Thoughts on modeling plant canopies: Insights from the Canopy Horizontal Array Turbulence Study (CHATS)

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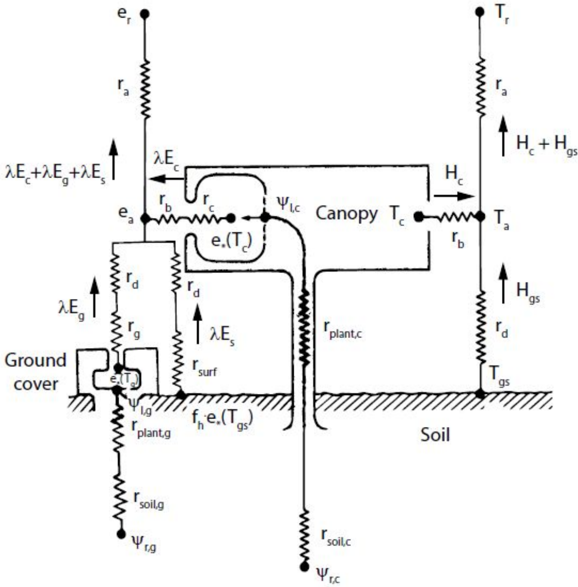
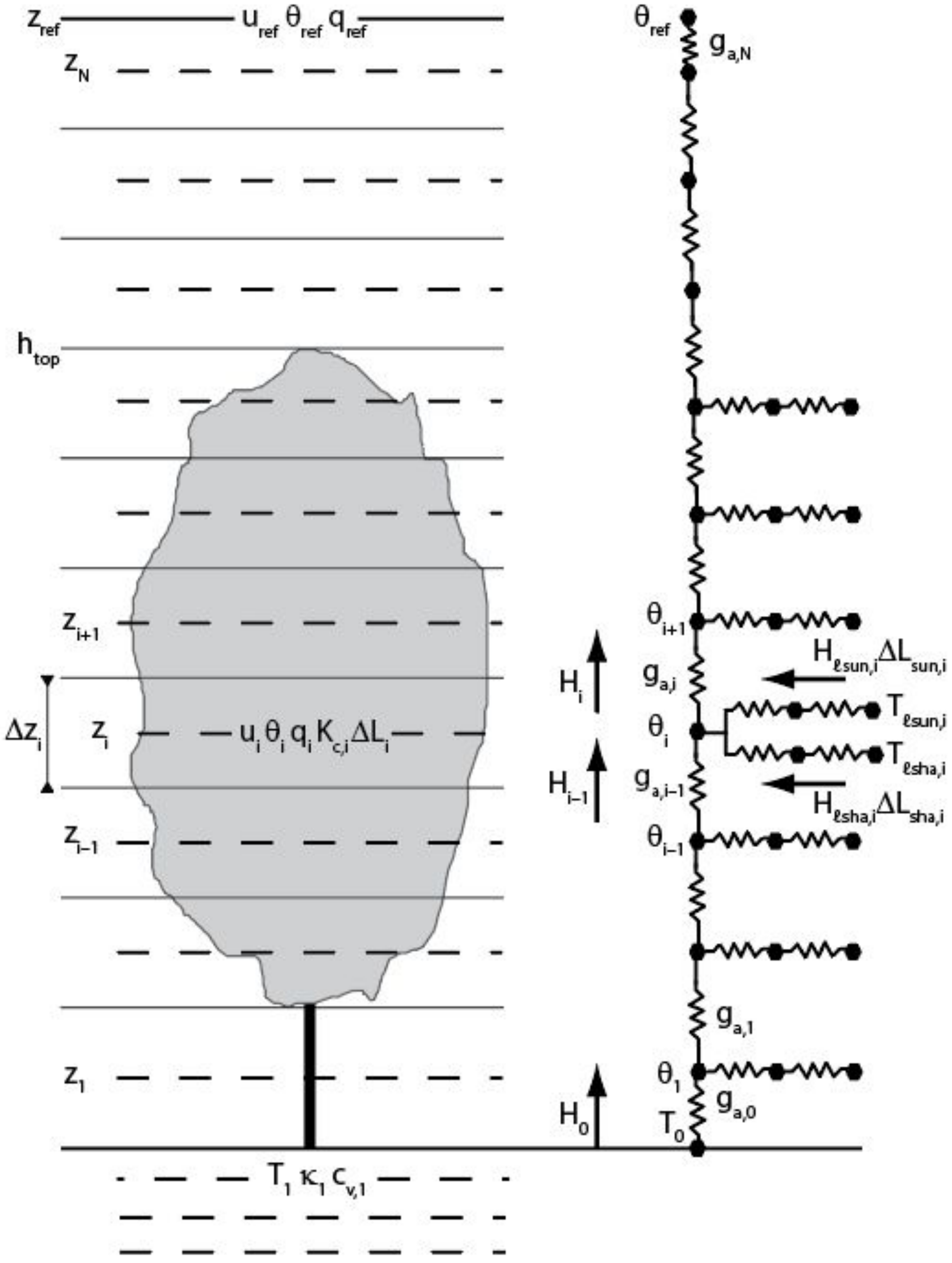
Boulder, Colorado, USA

