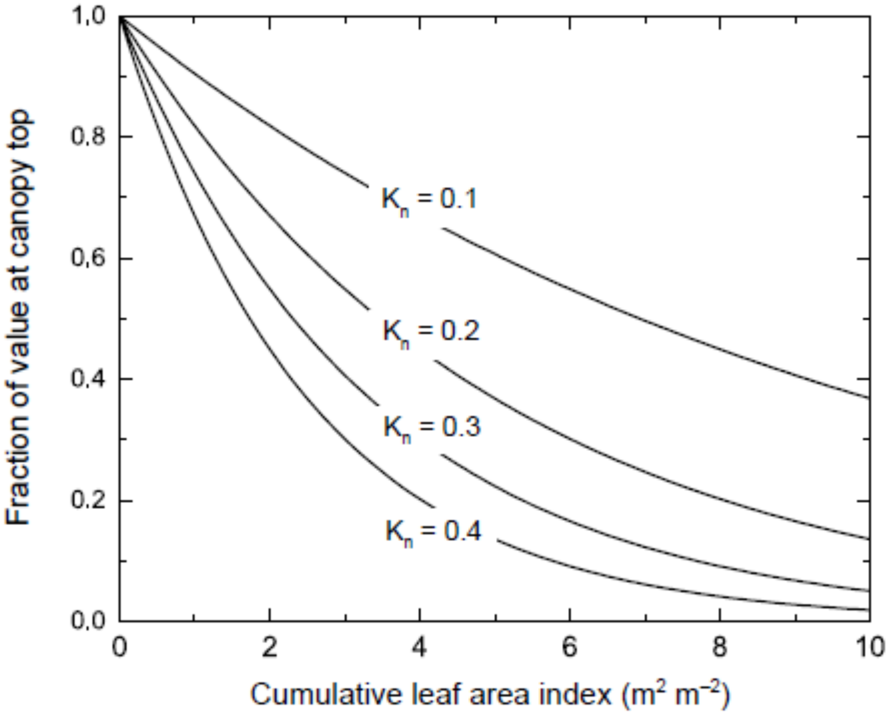
Calculate photosynthesis and stomatal conductance for sunlit and shaded leaves

Aggregate leaf conductances to a single canopy conductance

Calculate canopy temperature and energy fluxes

Nitrogen profile

Decline in foliage N (per unit area) with depth in canopy yields decline in photosynthetic capacity (V_{cmax}, J_{max})



$$V_{c\max}(x) = V_{c\max}(0)\, e^{-K_n x}$$

$$f_{sun}(x) = e^{-K_b x}$$

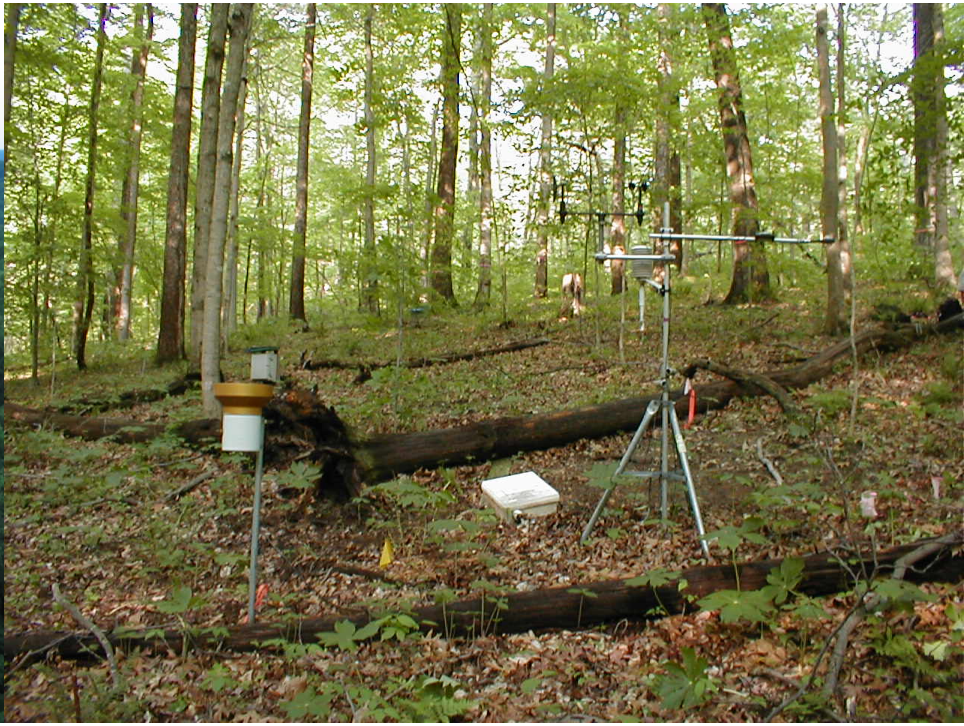
$$V_{c\max}(\text{sun}) = \int_0^L V_{c\max}(x)\, f_{sun}(x)\, dx$$

