Center for Multiscale Modeling of Atmospheric Processes
CMMAP
Reach for the sky.

A multi-layer plant canopy model for CLM

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CESM Land Model Working Group Meeting
Boulder, Colorado
24 February 2014

NCAR is sponsored by the National Science Foundation

Prevailing stomatal paradigm: Ball-Berry

NCAR model, 1995

JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 100, NO. D2, PAGES 2817–2831, FEBRUARY 20, 1995

Land-atmosphere CO_2 exchange simulated by a land surface process model coupled to an atmospheric general circulation model

Gordon B. Bonan
National Center for Atmospheric Research, Boulder, Colorado

676 JOURNAL OF CLIMATE VOLUME 9

CSU-SiB, 1996

A Revised Land Surface Parameterization (SiB2) for Atmospheric GCMs. Part I: Model Formulation

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(Manuscript received 23 June 1995, in final form 1 August 1995)

Photosynthesis & stomatal conductance

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

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

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

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

ELSEVIER Journal of Hydrology 212–213 (1998) 79–94 Journal of Hydrology

A canopy conductance and photosynthesis model for use in a GCM land surface scheme

Hadley Centre, 1998

P.M. Cox[a,*], C. Huntingford[b], R.J. Harding[b]

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Received 16 February 1996; accepted 7 October 1996

Stomatal optimization

An alternative approach models stomatal conductance by optimizing water use efficiency (A_n/E)

With simplifying assumptions, the Ball-Berry style model can be derived from optimization theory

$g_s = g_0 + 1.6\,(1 + g_1 D_s^{-1/2})\, A_n / c_s$ (Medlyn et al. 2011)

Annals of Botany **105**: 431–442, 2010
doi:10.1093/aob/mcp292, available online at www.aob.oxfordjournals.org
ANNALS OF BOTANY

A stomatal optimization theory to describe the effects of atmospheric CO_2 on leaf photosynthesis and transpiration

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Received: 4 August 2009 Returned for revision: 21 October 2009 Accepted: 10 November 2009 Published electronically: 8 December 2009

Global Change Biology (2011) **17**, 2134–2144, doi: 10.1111/j.1365-2486.2010.02375.x

Reconciling the optimal and empirical approaches to modelling stomatal conductance

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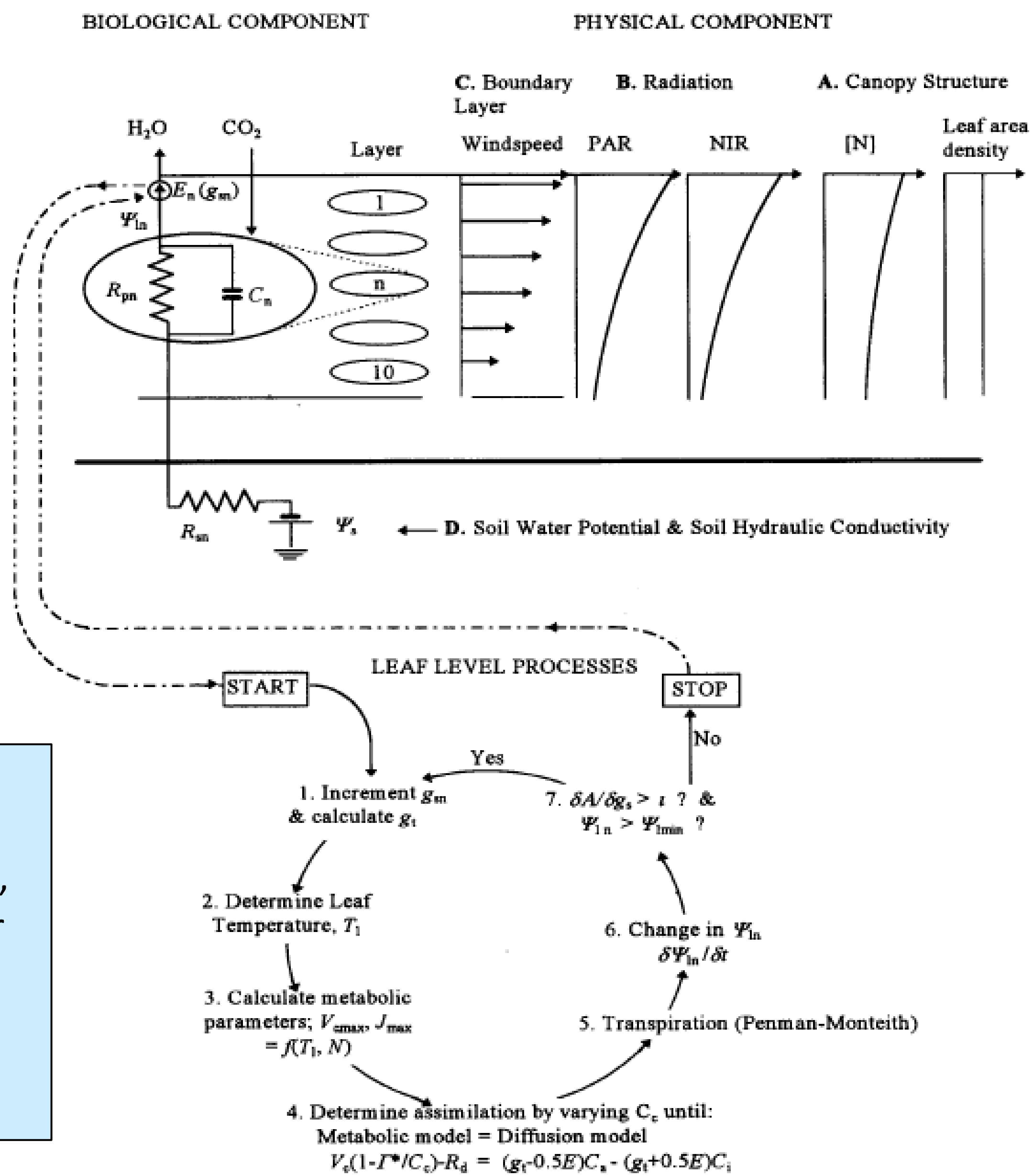
Soil-Plant-Atmosphere (SPA) model

