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From leaf to canopy to global: using flux data to test and improve terrestrial biosphere models across scales

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Boulder, Colorado, USA

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Bloomington, Indiana
24 October 2018

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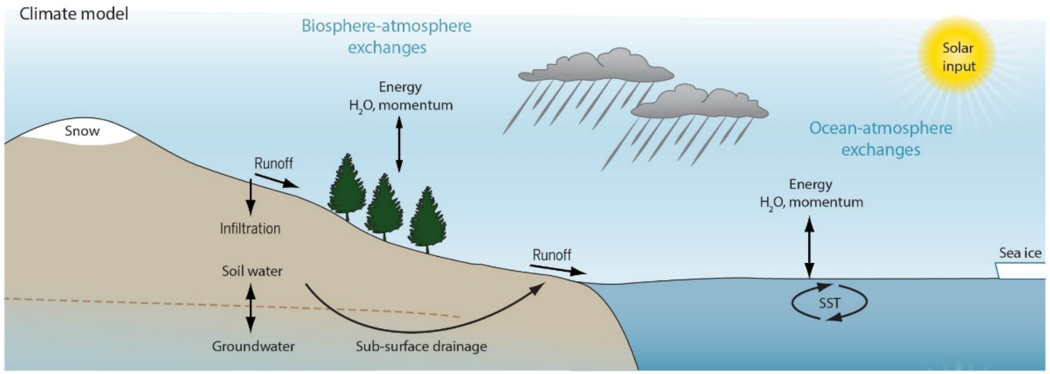
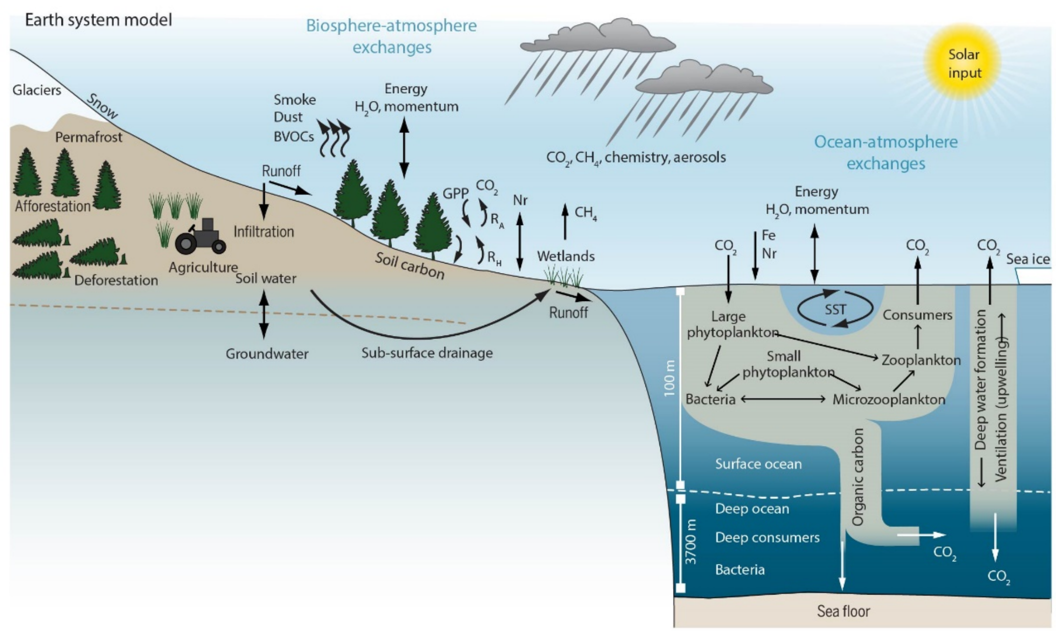
Earth system models

Physical representation of climate



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

Earth system perspective with terrestrial ecosystems and biogeochemical cycles

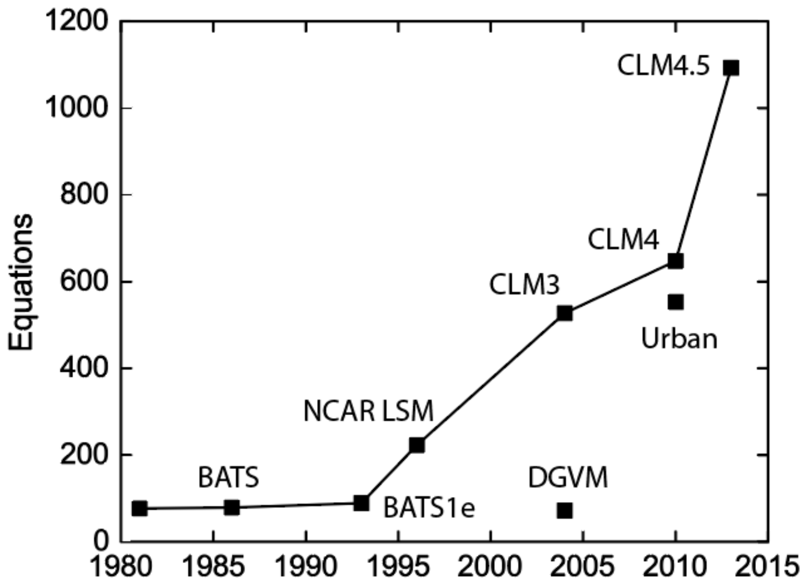


The models provide a comprehensive understanding of the processes by which people and ecosystems **affect**, **adapt to**, and **mitigate** global environmental change

Can we manage the Earth system, especially its ecosystems, to create a sustainable future?