$$V_{c\max}(\text{sha}) = \int_0^L V_{c\max}(x)\left[1 - f_{sun}(x)\right] dx$$

Note: CLM5 has a more complex canopy optimization (LUNA)

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

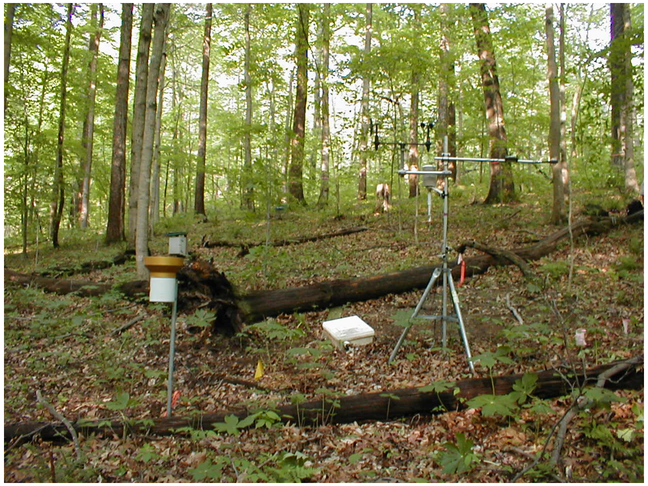
A vertically-structured canopy

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.



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

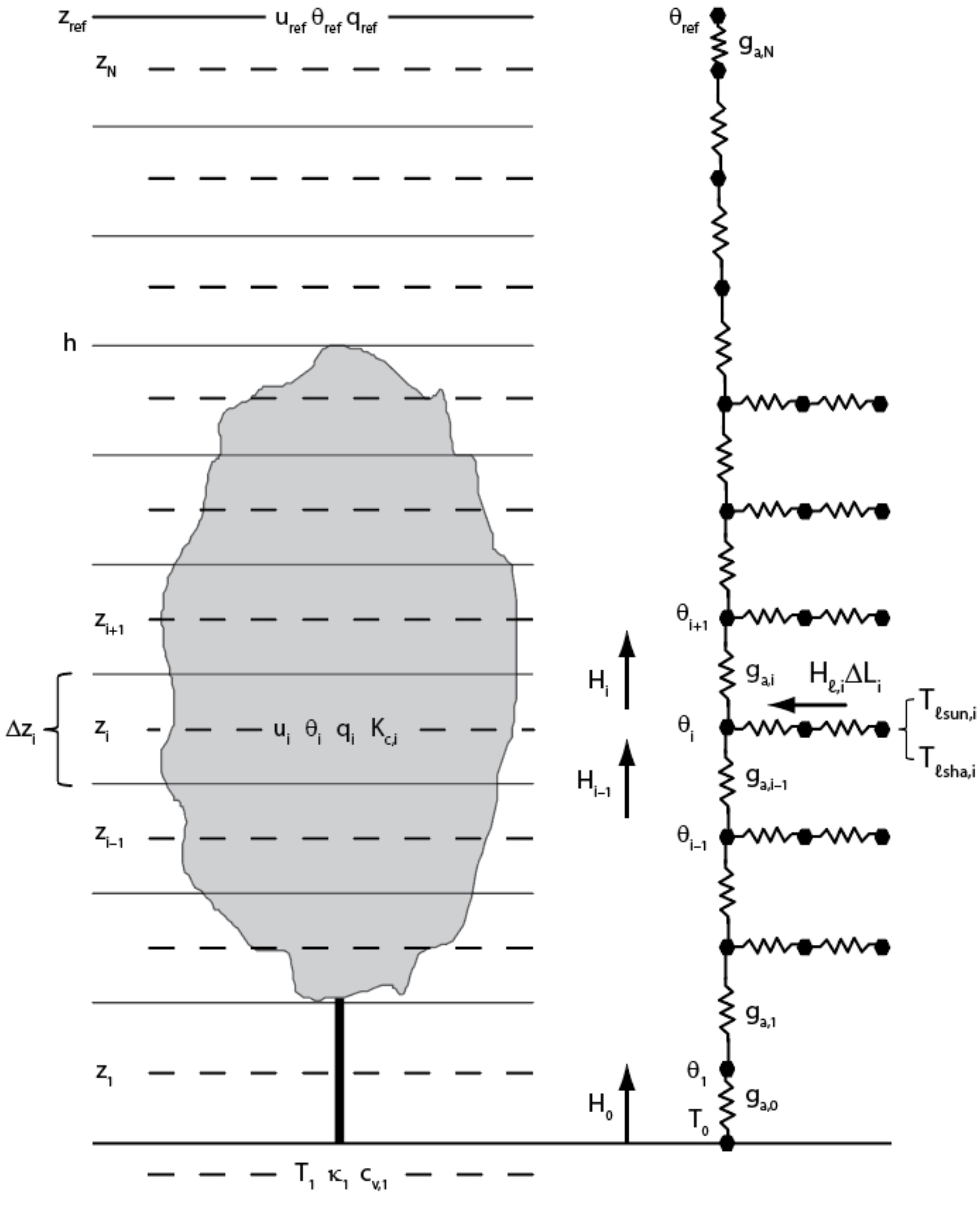
Environmental Biology, Research School of Biological Sciences, Institute of Advanced Studies, The Australian National University, Canberra, ACT, Australia

