Modeling terrestrial ecosystems: Biogeophysics & canopy processes

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

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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 actually not that high (~10% of fully coupled model)

Role of land surface in Earth system models

The land surface model solves (at each timestep)

Surface energy balance (and other energy balances, e.g. in canopy, snow, soil)

S⍰ + L⍰ = S⍰ + L⍰ + ⍰E + H + G

- S⍰, S⍰ are down(up)welling solar radiation
- L⍰ , L⍰ are down(up)welling longwave radiation
- ⍰ is latent heat of vaporization, E is evapotranspiration
- H is sensible heat flux
- G is ground heat flux

Surface water balance (and other water balances such as snow and soil water)

$$P = (E_S + E_T + E_C) + (R_{Surf} + R_{Sub\text{-}Surf}) + \Delta SM / \Delta t$$

- P is rainfall
- E_S is soil evaporation, E_T is transpiration, E_C is canopy evaporation
- R_{Surf} is surface runoff, $R_{Sub\text{-}Surf}$ is sub-surface runoff
- $\Delta SM / \Delta t$ is the change in soil moisture over a timestep

Carbon balance (and plant and soil carbon pools)

$$NPP = GPP - R_a = (\Delta C_f + \Delta C_s + \Delta C_r) / \Delta t$$

$$NEP = NPP - R_h$$

$$NBP = NEP - Fire - Land\ Use$$

- NPP is net primary production, GPP is gross primary production
- R_a is autotrophic (plant) respiration, R_h is heterotrophic (soil) respiration
- ΔC_f, ΔC_s, ΔC_r are foliage, stem, and root carbon pools
- NEP is net ecosystem production, NBP is net biome production

Model design philosophy

Coupling with the atmosphere every model timestep is a fundamental constraint (< 30 minute timestep)

So is the need to represent the global land surface, including Antarctica, the Tibetan Plateau along with forests, grassland, croplands, tundra, desert scrub vegetation, and cities

Conservation of energy and mass is required

We strive to develop a process-level understanding across multiple ecosystems and at multiple timescales (instantaneous, seasonal, annual, decadal, centuries)

Top-down, empirical modeling

Thornthwaite: Monthly potential evapotranspiration driven by air temperature

$$E_p = 16\left(\frac{L}{12}\right)\left(\frac{N}{30}\right)\left(\frac{10T}{I}\right)^a$$

Priestley–Taylor equation: Daily potential evapotranspiration driven by radiation

$$E_p = \alpha \frac{s}{s+\gamma}\frac{R_n}{\lambda}$$

Production efficiency model driven by radiation and empirical scalars

$$GPP = \varepsilon S\downarrow f_1(T) f_2(\theta) f_3(VPD)$$

Annual NPP driven by temperature and precipitation

$$NPP = \min\left\{\frac{3000}{1+\exp(1.315-0.119T)}, 3000\left[1-\exp(-0.000664P)\right]\right\}$$

Process modeling

Penman-Monteith equation
FvCB photosynthesis model
Ball-Berry stomatal conductance model
Fick's law of diffusion
Darcy's law and Richards equation (soil water)
Fourier's law (heat conduction)

Lack of a common language

Flux is proportional to the driving force:

Flux = proportionality constant * gradient of driving potential

Describes heat flow in soil (Fourier's law), water flow in soil (Darcy's law), turbulent fluxes (Fick's law)

Dimensionless drag coefficient (C_w); Dimensionless soil moisture factor (β)

E: kg m^{-2} s^{-1}; ρ: kg m^{-3}; u: m s^{-1}; q: kg kg^{-1}

Atmospheric models: $E = \rho C_w u \left(q_s - q_a \right) \beta$

Land surface models: $E = \dfrac{\rho \left(q_s - q_a \right)}{r_a + r_s}$ ← resistance (s m^{-1})

e: Pa; g_w: m s^{-1}

Biometeorology: $\lambda E = \dfrac{c_p}{\gamma} \left(e_s - e_a \right) g_w$

E: mol m^{-2} s^{-1}; q: mol mol^{-1}; g_w: mol m^{-2} s^{-1}

Plant physiology: $E = \left(q_s - q_a \right) g_w$

Model name

Model name depends on discipline:

Atmospheric sciences
land surface model
soil–vegetation–atmosphere–transfer model

Hydrology
hydrologic model (SVAT with lateral fluxes)

Ecology
biogeochemical model
dynamic global vegetation model
ecosystem demography model

The Community Land Model

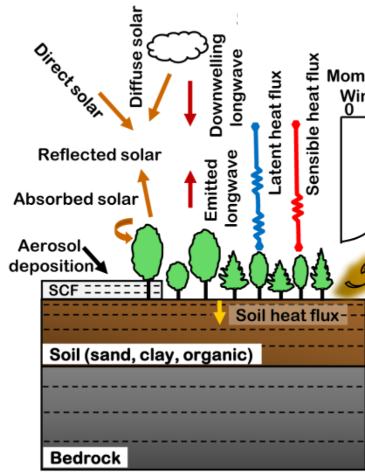
Fluxes of energy, water, CO_2, CH_4, BVOCs, and Nr and the processes that control these fluxes in a changing environment

Oleson et al. (2013) NCAR/TN-503+STR (420 pp)

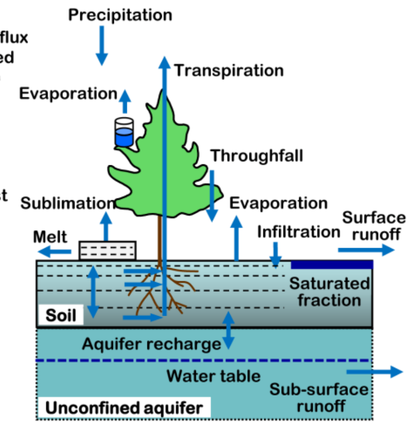
Lawrence et al. (2011) J. Adv. Mod. Earth Syst., 3, doi: 10.1029/2011MS000045

Lawrence et al. (2012) J Climate 25:2240-2260

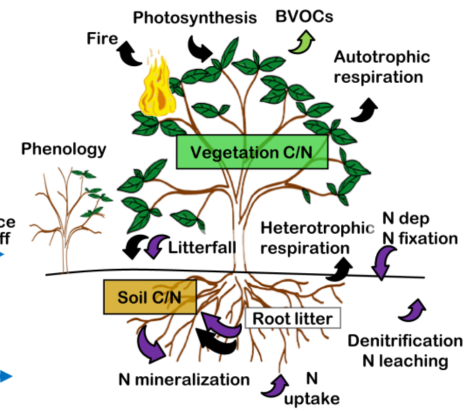
Surface energy fluxes



Hydrology



Biogeochemistry

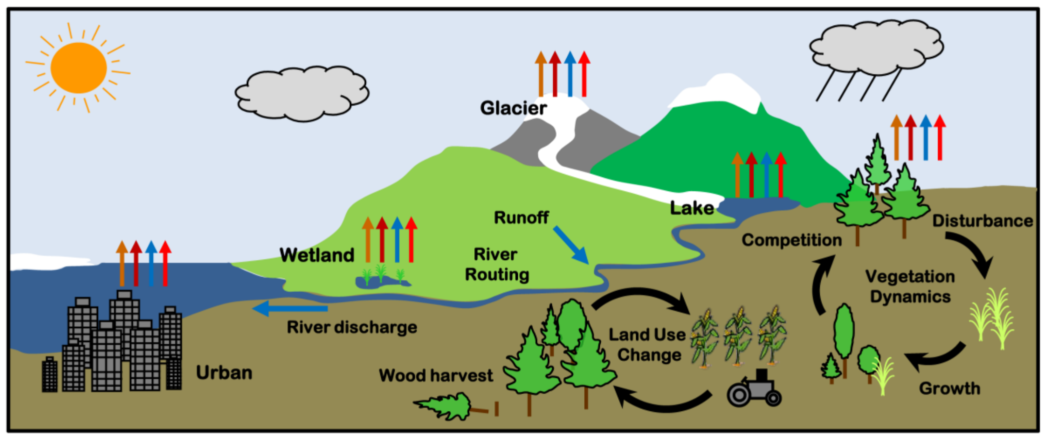


Spatial scale

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

Temporal scale

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

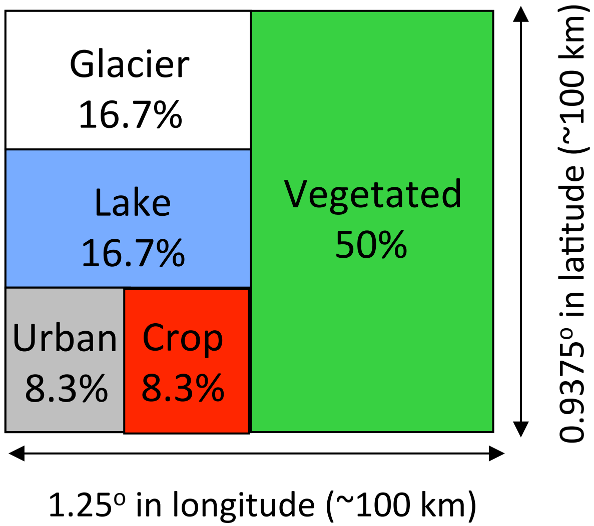


Landscape dynamics

Land surface heterogeneity

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 up to 5 primary land units. Each land unit can have multiple columns. Vegetated land is further represented as patches of individual plant functional types

Sub-grid land cover and plant functional types



Surface energy balance and surface temperature

Surface energy balance:

$(S? - S?) + ?L? - ?\,\sigma T_s^4 - H[T_s] - ?E[T_s]$ = soil heat storage

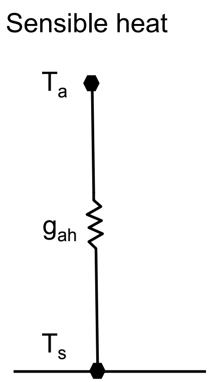
Soil heat storage:

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

Flux = Δ concentration * conductance

$$H = c_p (T_s - T_a) g_{ah}$$

$$\lambda E = \lambda \frac{(q_*[T_s] - q_a)}{g_{ah}^{-1} + g_c^{-1}}$$



Atmospheric forcing

S? - Solar radiation (vis, nir; direct, diffuse)

L? - Longwave radiation

T_a - air temperature

q_a - atmospheric water vapor

u - wind speed

P - surface pressure

Surface properties

S? - reflected solar radiation (albedo)

? - emissivity

g_{ah} - aerodynamic conductance (roughness length)

g_c - surface conductance

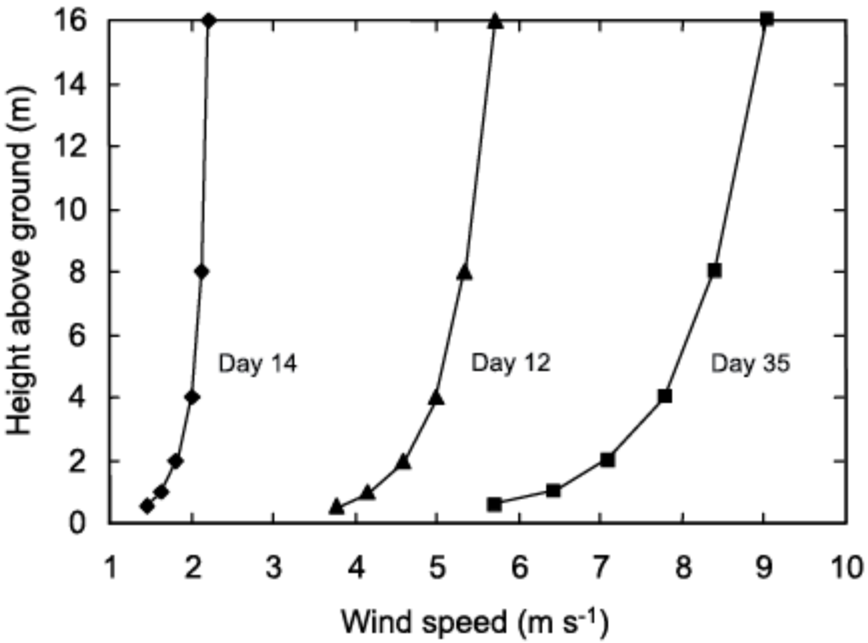
k - thermal conductivity

c_v - soil heat capacity

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

Turbulent fluxes – logarithmic profiles

Logarithmic wind profile in atmosphere near surface



$$\bar{u}(z) = \frac{u_*}{k}\left[\ln\left(\frac{z-d}{z_0}\right) - \psi_m(\zeta)\right]$$