CESM Land Model Working Group
24 February 2025



NCAR is a major facility sponsored by the National Science Foundation under Cooperative Agreement No. 1852977

Multilayer canopy



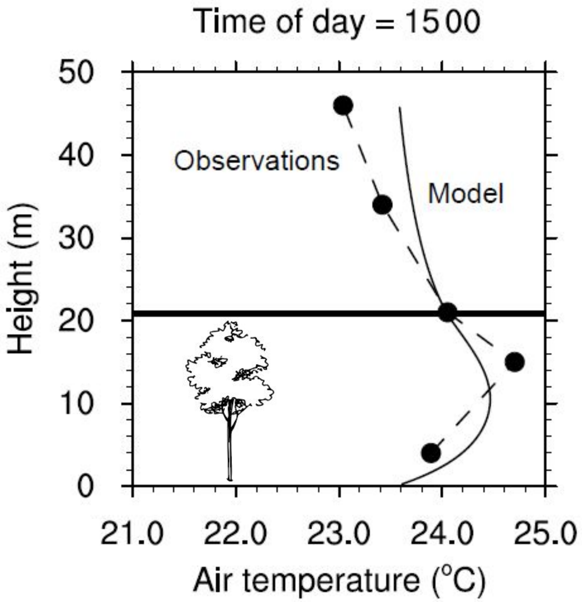
The physics and physiology of the multilayer canopy are simpler and more consistent with theory (and directly observable) than is the CLM5/6 big-leaf canopy (with many ad-hoc parameterizations and much technical debt), and the model enables new science

Bonan, Williams et al. (2014) *Geosci. Model Dev.*, 7, 2193-2222

Bonan, Patton, et al. (2018) *Geosci. Model Dev.*, 11, 1467-1496

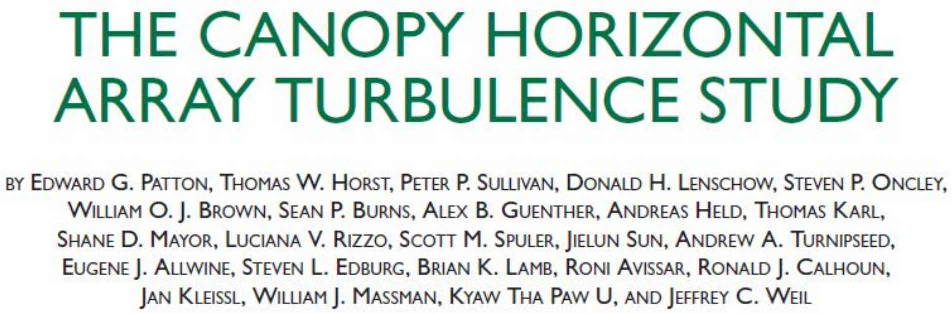
Bonan, Patton, Finnigan, et al. (2021) *Agric. For. Meteorol.*, 306, 108435

Bonan, Burns & Patton (2025), in prep.