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

Water-use efficiency optimization while preventing leaf desiccation ($\psi_\ell > \psi_{\ell min}$; plant hydraulics)

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

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

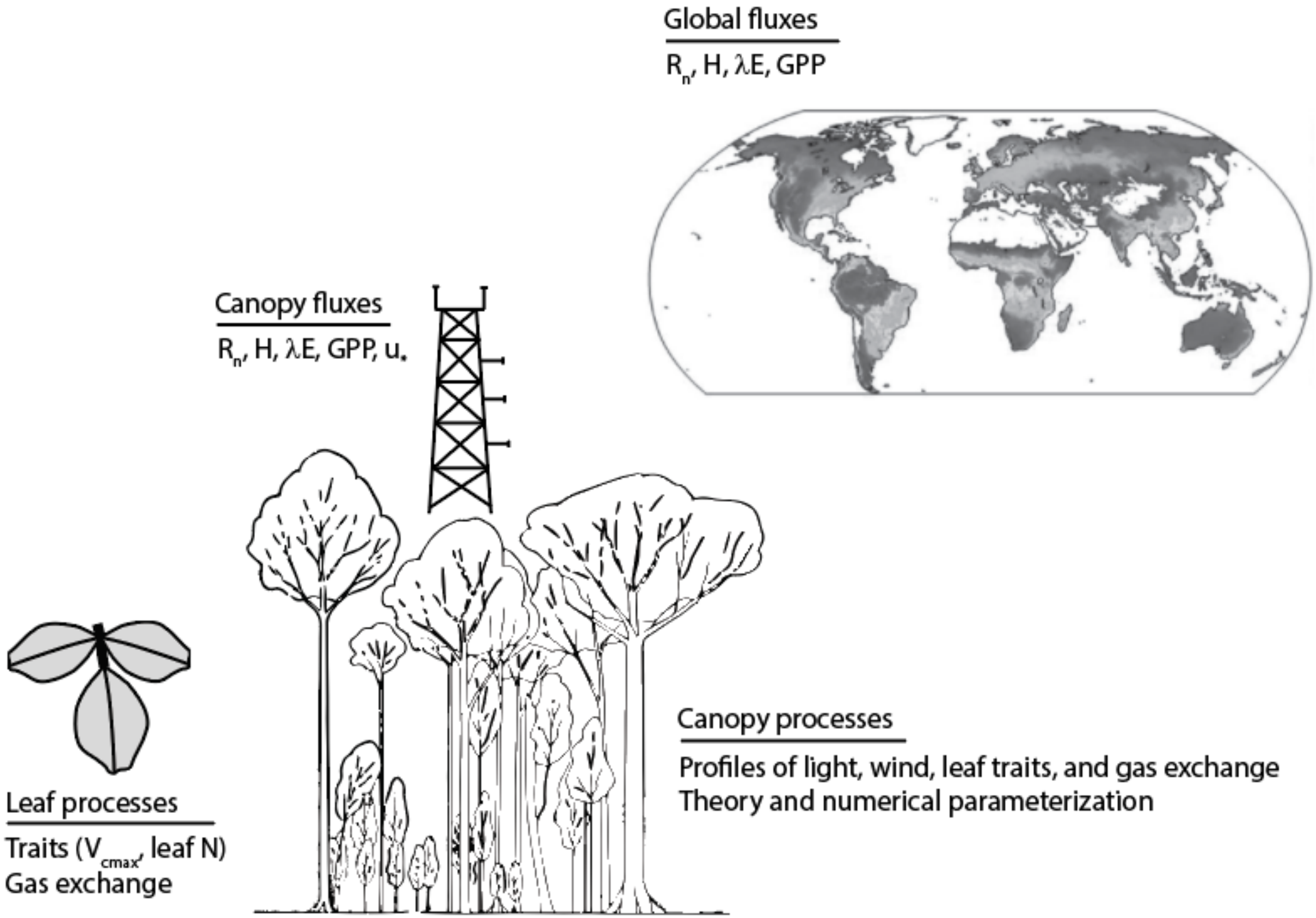
Canopy turbulence and roughness sublayer