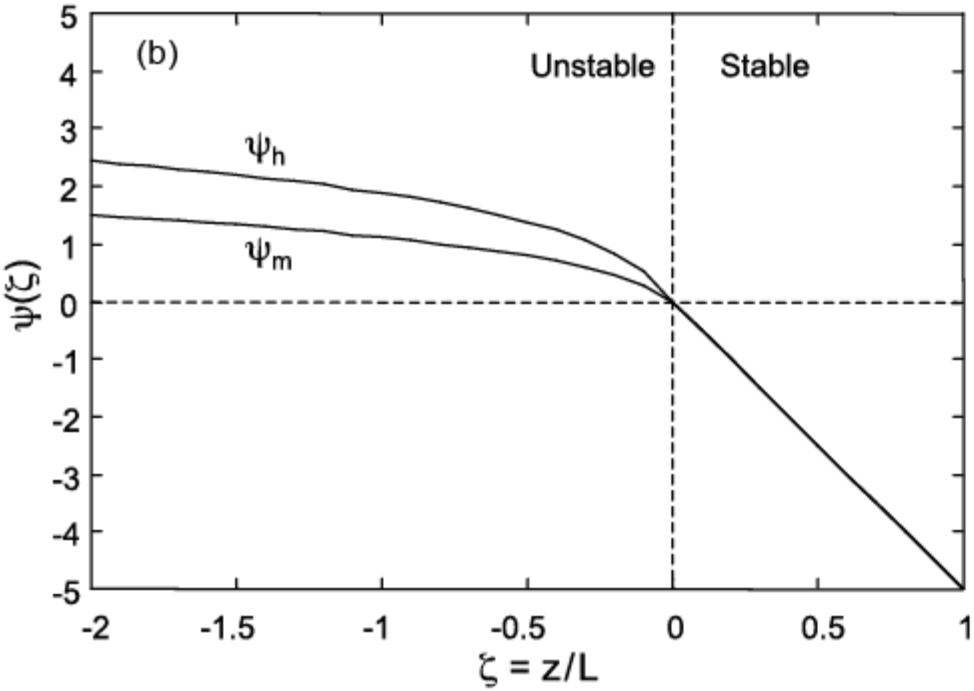
$$\bar{\theta}(z) - \bar{\theta}_s = \frac{\theta_*}{k}\left[\ln\left(\frac{z-d}{z_{0h}}\right) - \psi_h(\zeta)\right]$$

$$\bar{q}(z) - \bar{q}_s = \frac{q_*}{k}\left[\ln\left(\frac{z-d}{z_{0h}}\right) - \psi_w(\zeta)\right]$$

with z_0 roughness length, d displacement height, and $\psi(\zeta)$ corrects for atmospheric stability

Bonan (2016) Ecological Climatology, 3rd ed (Cambridge Univ. Press)

Turbulent fluxes – logarithmic profiles



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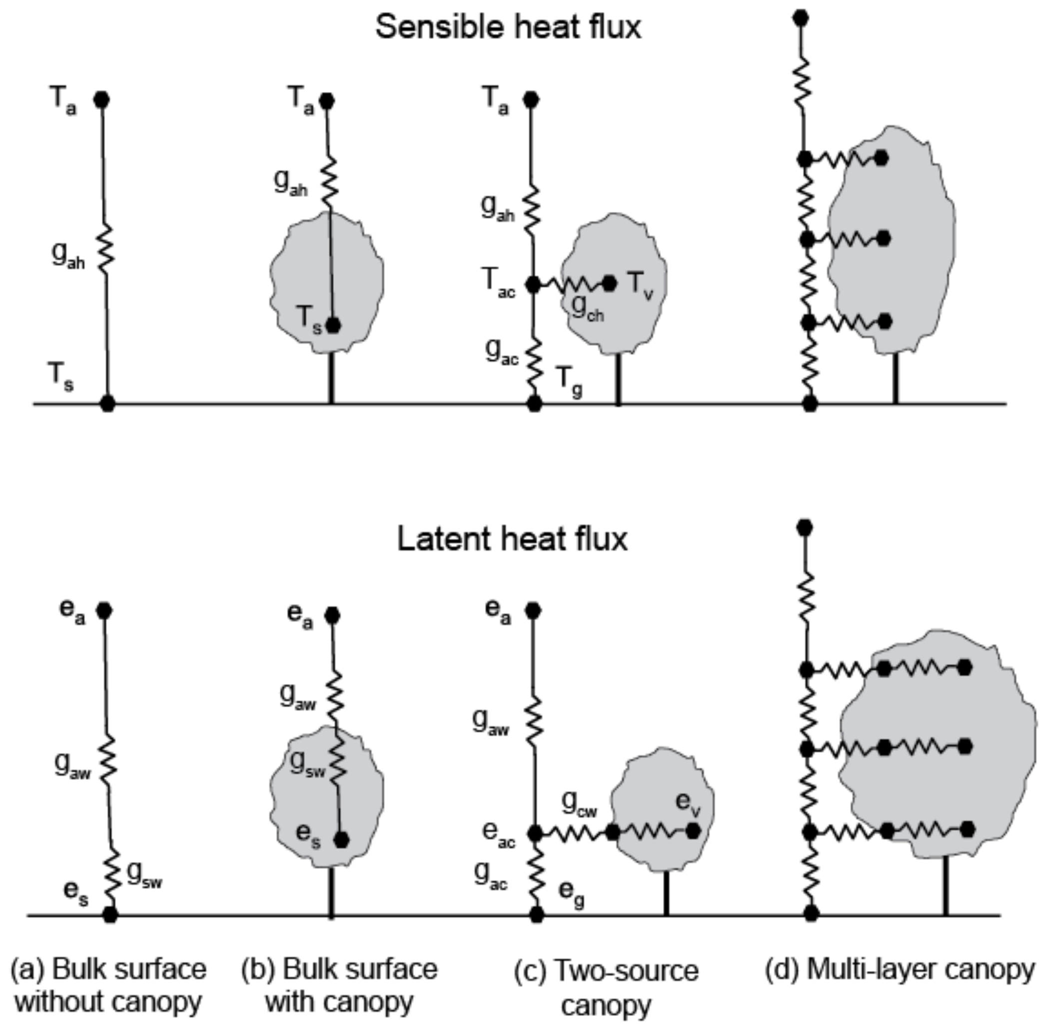
Plant canopies

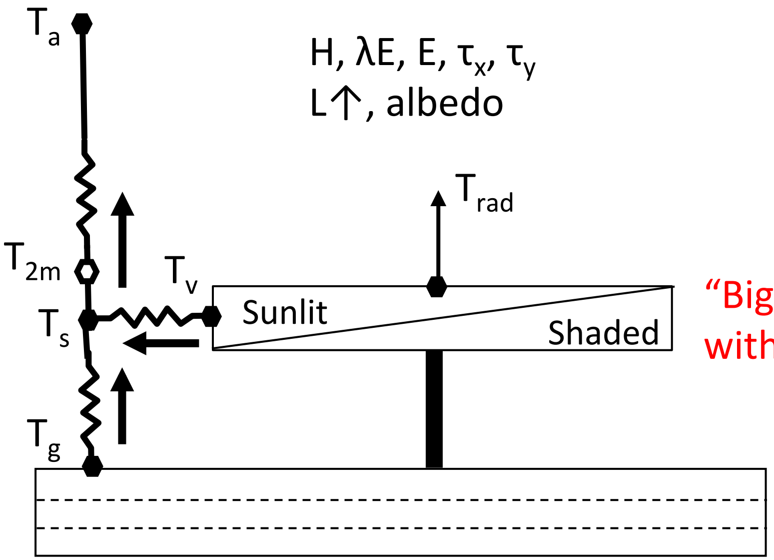


Bonan (2016) Ecological Climatology, 3rd ed (Cambridge Univ. Press)

CLM perspective of the land surface

Flux to atmosphere uses MOST

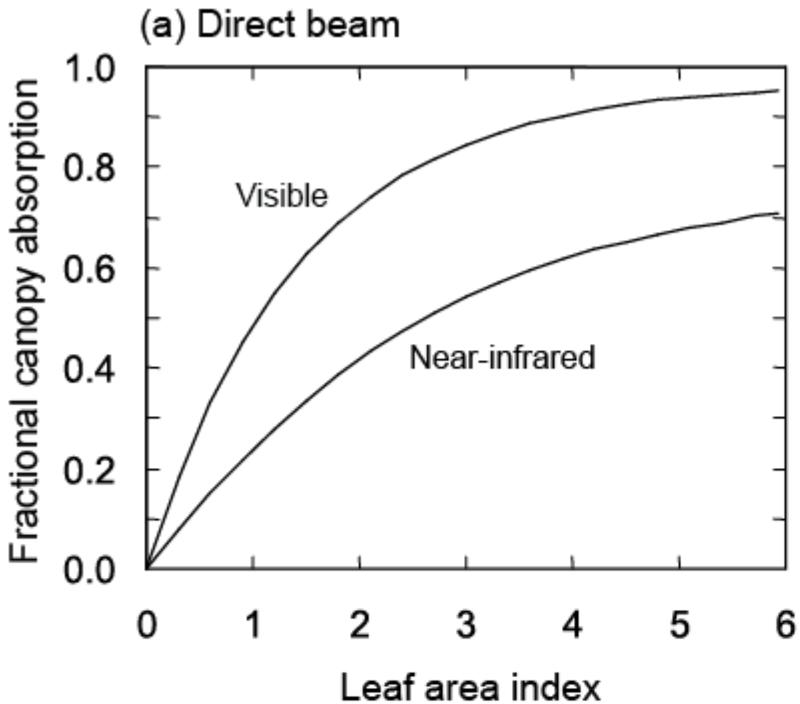
"Surface" is an imaginary height (where wind speed extrapolates to zero)