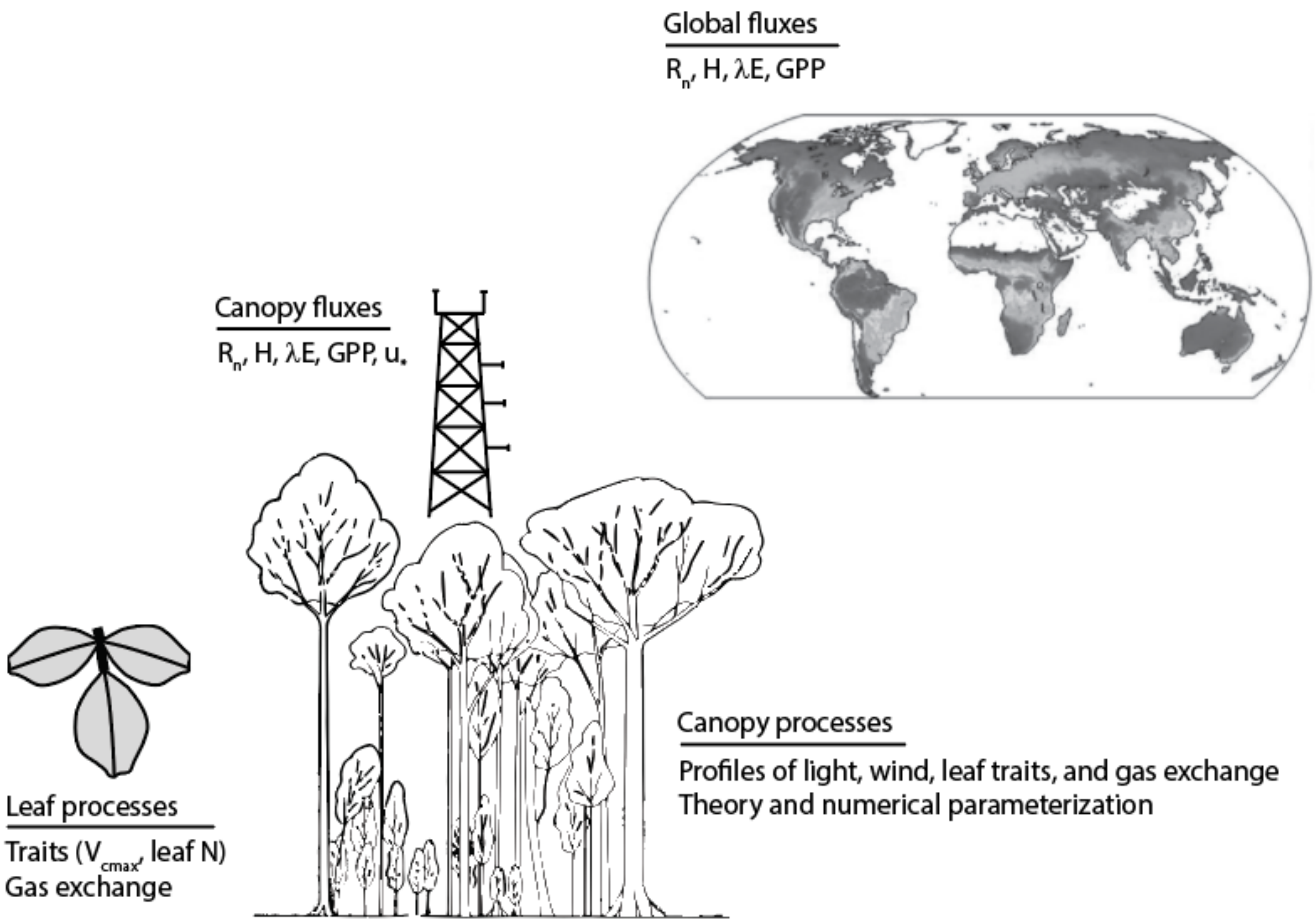
Increasing model complexity

Breadth and complexity of land surface models
as documented by NCAR technical notes



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

Multi-scale model evaluation



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

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

- **top down vs. bottom up**

Stomatal conductance

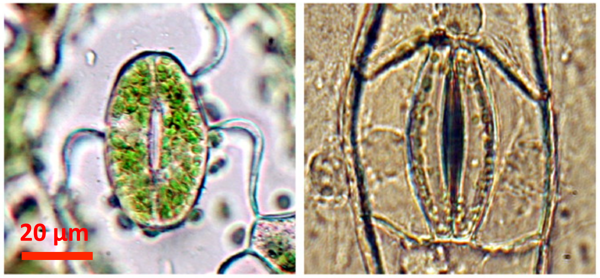
Ball-Berry (1987)

$$g_{sw} = \underbrace{g_0 + g_{1B}}_{\text{Empirical parameters}} \overbrace{A_n h_s}^{\frac{\text{photosynthesis * surface humidity}}{CO_2\ \text{concentration}}} / c_s$$

Empirical relationship between stomatal conductance and photosynthesis. Parameters obtained from leaf gas exchange data. Simple to scale over a canopy. But how to apply soil moisture stress?

Medlyn (2011)

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



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

Optimization theory (1977)

