Modeling terrestrial ecosystems: Biogeophysics & canopy processes

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CLM Tutorial 2014

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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, surface temperature, turbulent fluxes (momentum, sensible heat, latent heat, water vapor)
- Partitions available energy at the surface into sensible and latent heat flux, soil heat storage, and snow melt
- Partitions rainfall into runoff and evaporation
  - Evaporation 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, carbon pools

- 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)

$$S^{\downarrow} + L^{\downarrow} = S^{\uparrow} + L^{\uparrow} + \lambda E + H + G$$

- $S^{\downarrow}$, $S^{\uparrow}$ are down(up)welling solar radiation
- $L^{\downarrow}$, $L^{\uparrow}$ are down(up)welling longwave radiation
- λ is latent heat of vaporization, E is evaporation
- 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
Farquhar 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)

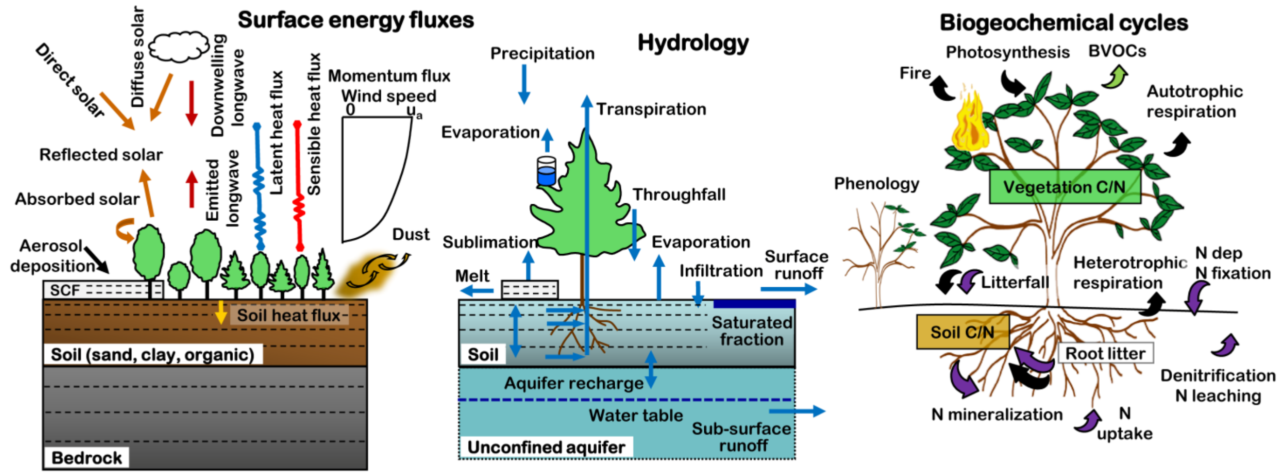
The Community Land Model (CLM4.5)

Fluxes of energy, water, carbon, and nitrogen and the dynamical processes that control these fluxes in a changing environment

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

D. Lawrence et al. (2011) JAMES, 3, doi: 10.1029/2011MS000045

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

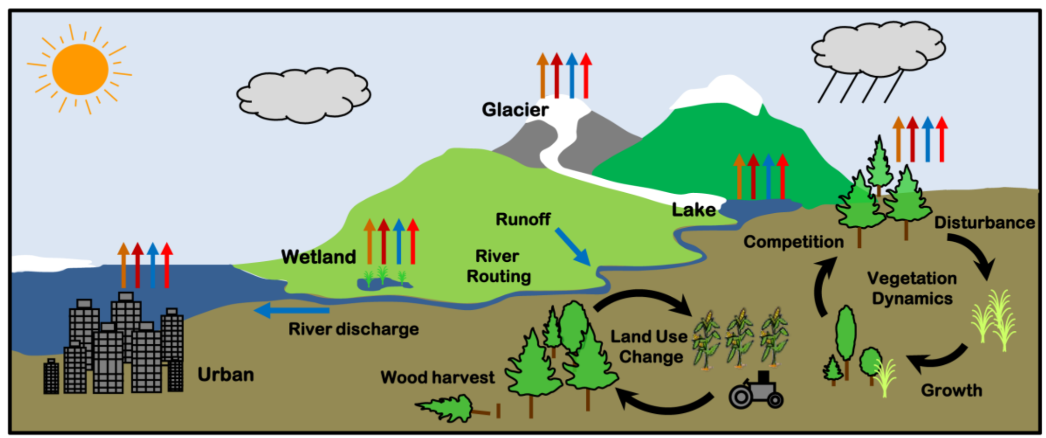


Spatial scale

- 1.25° longitude × 0.9375° latitude (288 × 192 grid)

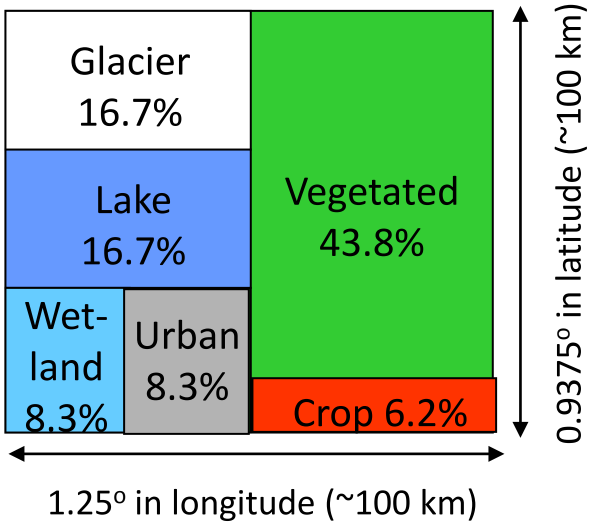
Temporal scale

- 30-minute coupling with atmosphere
- Seasonal-to-interannual (phenology)
- Decadal-to-century climate (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 up to 6 primary land cover tiles. Vegetated land is further represented as tiles of individual plant functional types





Bonan et al. (2002) GBC, 16, doi:10.1029/2000GB001360

Surface energy balance and surface temperature

Surface energy balance

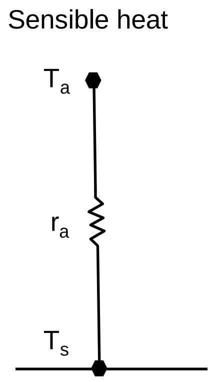
$(S\downarrow - S\uparrow) + \varepsilon L\downarrow = \varepsilon\, \sigma T_s^4 + H[T_s] + \lambda E[T_s] + G[T_s]$

Flux = Δ concentration * conductance

$$H = -\rho c_p \frac{(T_a - T_s)}{r_a}$$

$$\lambda E = -\frac{\rho c_p}{\gamma} \frac{\left(e_a - e_*[T_s]\right)}{r_a + r_c}$$

$$G = k \frac{\left(T_s - T_{soil}\right)}{\Delta z}$$



Atmospheric forcing

$S\downarrow$ - incoming solar radiation (vis, nir; diffuse fraction)
$L\downarrow$ - incoming longwave radiation
T_a - air temperature
e_a - vapor pressure
u - wind speed
P - surface pressure

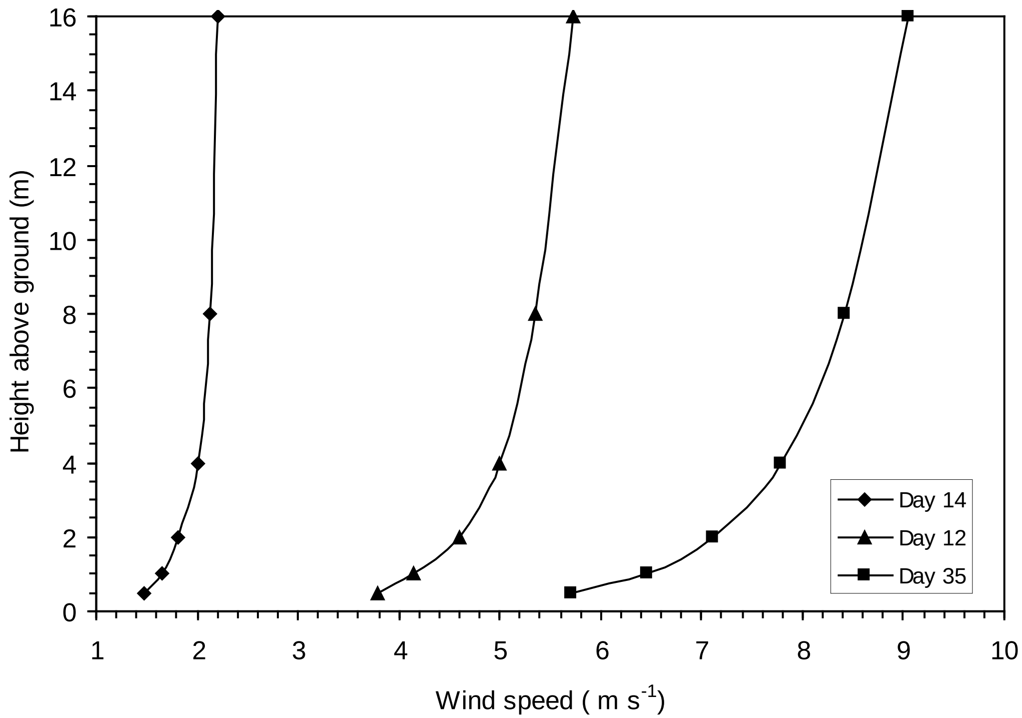
Surface properties

$S\uparrow$ - reflected solar radiation (albedo)
ε - emissivity
r_a - aerodynamic resistance (roughness length)
r_c - canopy resistance
T_{soil} - soil temperature
k - thermal conductivity
Δz - soil depth

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



$$\left(z/u_*\right)\partial\overline{u}/\partial z = 1/k \quad \Rightarrow \quad \overline{u}_2 - \overline{u}_1 = \left(u_*/k\right)\ln\left(z_2/z_1\right) \quad \Rightarrow \quad \overline{u}(z) = \left(u_*/k\right)\ln\left(z/z_0\right) \quad \Rightarrow \quad \overline{u}(z) = \frac{u_*}{k}\left[\ln\left(\frac{z-d}{z_0}\right) - \psi_m(\zeta)\right]$$

Because u_1=0 at z_1=z_0

$$\overline{\theta}(z) - \overline{\theta}_s = \frac{\theta_*}{k}\left[\ln\left(\frac{z-d}{z_0}\right) - \psi_h(\zeta)\right]$$

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

$$\overline{q}(z) - \overline{q}_s = \frac{q_*}{k}\left[\ln\left(\frac{z-d}{z_0}\right) - \psi_w(\zeta)\right]$$

