# Canopy processes in the Community Land Model

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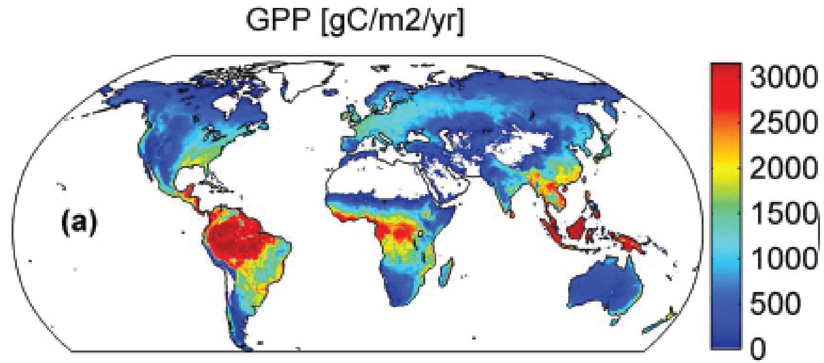
NCAR is sponsored by the National Science Foundation

# Multi-scale model evaluation

***Canopy fluxes***

Net radiation, latent heat flux, sensible heat flux, GPP

AmeriFlux, FLUXNET




***Global vegetation***

GPP, latent heat flux

Upscaled FLUXNET products

***Canopy processes***

Theory

Numerical parameterization

Profiles of light, temperature, wind, water stress, nitrogen, and leaf traits

***Leaf traits***

Nitrogen concentration, $V_{cmax}$

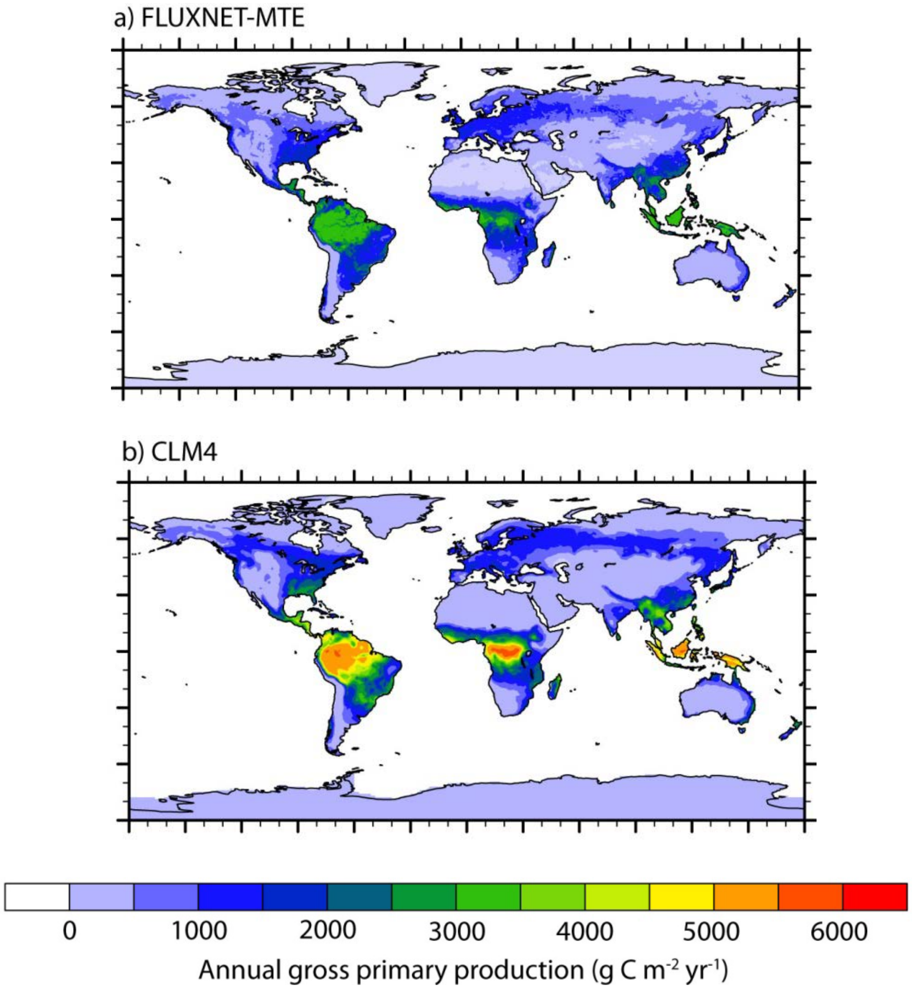
Glopnet, TRY

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

# CLM4 multi-scale evaluation

| | CLM4 | CLM4.5 |
|---|---|---|
| **Leaf** | | |
| $V_{cmax}$ | Too low compared with TRY database | ☑ |
| $K_c$, $K_o$, $\Gamma_*$ | Inconsistent with physiological measurements | ☑ |
| $J_{max}$ | – | ☑ |
| **Canopy scaling** | | |
| Sunlit/shaded leaves | Shaded leaves absorb too much diffuse radiation compared with radiative transfer theory | ☑ |
| Leaf nitrogen profile ($K_n$) | Too shallow compared with observations | ☒ |
| **Canopy** | | |
| GPP | Too high compared with global FLUXNET product | ☑ |

# Gross primary production biases




***Causes of GPP bias***

*Model structural error*

Canopy radiative transfer
- Shaded leaf light absorption

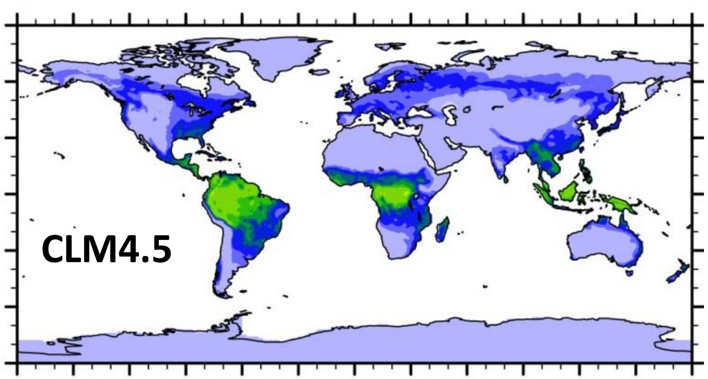
Photosynthesis-stomatal conductance
- Rubisco and RuBP limited rates