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

$$\partial A_n/\partial E = \iota \text{ with } \psi_\ell > \psi_{\ell min}$$

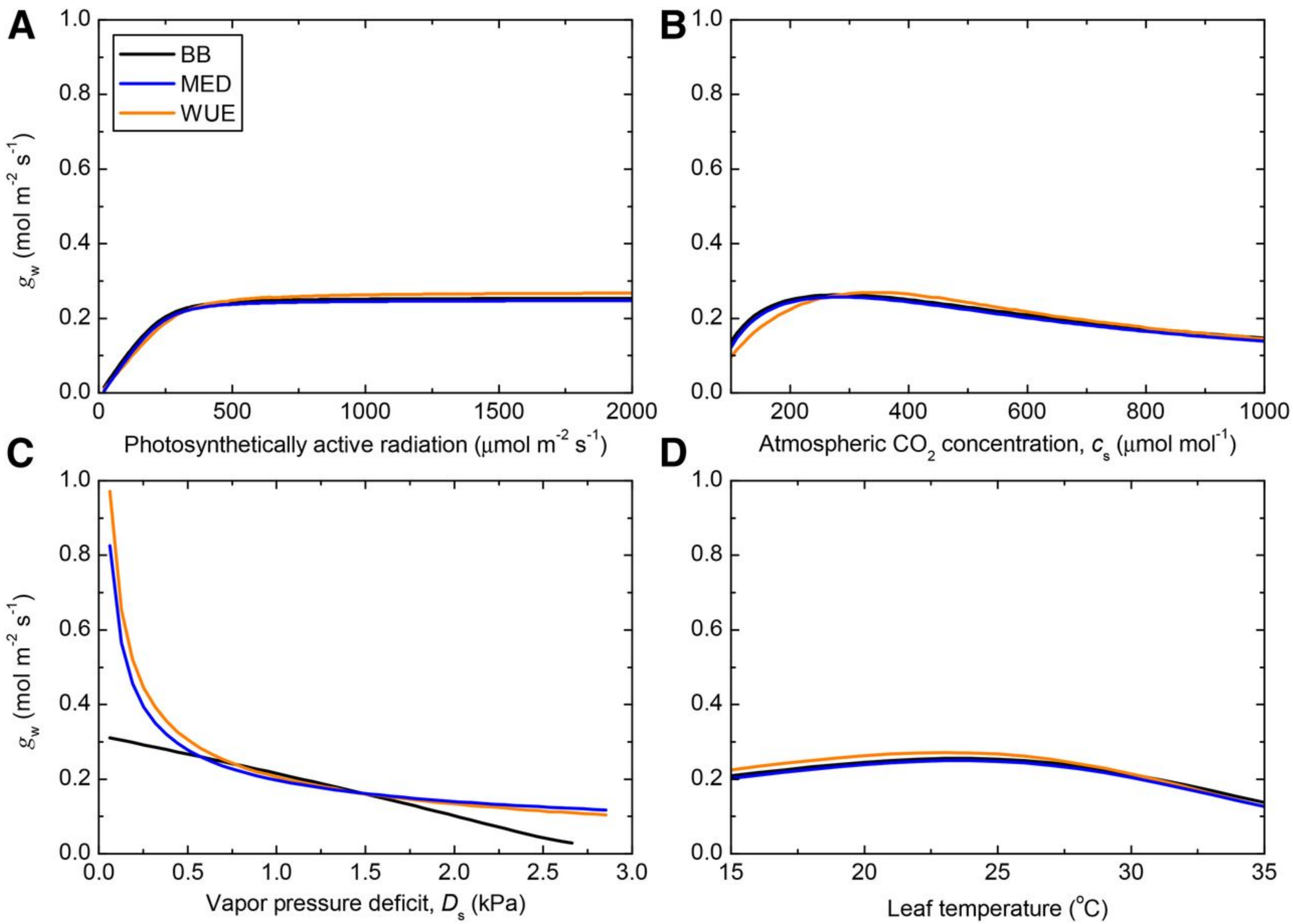
Need to specify ι. Cannot analytically scale over a canopy. Requires ψ_ℓ at each layer in canopy calculated from soil-plant-atmosphere continuum theory. Soil moisture stress emerges from plant hydraulics

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

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

Model behavior

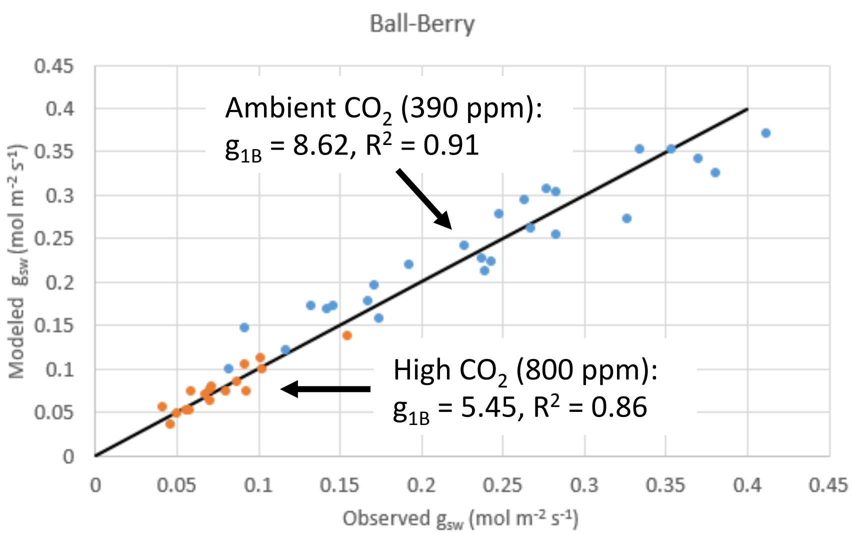
Using comparable g_{1B}, g_{1M}, and ι values gives similar results



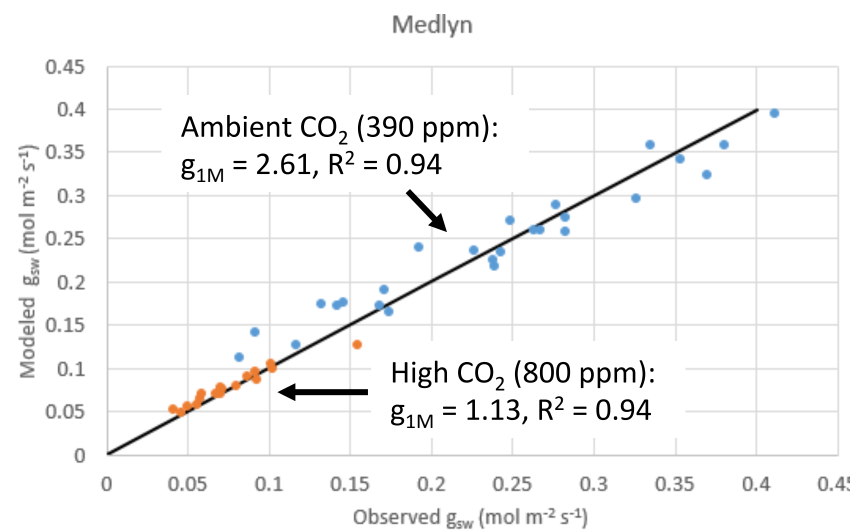
Franks et al. (2017) Plant Physiol., 174, 583-602