University of Michigan Biological Station

Observational dataset

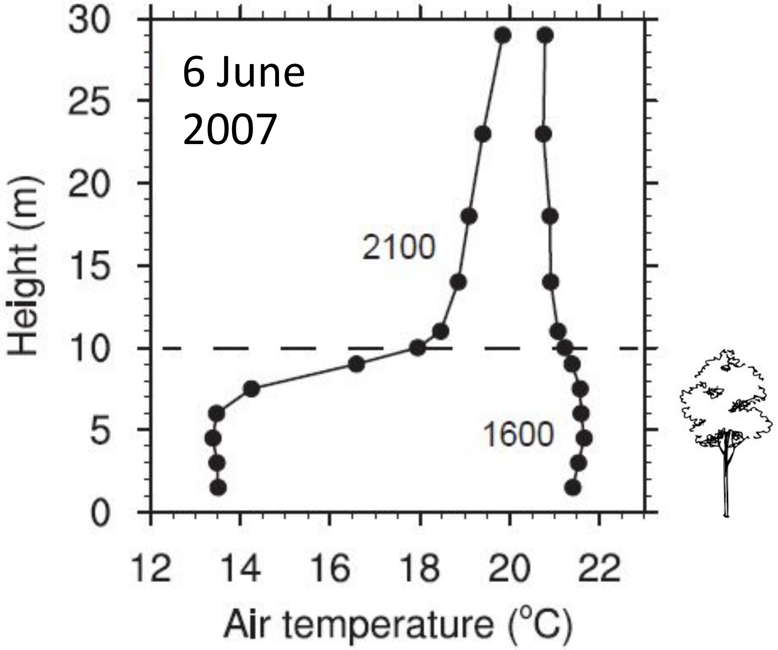


THE CANOPY HORIZONTAL ARRAY TURBULENCE STUDY

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

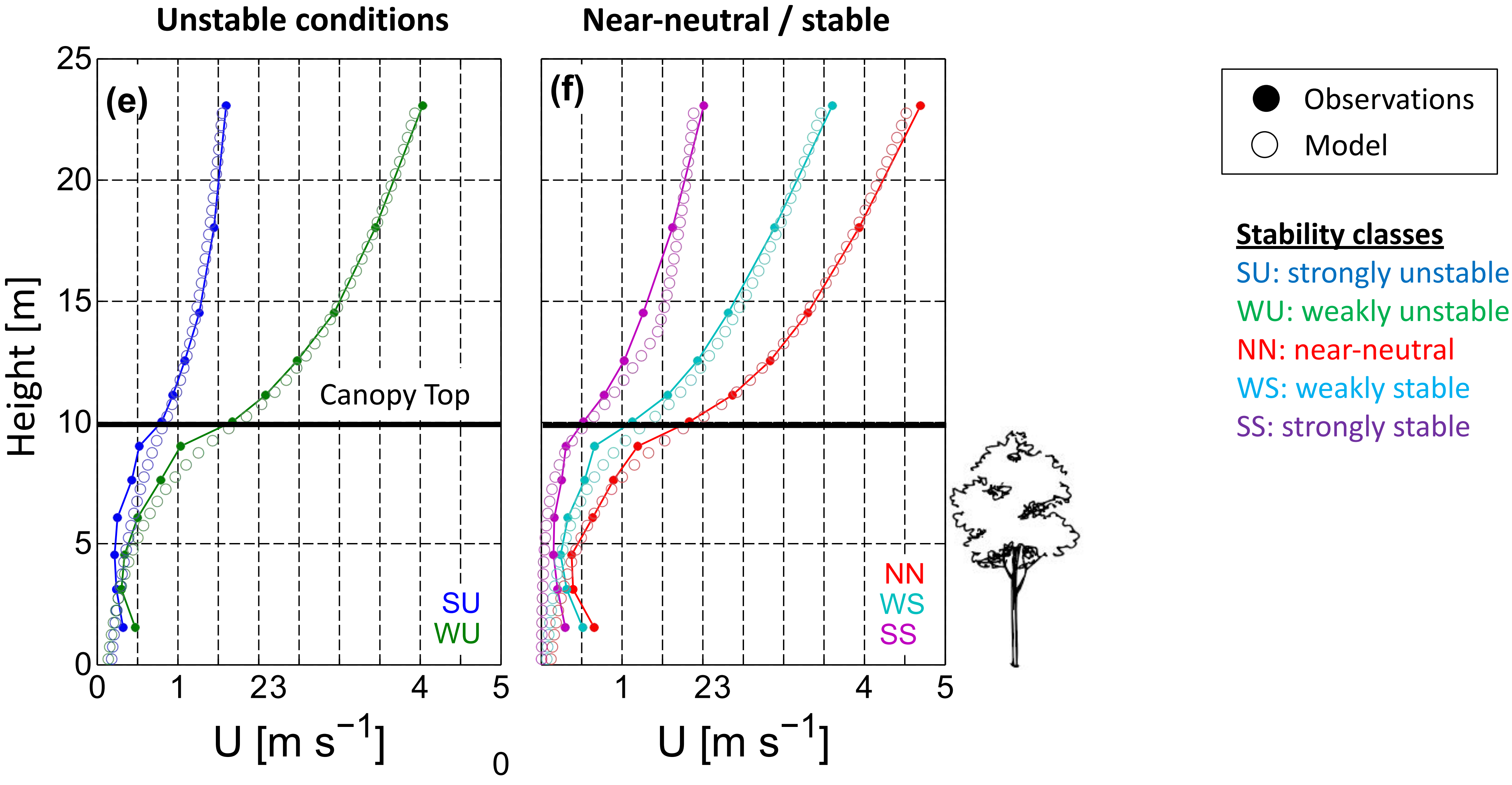
Patton et al. (2011) *BAMS*, 92, 593-611

mid-March – mid-June 2007



6 June 2007

Wind speed (May 2007)