Turbulent fluxes – bulk transfer equations

Momentum flux

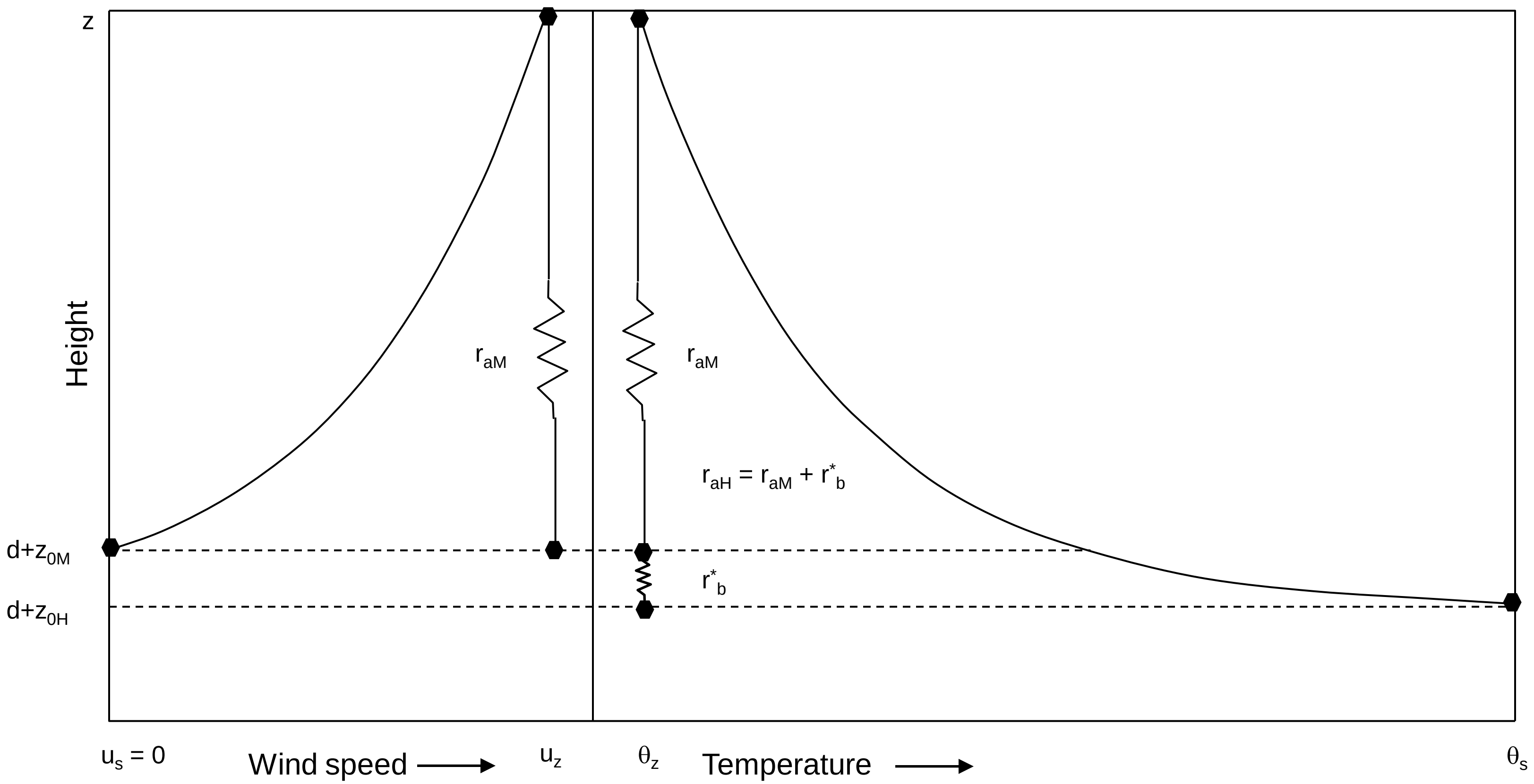
$u_* u_* = \tau / \rho$ and $\tau = \rho(u_a - u_s)/r_{aM} = \rho u / r_{aM}$ ➡ $r_{aM} = \frac{1}{k^2 u}\left[\ln\left(\frac{z-d}{z_{0M}}\right) - \psi_m(\zeta)\right]^2$

Sensible heat flux

$\theta_* u_* = -H/(\rho c_p)$ and $H = -\rho c_p(\theta_a - T_s)/r_{aH}$ ➡ $r_{aH} = \frac{1}{k^2 u}\left[\ln\left(\frac{z-d}{z_{0M}}\right) - \psi_m(\zeta)\right]\left[\ln\left(\frac{z-d}{z_{0H}}\right) - \psi_h(\zeta)\right]$

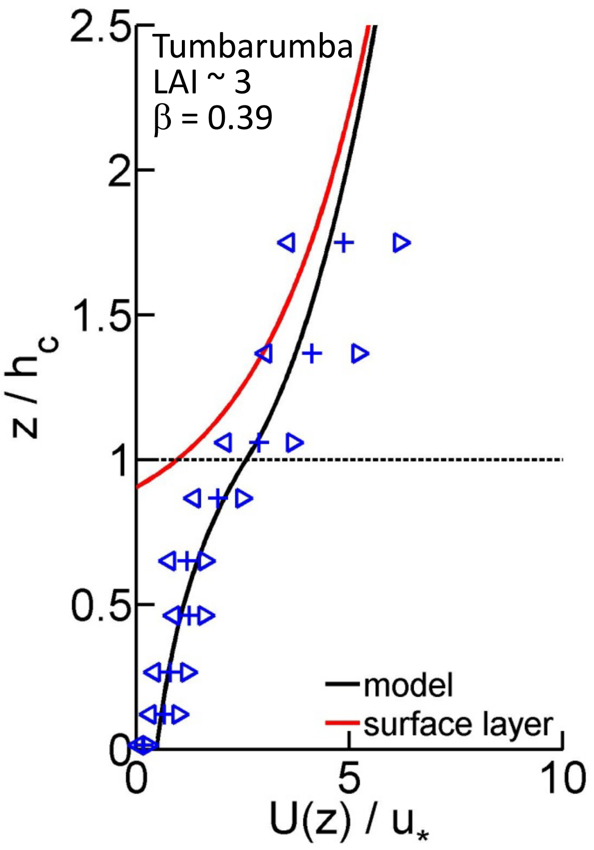
Evaporation

$q_* u_* = -E/\rho$ and $E = -\rho(q_a - q_s)/r_{aW}$ ➡ $r_{aW} = \frac{1}{k^2 u}\left[\ln\left(\frac{z-d}{z_{0M}}\right) - \psi_m(\zeta)\right]\left[\ln\left(\frac{z-d}{z_{0W}}\right) - \psi_w(\zeta)\right]$

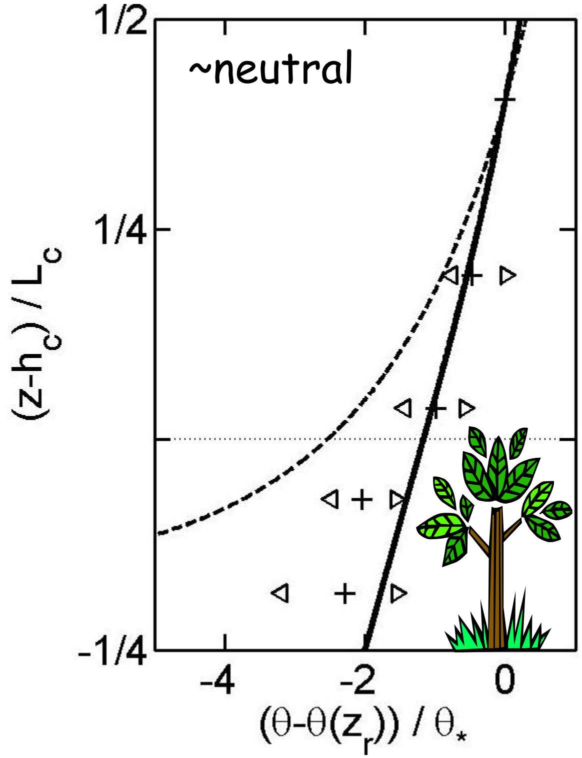


Canopy turbulence and the roughness sub-layer

Flow within 2-3 canopy heights above/within tall (plant) canopies does not conform to Monin-Obukhov Similarity Theory (MOST); this region is called the roughness sub-layer (RSL).



Harman and Finnigan (2007)

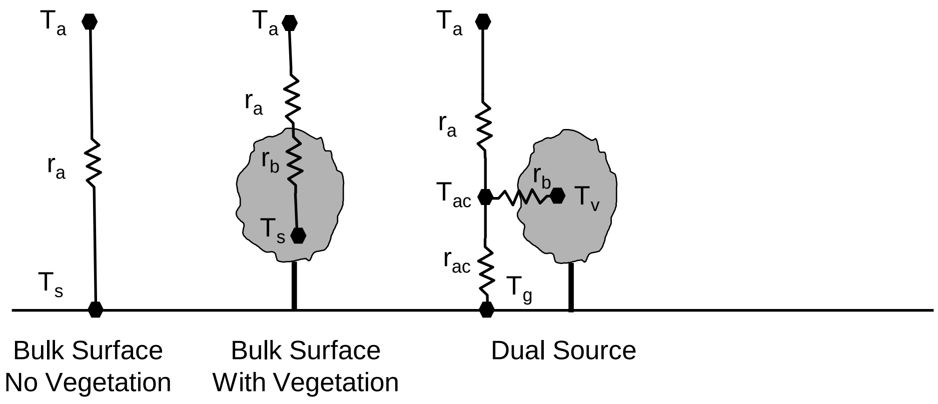


Harman and Finnigan (2008)

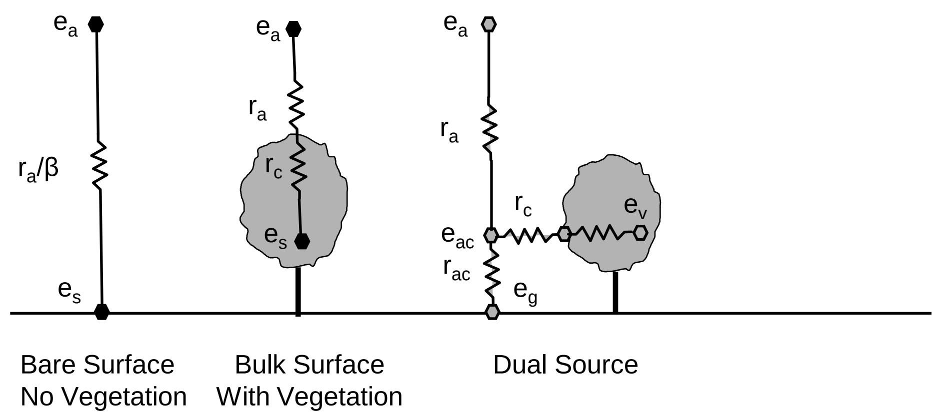
Courtesy Ned Patton (NCAR)