Leaf gas exchange data

Harvard Forest – Red oak



$g_{sw} = g_{1B}\, A_n h_s / c_s$



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

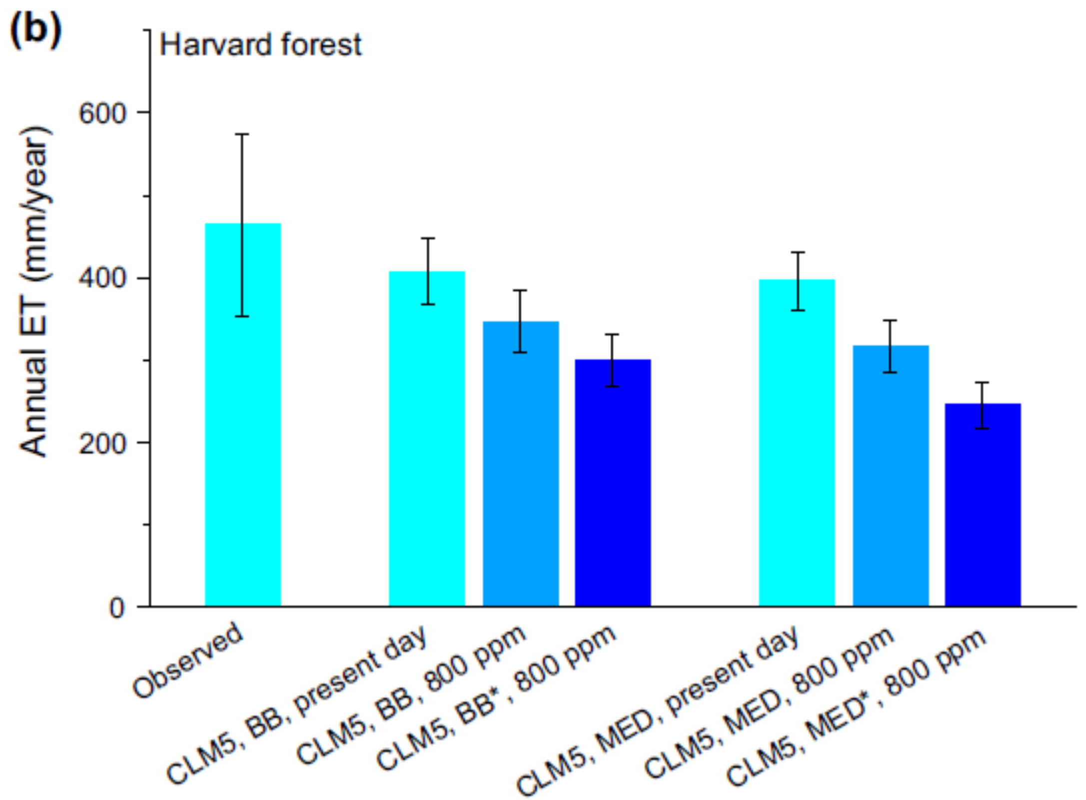
Both models fit the data equally well

g_1 decreases with elevated CO_2

Franks et al. (2018) Glob. Change Biol., doi:10.1111/gcb.14445

Simulations for Harvard Forest

Annual evapotranspiration simulated by the Community Land Model (CLM5) with Ball-Berry and Medlyn stomatal models

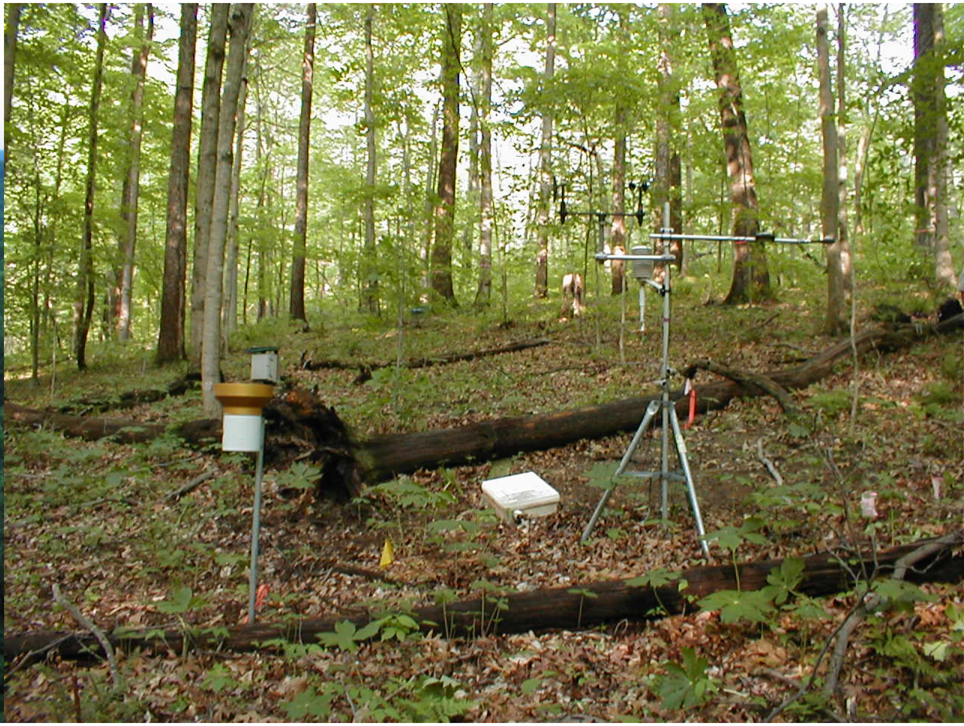


Both stomata models give annual ET consistent with observations
Elevated CO_2 reduces ET similarly for both models
Reduced g_1 with elevated CO_2 further decreases ET