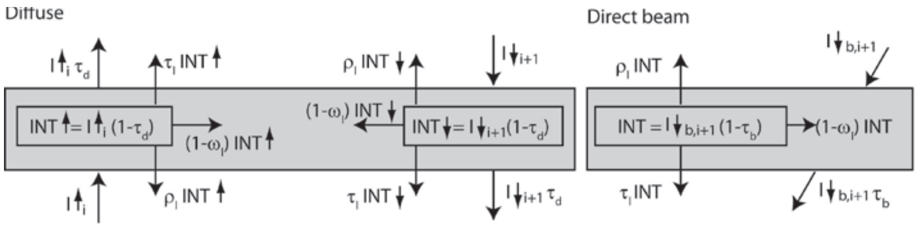


A multi-layer plant canopy model: g_s for each canopy layer is numerically iterated to maximize A_n, within the limitations of plant water storage and soil-to-canopy water transport ($\psi_L > \psi_{Lmin}$)

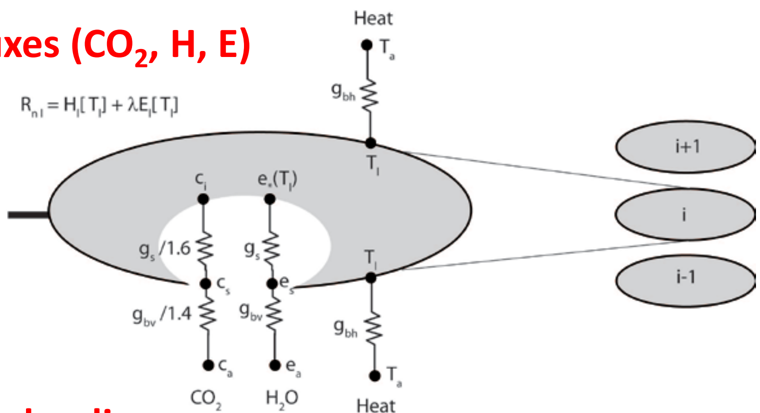
Williams et al. (1996) Plant Cell Environ. 19:911–927

A multi-layer SPA-enabled canopy model for use with CLM

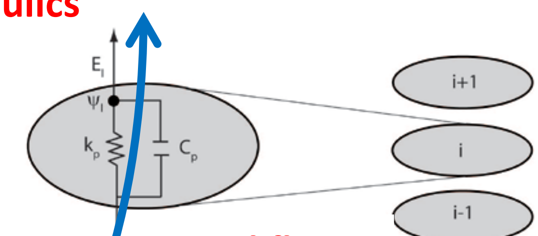
1. Radiative transfer



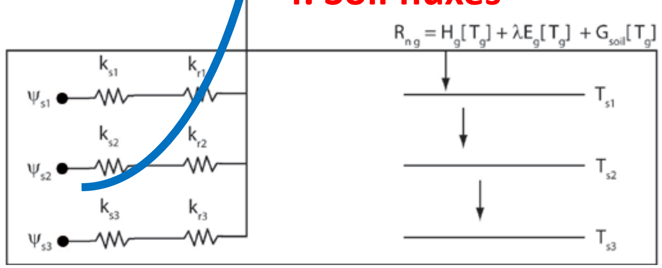
2. Leaf fluxes (CO_2, H, E)



3. Plant hydraulics



4. Soil fluxes



Within this framework, evaluate Ball-Berry model and two different stomatal optimizations:

iWUE: $\Delta A_n/\Delta g_s > \iota_*$ and $\psi_L > \psi_{Lmin}$
WUE: $\Delta A_n/\Delta E > \iota$ and $\psi_L > \psi_{Lmin}$