Plant canopies

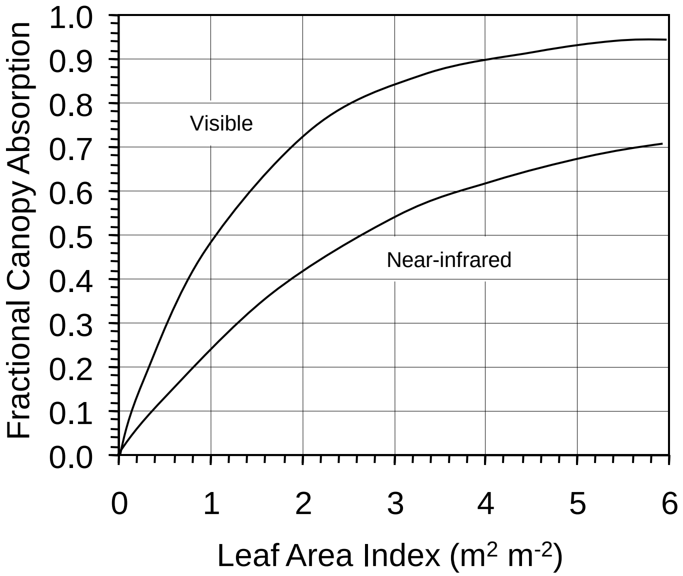
Sensible Heat

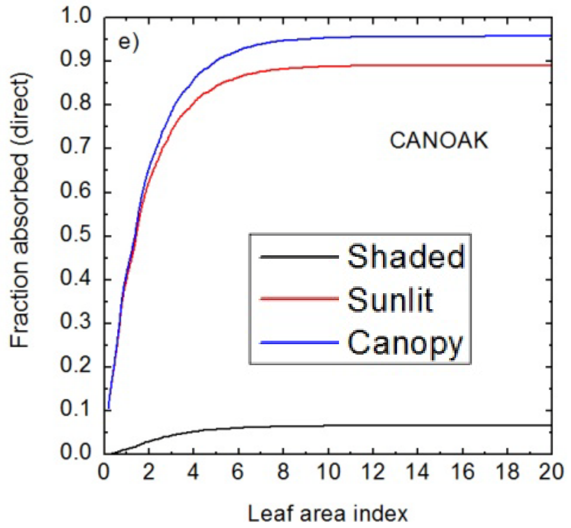


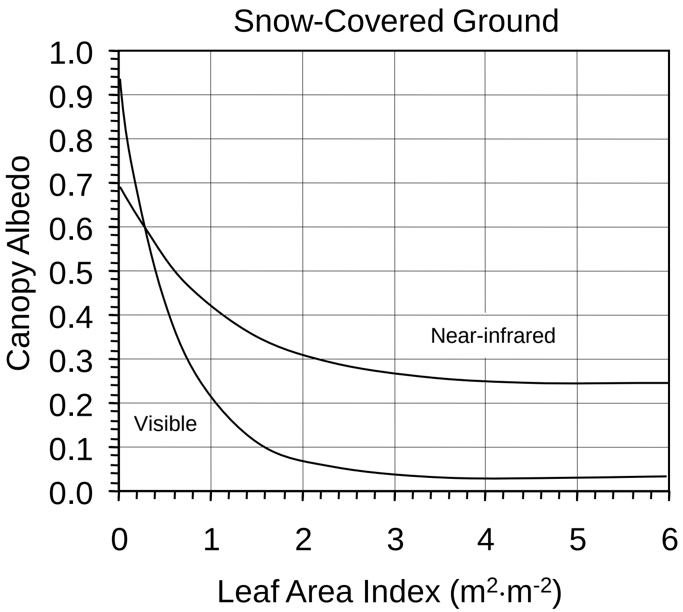
Latent Heat

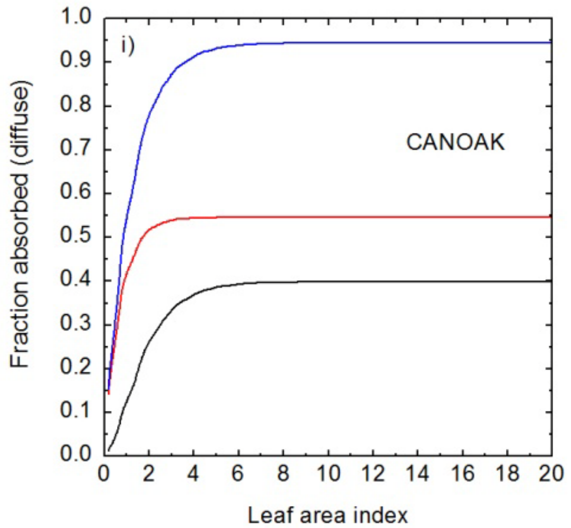


Radiative transfer



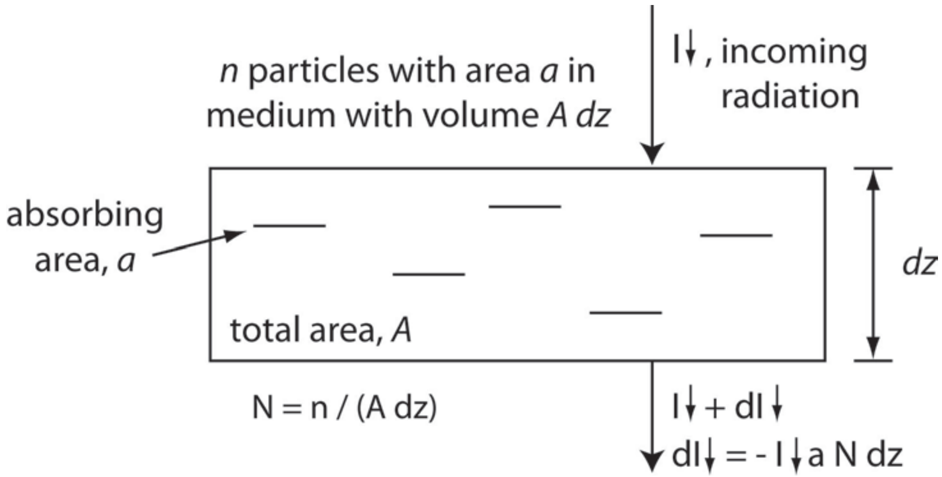




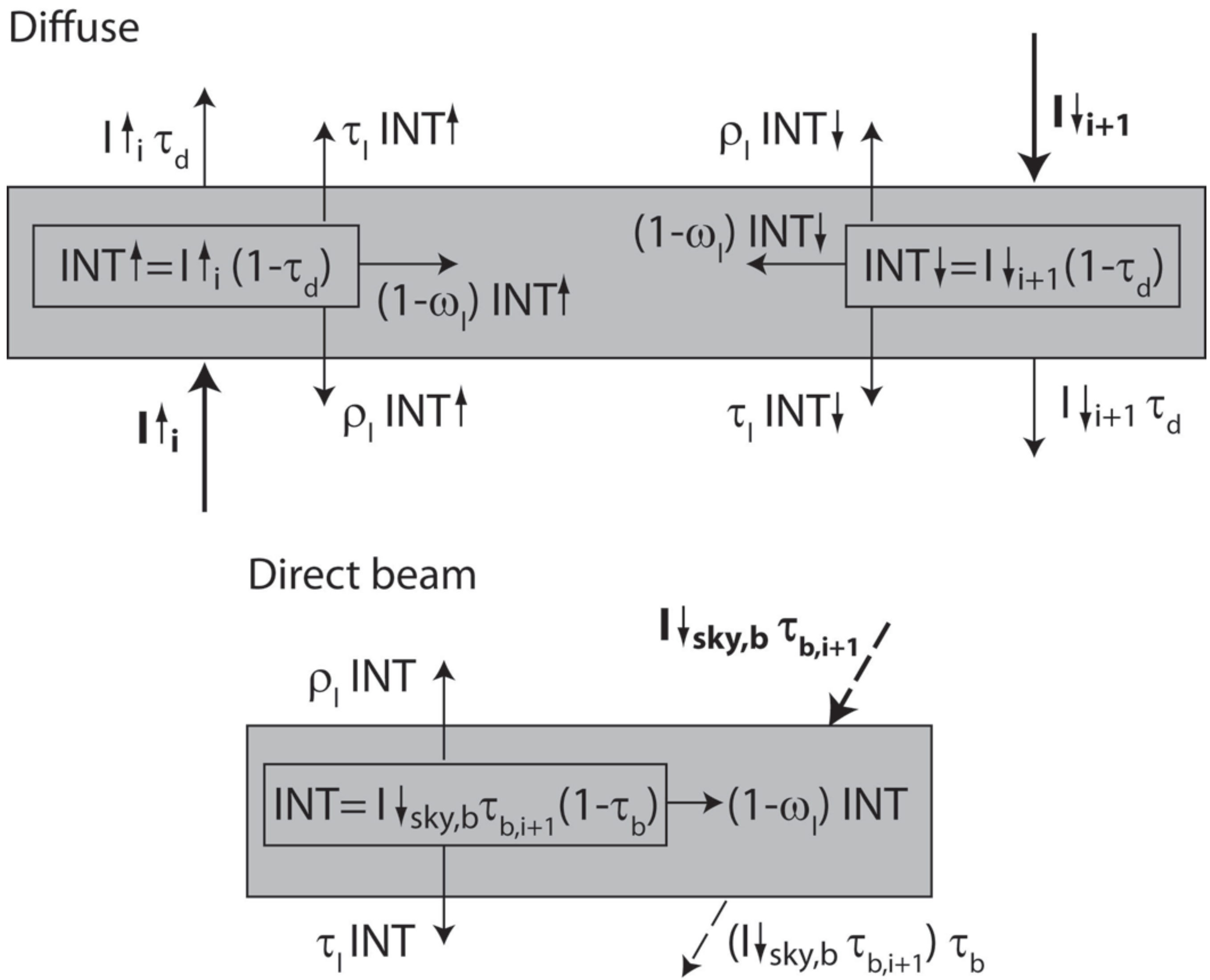


Fundamentals of radiative transfer

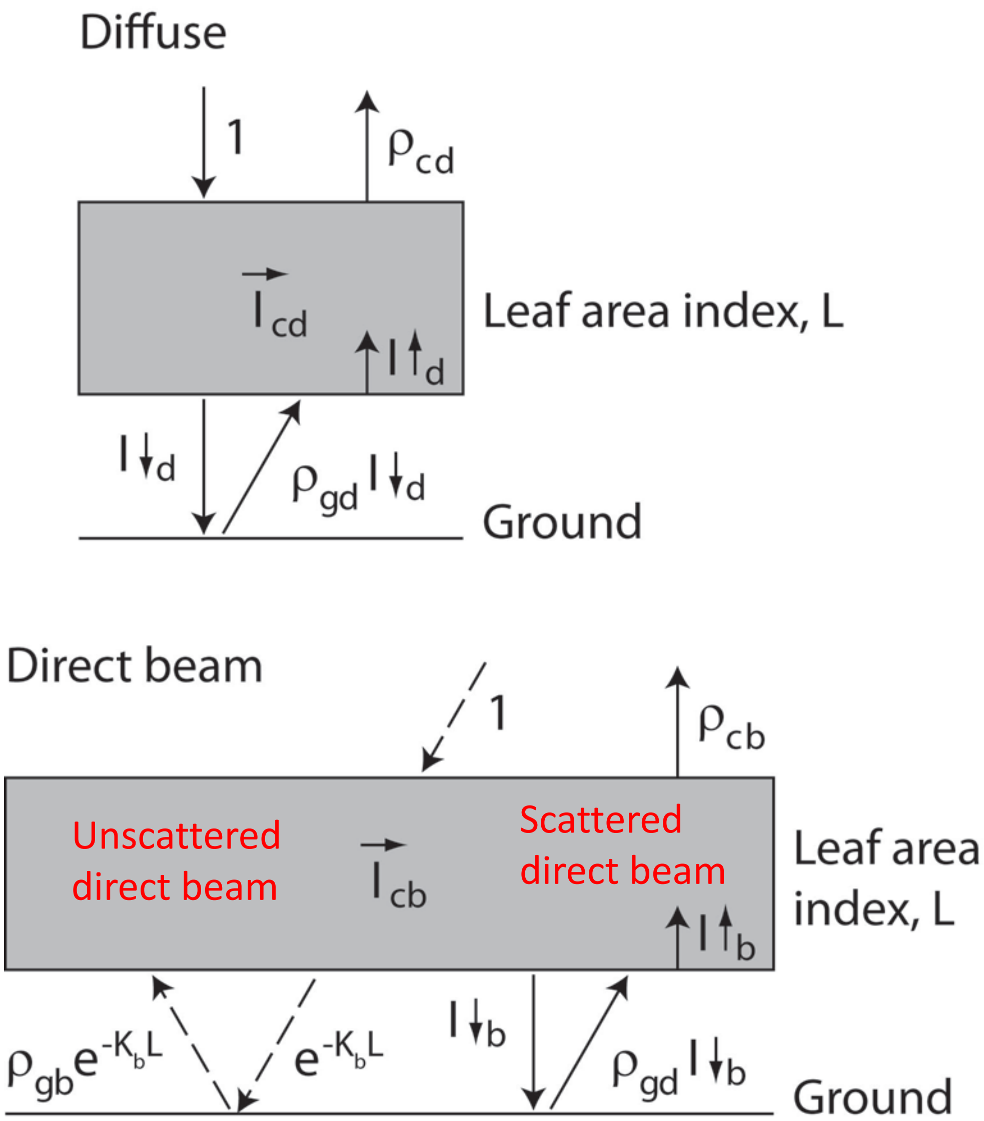
Light attenuation through the canopy (Beer's law)