Franks et al. (2018) Glob. Change Biol., doi:10.1111/gcb.14445

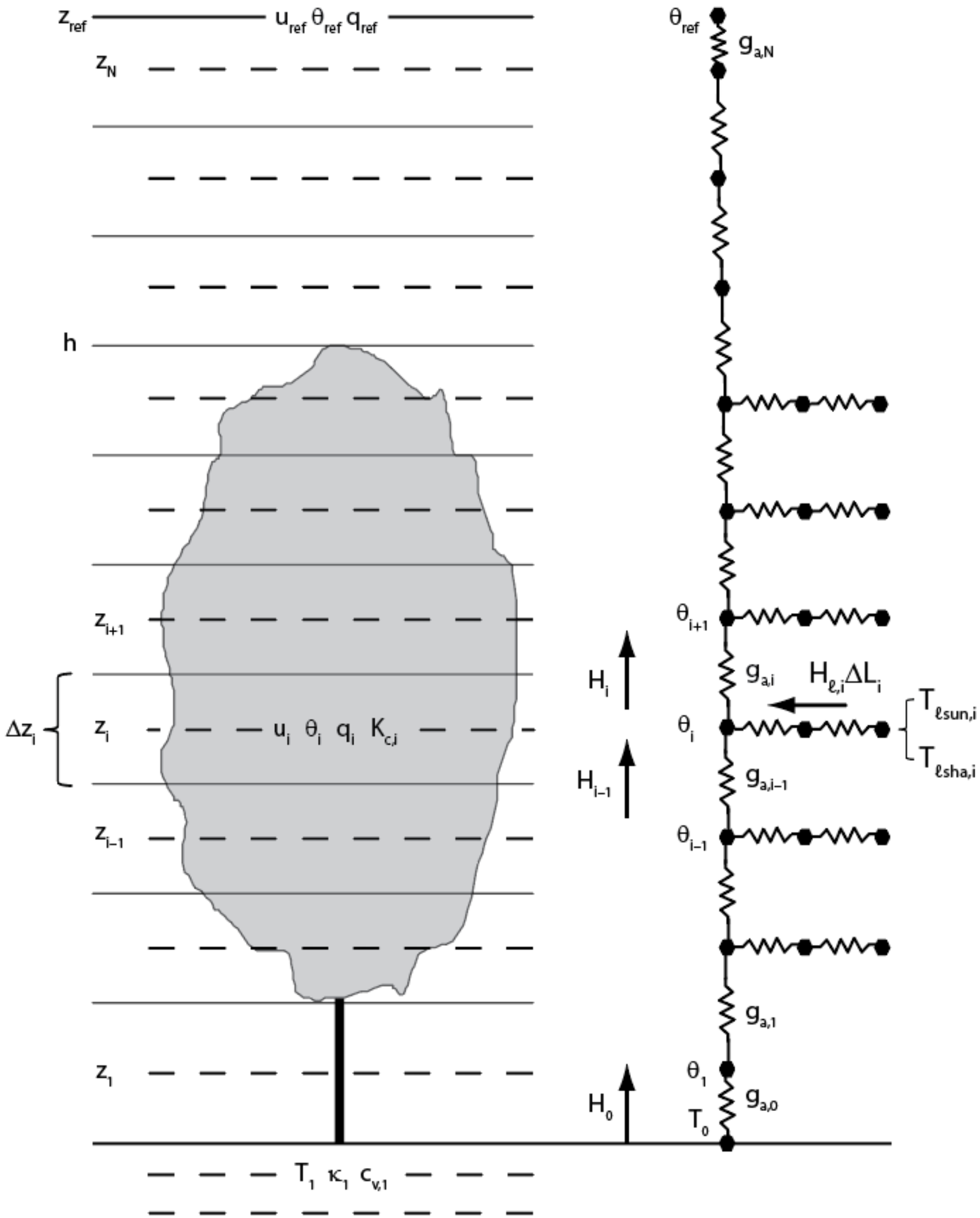
Two ways to model plant canopies

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



Multilayer canopy

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

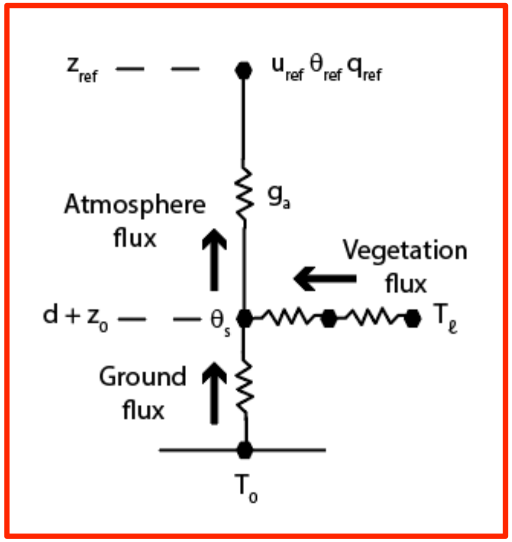
Williams et al. (1996) Plant Cell Environ. 19:911-927