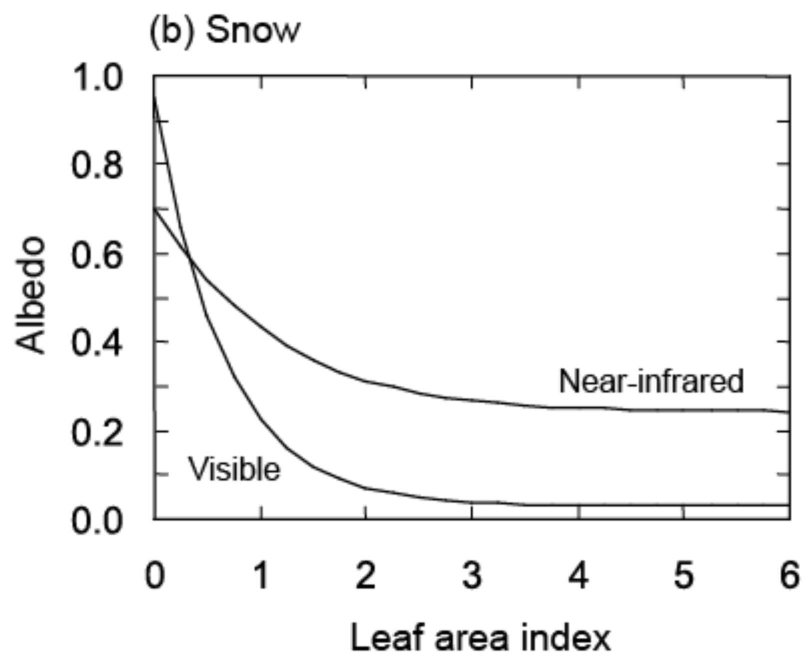


"Big-leaf" canopy without vertical structure

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

Radiative transfer





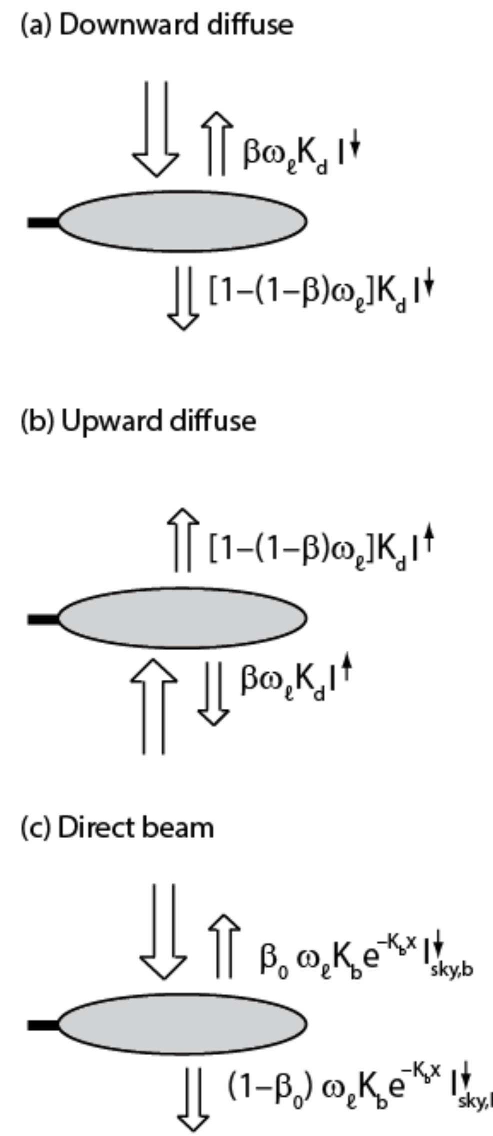
Bonan (2016) Ecological Climatology, 3rd ed (Cambridge Univ. Press)

Two-stream radiative transfer

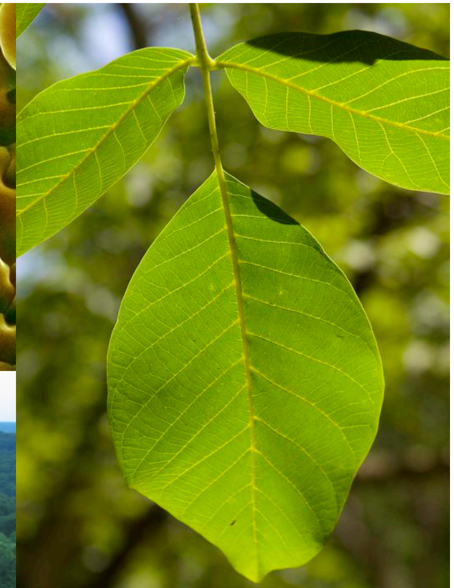
CLM uses the two-stream approximation (Dickinson, Sellers)

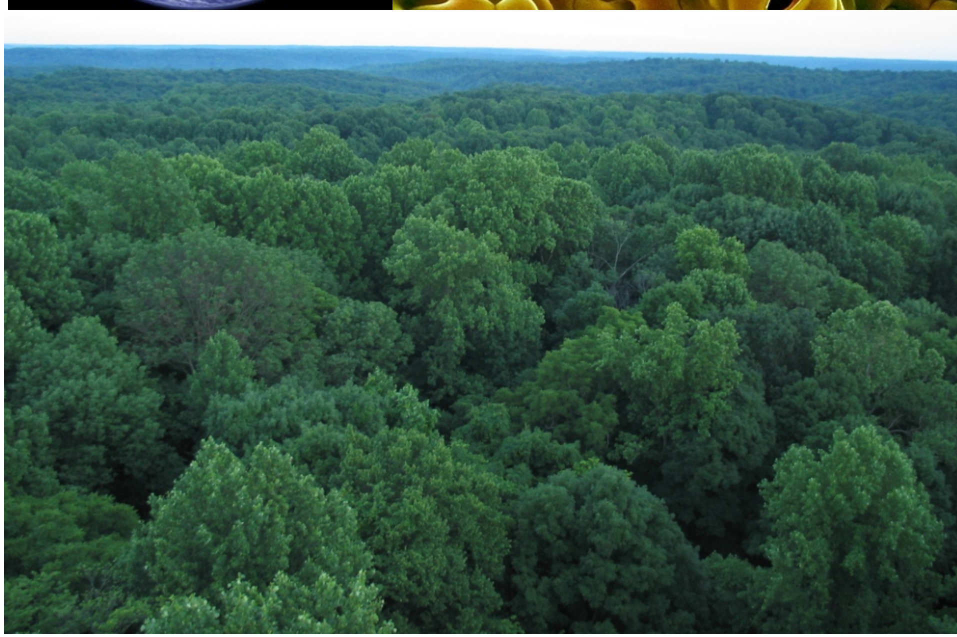
$$\frac{dI^{\uparrow}}{dx} = \left[1-(1-\beta)\,\omega_l\right]K_d I^{\uparrow} - \beta\omega_l K_d I^{\downarrow} - \beta_0\omega_l K_b I^{\downarrow}_{sky,b}e^{-K_b x}$$

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



How do we scale from leaf to canopy?





Leaf temperature and fluxes

Leaf energy balance:

$$c_L \frac{\partial T_l}{\partial t} = Q_a - 2\varepsilon_l \sigma T_l^4 + 2c_p\left(T_l - T_a\right)g_{bh} + \lambda\left[q_*\left(T_l\right) - q_a\right]g_l$$