Stability classes

SU: strongly unstable

WU: weakly unstable

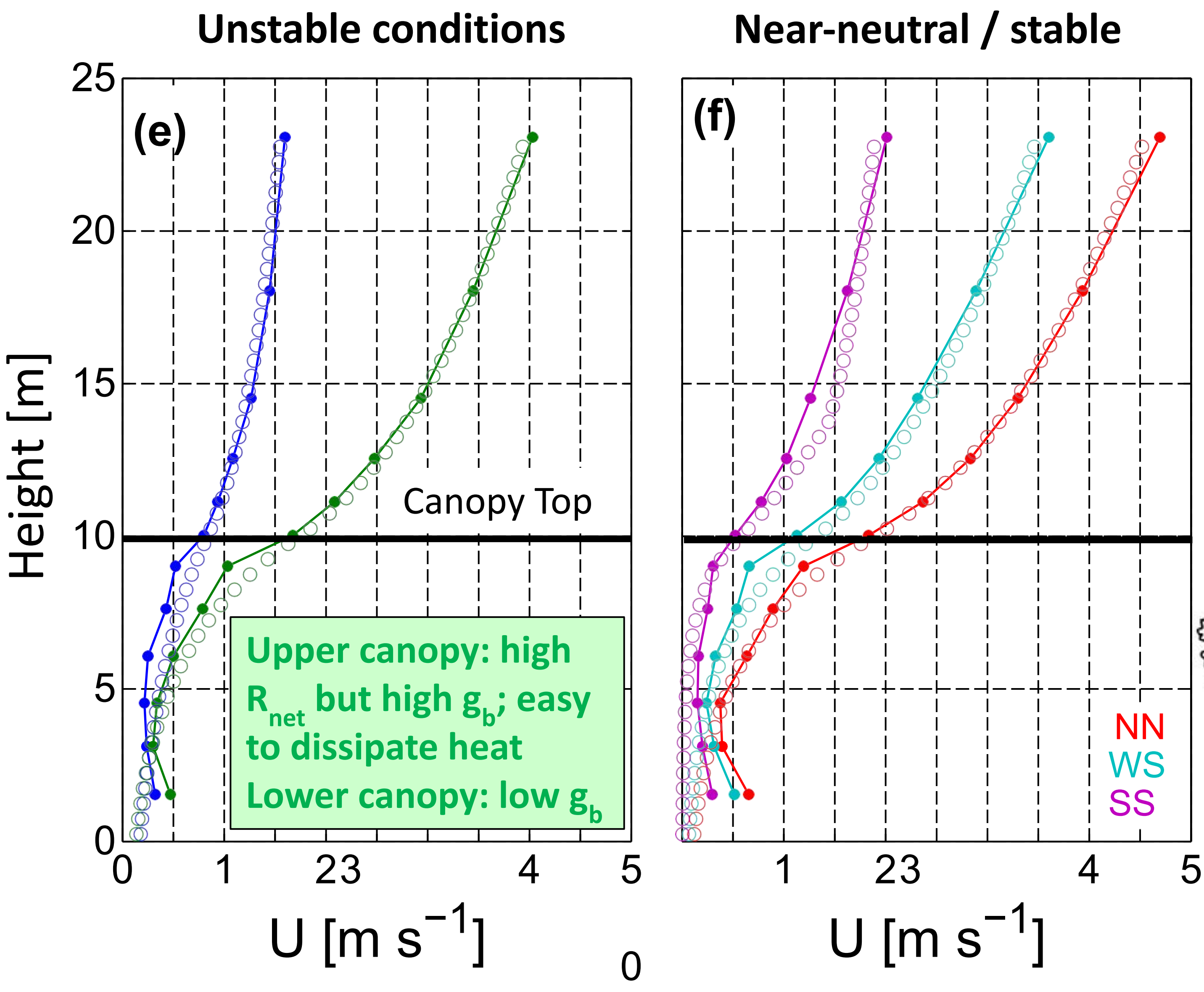
NN: near-neutral

WS: weakly stable

SS: strongly stable

Bonan, Burns & Patton (unpublished)

Wind speed (May 2007)



Upper canopy: high R_{net} but high g_b; easy to dissipate heat

Lower canopy: low g_b

● Observations
○ Model

Stability classes

SU: strongly unstable
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WS: weakly stable
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Analytical solution to the one-dimensional (vertical) momentum conservation equation

Bonan, Burns & Patton (unpublished)

CLM5/6 canopy physics: wind speed in canopy

1984

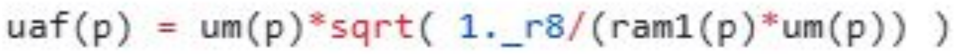
$U_{af} = u_*$

"The assumption that $U_{af} = u_*$ in general **is of adequate accuracy for the present model**, considering the uncertainty in the other aspects of the foliage conductance."