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

Canopy turbulence and roughness sublayer

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

Bonan et al. (2018) Geosci. Model Dev. 11:1467-1496



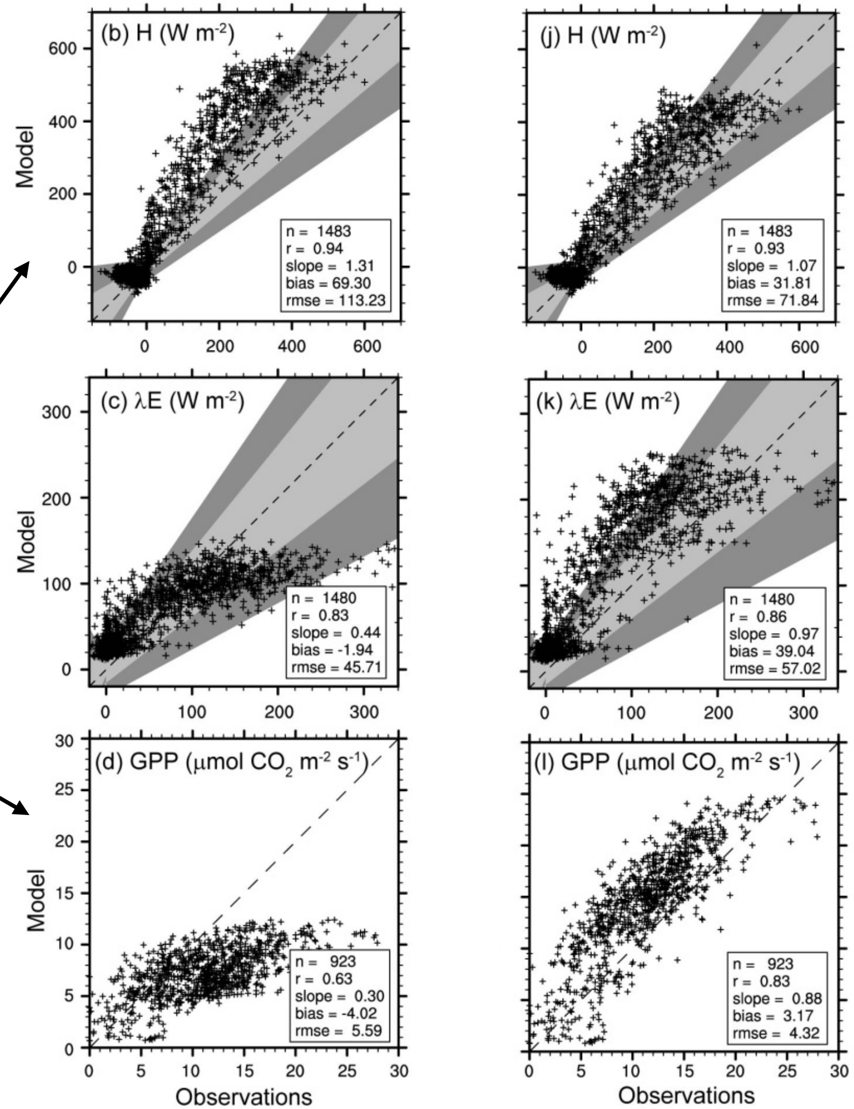
Drought stress: US-Me2, July 2002 (Ponderosa pine)

Shown are scatter plots of model (vertical axis) and observed (horizontal axis) 30-min fluxes for the month of July 2002

CLM4.5 Ball-Berry parameterization overestimates sensible heat flux, underestimates mid-day peak latent heat flux, and systematically underestimates GPP