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

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

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)

Multi-scale model evaluation



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

- **top down vs. bottom up**

Eddy covariance flux towers

Howland Forest (Maine)

Flux measurements
Albedo
Net radiation
Sensible heat flux
Latent heat flux
Net CO_2 flux
- Gross primary production
- Ecosystem respiration

Friction velocity

} To test models

Meteorological measurements
Air temperature, specific humidity, wind speed
Downwelling solar and longwave radiation
Surface pressure
Precipitation

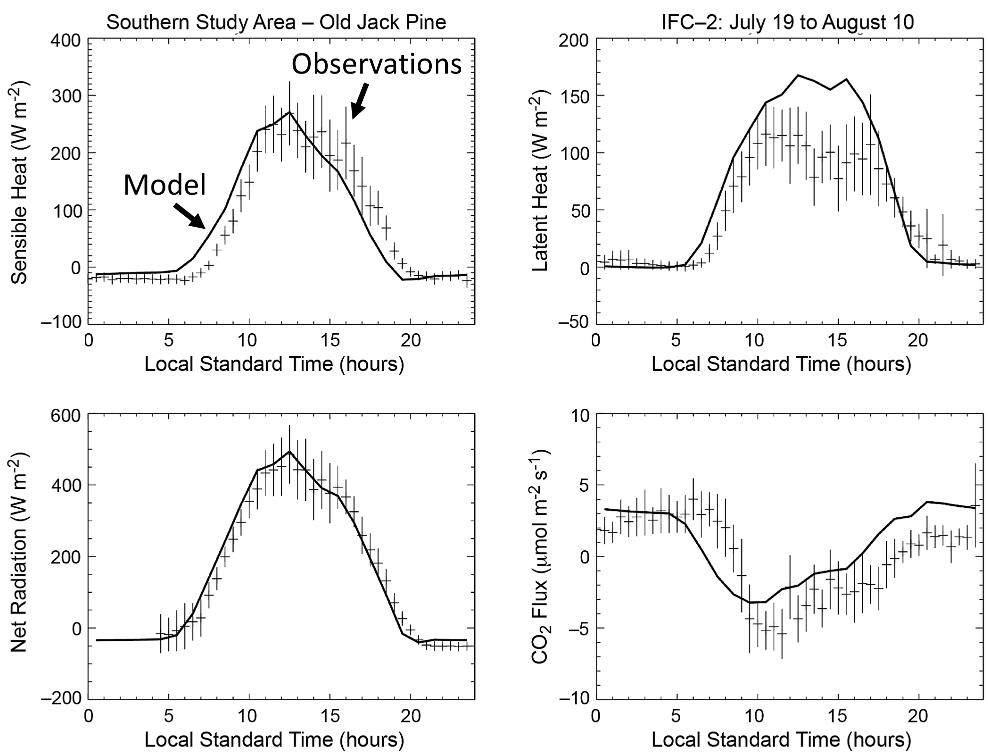
} To force models

Yes we can!

"I only feel comfortable modeling photosynthesis, and even there I get a little queasy above the level of a single leaf. I believe models have a great utility in summarizing existing knowledge and generating testable hypotheses, but remain more than a little skeptical about our ability to scale up to whole plants, let alone ecosystem processes."