Fundamentals of radiative transfer

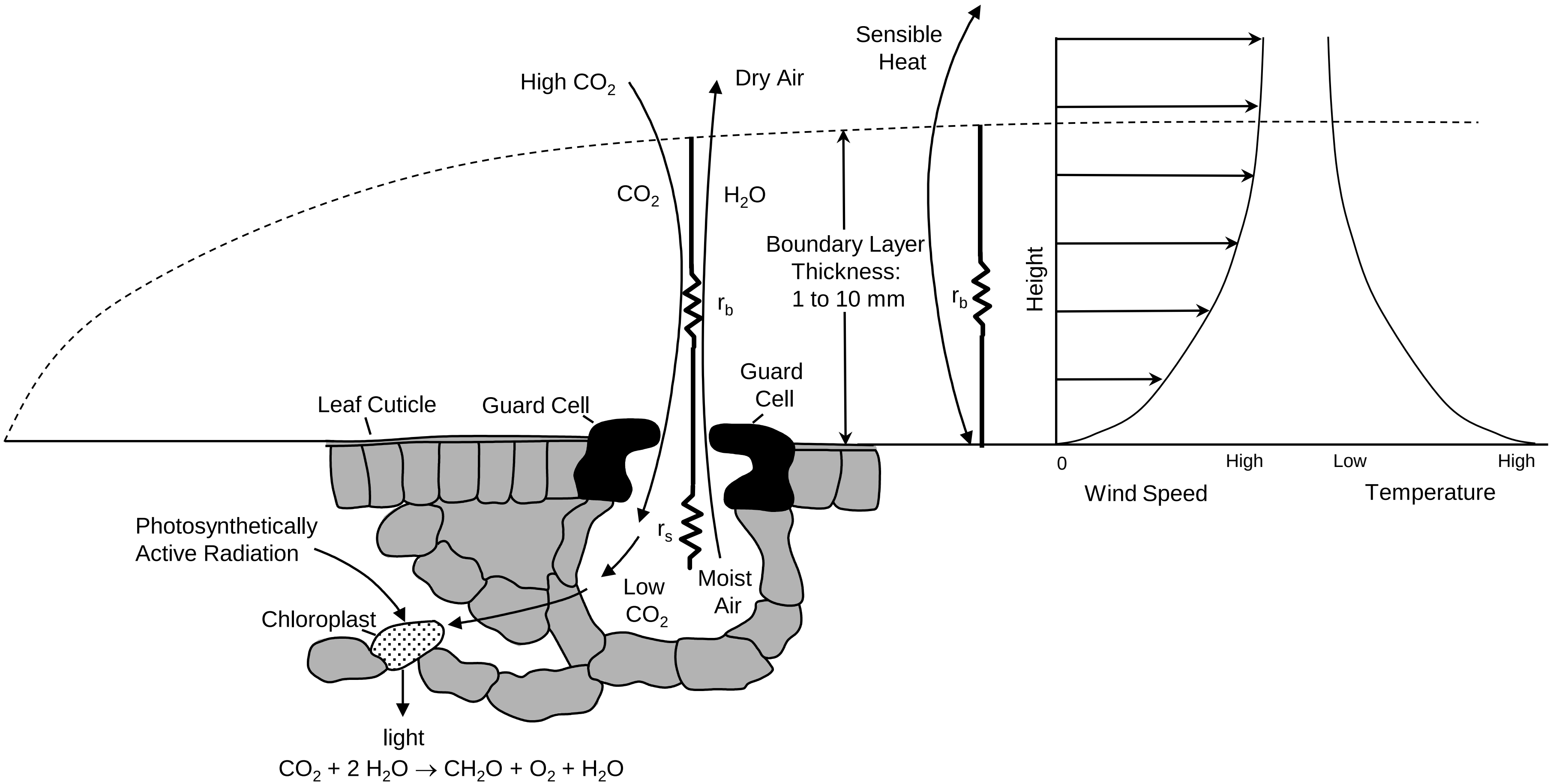


Two-stream radiative transfer

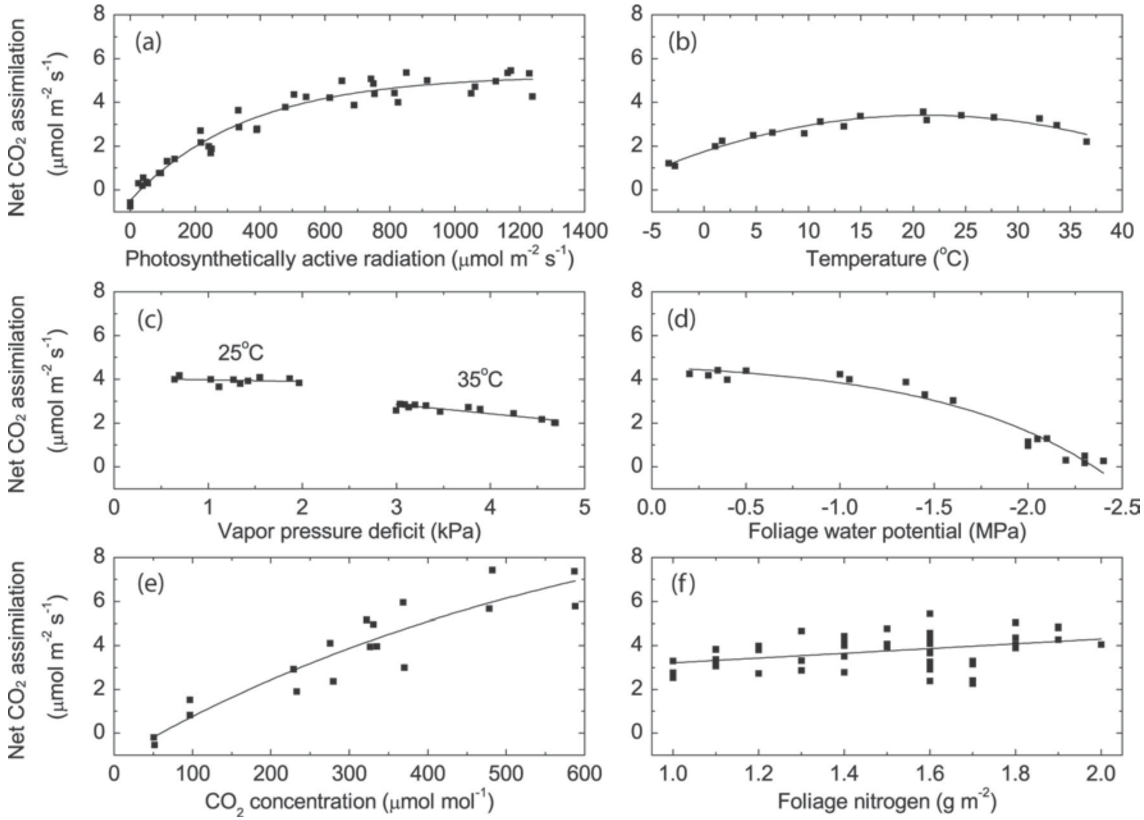


Radiative transfer uses the two-stream approximation (Dickinson, Sellers)

Leaf boundary layer



Leaf photosynthesis



Leaf temperature and fluxes

Leaf energy balance

$$Q_a = 2\varepsilon\sigma T_l^{\,4} + 2\rho c_p \frac{(T_l - T_a)}{r_b} + \frac{\rho c_p}{\gamma} \frac{\left(e_*[T_l] - e_a\right)}{r_s + r_b}$$

Atmospheric forcing

Q_a - radiative forcing (solar and longwave)

T_a - air temperature

e_a - vapor pressure

u - wind speed

P - surface pressure

Leaf properties

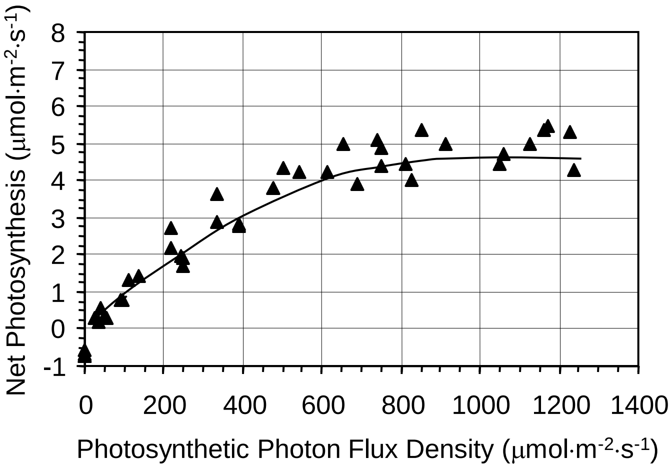
ε - emissivity

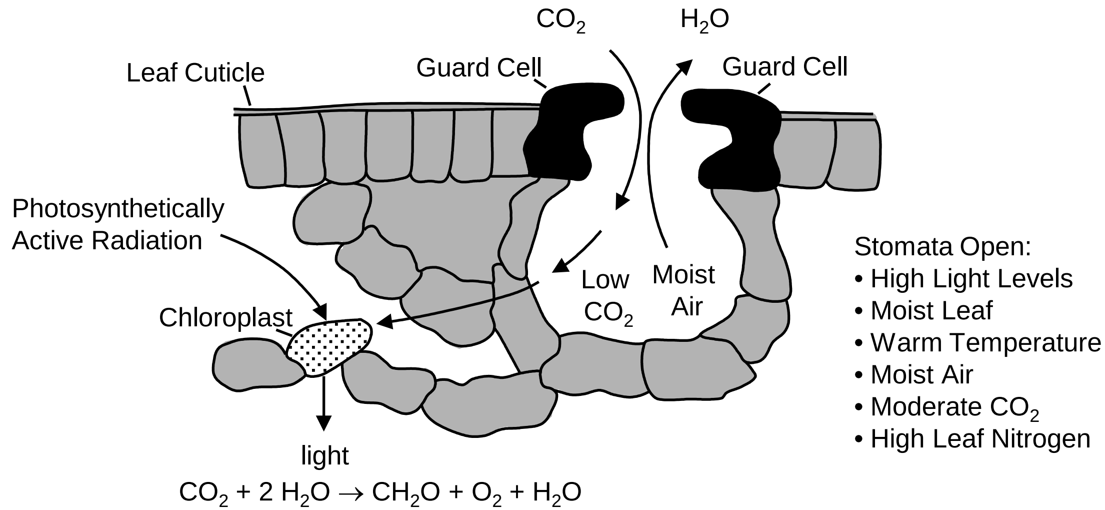
r_b - leaf boundary layer resistance

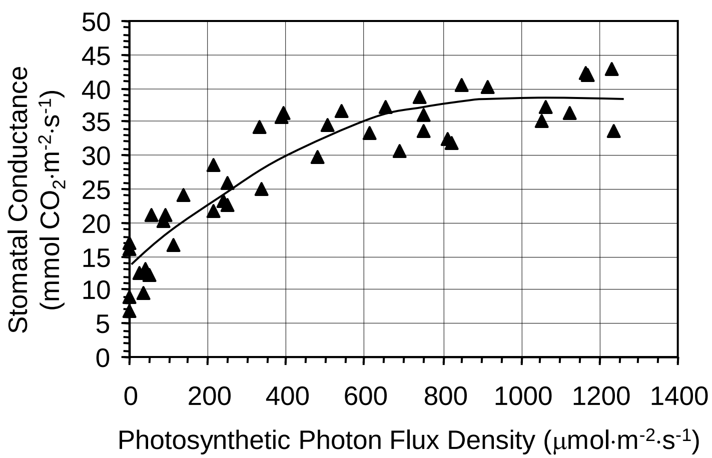
r_s - leaf stomatal resistance

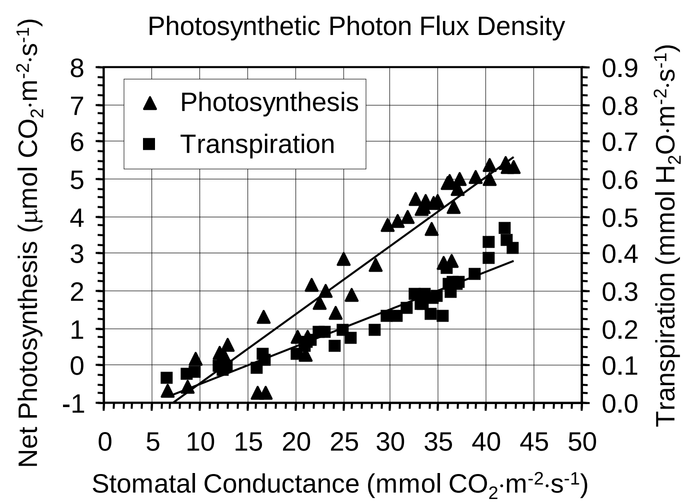
With atmospheric forcing and leaf properties specified, solve for temperature T_l that balances the energy budget

Stomatal gas exchange









Leaf stomatal conductance

Farquhar, von Caemmerer, Berry photosynthesis model

$$A_n = \min(w_c, w_j) - R_d$$

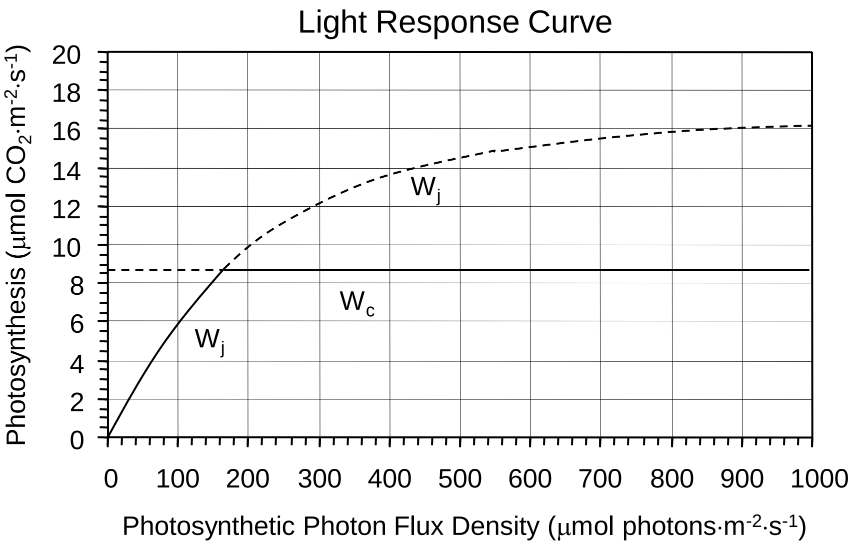
w_c is the rubisco-limited rate of photosynthesis, w_j is light-limited rate allowed by RuBP regeneration