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

[?]$_\ell$ - emissivity

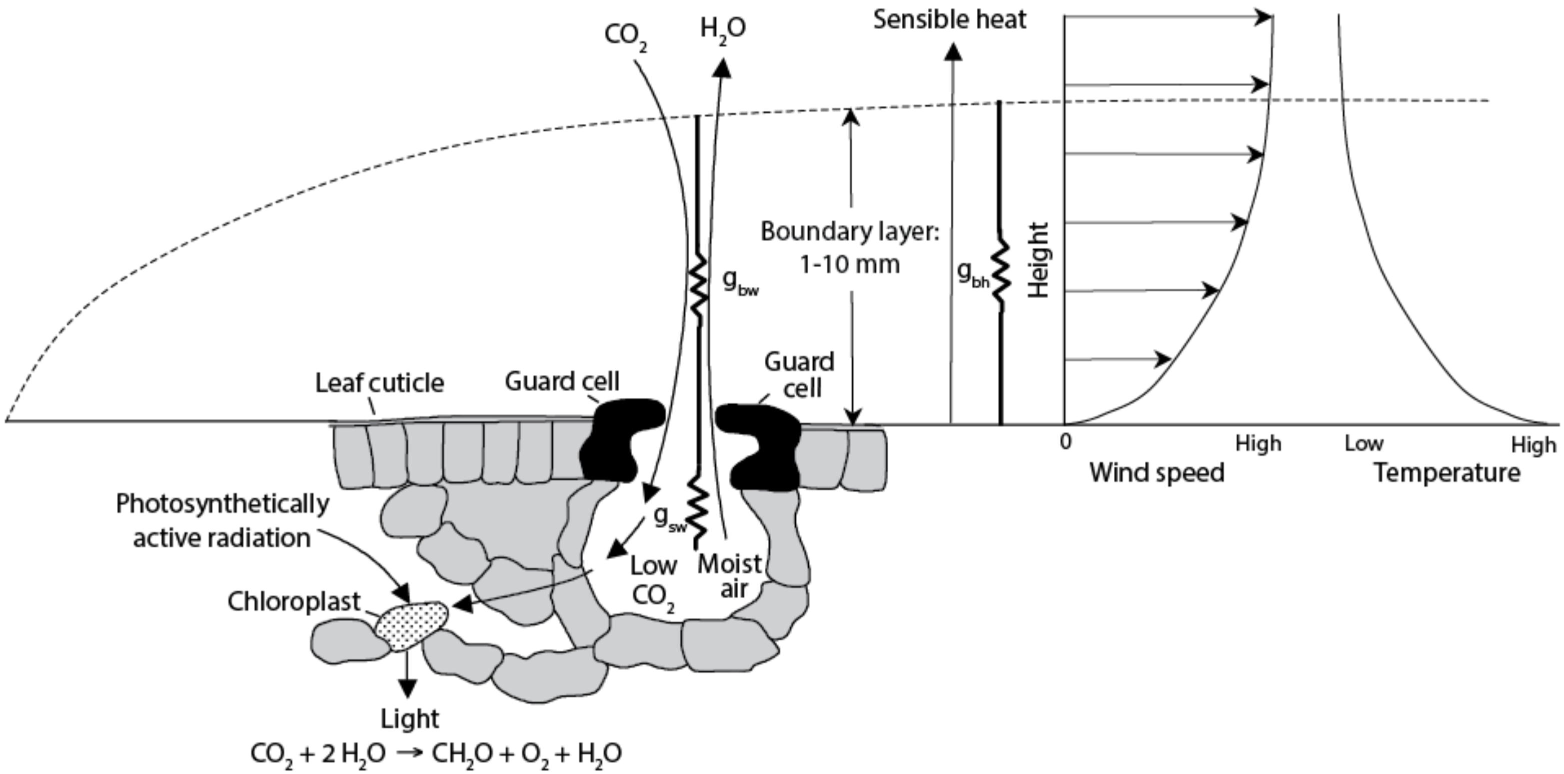
g_{bh} - leaf boundary layer resistance

g_ℓ - leaf resistance 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



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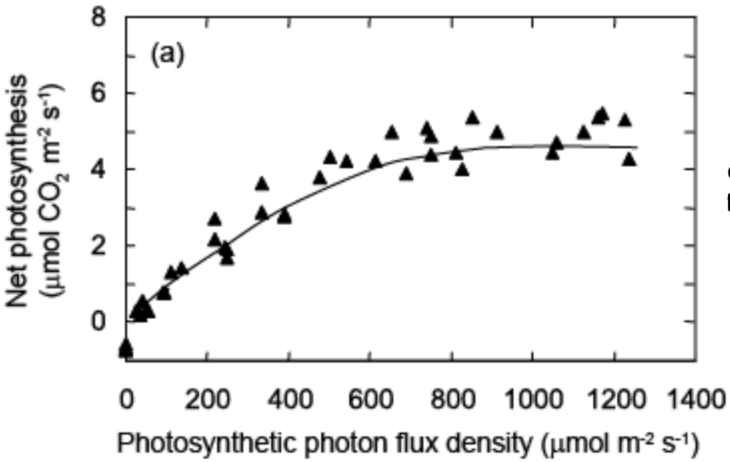
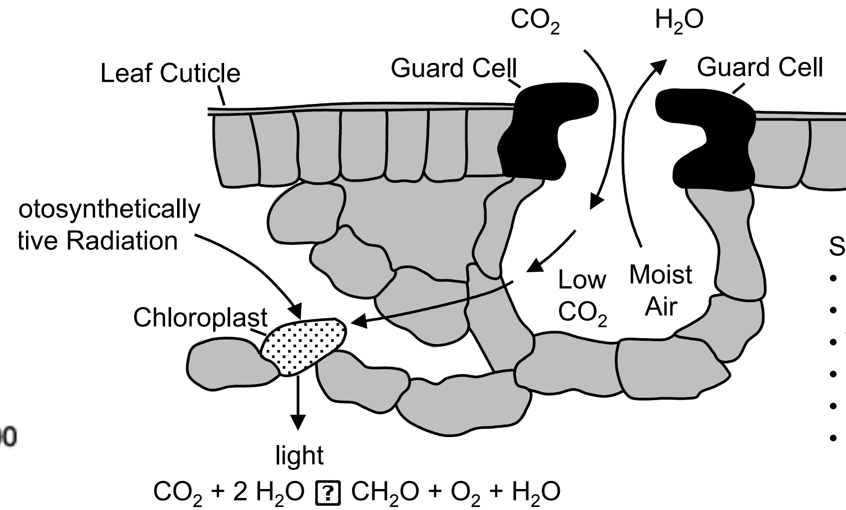
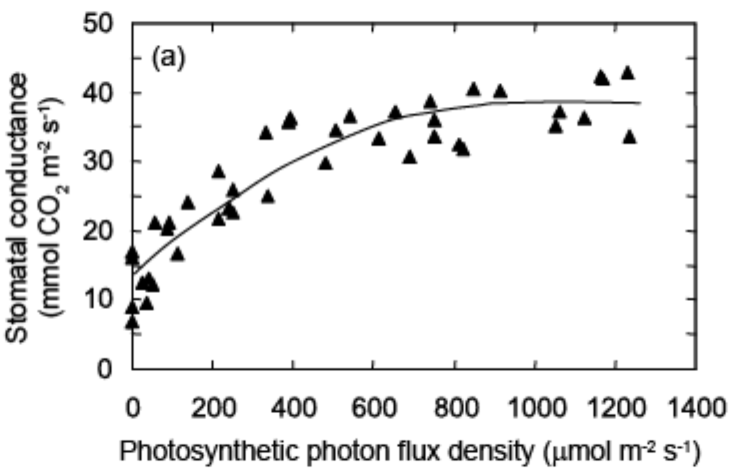
Stomatal gas exchange

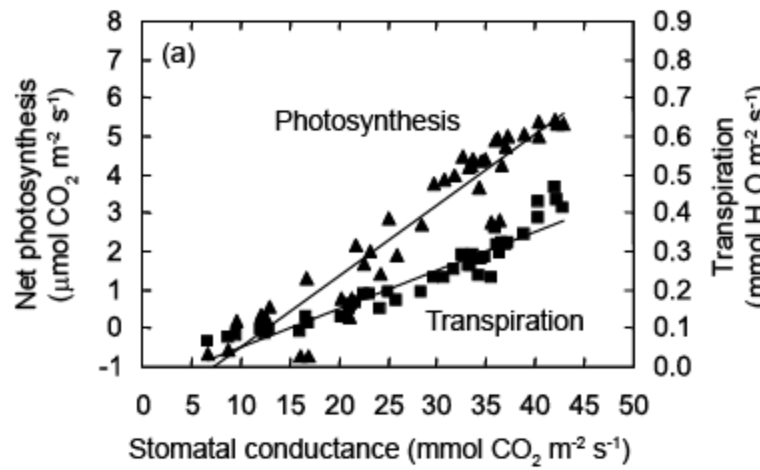




Stomata Open:

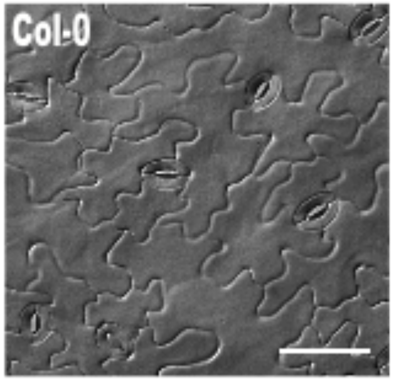
- High Light Levels
- Moist Leaf
- Warm Temperature
- Moist Air
- Moderate CO_2
- High Leaf Nitrogen





Bonan (2016) Ecological Climatology, 3rd ed (Cambridge Univ. Press)

Stomatal conductance



Scale bar 50 μm

Ball-Berry stomatal conductance model

$$g_s = g_0 + g_1 A_n h_s / c_s$$

Empirical relationship between stomatal conductance and photosynthesis and is applied separately to sunlit canopy and shaded canopy

Optimization theory

Stomata optimize photosynthetic carbon gain per unit transpiration water loss while preventing leaf desiccation

$$\Delta A_n \leq \iota D_s \Delta g_s \quad \text{and} \quad \psi_l > \psi_{l\,\min}$$

Williams et al. (1996) Plant Cell Environ. 19:911-927

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

Leaf photosynthesis

Farquhar, von Caemmerer, Berry photosynthesis model

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

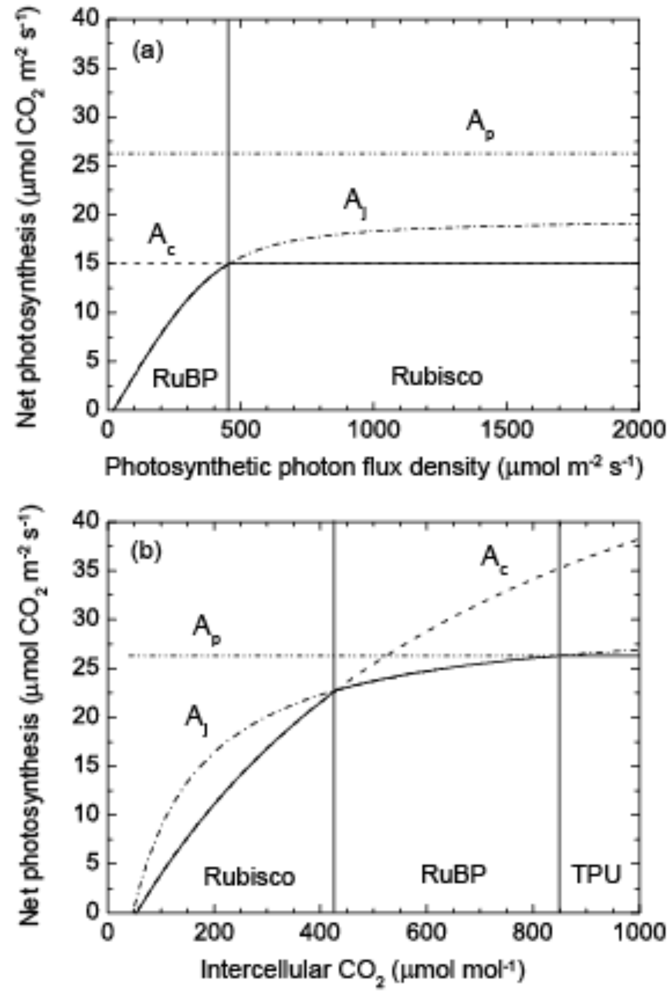
w_c is the rubisco-limited rate of photosynthesis, w_j is light-limited rate allowed by RuBP regeneration