Canopy integration
- Nitrogen and photosynthetic capacity

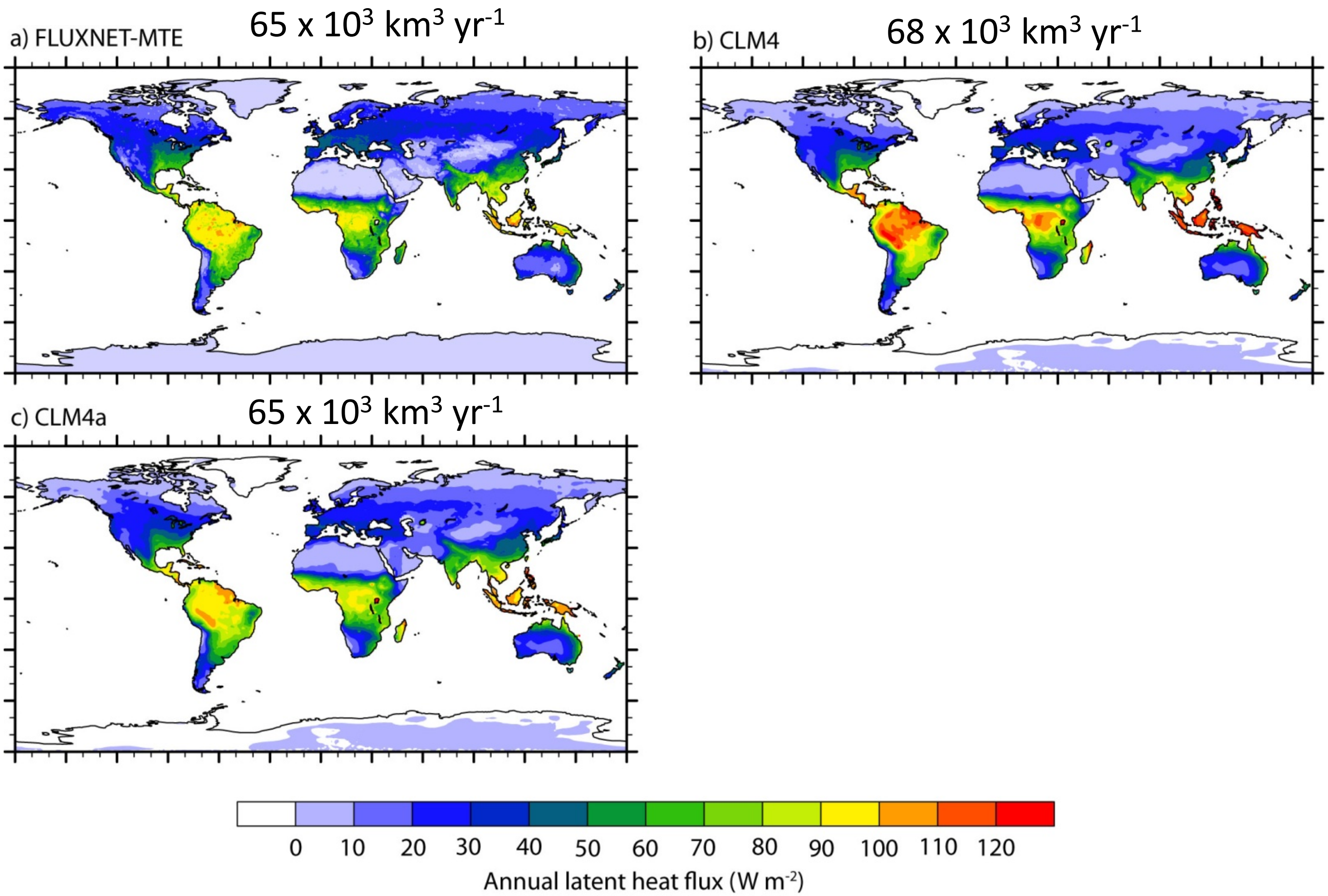
*Model parameter uncertainty*

$V_{cmax}$

Bonan et al. (2011) JGR, doi:10.1029/2010JG001593
Bonan et al. (2012) JGR, doi:10.1029/2011JG001913