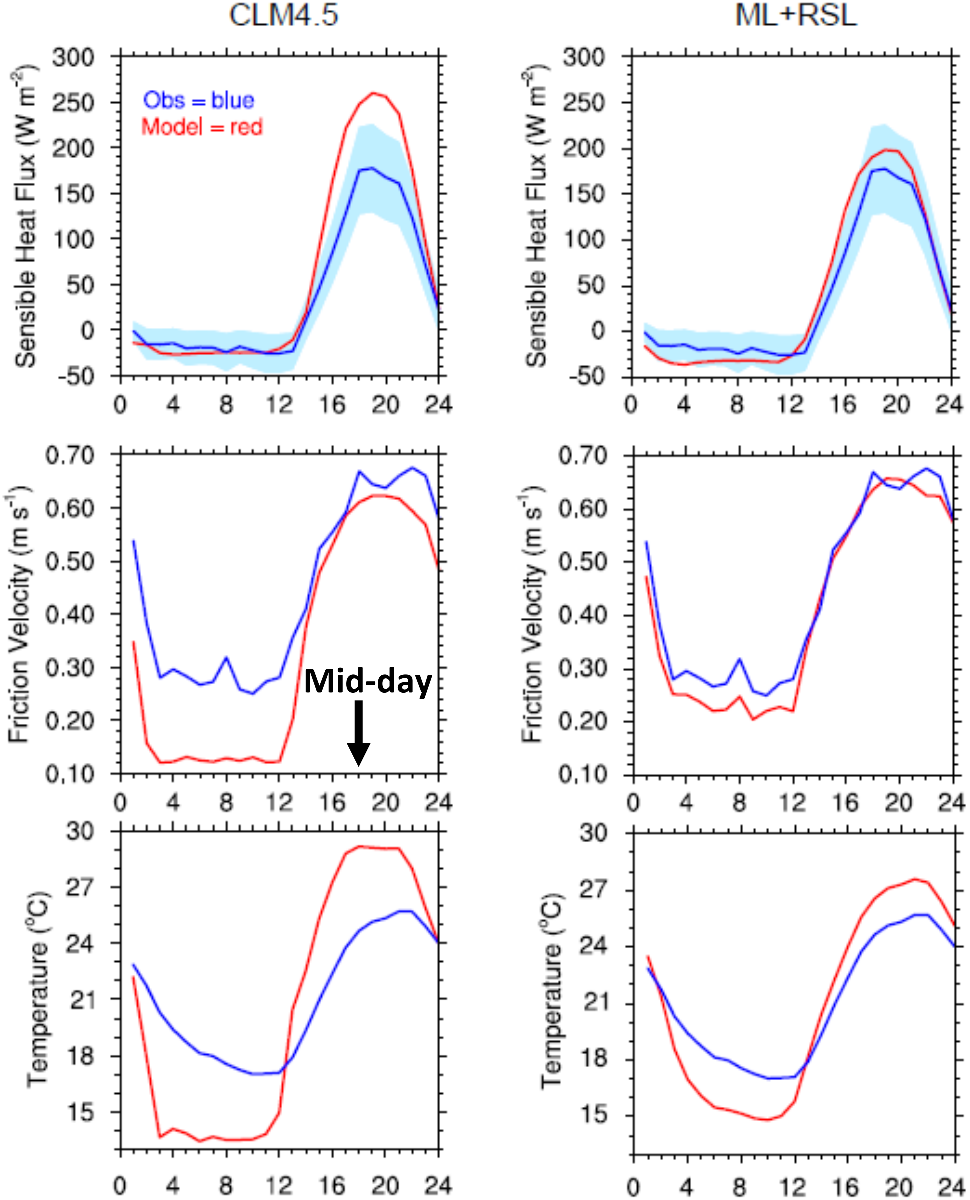
Ball-Berry with β factor

$\Delta A_n/\Delta E$ and ψ_ℓ optimization



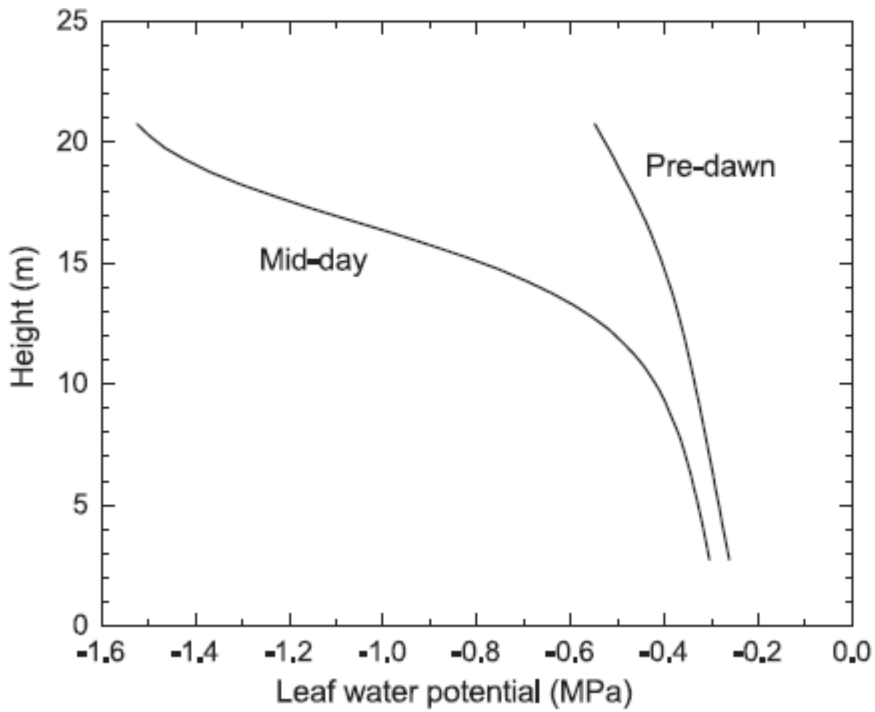
Bonan et al. (2014) Geosci. Model Dev. 7:2193-2222

US-UMB, July 2006 (DBF)



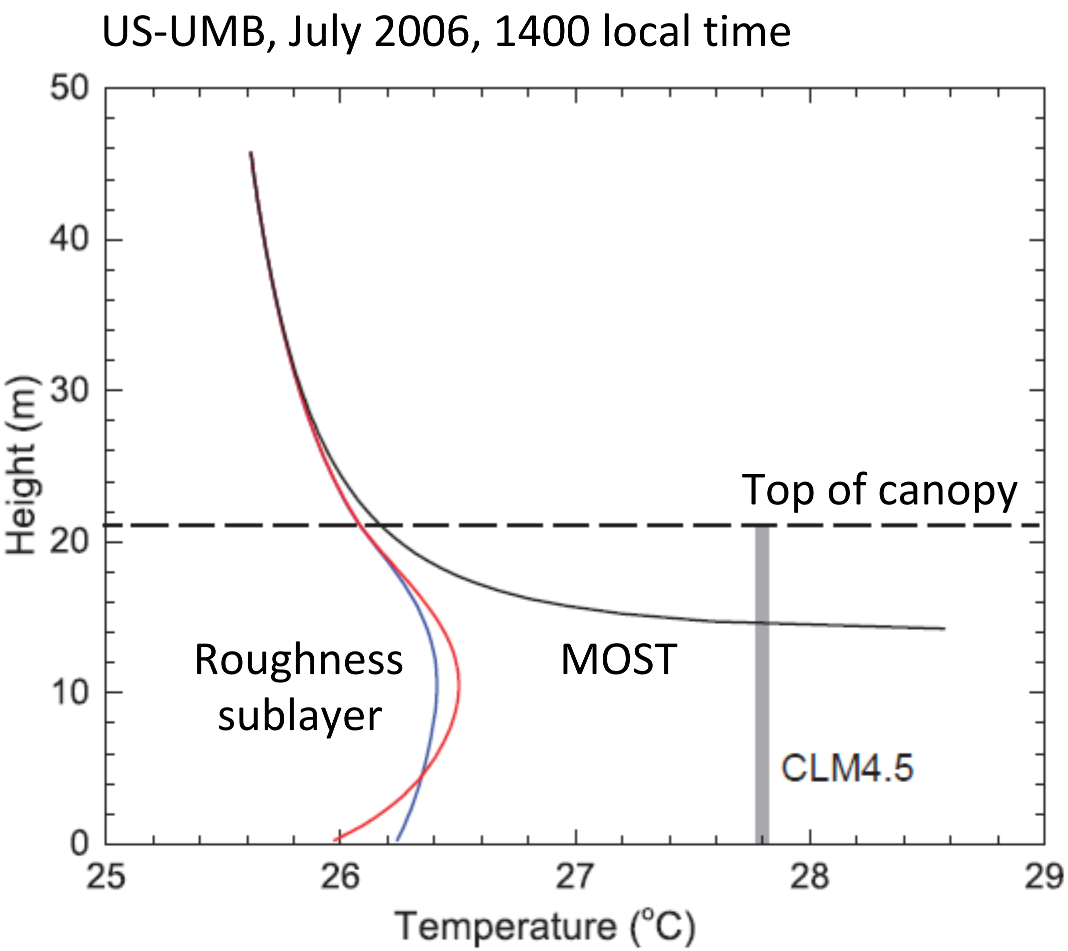
Bonan et al. (2018) Geosci. Model Dev. 11:1467-1496

US-UMB, July 2006 (DBF)