rubisco-limited rate is

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

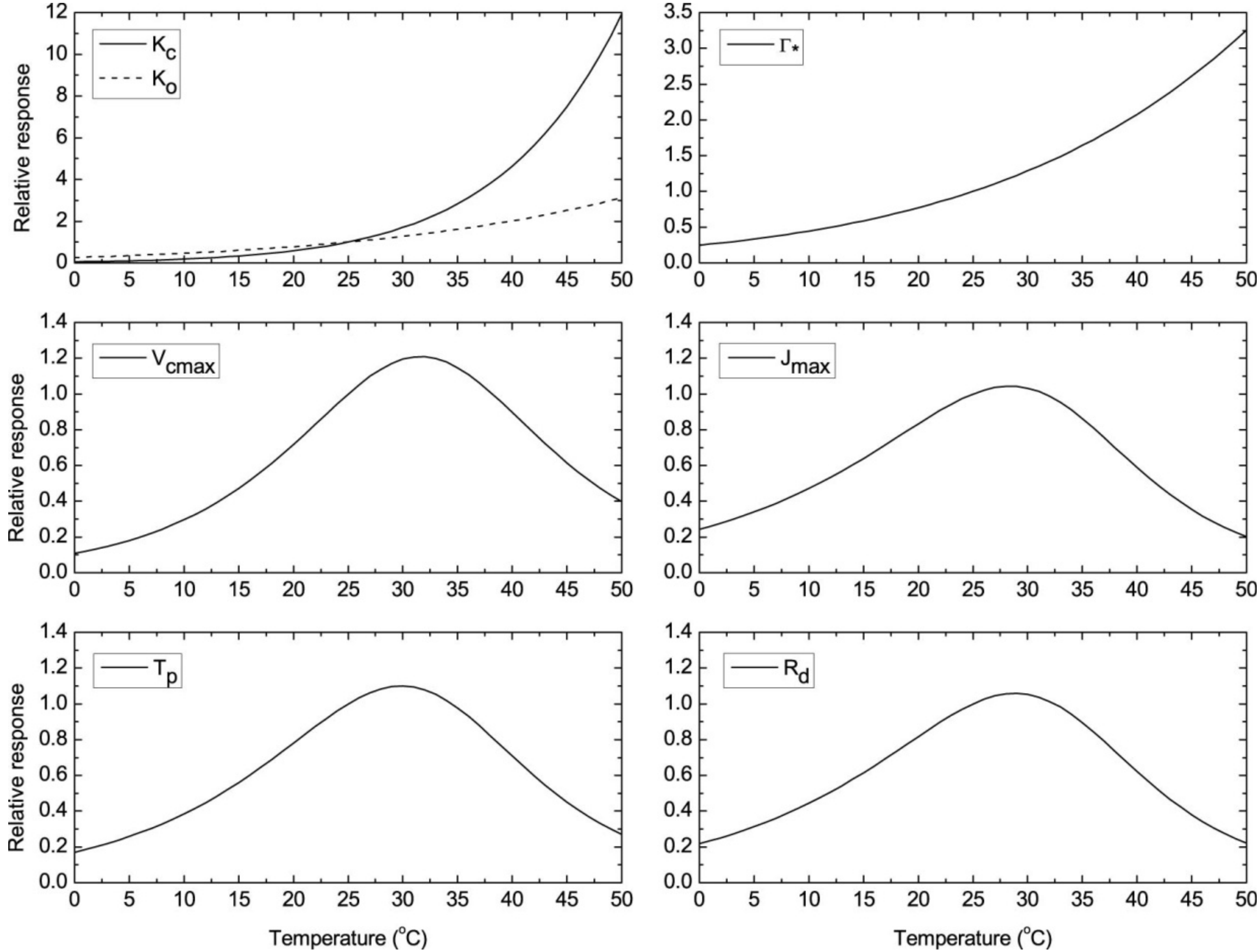
RuBP regeneration-limited rate is

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

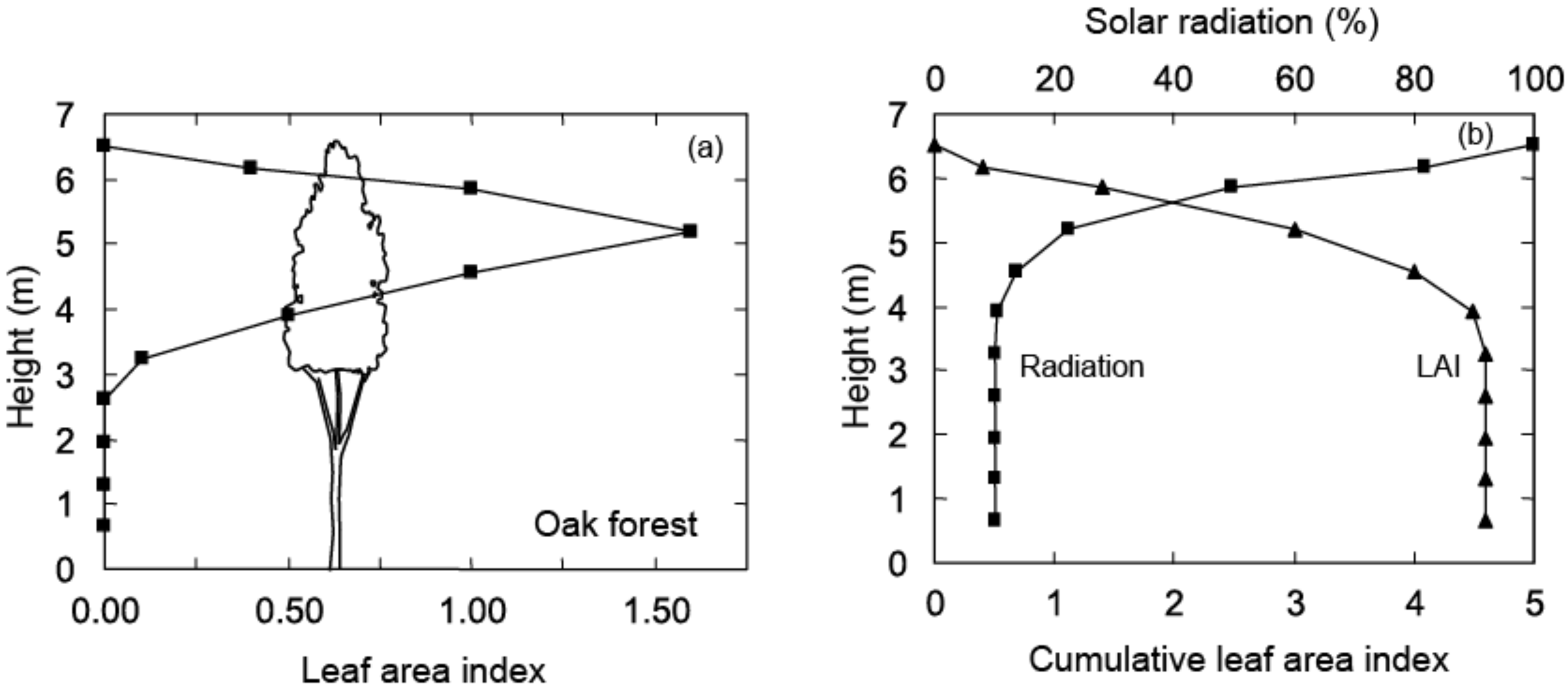


Bonan (2016) Ecological Climatology, 3rd ed (Cambridge Univ. Press)

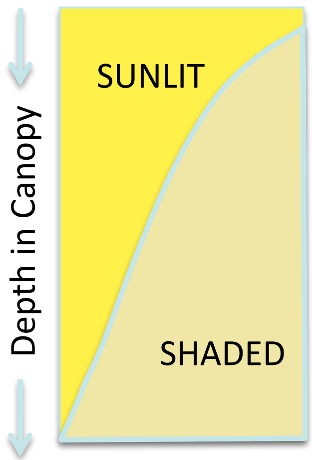
Leaf physiological parameters

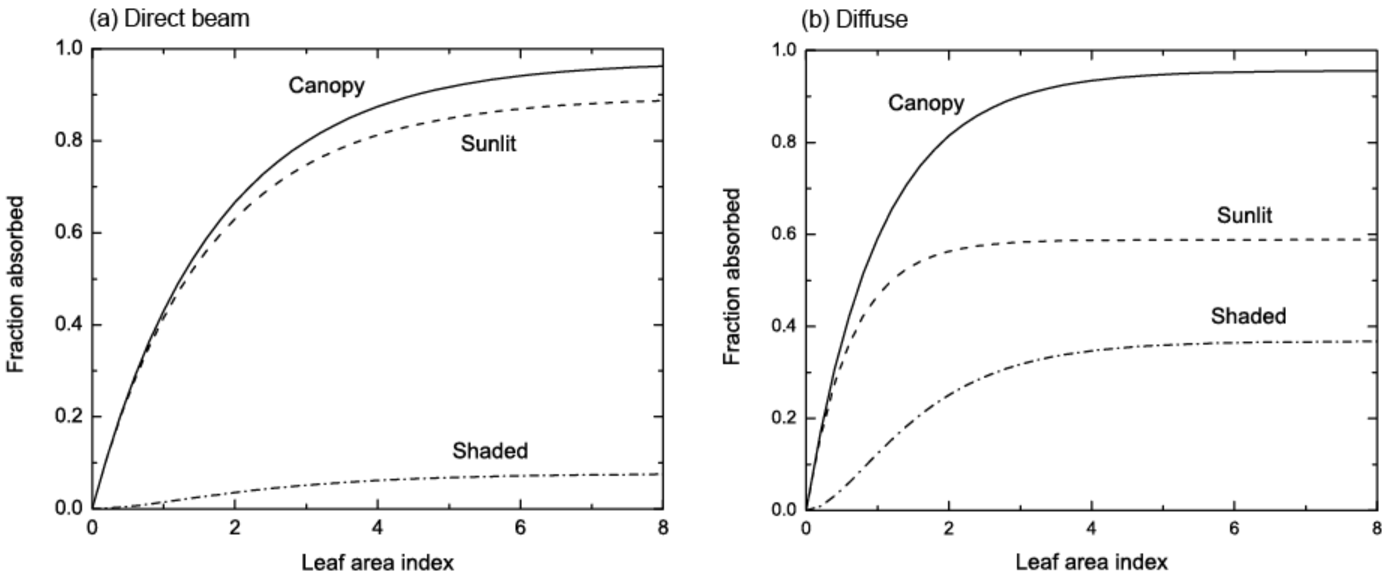


Canopy conductance – gradients of PAR



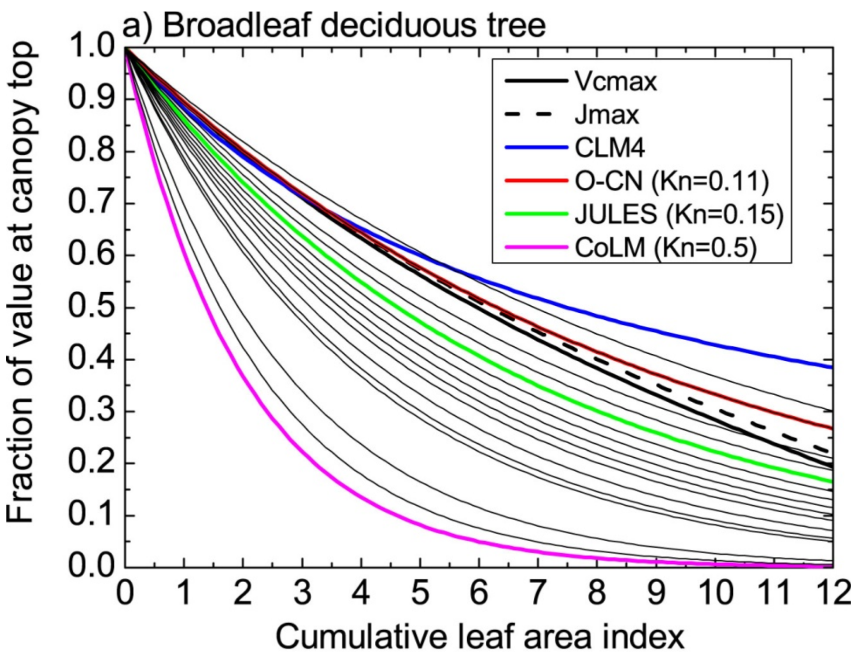
Sunlit and shaded canopy





Nitrogen profile

Decline in foliage N (per unit area) with depth in canopy yields decline in photosynthetic capacity (Vcmax, Jmax)



Bonan et al. (2011) JGR, doi:10.1029/2010JG001593

$$V_{c\max 25}(x) = V_{c\max 25}(0)\, e^{-K_n x}$$

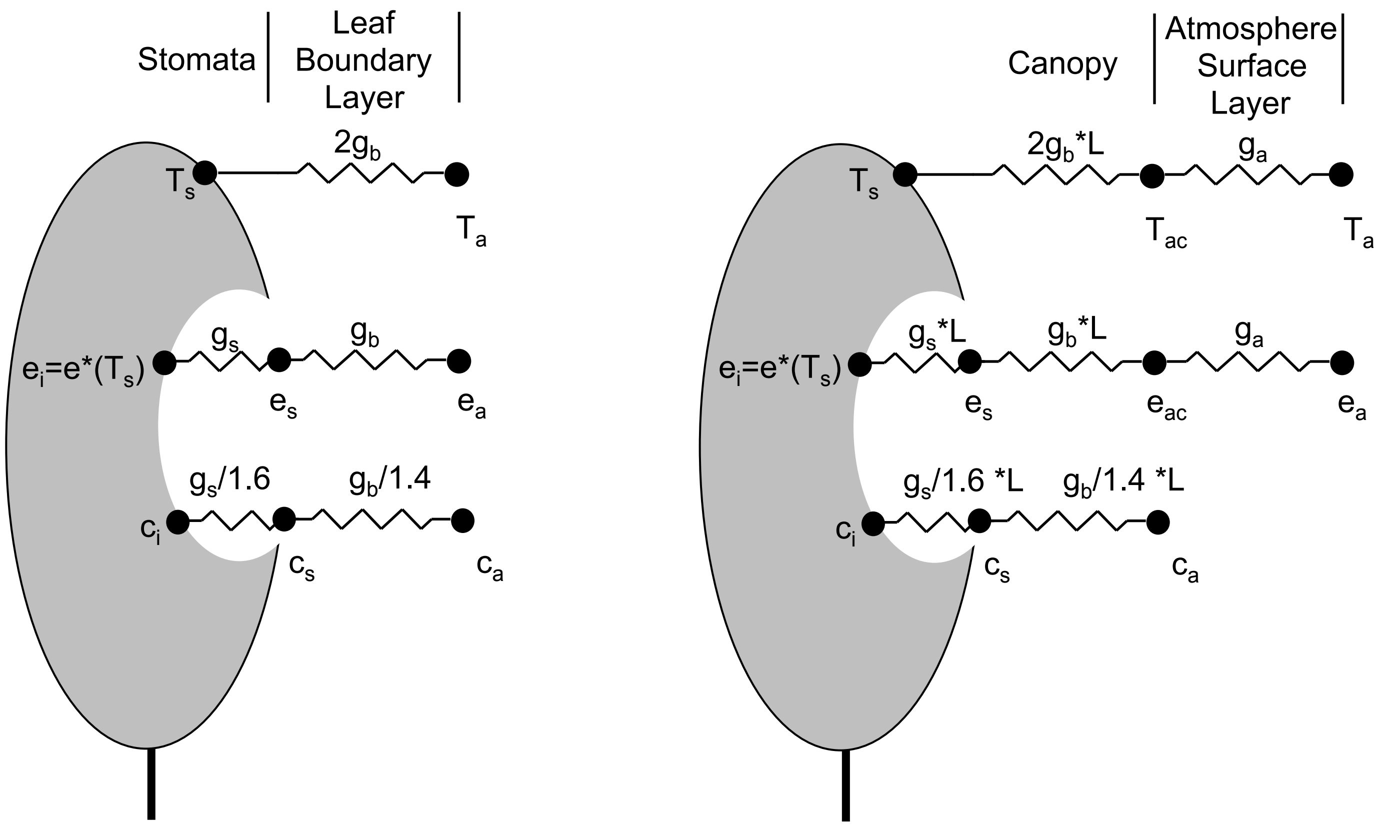
$$f_{sun}(x) = e^{-K_b x}$$

$$V_{c\max 25}(\text{sun}) = \int_0^L V_{c\max 25}(x)\, f_{sun}(x)\, dx$$

$$V_{c\max 25}(\text{sha}) = \int_0^L V_{c\max 25}(x)\left[1 - f_{sun}(x)\right] dx$$