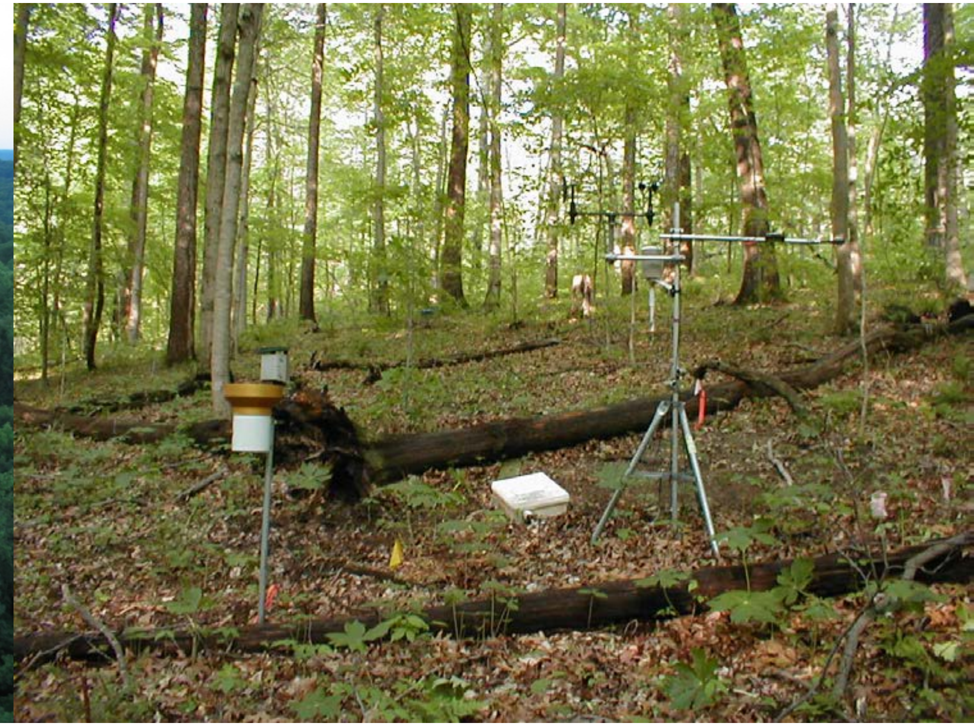
# Improved annual latent heat flux

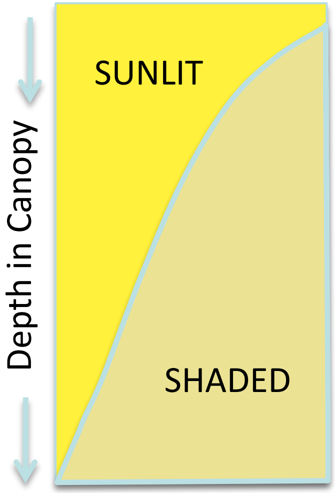



Bonan et al. (2011) JGR, doi:10.1029/2010JG001593

# Two ways to model plant canopies

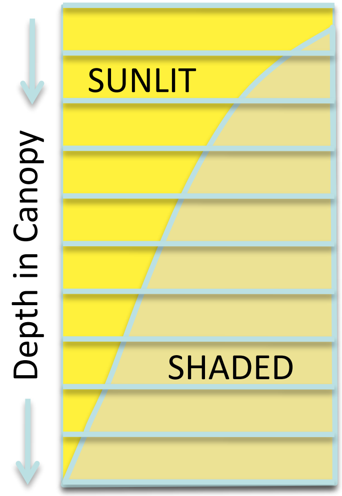
Photographs of Morgan Monroe State Forest tower site illustrate two different representations of a plant canopy: as a “big leaf” (below) or with vertical structure (right)






**Big-leaf canopy**

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




**Multi-layer canopy**

- Explicitly resolves sunlit and shaded leaves at each layer in the canopy
- Light, temperature, humidity, wind speed, H, E, $A_n$, $g_s$

# Debate “settled” two decades ago

*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

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

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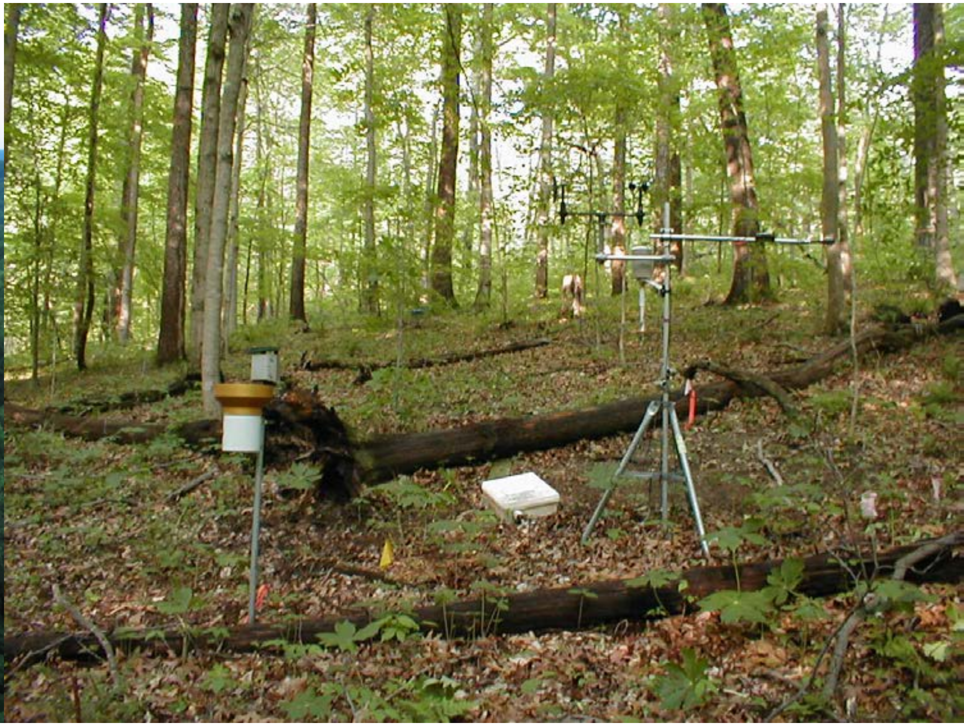
[a] *CSIRO Division of Atmospheric Research, PMB # 1, Aspendale, Vic 3195, Australia*
[b] *CSIRO Land and Water, FC Pye Laboratory, Canberra, ACT 2601, Australia*

# 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)

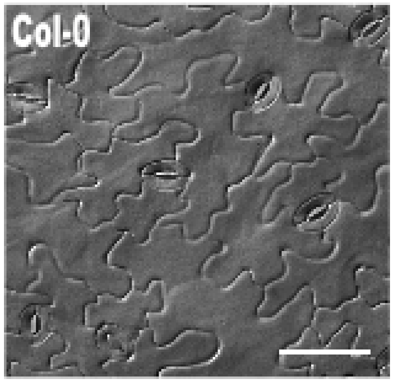


**big-leaf canopy ≠ multi-layer canopy …**

It can be tuned to look like a multi-layer canopy ($K_n$ is the key knob), but that is not very satisfying

A multi-layer canopy opens new opportunities for modeling stomatal conductance

# Stomatal conductance and water stress




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. Simple to scale over a canopy. But soil moisture stress applied through an ad-hoc wetness factor (btran) that reduces $g_0$ and $A_n$ ($V_{cmax}$)

Optimization theory

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

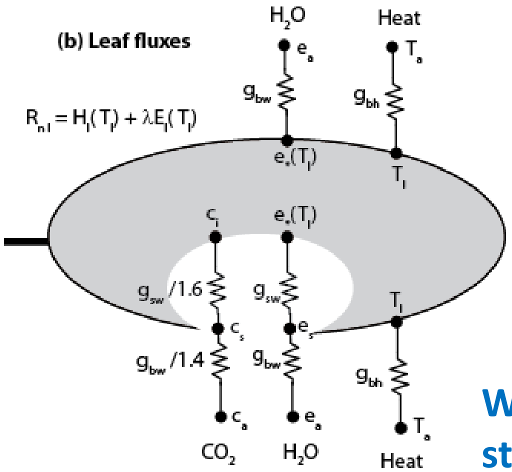
$$\Delta A_n \leq \iota D_s \Delta g_s \quad \text{and} \quad \psi_l > \psi_{l\min}$$