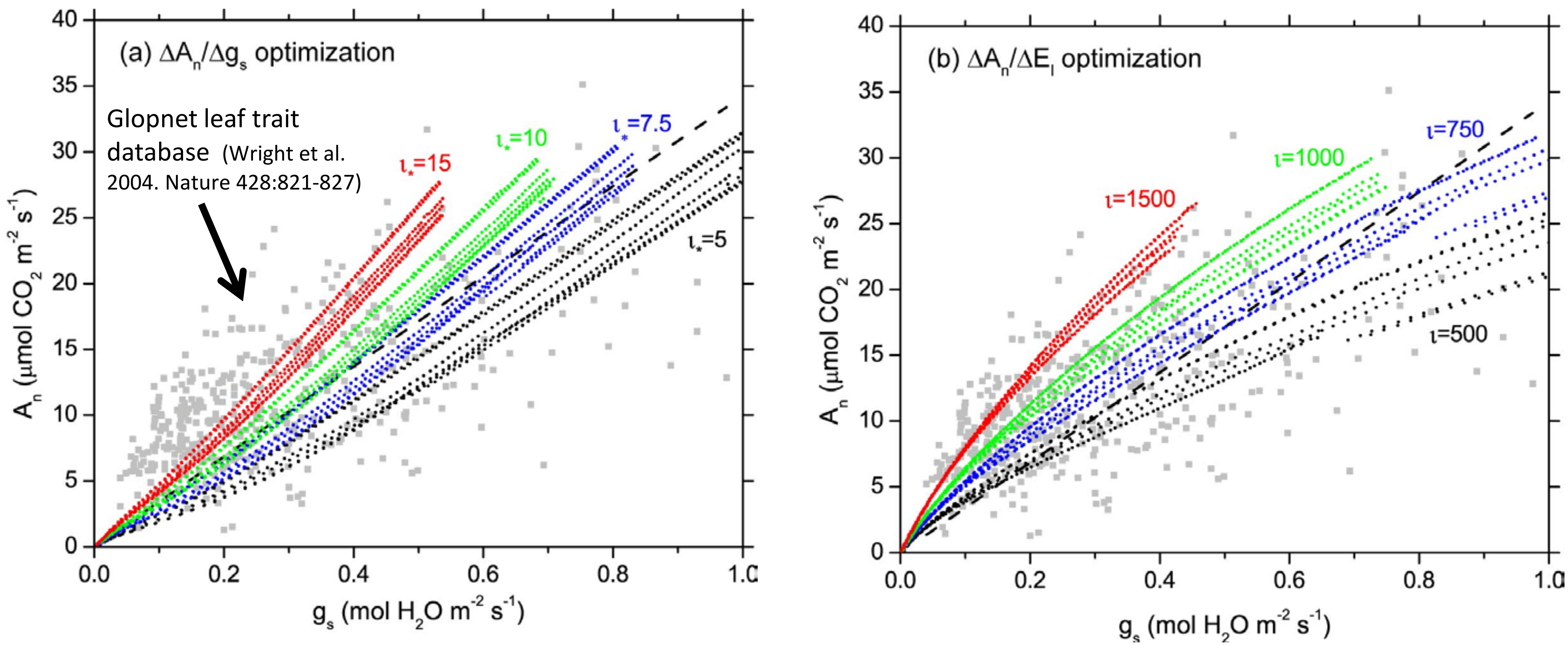
Difference relates to VPD: $\iota_* = \iota D_s$

5. Above- and within canopy turbulence and scalar profiles

Ned Patton (NCAR)
Ian Harman (CSIRO)

Stomatal efficiency determines maximum A_n and g_s

Leaf simulations for 4 values of iota (µmol CO_2 mol^{-1} H_2O)



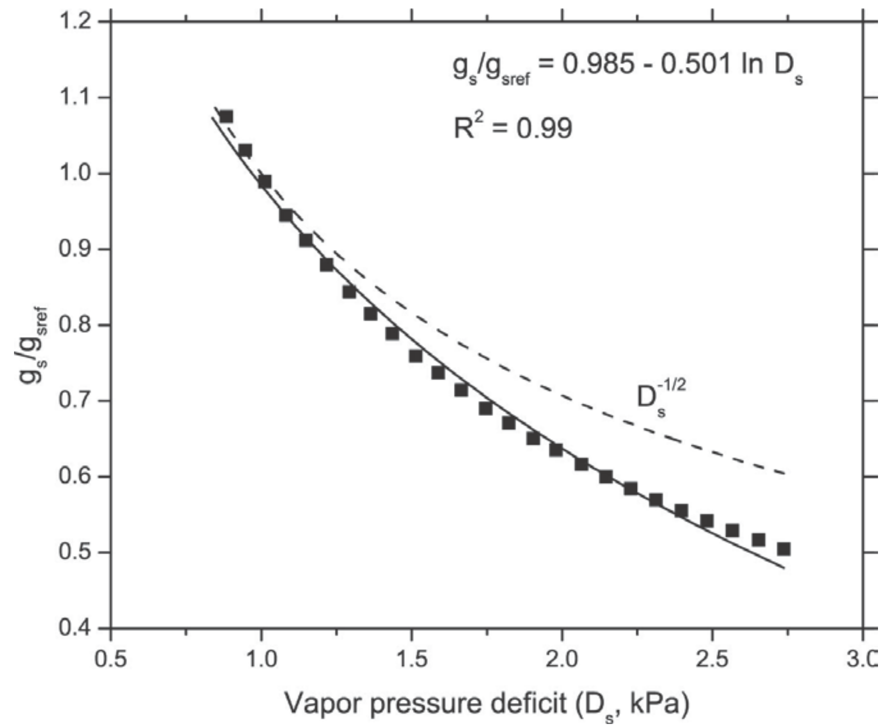
Functional relationships emerge from theory

VPD dependence (WUE optimization) is consistent with observations and theory:

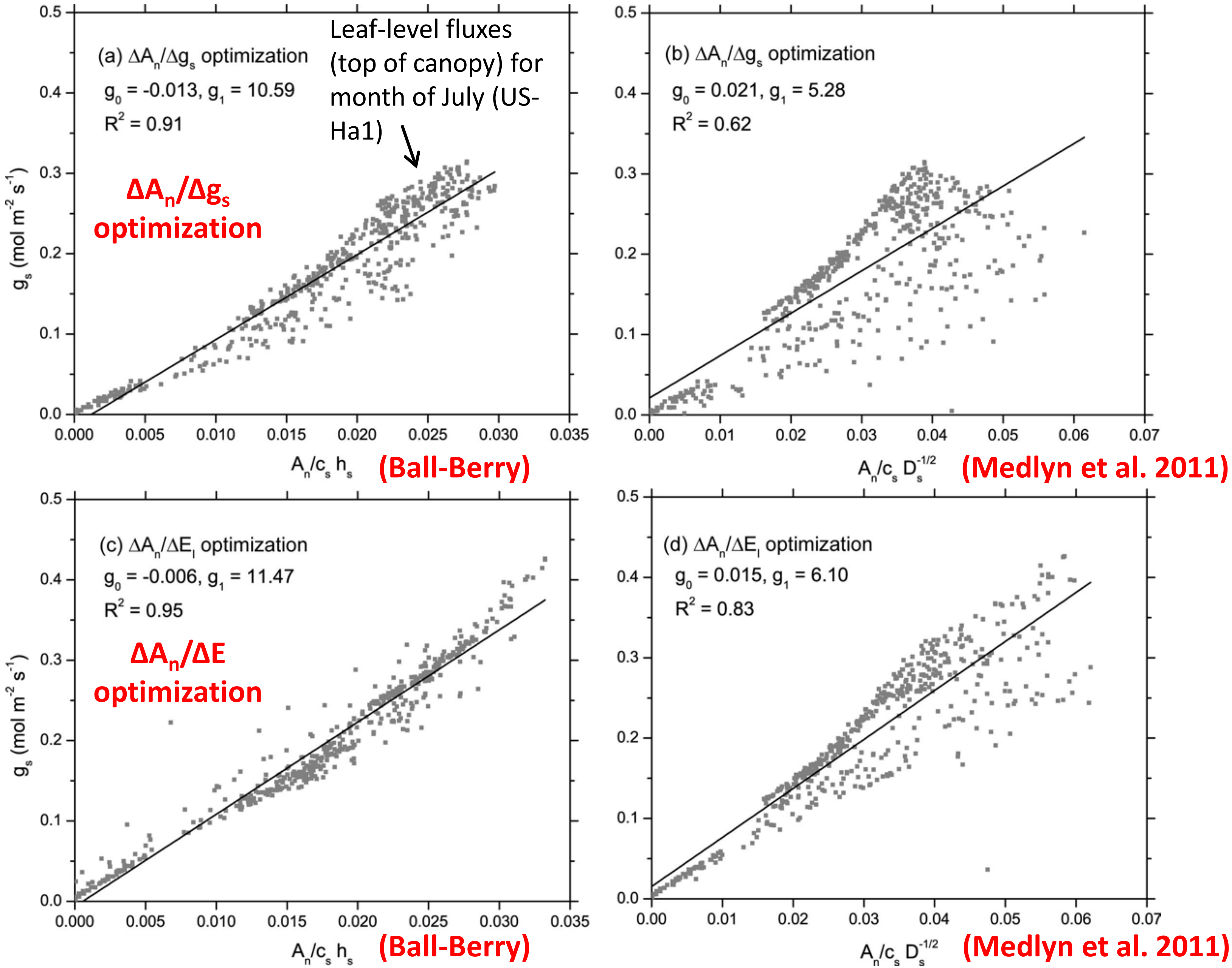
$g_s/g_{sref} = 1 – 0.5 \ln D_s$

Oren et al. (1999) Plant Cell Environ. 22:1515-1526
Katul et al. (2009) Plant Cell Environ. 32:968-979