rubisco-limited rate is

$$w_c = \frac{V_{c\max}(c_i - \Gamma *)}{c_i + K_c(1 + O_i/K_o)}$$

RuBP regeneration-limited rate is

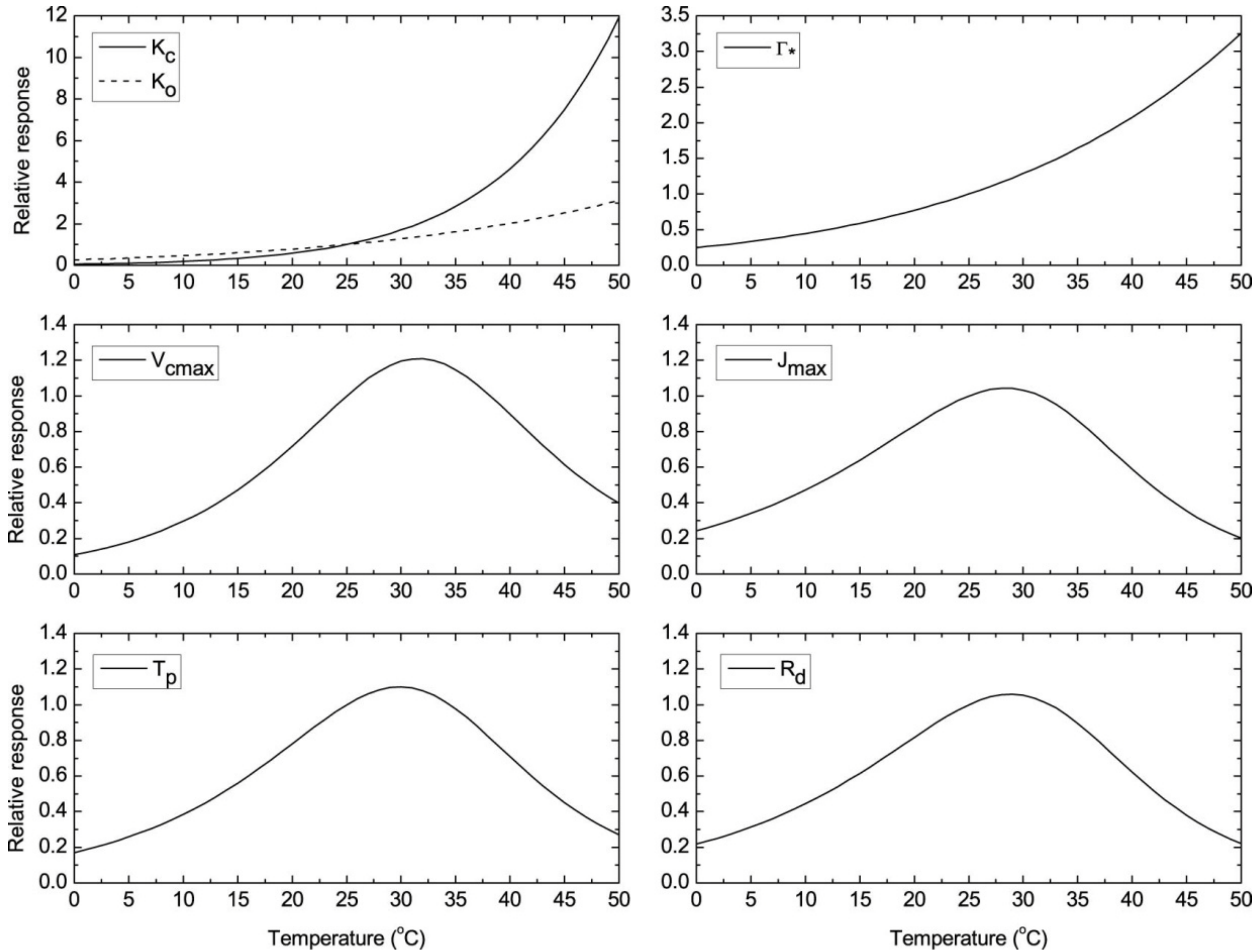
$$w_j = \frac{J(c_i - \Gamma *)}{4(c_i + 2\Gamma *)}$$



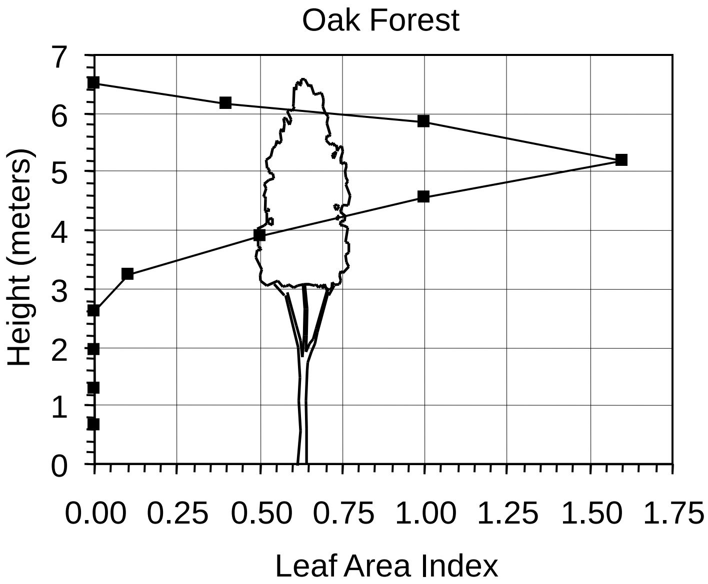
Ball-Berry stomatal conductance

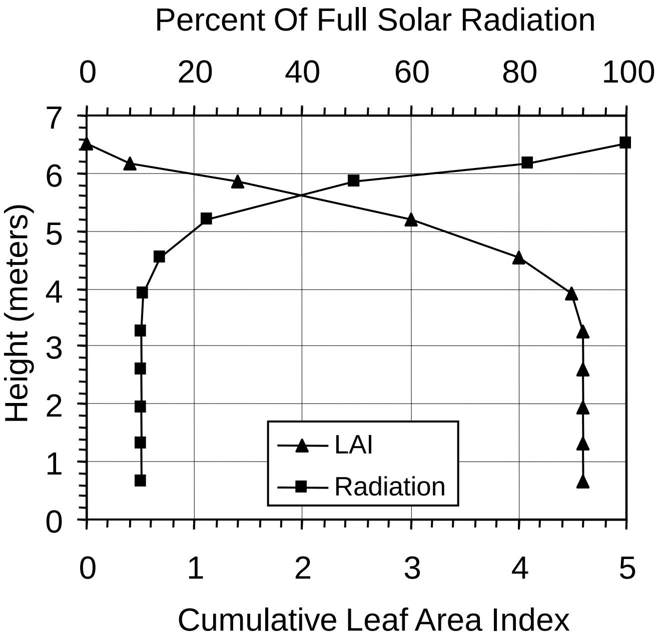
$$\frac{1}{r_s} = g_s = g_1 \frac{A_n h_s}{c_s} + g_0$$

Leaf physiological parameters



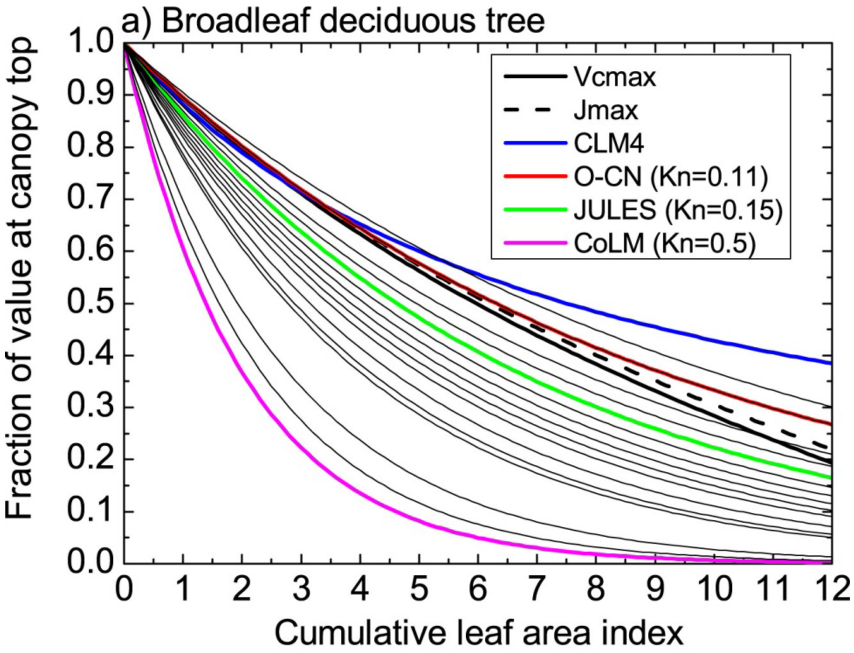
Canopy conductance – gradients of PAR





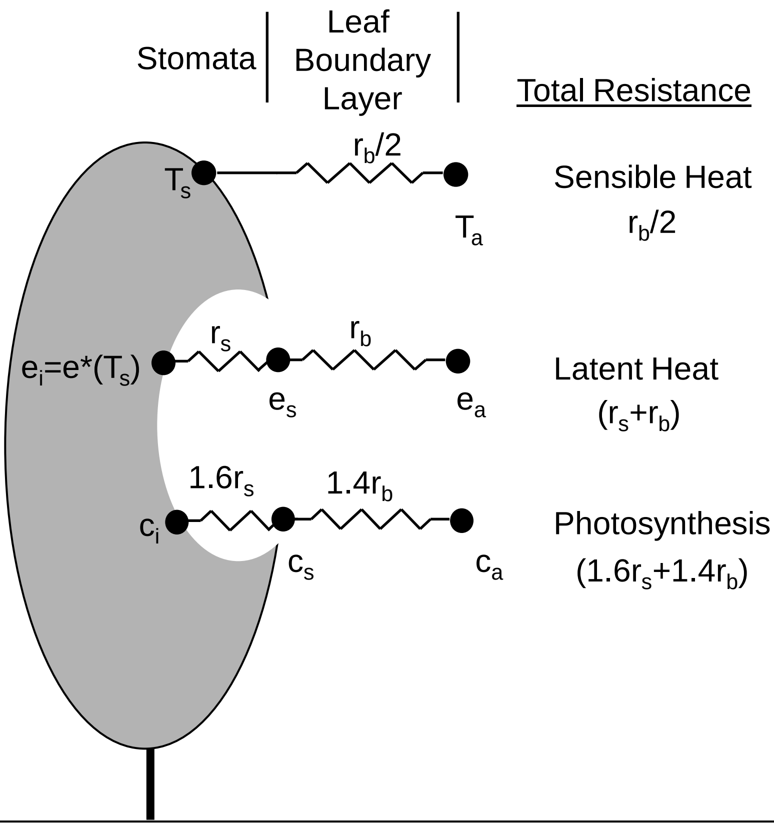
Canopy conductance – gradients of nitrogen

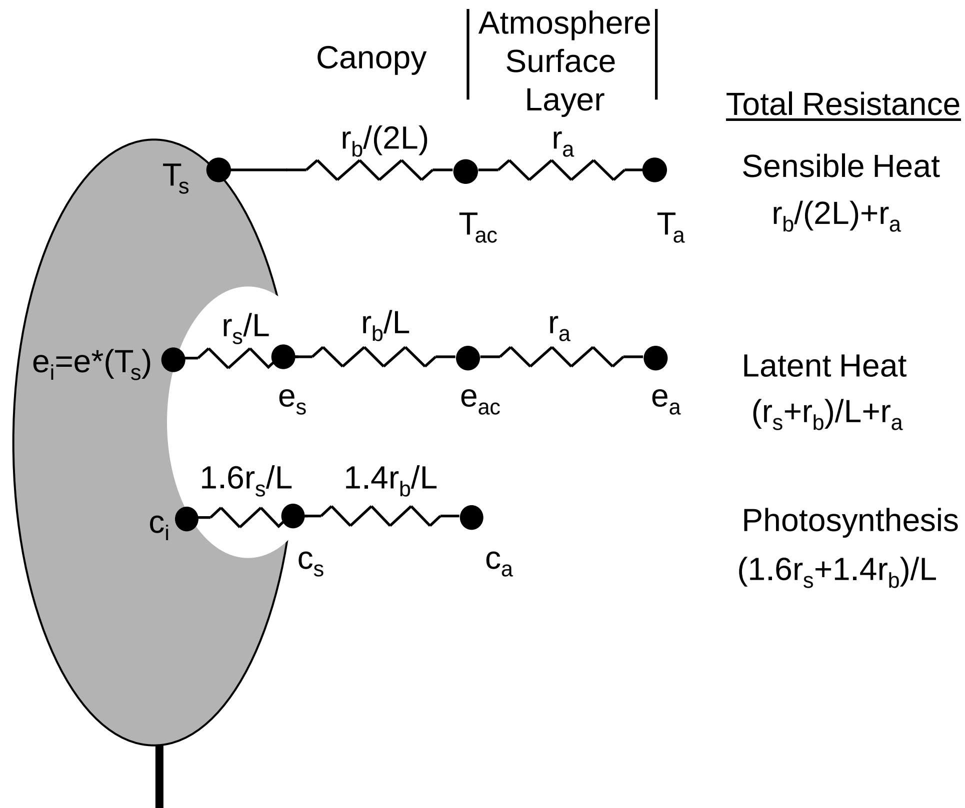
Decline in foliage N (per unit area) with depth in canopy yields decline in photosynthetic capacity (Vcmax, Jmax)