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

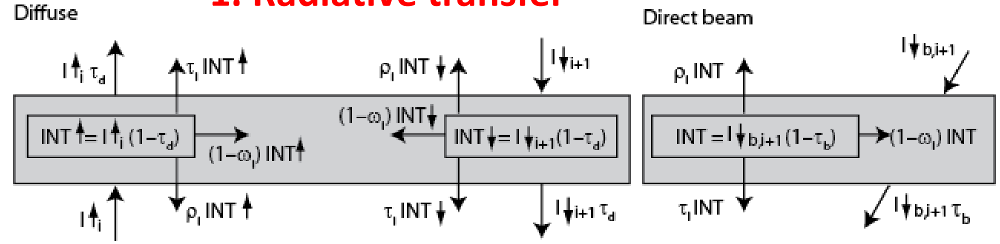
Cannot analytically scale over a canopy. Requires $\psi_L$ at each layer in canopy calculated from soil-plant-atmosphere continuum theory

# A multi-layer canopy model for use with CLM

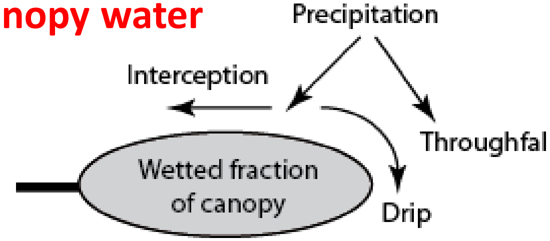
## 2. Leaf fluxes ($CO_2$, H, E)