Note: CLM5 has a more complex canopy optimization

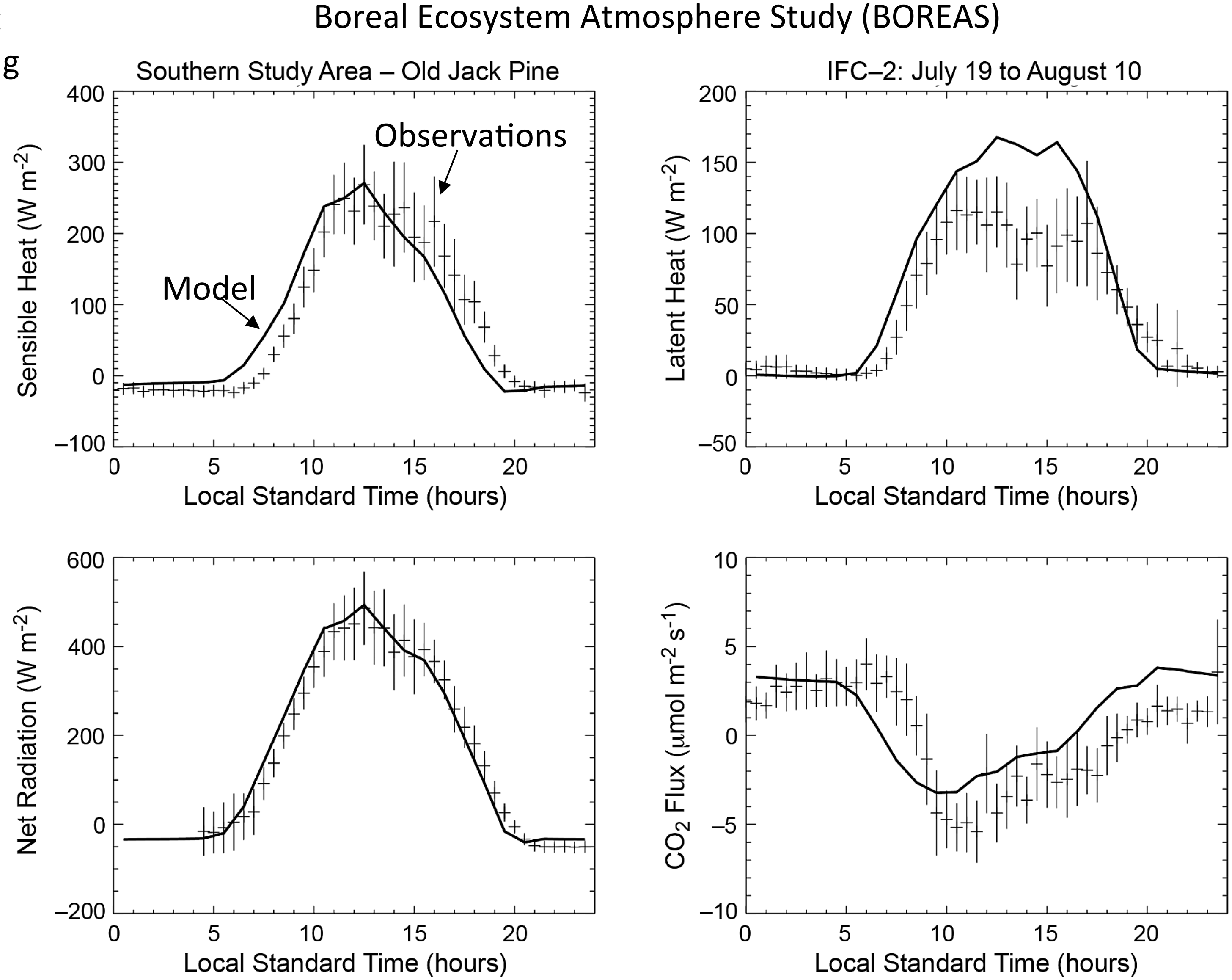
Plant canopy as a "big leaf"



Most models use two-leaves
(sunlit and shaded)

Flux towers & model validation

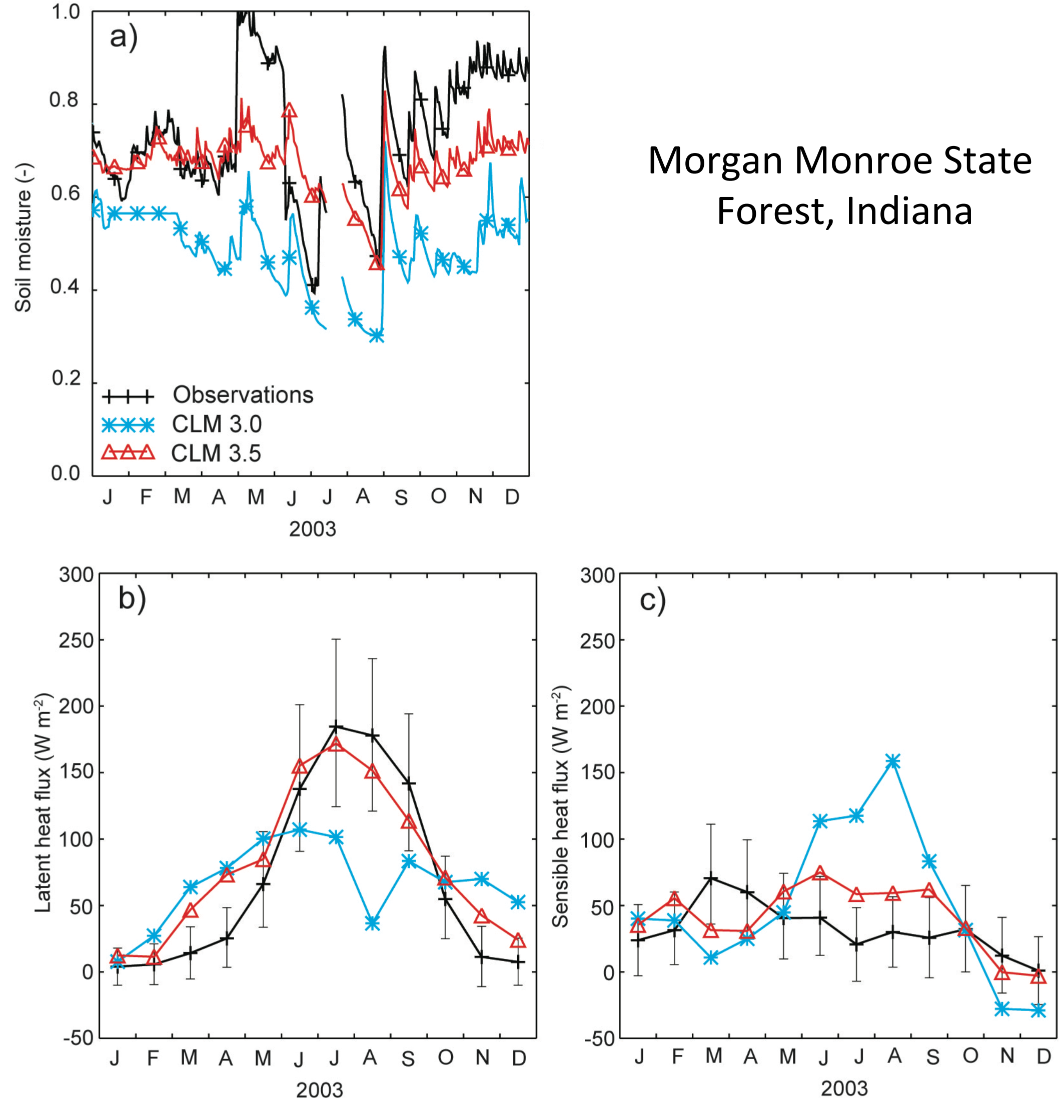
1990s: single site comparison, short intensive observing period



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

Flux towers & model validation

2000s: annual cycle, multi-site comparison (boreal to tropical)

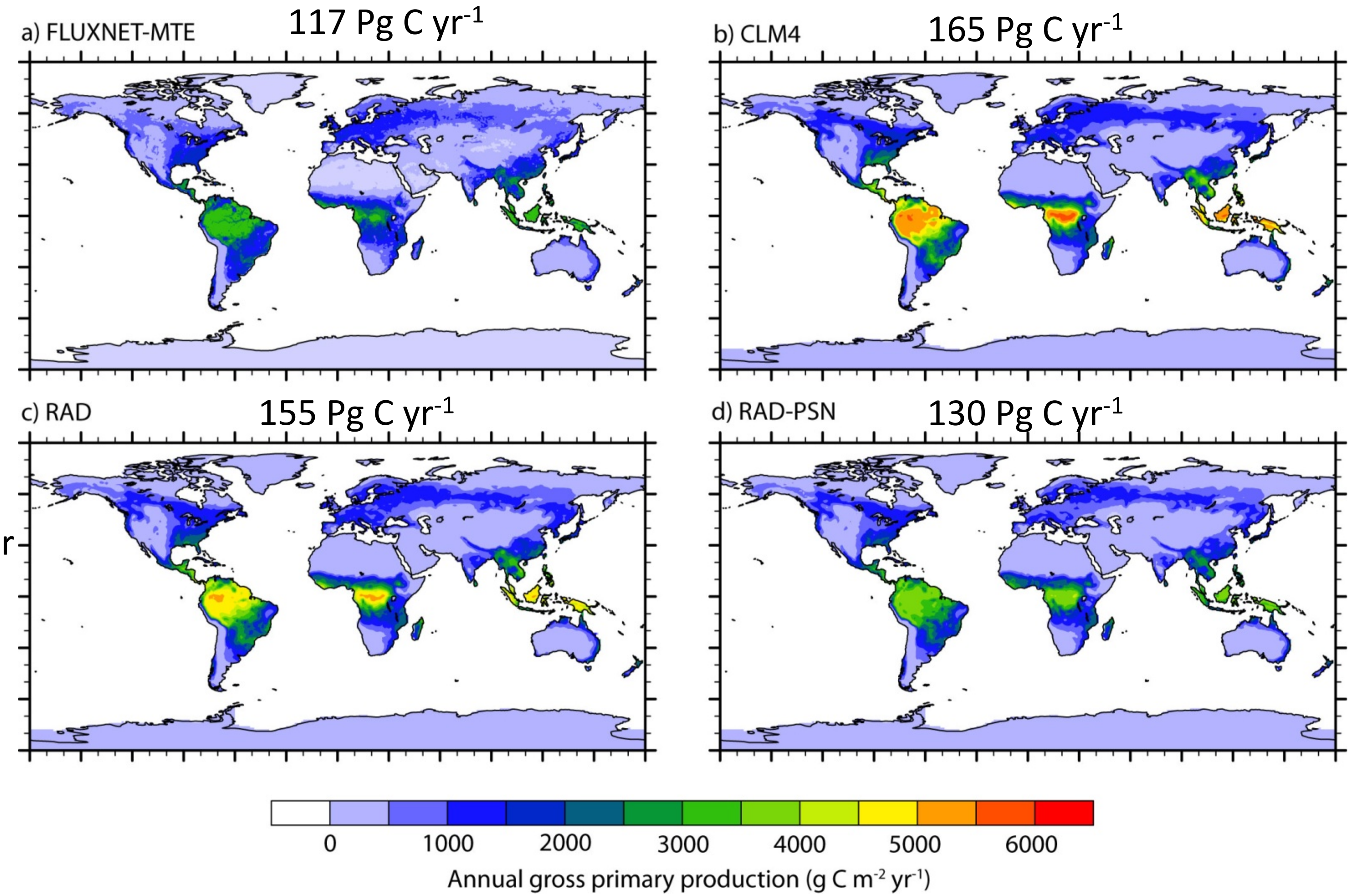


Morgan Monroe State Forest, Indiana

CLM3.0 – dry soil, low latent heat flux, high sensible heat flux
CLM3.5 – wetter soil and higher latent heat flux