… but red maple very different from aspen and red oak

Air temperature profiles

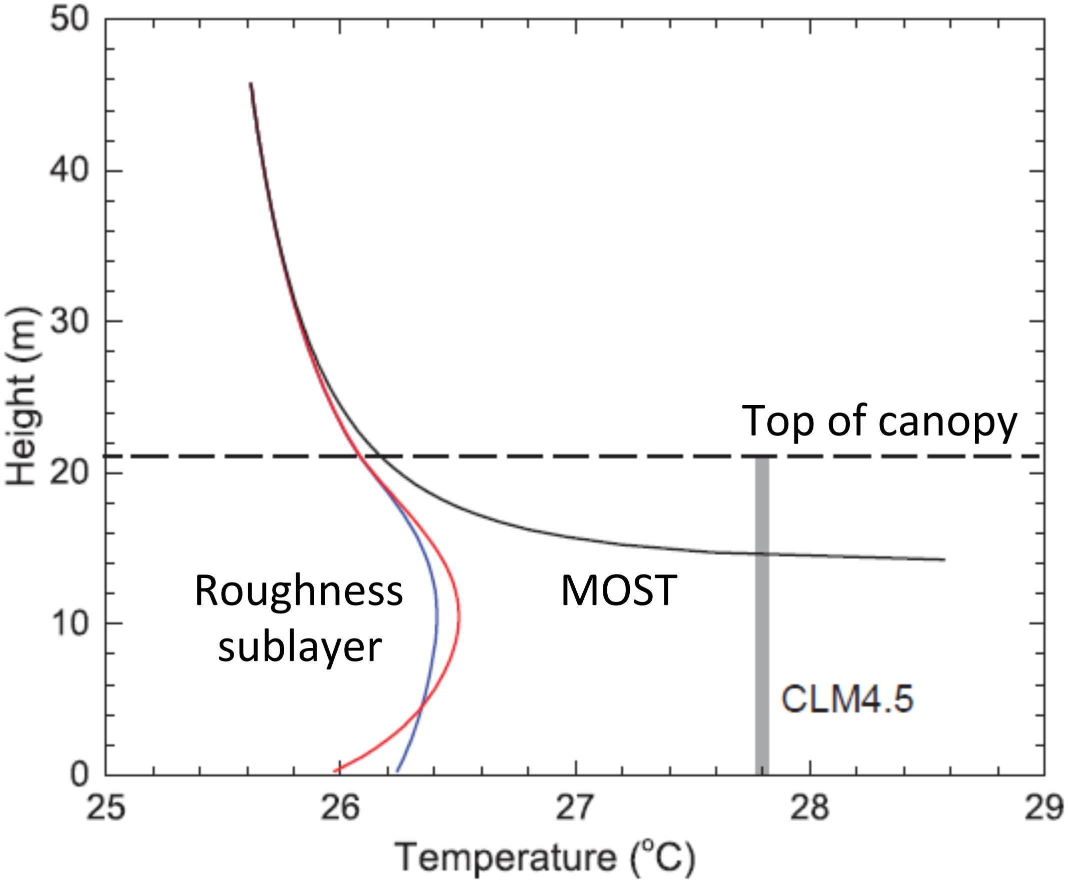


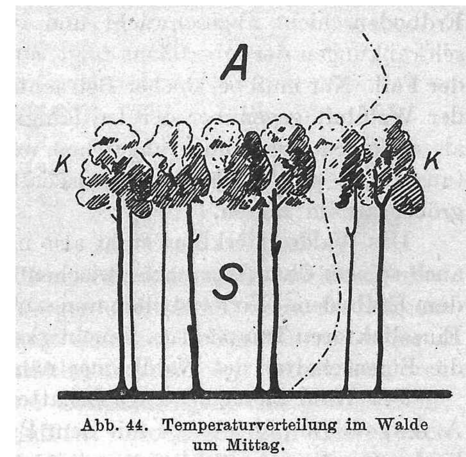
- CLM4.5 – Warm canopy air space consistent with MOST
- Multilayer model – More complex temperature structure in which mid-canopy is warmest (but 2°C cooler than MOST)

Bonan et al. (2018) Geosci. Model Dev. 11:1467-1496

Air temperature profiles

US-UMB, July 2006, 1400 local time





Geiger (1927) Das Klima der bodennahen Luftschicht

- CLM4.5 – Warm canopy air space consistent with MOST
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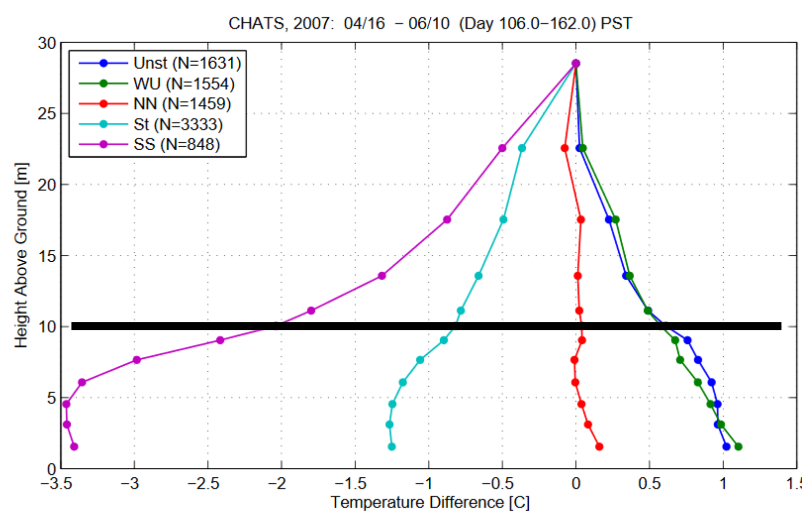
Bonan et al. (2018) Geosci. Model Dev. 11:1467-1496

CHATS – walnut orchard

THE CANOPY HORIZONTAL ARRAY TURBULENCE STUDY

BY EDWARD G. PATTON, THOMAS W. HORST, PETER P. SULLIVAN, DONALD H. LENSCHOW, STEVEN P. ONCLEY, WILLIAM O. J. BROWN, SEAN P. BURNS, ALEX B. GUENTHER, ANDREAS HELD, THOMAS KARL, SHANE D. MAYOR, LUCIANA V. RIZZO, SCOTT M. SPULER, JIELUN SUN, ANDREW A. TURNIPSEED, EUGENE J. ALLWINE, STEVEN L. EDBURG, BRIAN K. LAMB, RONI AVISSAR, RONALD J. CALHOUN, JAN KLEISSL, WILLIAM J. MASSMAN, KYAW THA PAW U, AND JEFFREY C. WEIL



(Sean Burns, CU/NCAR)