Dickinson (1984) in *Climate Processes and Climate Sensitivity* (Hansen & Takahashi, eds.; AGU)

2025: CLM6

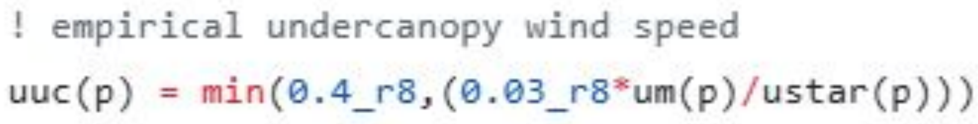
CLM6 has a bulk wind speed in the canopy (uaf) that is equal to u_*. uaf is used to calculate leaf boundary layer conductance.



```
uaf(p) = um(p)*sqrt( 1._r8/(ram1(p)*um(p)) )
```

Simplifies to u_*

Introduces an under-canopy wind speed (uuc)



```
! empirical undercanopy wind speed
uuc(p) = min(0.4_r8,(0.03_r8*um(p)/ustar(p)))
```

CLM5/6 canopy physics: wind speed in canopy

1984

$U_{af} = u_*$

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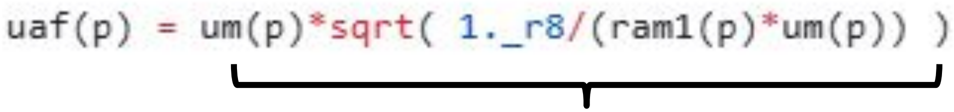
Dickinson (1984) in *Climate Processes and Climate Sensitivity* (Hansen & Takahashi, eds.; AGU)

CLM6: multiple wind speeds
uaf: u_* is a measure of turbulence not wind
uuc: introduced with biomass heat storage
u10 (10-m wind) and fire spread (?)

2025: CLM6

CLM6 has a bulk wind speed in the canopy (uaf) that is equal to u_*. uaf is used to calculate leaf boundary layer conductance.



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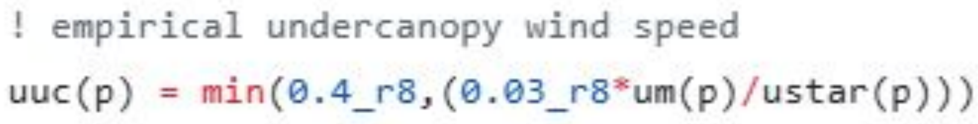