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

Plant canopy as a "big leaf"





A Two-Big-Leaf Model for Canopy Temperature, Photosynthesis, and Stomatal Conductance

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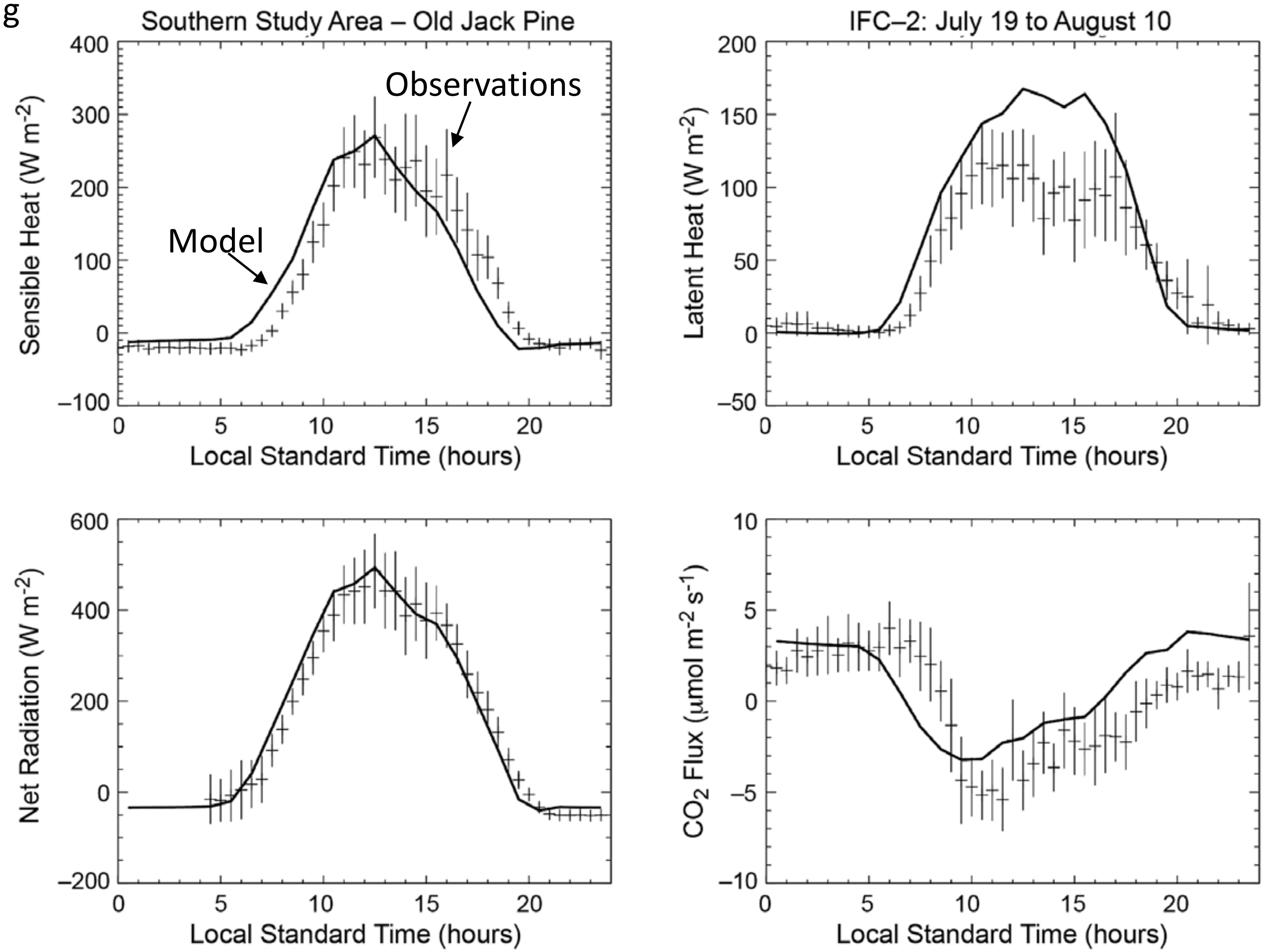
Dai et al. (2004) J Climate 17:2281-2299

Most models use two-leaves (sunlit and shaded)

Flux towers & model validation

1990s: single site comparison, short intensive observing period

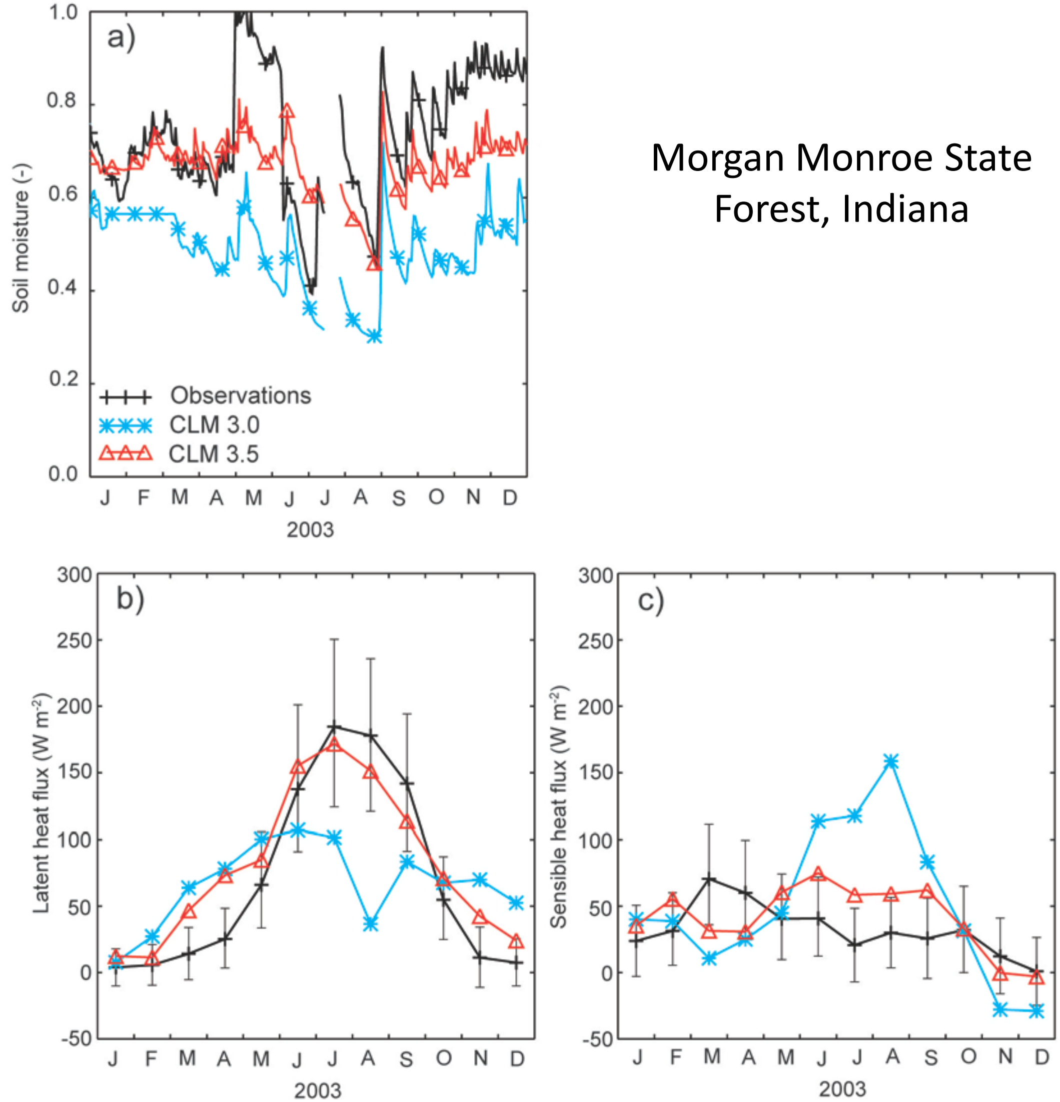
Boreal Ecosystem Atmosphere Study (BOREAS)