## 1. Radiative transfer



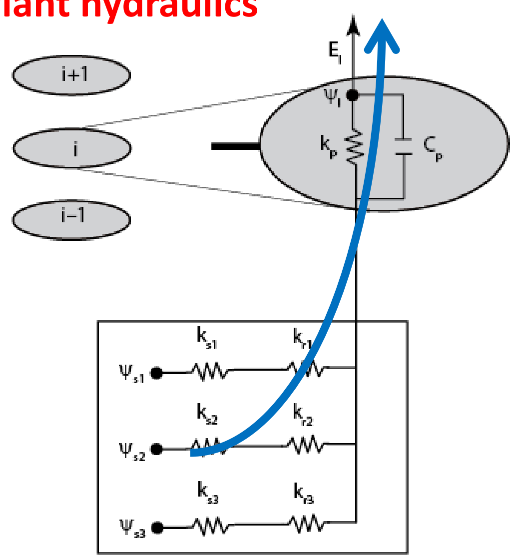

## 4. Canopy water



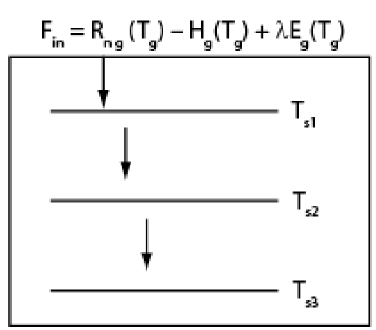

**Water-use efficiency stomatal optimization:**

$\Delta A_n/\Delta E_l > \iota$ and $\psi_L > \psi_{Lmin}$

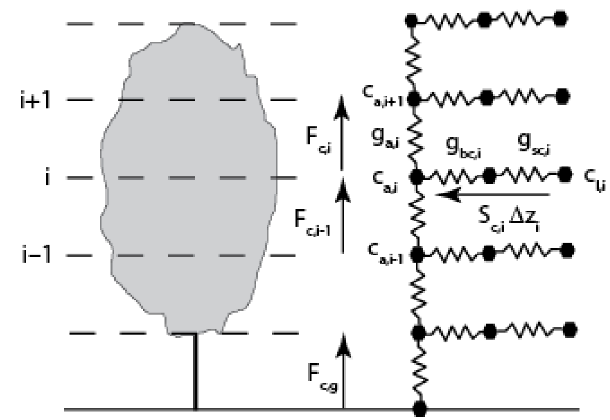
## 3. Plant hydraulics




## 5. Soil fluxes

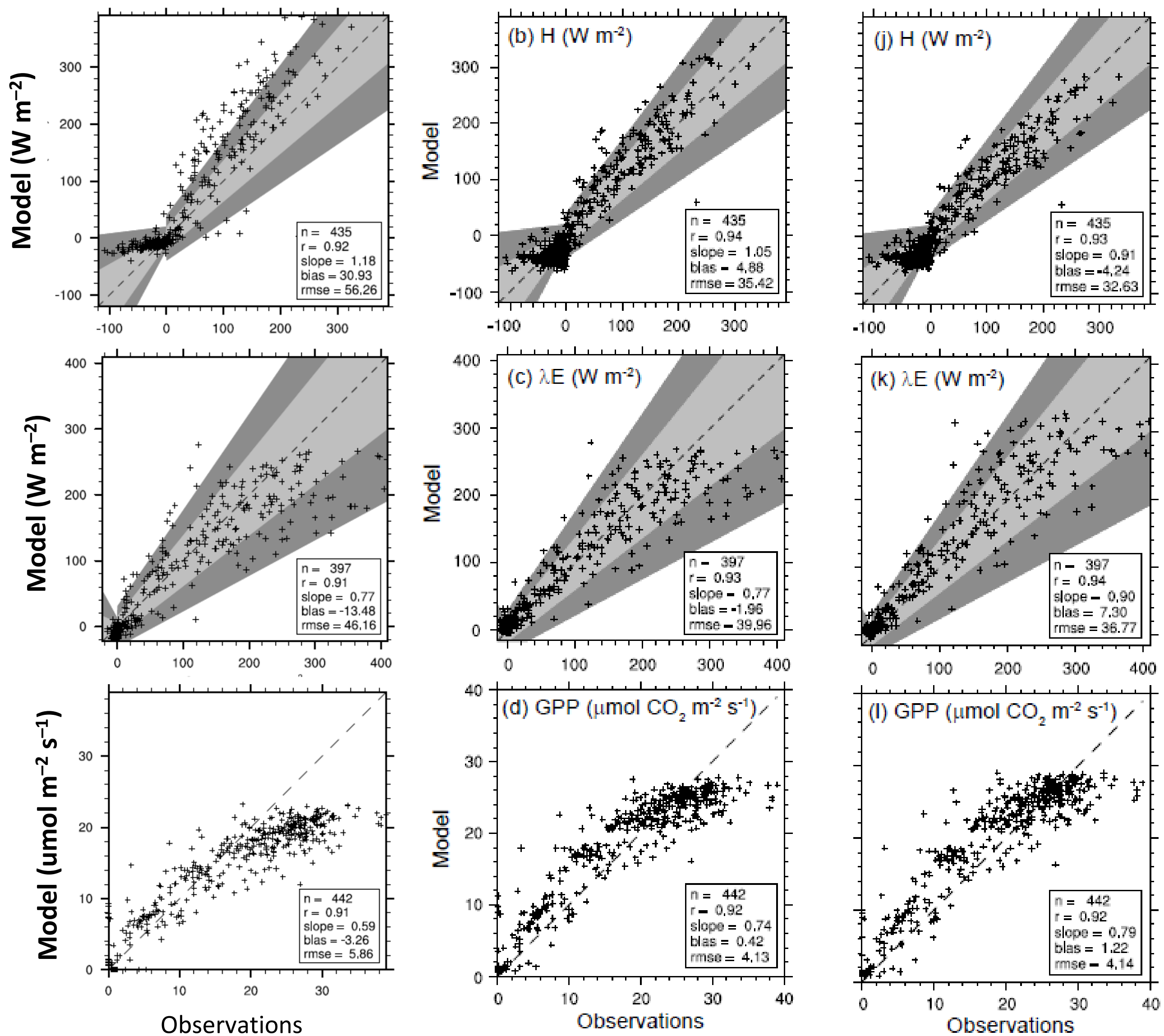



## 6. Above- and within canopy turbulence and scalar profiles



# US-Ha1, July 2001 (broadleaf deciduous forest)

**CLM4.5** | **CLMml Ball-Berry** | **CLMml optimal WUE**




**Sensible heat flux**

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

**Latent heat flux**

**GPP**

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

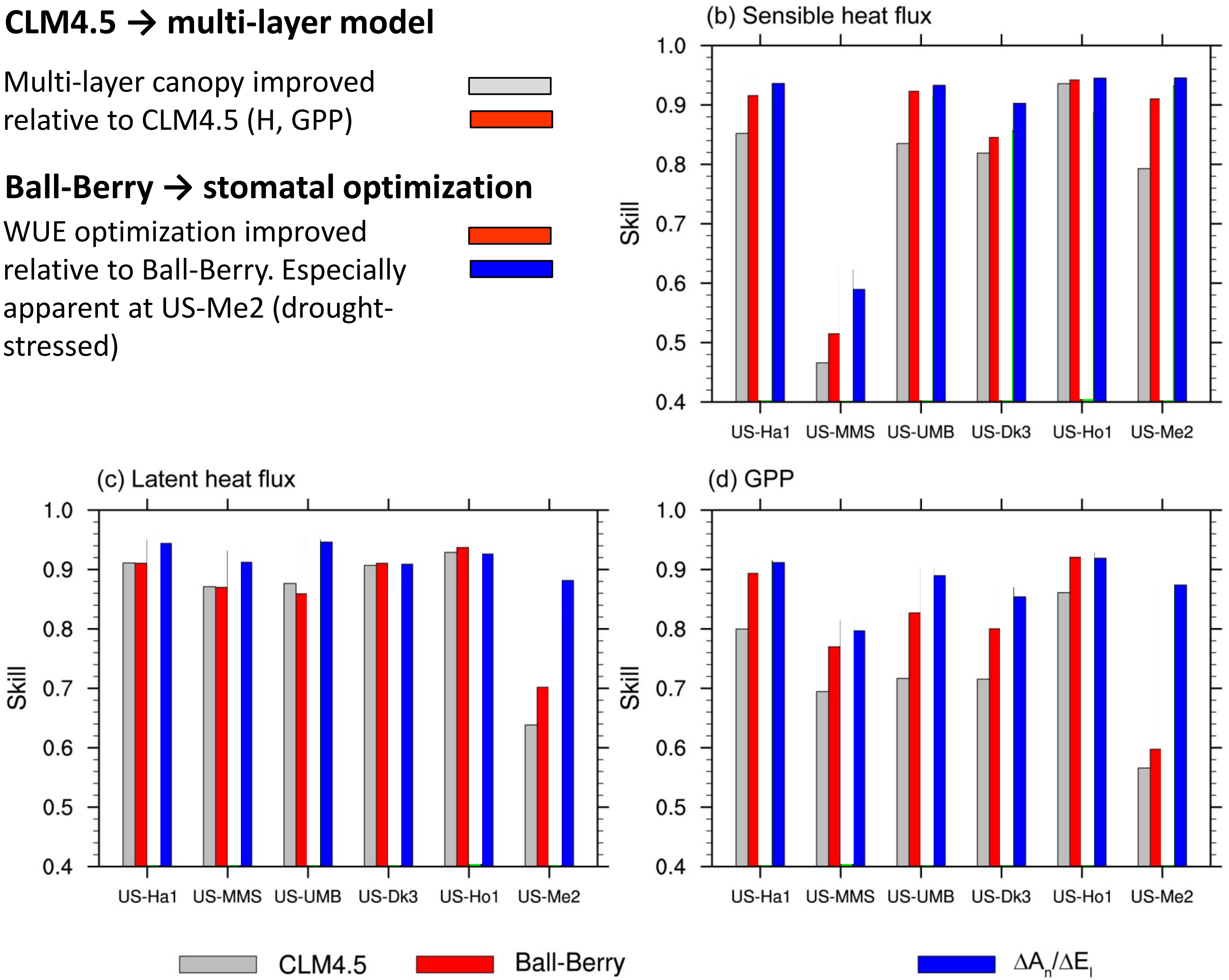
# Site x year summary of model skill

**CLM4.5 → multi-layer model**

Multi-layer canopy improved relative to CLM4.5 (H, GPP)