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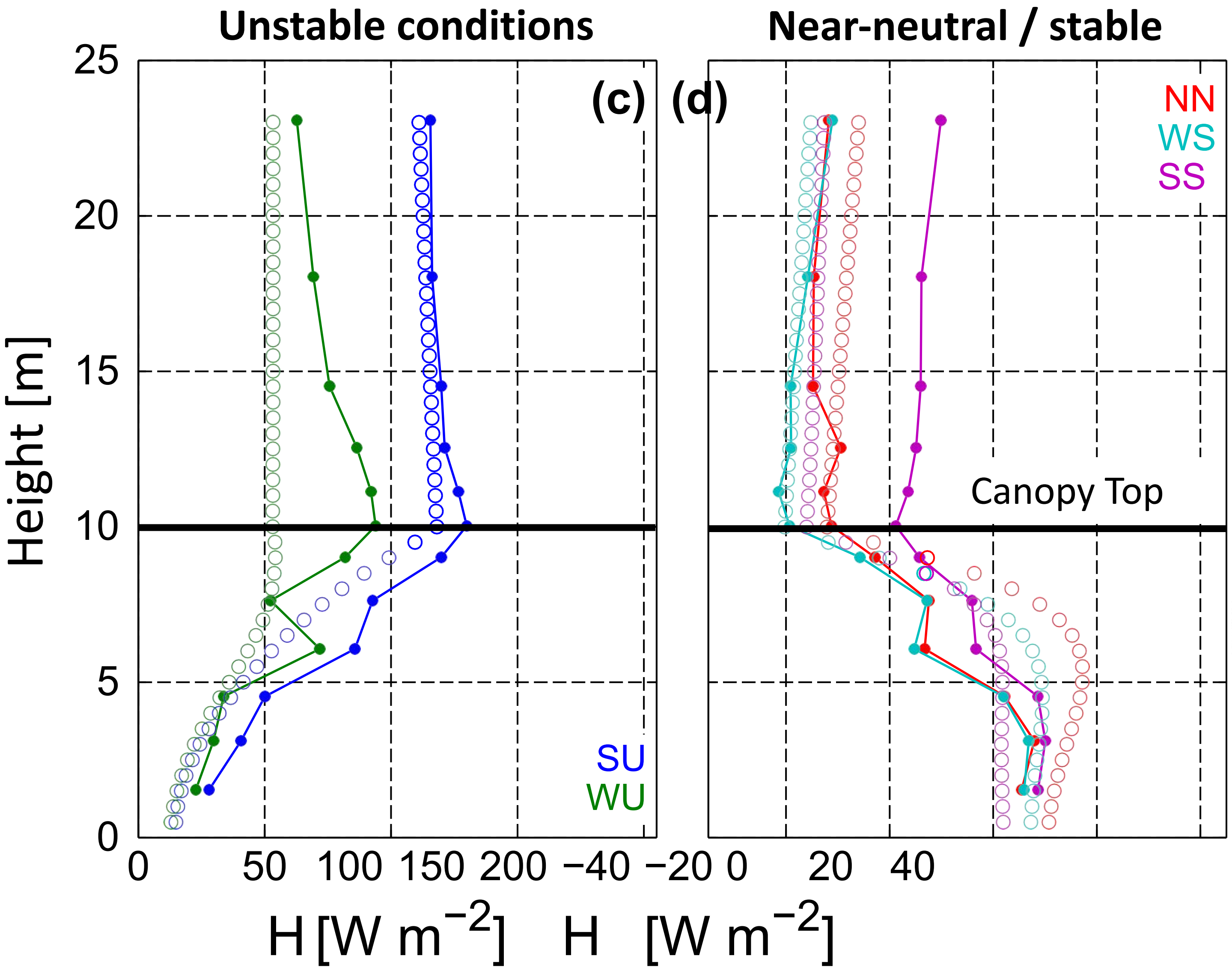
```

Sensible heat flux



● Observations
○ Model

Stability classes

SU: strongly unstable
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WS: weakly stable
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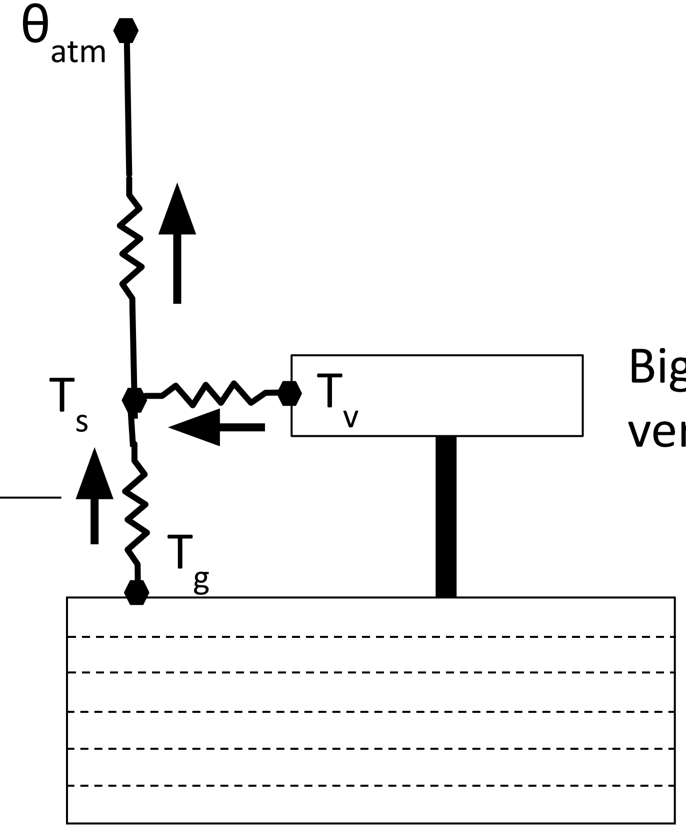
Uses first-order turbulence closure

Bonan, Burns & Patton (unpublished)

CLM5/6 perspective of the land surface



Big-leaf canopy without vertical structure

$H_{soil} = \rho_{atm}\, c_p\, (T_g - T_s) / r'_{ah}$

Bulk flux of sensible heat from ground to canopy air

What is r'_{ah}?

CLM5/6 canopy physics: under-canopy turbulence

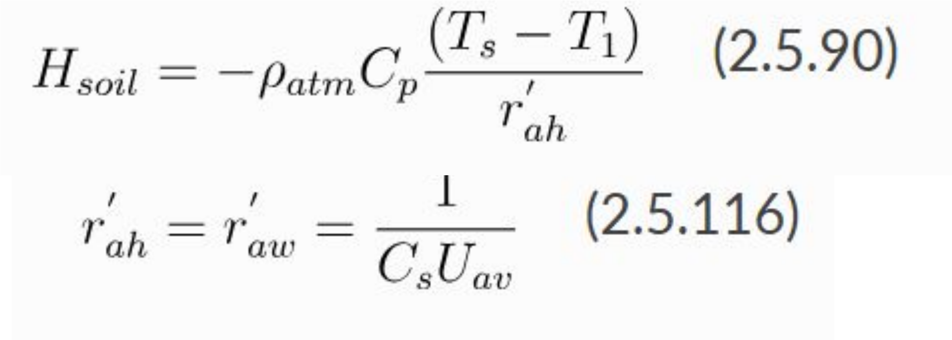
1984

Under-canopy H