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

Flux towers & model validation

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

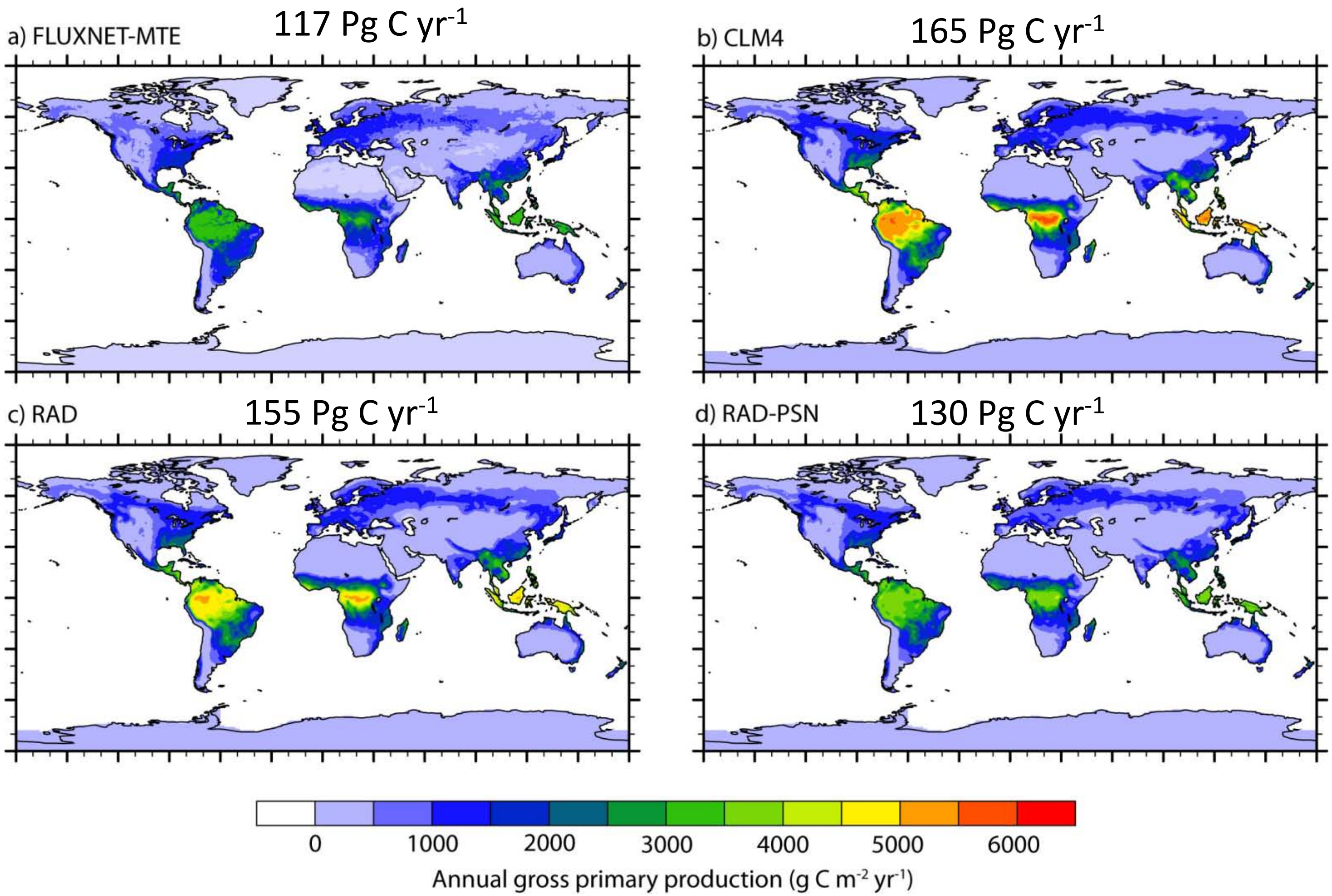


Morgan Monroe State Forest, Indiana

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

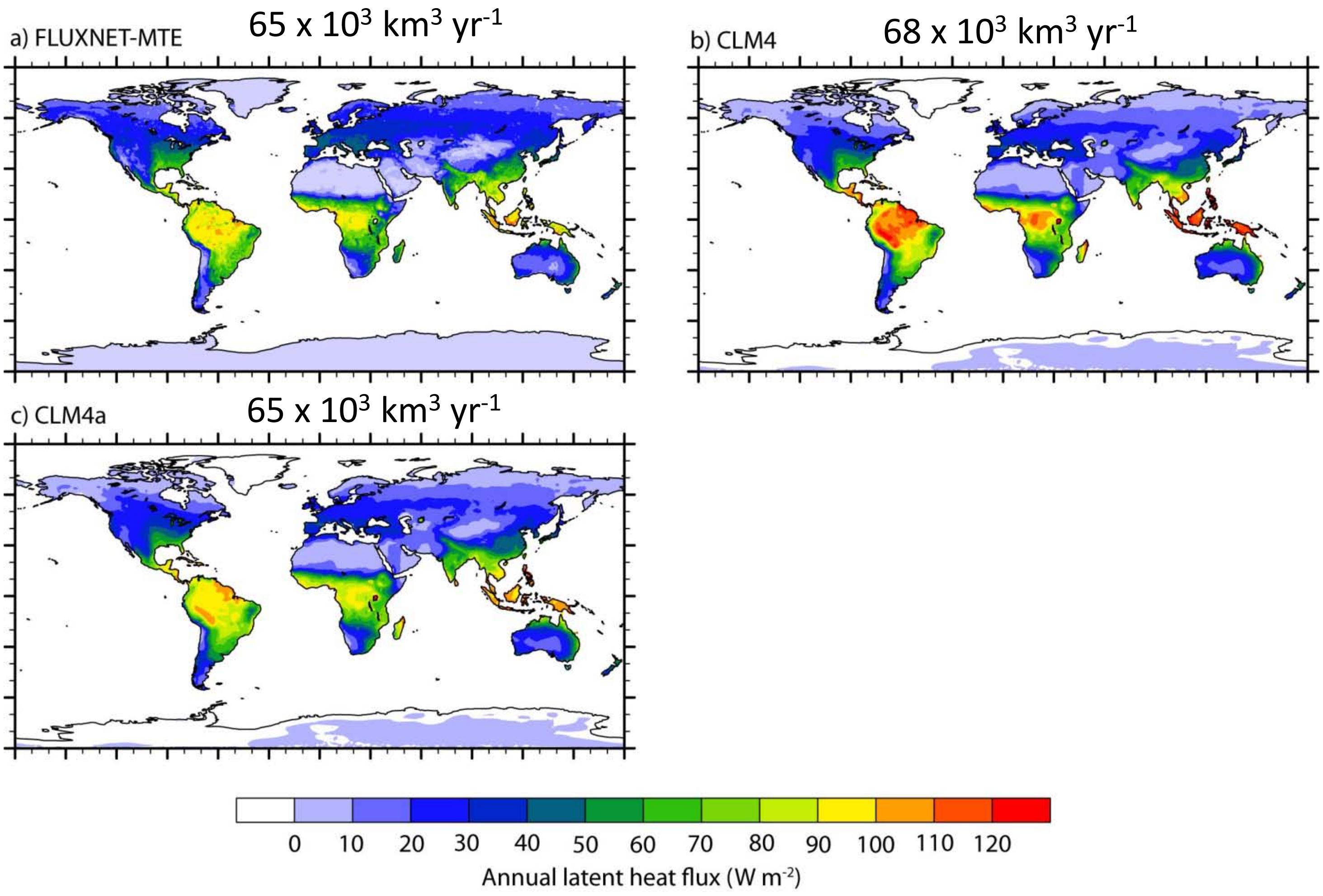
Radiative transfer and photo-synthesis

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



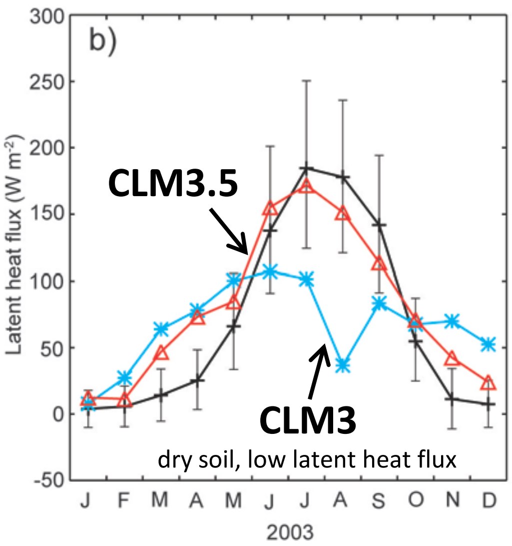
Model improvements reduce ET biases, especially in tropics, and improve monthly fluxes

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

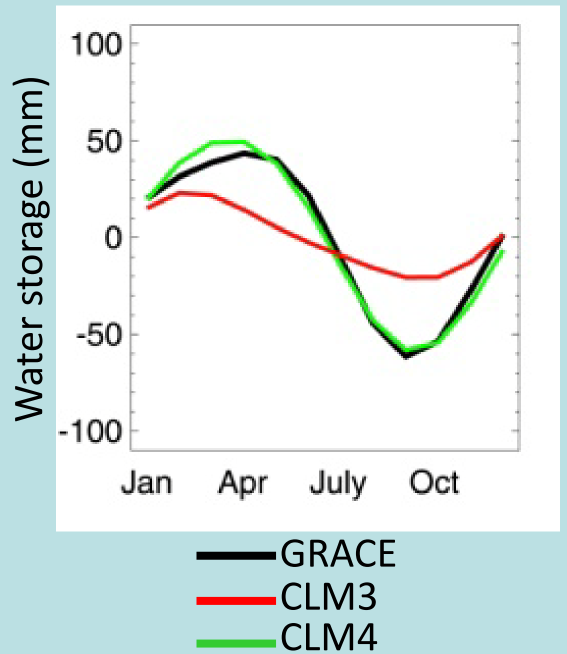
Modeling across scales

Tower → Large basin → Global

Morgan Monroe State Forest

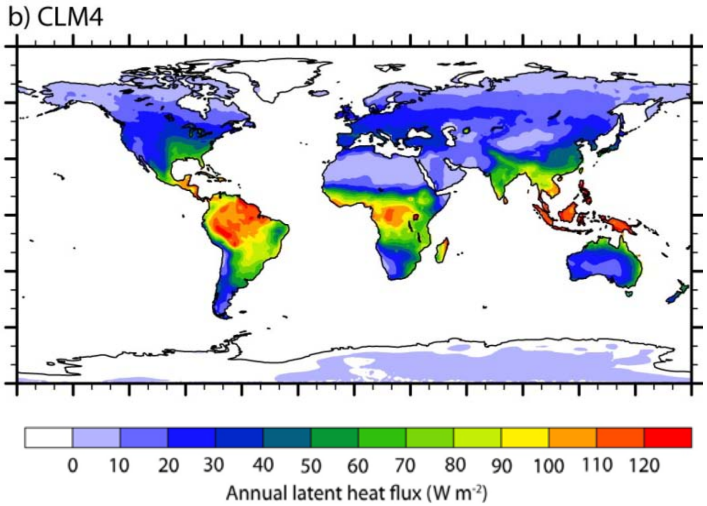


Stöckli et al. (2008) JGR, 113, doi:10.1029/2007JG000562



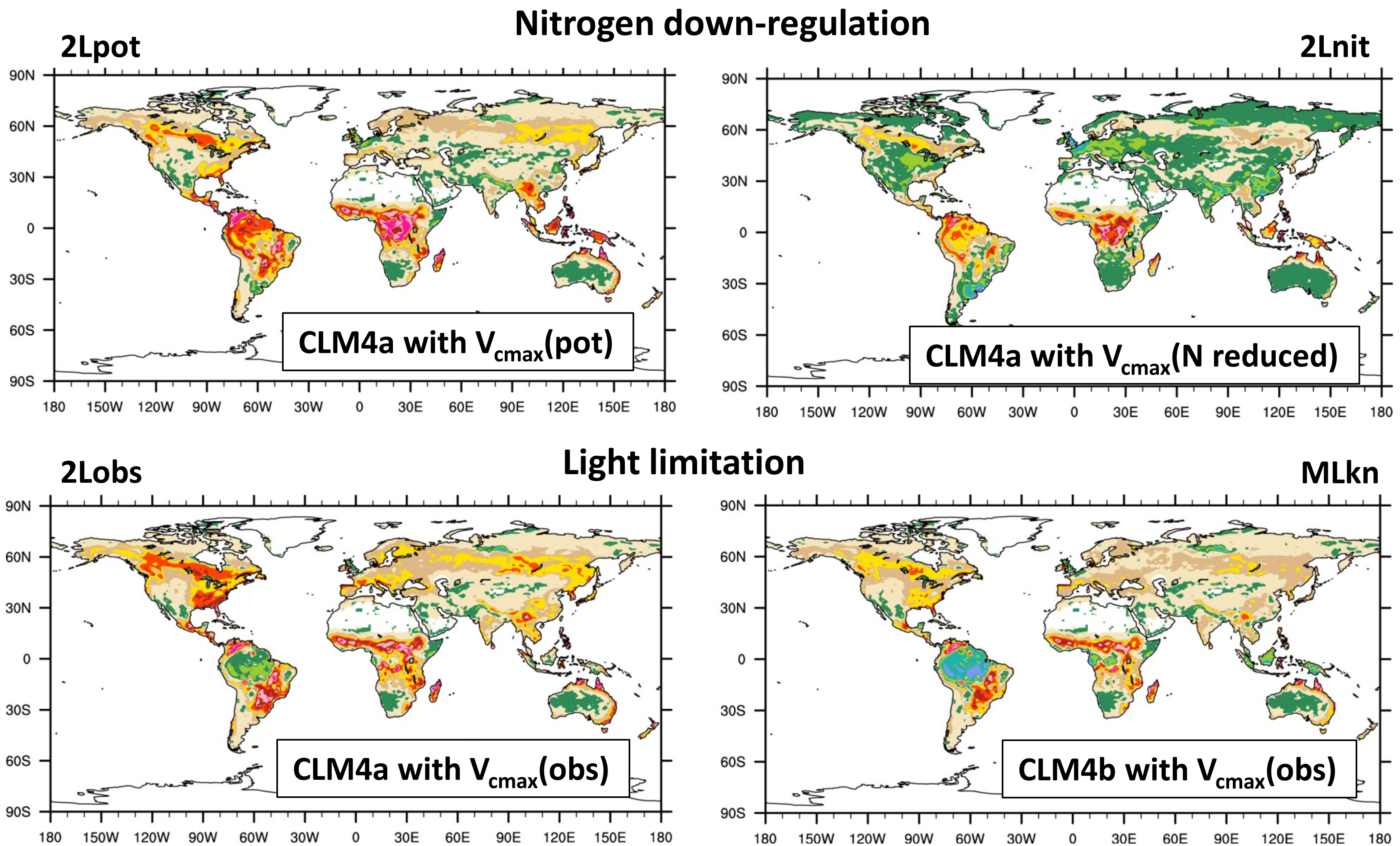
D. Lawrence et al. (2012) J Climate 25:2240-2260

Annual latent heat flux



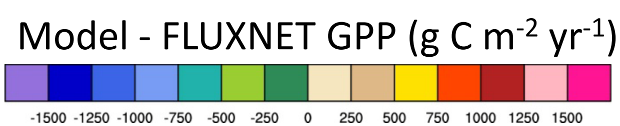
Bonan et al. (2011) JGR, doi:10.1029/2010JG001593