**Ball-Berry → stomatal optimization**

WUE optimization improved relative to Ball-Berry. Especially apparent at US-Me2 (drought-stressed)




AmeriFlux
3 DBF, 3 ENF
51 site x years

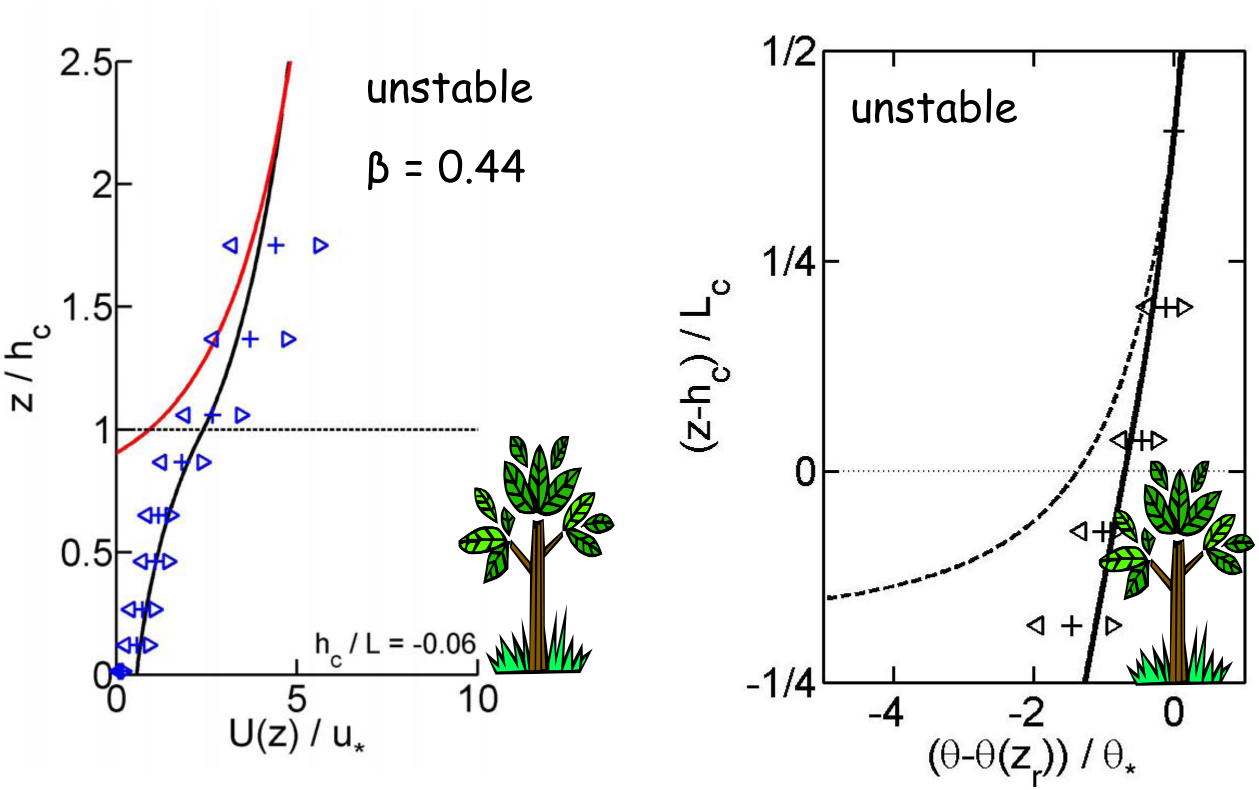
Bonan et al. (2014) Geosci. Model Dev. 7:2193-2222