Stöckli et al. (2008) JGR, 113, doi: 10.1029/2007JG000562

Flux towers & model validation



Control

Radiative transfer for sunlit and shaded canopy

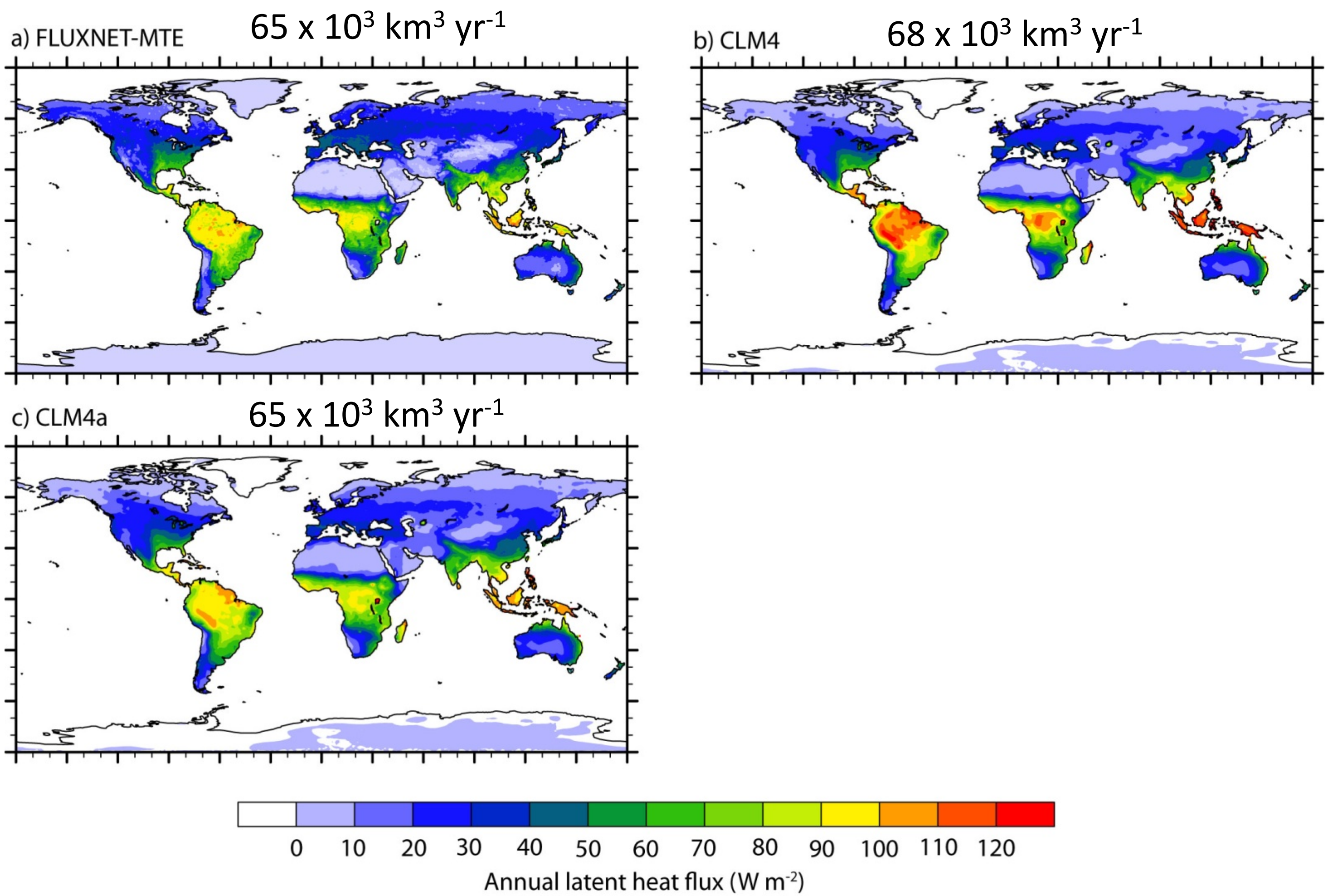
Radiative transfer and photo-synthesis

CLM4 overestimates GPP. Model revisions improve GPP. Similar improvements are seen in evapotranspiration

FLUXNET-MTE data from Martin Jung and Markus Reichstein (MPI-BGC, Jena)

Bonan et al. (2011) JGR, doi:10.1029/2010JG001593

Improved annual latent heat flux



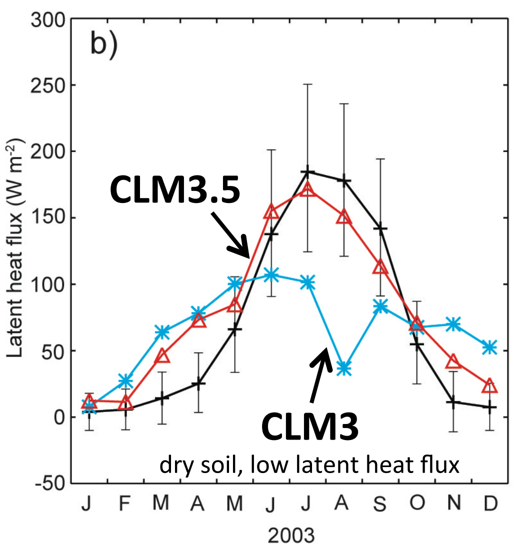
Model improvements reduce ET biases, especially in tropics, and improve monthly fluxes

Bonan et al. (2011) JGR, doi:10.1029/2010JG001593

Modeling across scales

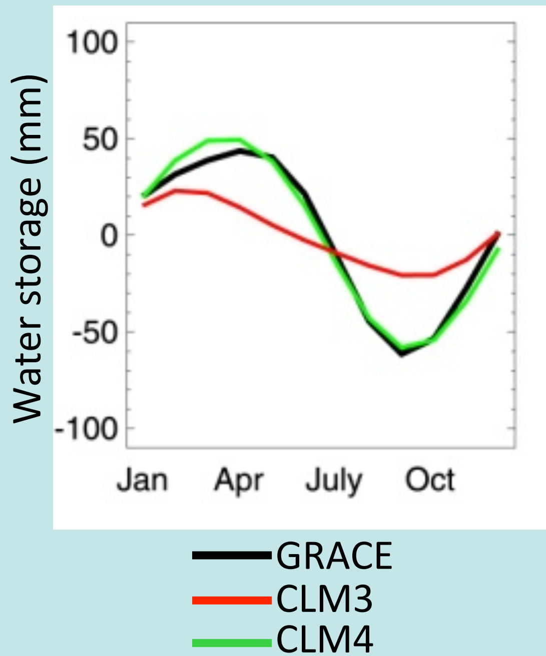
Tower → Large basin → Global

Morgan Monroe State Forest



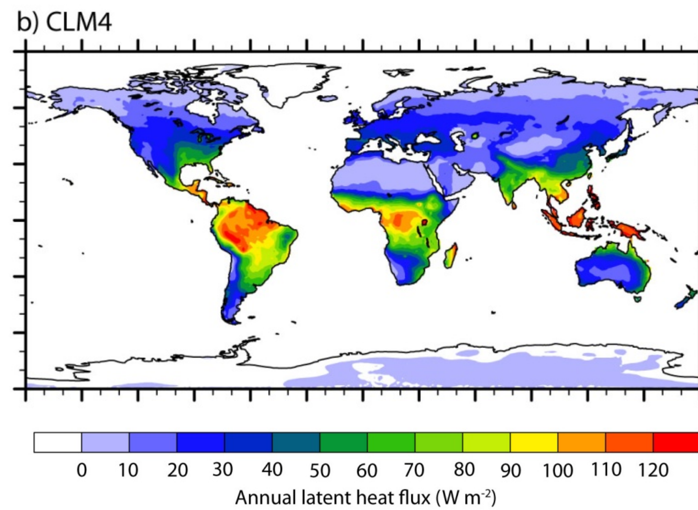
Stöckli et al. (2008) JGR, 113, doi: 10.1029/2007JG000562

Mississippi basin



D. Lawrence et al. (2012) J Climate 25:2240-2260

Annual latent heat flux



Bonan et al. (2011) JGR, doi:10.1029/2010JG001593

Research areas

Surface fluxes
Roughness sublayer, multilayer canopies

Radiative transfer
3D structure, canopy gaps

Photosynthesis
Temperature acclimation, CO_2 response, product-limited rate, C4 plants

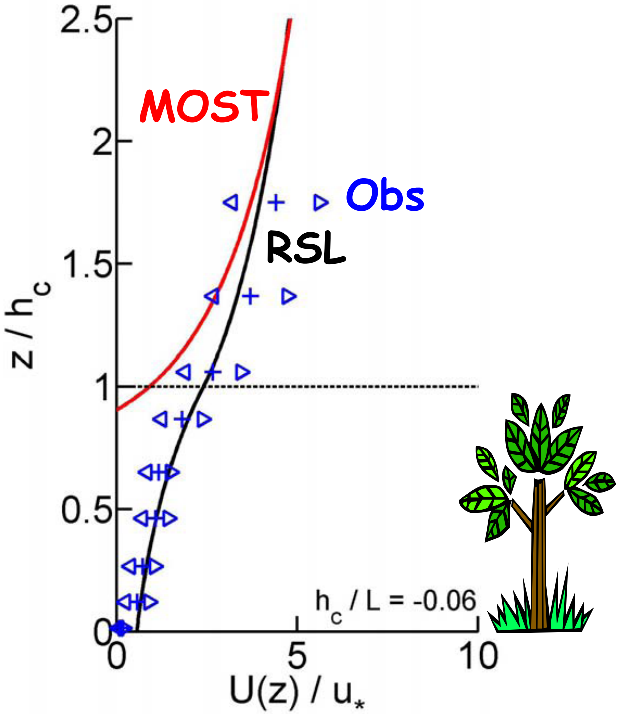
Stomatal conductance
Soil moisture stress, WUE optimization, CO_2 response

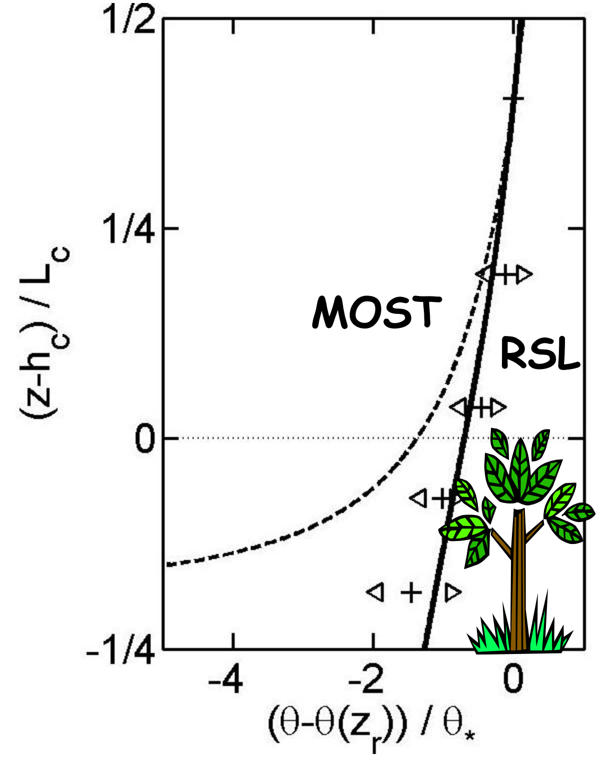
Canopy scaling
Optimal distribution of nitrogen