Two ways to get similar GPP

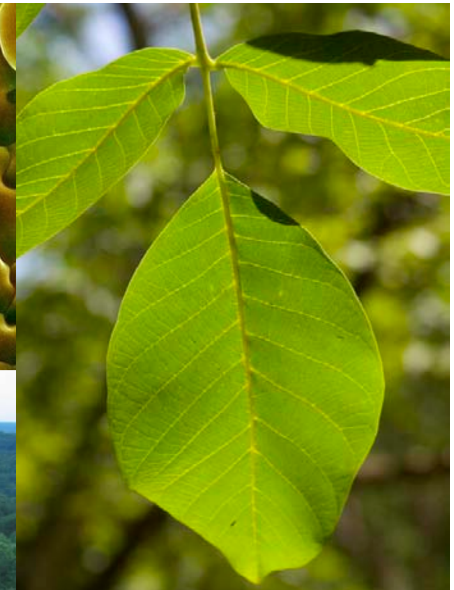


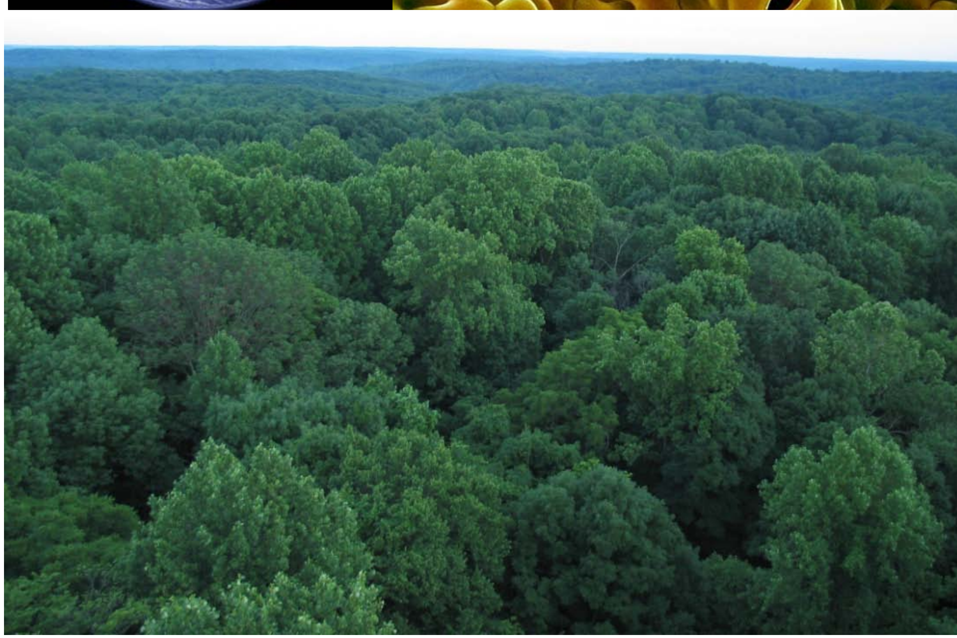
Biases in CLM4b are comparable to, though of opposite sign, those of CLM4a

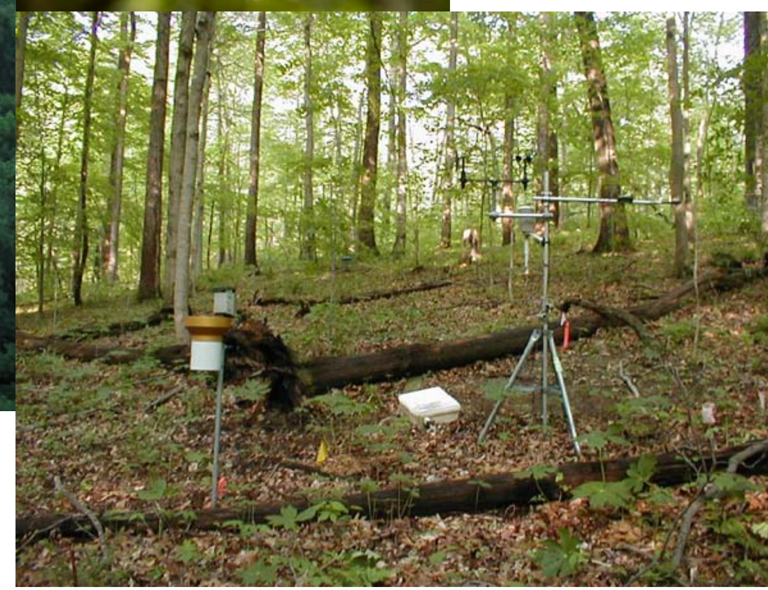
Two-leaf canopy does not capture non-linearity of radiative transfer and photosynthesis



How well do we scale from leaf to globe?



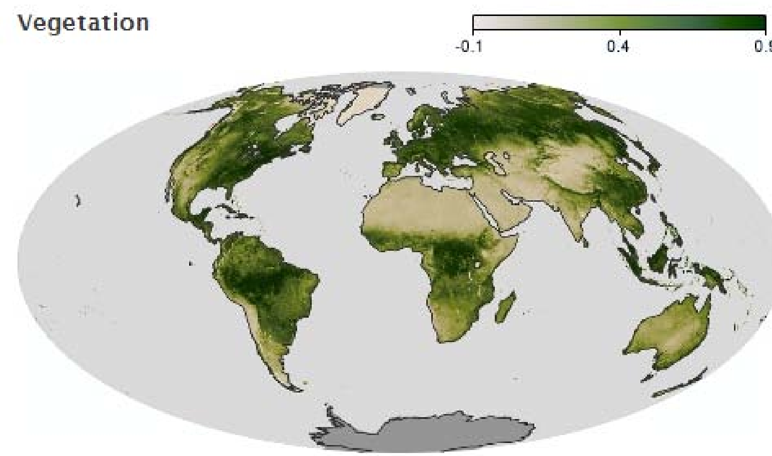




Multi-scale model evaluation

Canopy fluxes
GPP, latent heat flux

Lasslop et al. (2010) GCB 16:187-208



Global vegetation
GPP, latent heat flux

Jung et al. (2011) JGR, 116, doi:10.1029/2010JG001566

Canopy processes
Theory
Numerical parameterization

Profiles of light, leaf traits, and photosynthesis

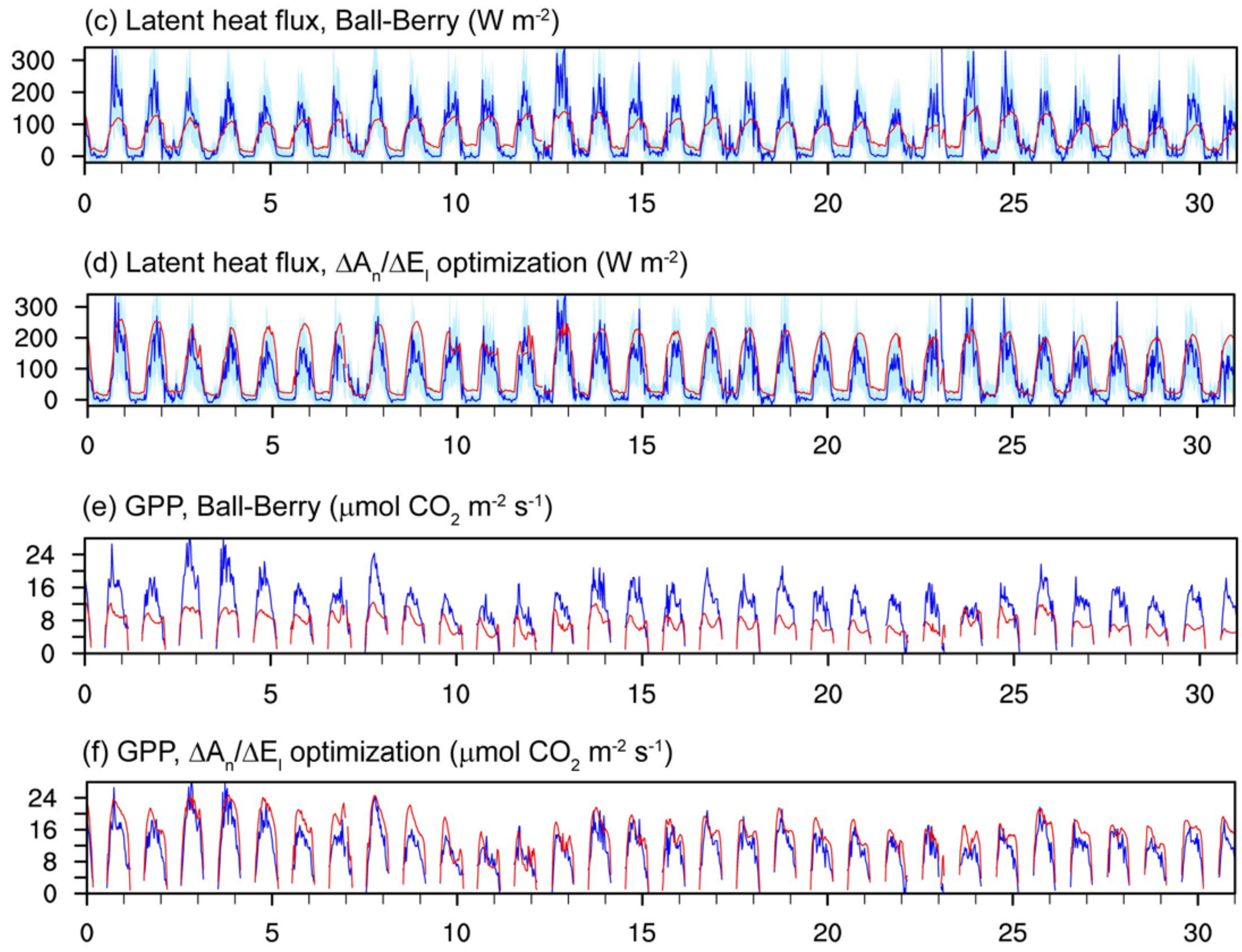
Leaf traits
Nitrogen concentration, V_{cmax}

Kattge et al. (2009) GCB 15:976-991

Consistency among parameters, theory, and observations across scales (leaf, canopy, global)

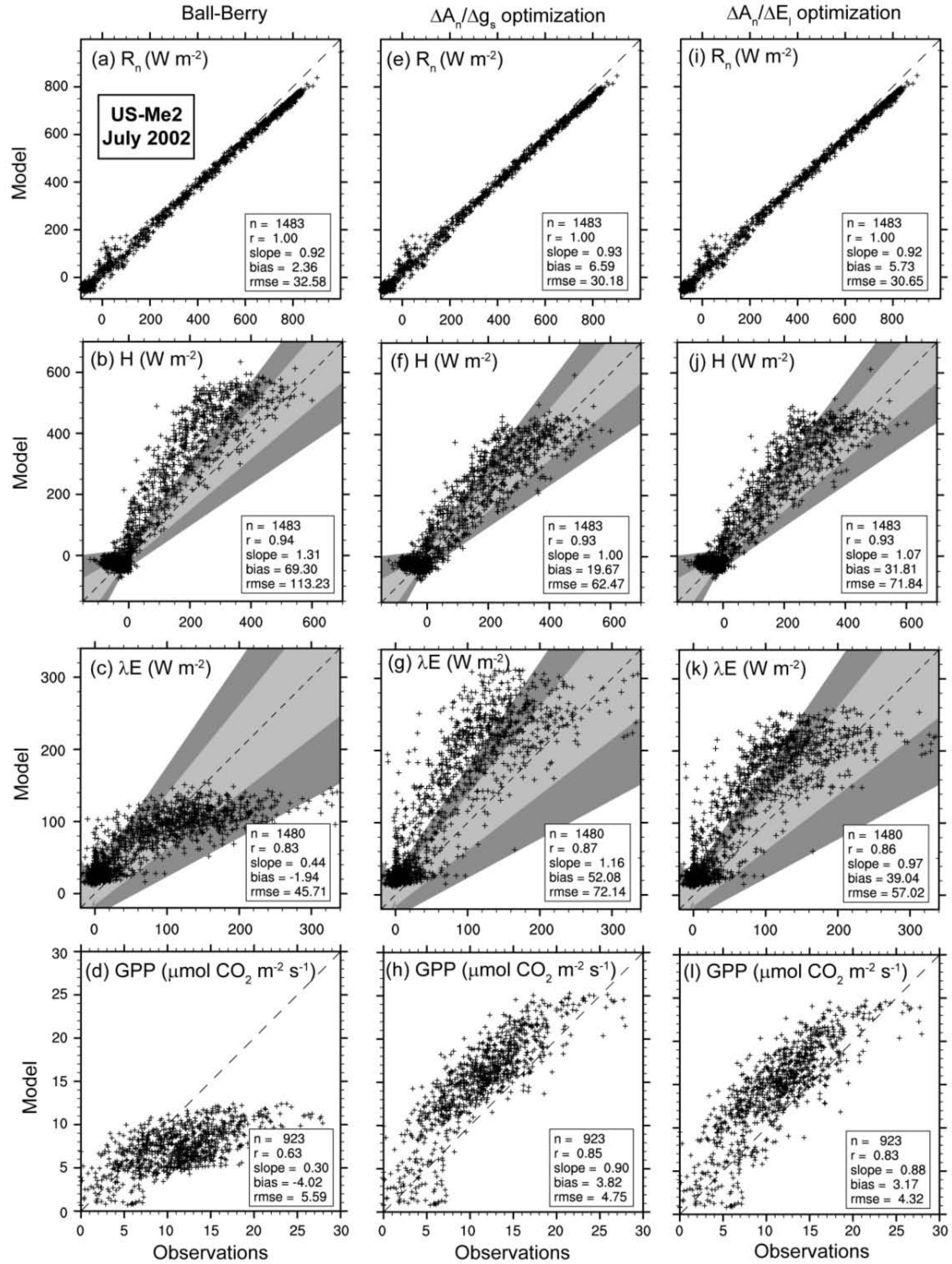
Model evaluation

US-Me2, July 2002



Model evaluation

US-Me2, July 2002



Model evaluation

US-Me2, July 2002-2007