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

# Canopy turbulence and the roughness sublayer

Profiles from the CSIRO flux station near Tumbarumba

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

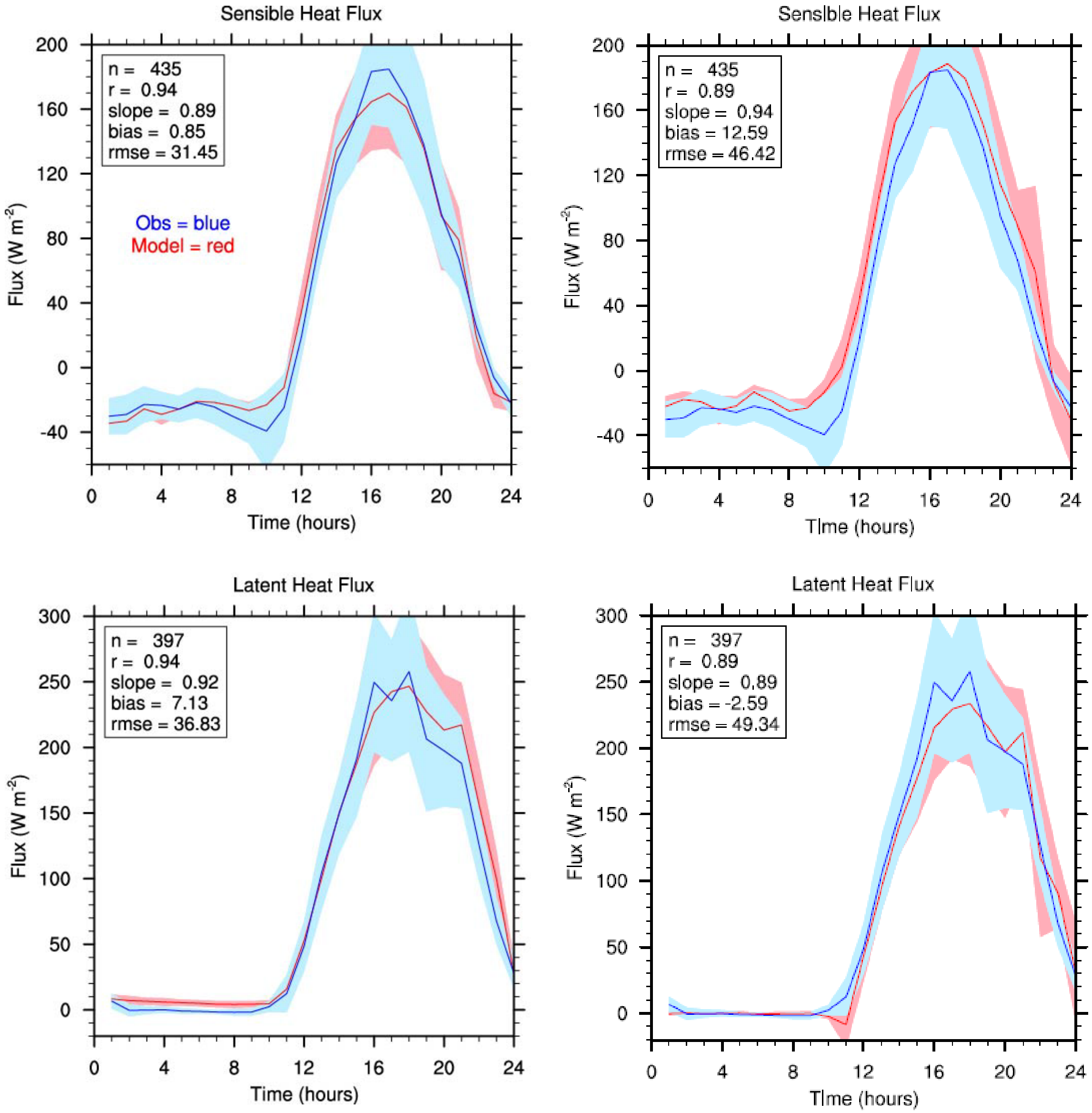



Collaborators:
Ned Patton (NCAR)
Ian Harman (CSIRO Marine and Atmospheric Research)


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

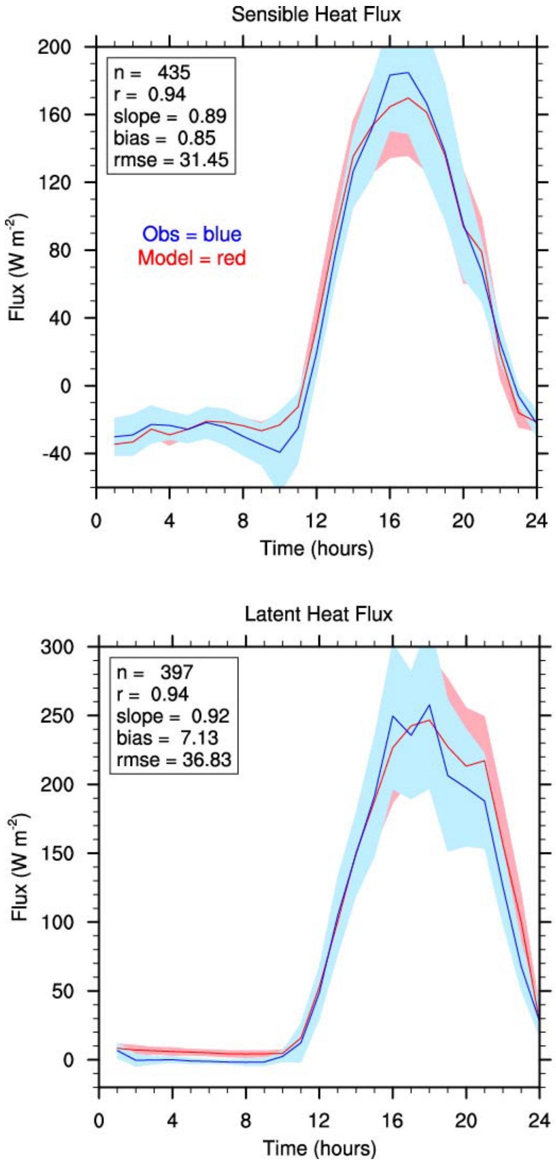
# US-Ha1, July 2001 (broadleaf deciduous forest)