Leaf simulations in response to VPD



Consistent with empirical and optimal models



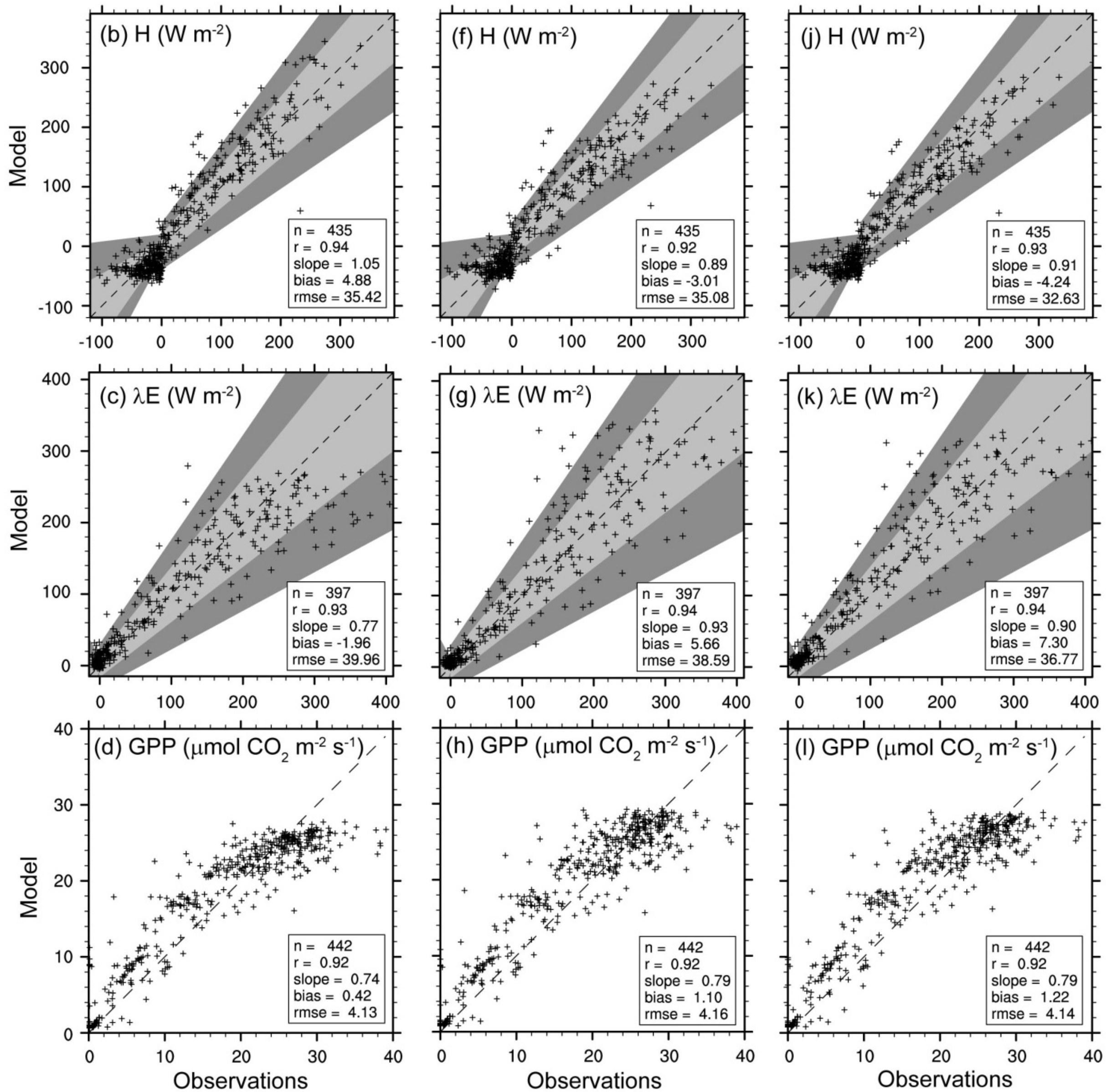
Scatter plots US-Ha1, July 2001

Ball-Berry | **$\Delta A_n/\Delta g_s$ opt.** | **$\Delta A_n/\Delta E$ opt.**

Sensible heat flux

Latent heat flux

GPP



Shading shows ± 1 and ± 2 std. dev. random flux error

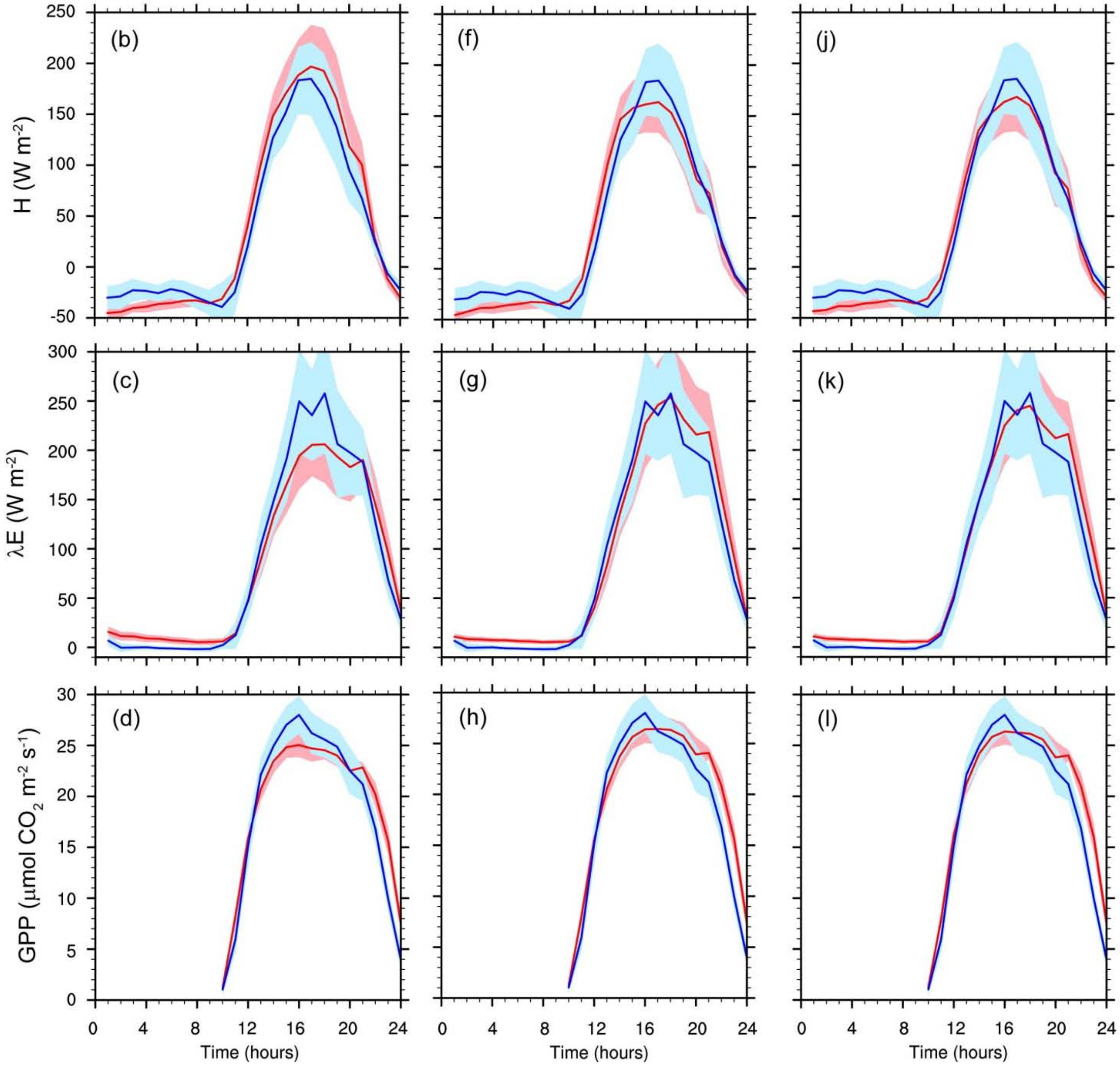
Mean diurnal cycle US-Ha1, July 2001

Ball-Berry | **$\Delta A_n / \Delta g_s$ opt.** | **$\Delta A_n / \Delta E$ opt.**