Anonymous reviewer (circa early 1990s)

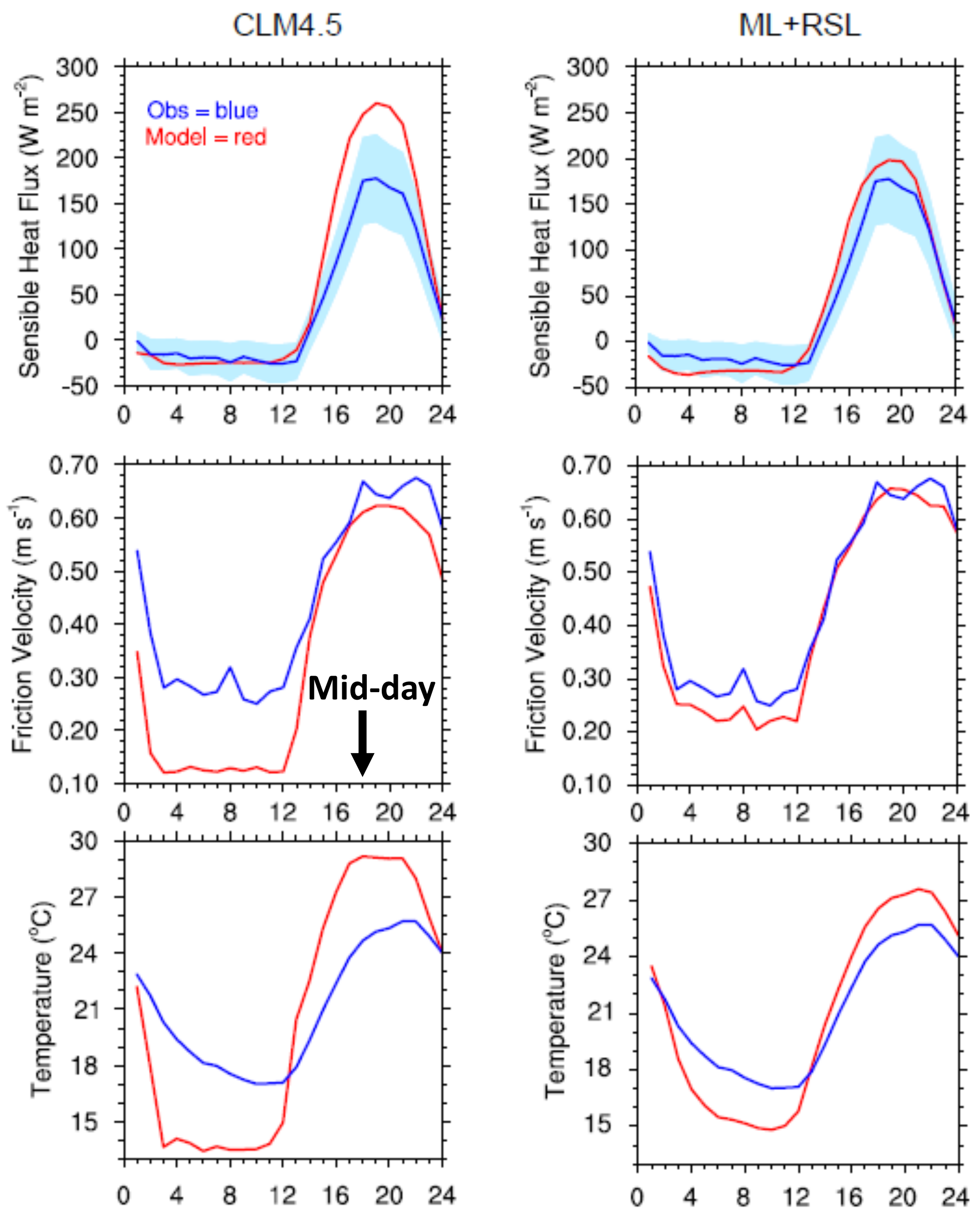
Boreal Ecosystem Atmosphere Study (BOREAS)



Bonan et al. (1997) *JGR*, 102D, 29065-75

But much work still to do

US-UMB, July 2006 (DBF)



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

Research areas

Surface fluxes
Roughness sublayer, multilayer canopies, canopy storage

Radiative transfer
3D structure, canopy gaps

Photosynthesis
Temperature acclimation, product-limited rate (TPU), C_4 plants

Stomatal conductance
Soil moisture stress, plant hydraulics, water-use efficiency optimization, CO_2 response

Canopy scaling
Optimal distribution of nitrogen