$$H_g = \rho_a \, c_p \, C_D \, u_{af} \, (T_g - T_{af})$$

Dickinson (1984) in *Climate Processes and Climate Sensitivity* (Hansen & Takahashi, eds.; AGU)

2025: CLM5/6



$$H_{soil} = -\rho_{atm} C_p \frac{(T_s - T_1)}{r'_{ah}} \qquad (2.5.90)$$

$$r'_{ah} = r'_{aw} = \frac{1}{C_s U_{av}} \qquad (2.5.116)$$

https://escomp.github.io/ctsm-docs/versions/release-clm5.0/html/tech_note/index.html

CLM5/6 canopy physics: under-canopy turbulence

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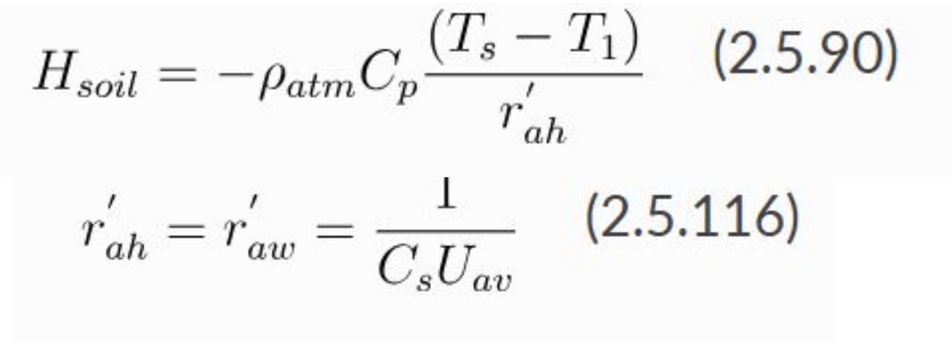

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https://escomp.github.io/ctsm-docs/versions/release-clm5.0/html/tech_note/index.html

Year	Model	Implementation
1993	BATS1e	$C_s = 0.004$
2004	CLM3	$C_s = 0.004$ (dense canopy) ⟶ bare soil as PAI = 0