Sensible heat flux

Latent heat flux

GPP



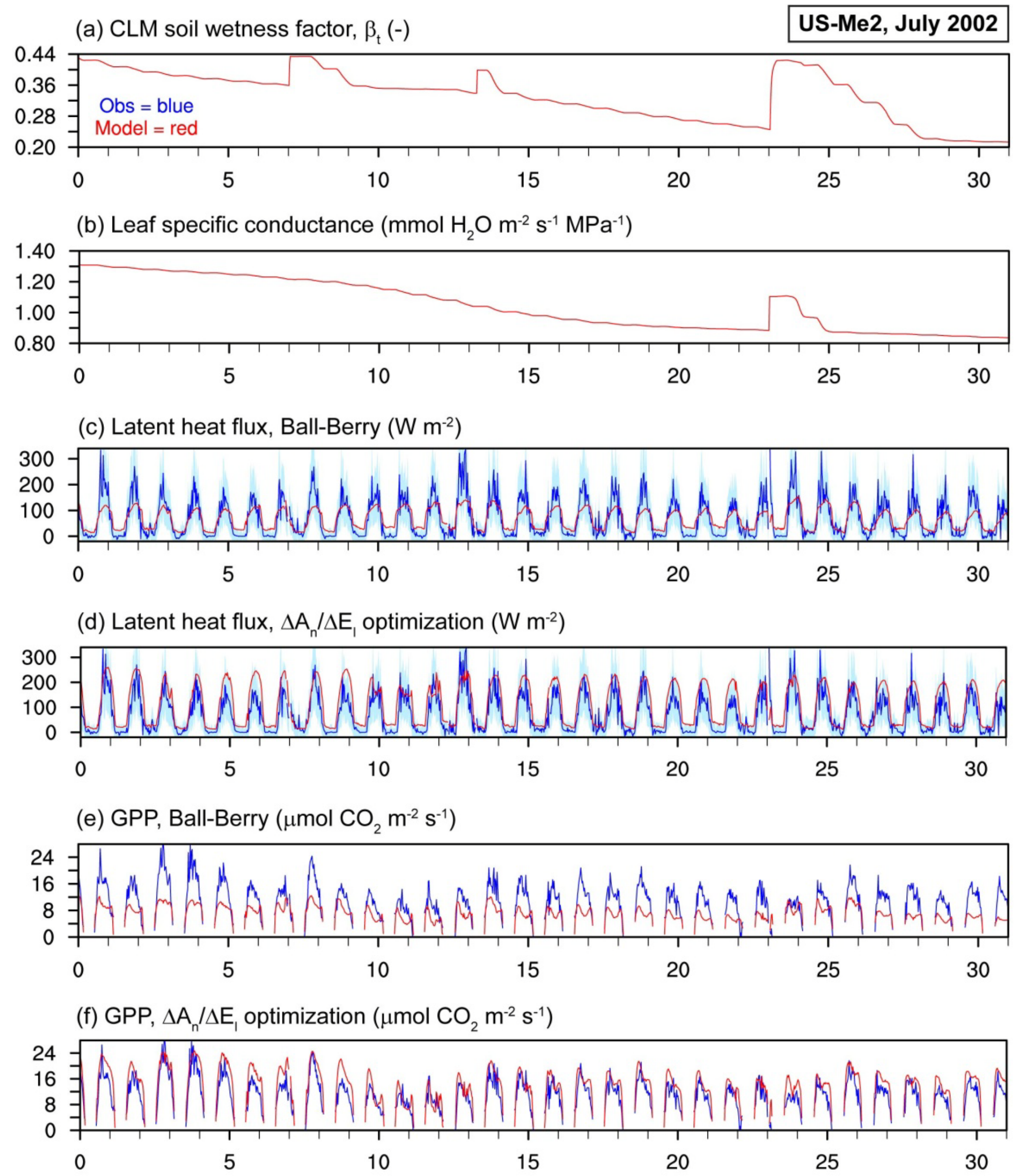
Model = red
Obs = blue

Prolonged drought: US-Me2, July 2002

Dry soil that gets drier over time

Ball-Berry underestimates mid-day peak latent heat flux

Ball-Berry systematically underestimates GPP

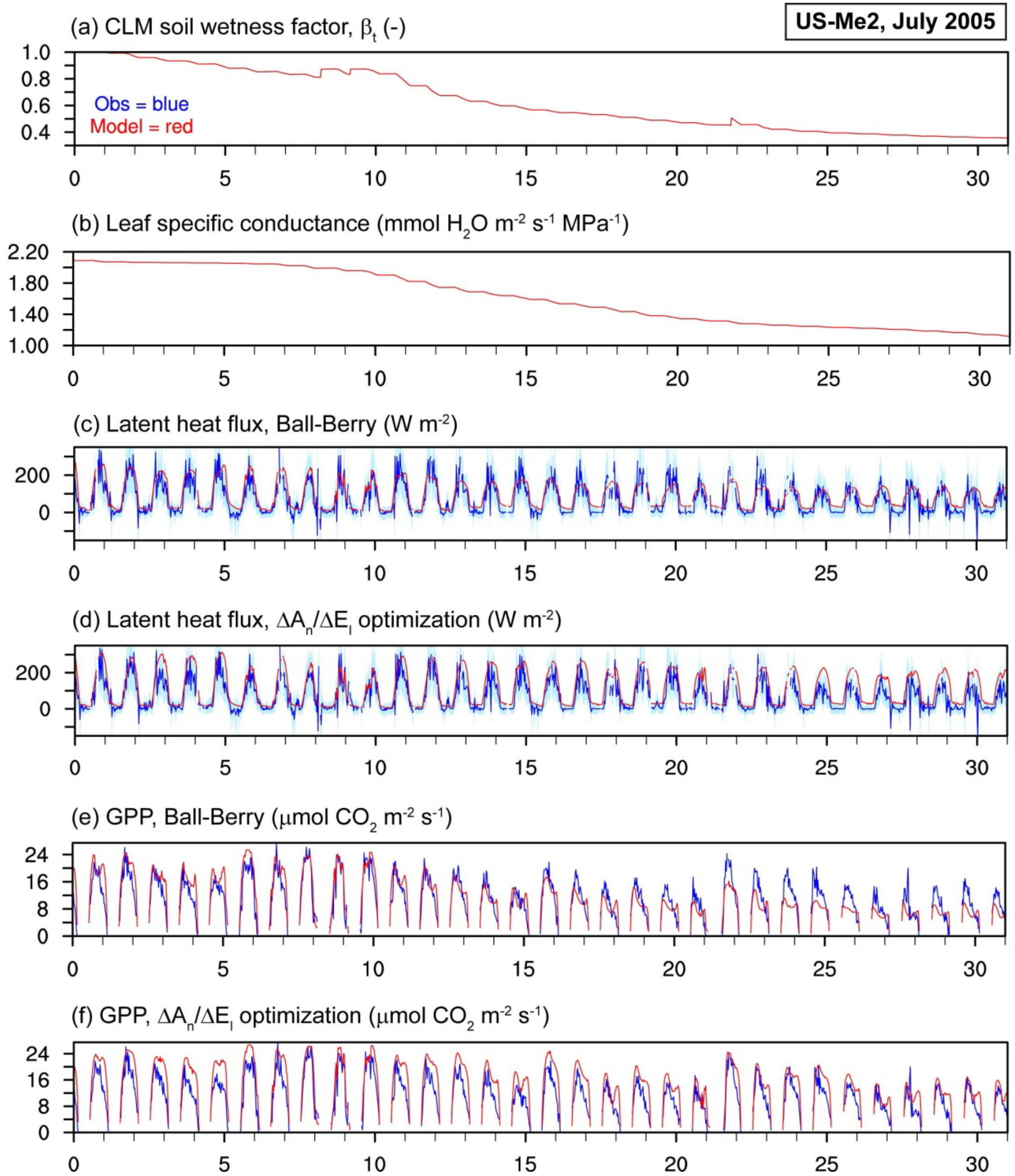


Evolving drought: US-Me2, July 2005

Wet soil that gets drier over time

Both stomatal models capture decline in ET as drought evolves

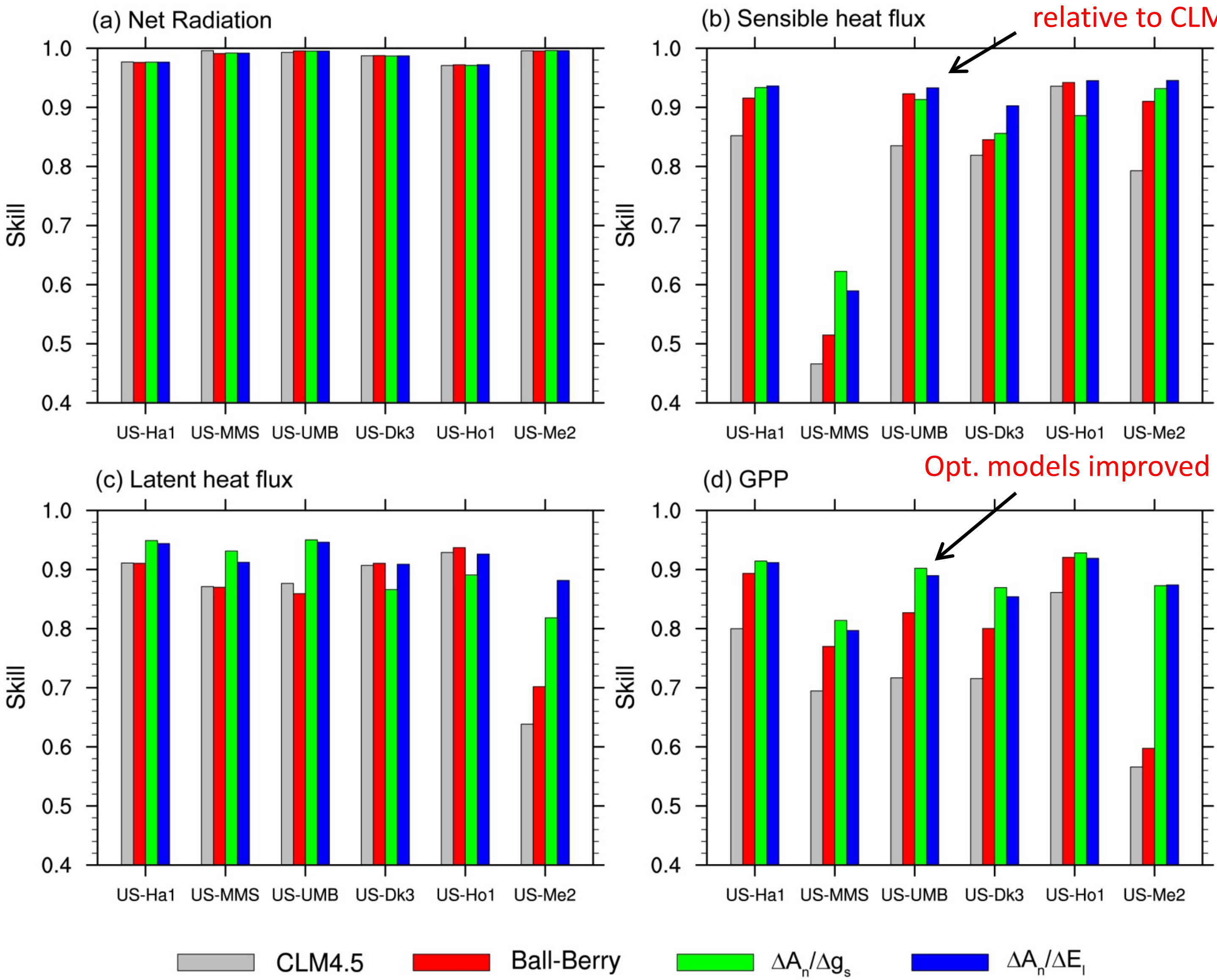
Ball-Berry underestimates GPP as drought evolves



Site x year summary of model skill

Multi-layer canopy improved relative to CLM4.5

Opt. models improved relative to Ball-Berry



AmeriFlux
3 DBF, 3 ENF
51 site x years

Skill score from Taylor (2001) JGR 106D:7183-7192

Model parameters