Canopy turbulence and the roughness sublayer

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

Profiles from the CSIRO flux station near Tumbarumba

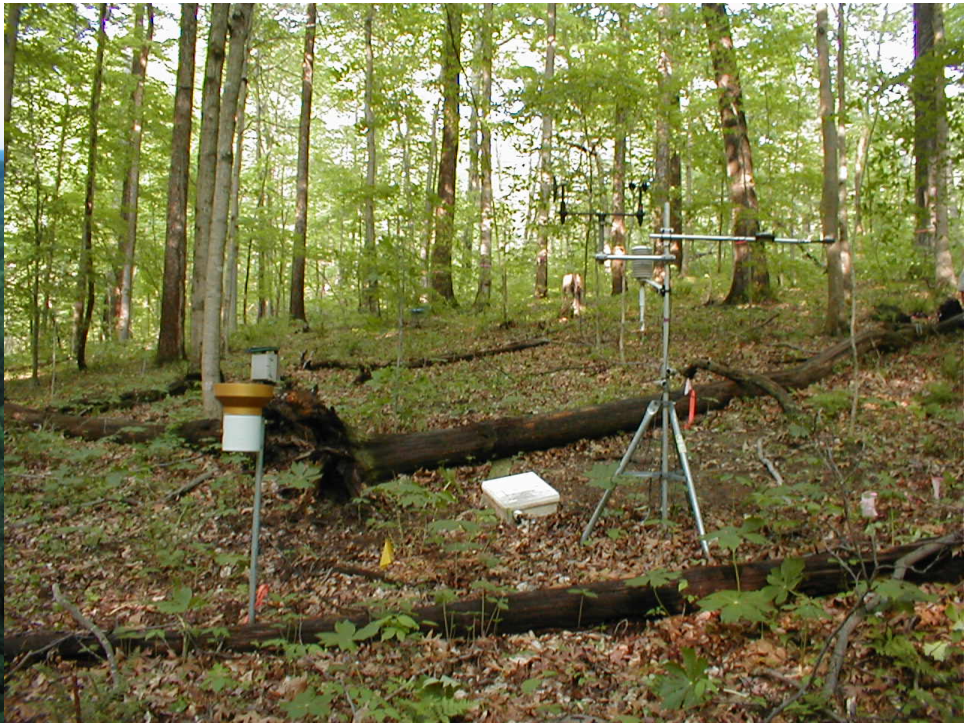


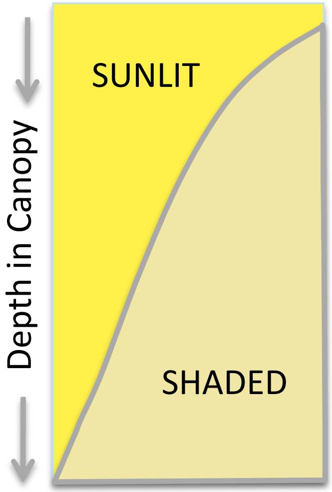


Harman & Finnigan (2007) Boundary-Layer Meteorol. 123:339-363
Harman & Finnigan (2008) Boundary-Layer Meteorol. 129:323-351

Two ways to model plant canopies

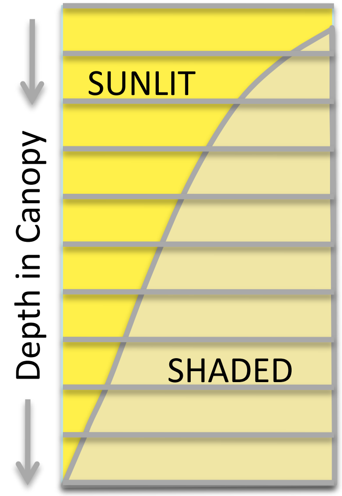
Photographs of Morgan Monroe State Forest tower site illustrate two different representations of a plant canopy: as a "big leaf" (below) or with vertical structure (right)





Big-leaf canopy

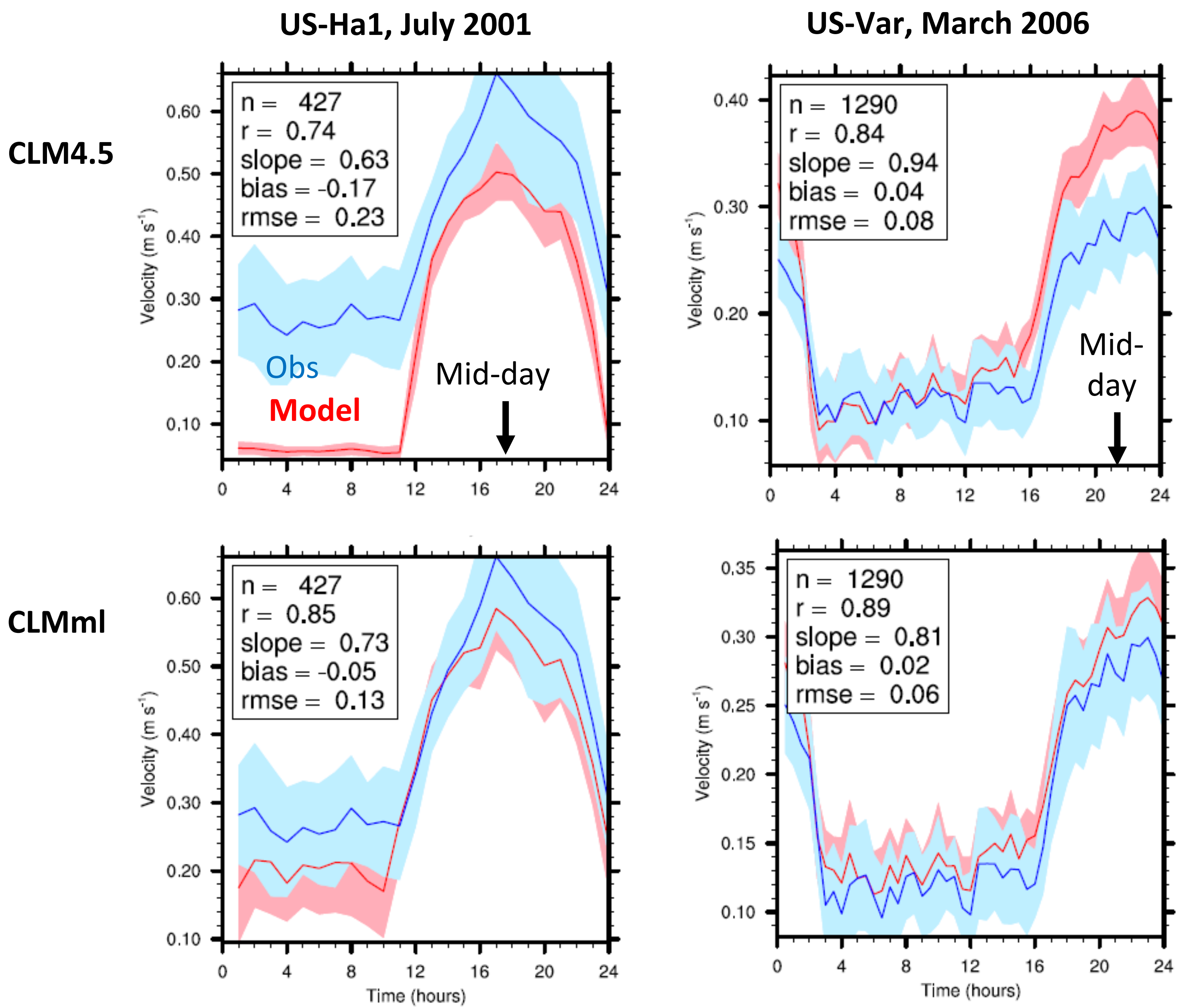
- Two "big-leaves" (sunlit, shaded)
- Radiative transfer integrated over LAI (two-stream approximation)
- Photosynthesis calculated for sunlit and shaded big-leaves



Multilayer canopy

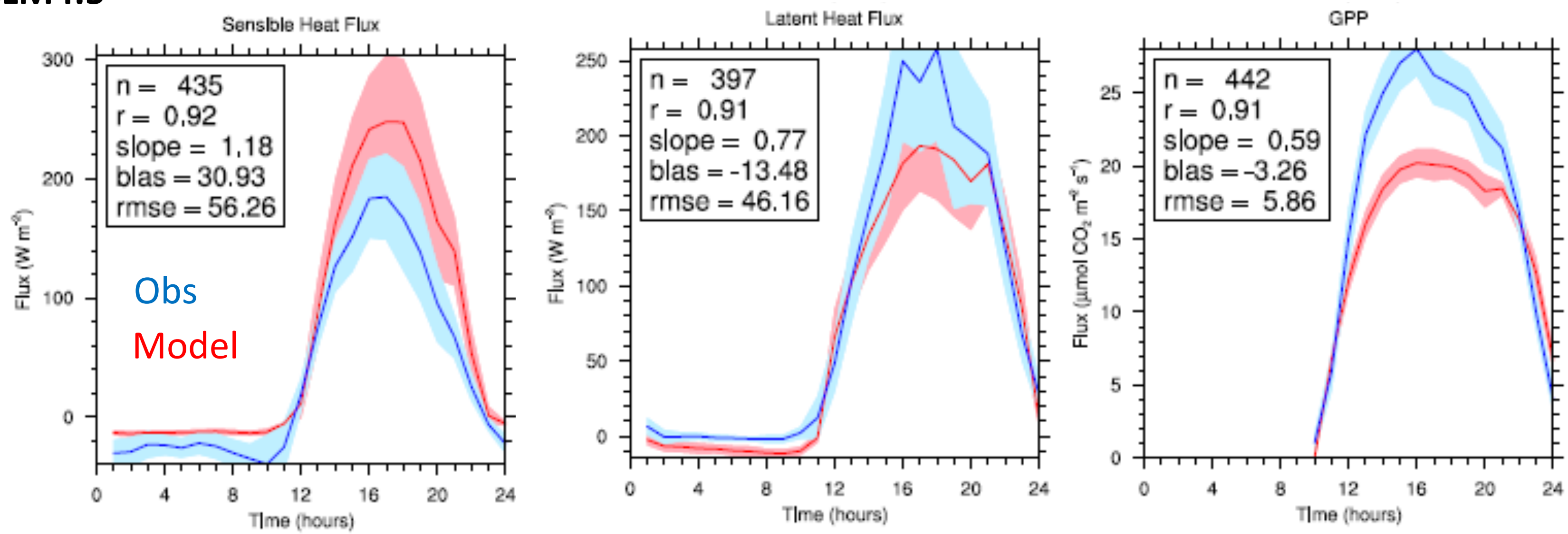
- Explicitly resolves sunlit and shaded leaves at each layer in the canopy
- Light, temperature, humidity, wind speed, H, E, A_n, g_s, ψ_L
- New opportunities to model stomatal conductance from plant hydraulics (g_s, ψ_L)

Friction velocity (momentum flux)



US-Ha1, July 2001 (DBF)

CLM4.5



CLMml