**CLMml + WUE** | **CLMml + WUE + RSL**

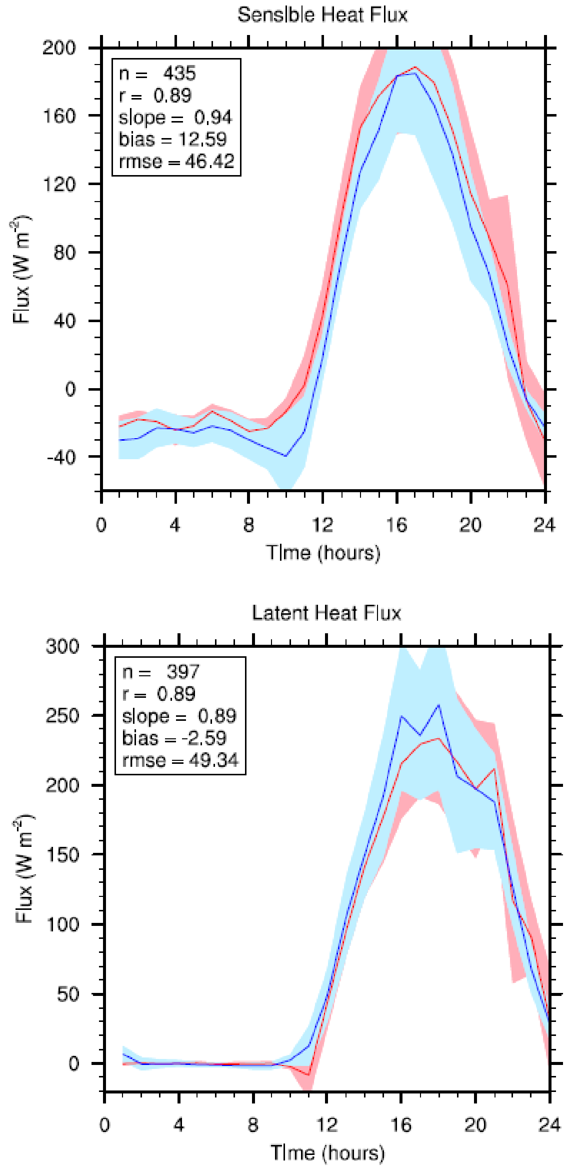


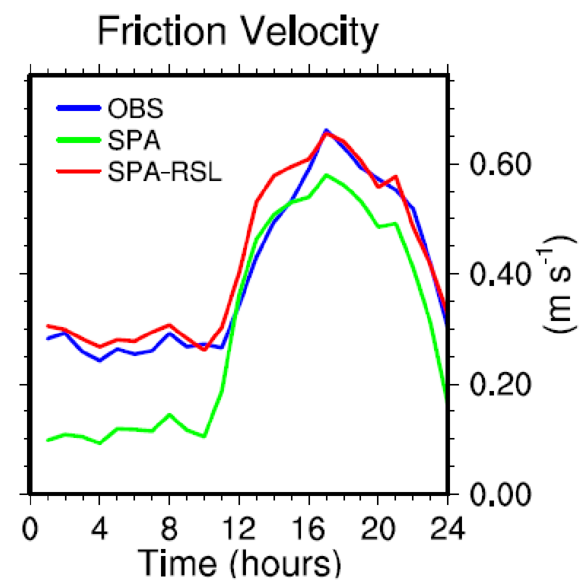
# US-Ha1, July 2001 (broadleaf deciduous forest)

**CLMml + WUE**




**CLMml + WUE + RSL**

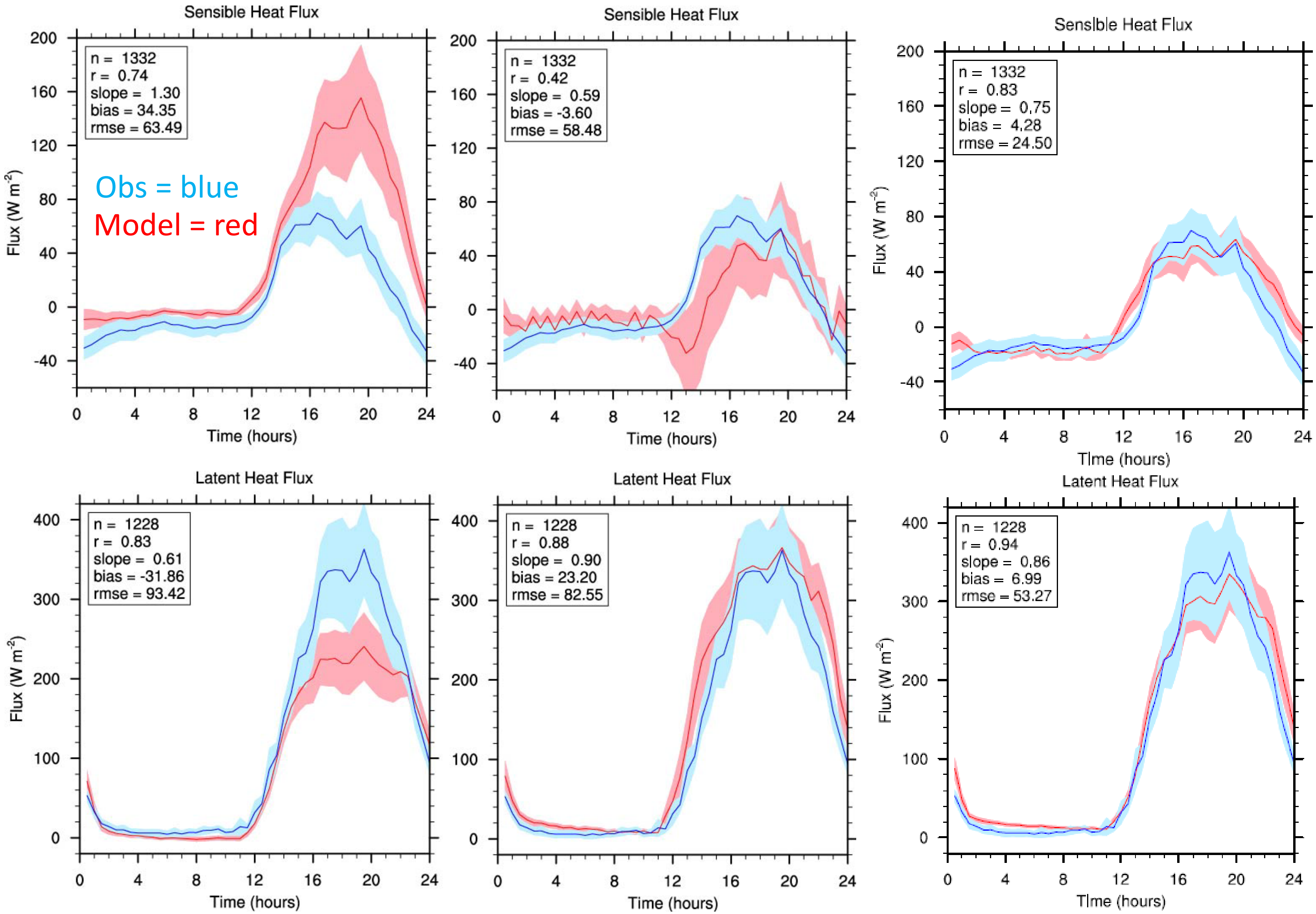



(Ned Patton)

# US-IB1, July 2006 (crop)

**CLM4.5** | **CLMml + WUE** | **CLMml + WUE + RSL**



# Status and new directions with a multi-layer canopy

1. CLM4.5 uses a sunlit/shaded big-leaf canopy model with revised leaf photosynthesis, $V_{cmax}$, radiative transfer, and canopy scaling (light, nitrogen)
2. Multi-layer canopy is not ready for CLM5:

   Still implementing canopy turbulence and roughness sublayer

   Testing for forest, grassland and cropland

   To do: tropical forest and savanna; $C_4$ stomatal optimization; interception and evaporation
3. Links to other CLM parameterizations: dry deposition, BVOCs, isotopes, ozone damage, fluorescence
4. New frontier: canopy chemistry – how does the chemical environment affect surface fluxes, e.g., BVOCs-$O_3$-stomata?