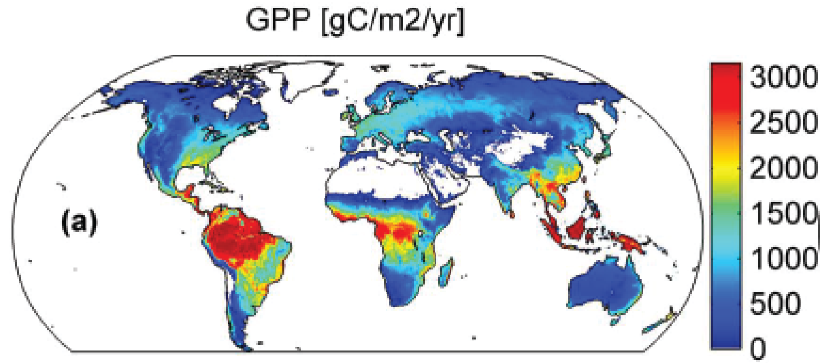
Symbol	Description	Units
V_{cmax25}	Maximum carboxylation rate at 25 °C	µmol m^{-2} s^{-1}
r_a	CLM rooting distribution parameter	m^{-1}
r_b	CLM rooting distribution parameter	m^{-1}
Ball–Berry model		
g_0	Minimum leaf conductance	mol H_2O m^{-2} s^{-1}
g_1	Slope parameter	–
Optimization model		
ψ_{lmin}	Minimum leaf water potential	MPa
k_p	Leaf-specific stem hydraulic conductance	mmol H_2O m^{-2} s^{-1} MPa^{-1}
C_p	Plant capacitance	mmol H_2O MPa^{-1} m^{-2}
ι	Stomatal efficiency	µmol CO_2 mol^{-1} H_2O
M_T	Fine root biomass	g m^{-2}
r_r	Fine root radius	m
r_d	Specific root density (fine root)	g biomass m^{-3} root
R_r^*	Fine root hydraulic resistivity	MPa s g $mmol^{-1}$ H_2O

Parameter sensitivity analyses fail to find optimal g_0 and g_1 to minimize RMSE (tradeoff between parameters), but does find optimal ι and R_r^* (because these two parameters explain most of RMSE)

Multi-scale model evaluation

Canopy fluxes
GPP, latent heat flux

AmeriFlux
FLUXNET



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, processes, and observations across multiple scales, from leaf to canopy to global

New directions with a multi-layer plant canopy

1. Optimization vs empirical stomatal models

   Functional relationships emerge from numerical optimization rather than being empirically imposed
2. Canopy turbulence (Ned Patton, NCAR; Ian Harman, CSIRO)
3. Dry deposition (biases in CLM4, Maria Val Martin, CSU)
4. BVOCs (already in CLM4.5)
5. Isotopes (already in CLM4.5)
6. Canopy chemistry – how does the chemical environment affect surface fluxes?