2010	CLM4	C_s modified for under-canopy stability
2018	CLM5	C_s under-canopy stability removed
2025	CLM6	Replace uaf with uuc (biomass heat storage)

CLM5/6 canopy physics: under-canopy turbulence

1984

Under-canopy H

$$H_g = \rho_a\, c_p\, C_D\, u_{af}\, (T_g - T_{af})$$

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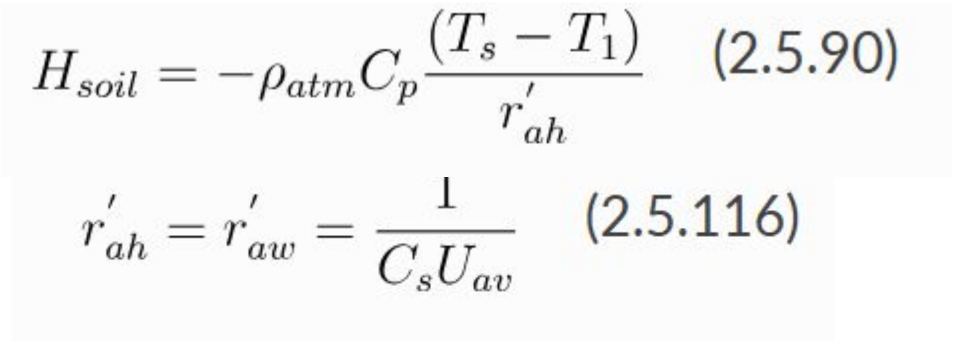
2025: CLM5/6



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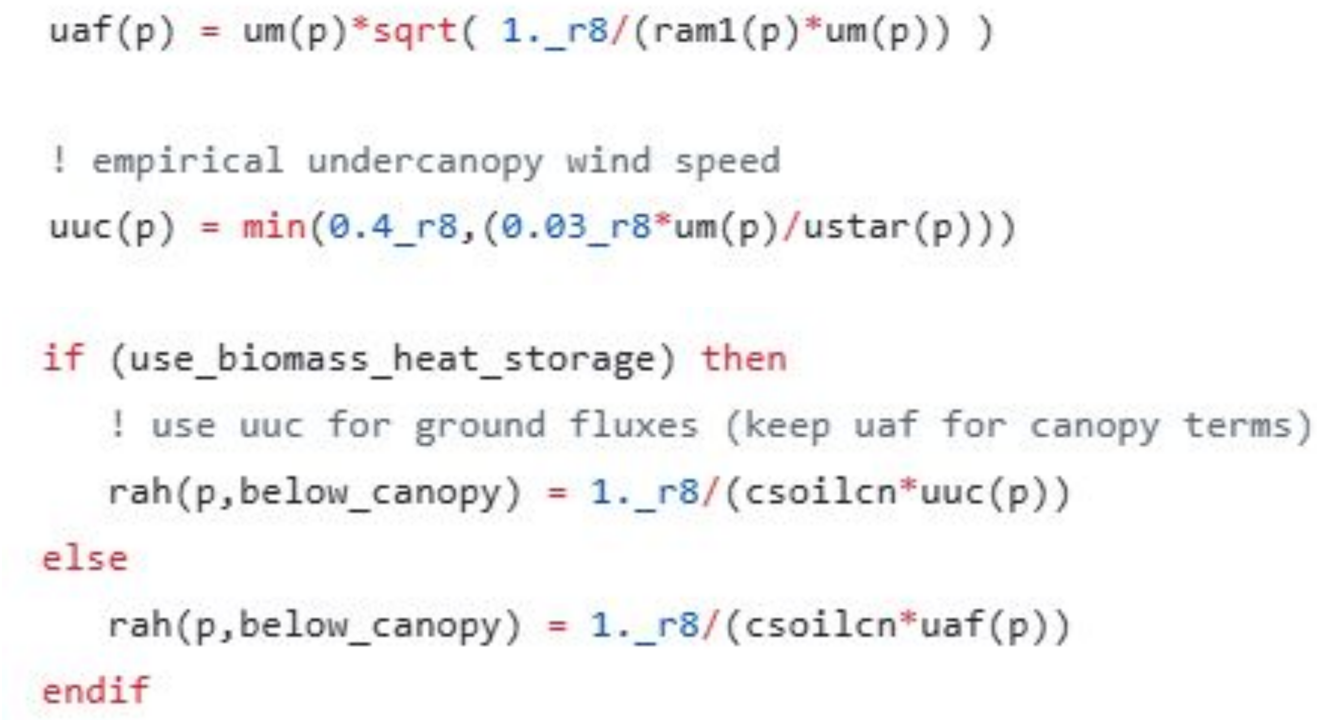
2025: CLM6



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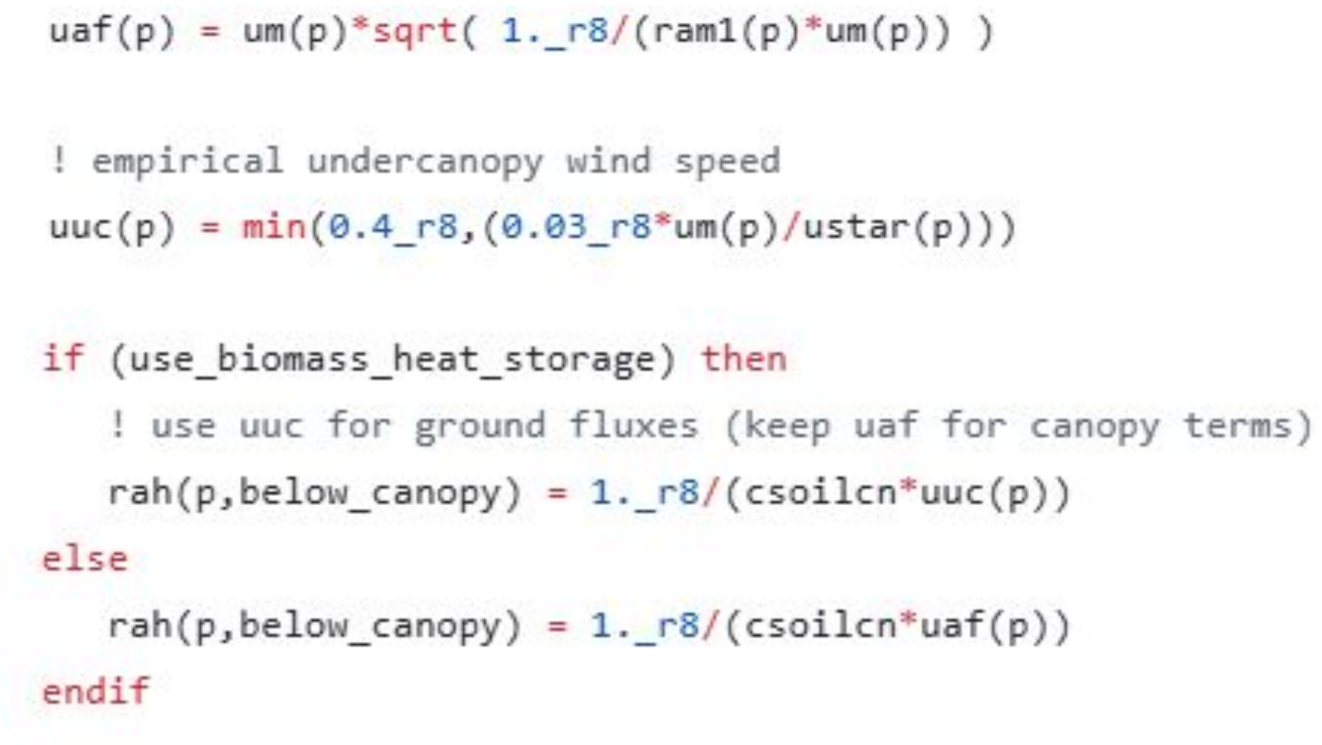
! empirical undercanopy wind speed
uuc(p) = min(0.4_r8,(0.03_r8*um(p)/ustar(p)))

if (use_biomass_heat_storage) then
   ! use uuc for ground fluxes (keep uaf for canopy terms)
   rah(p,below_canopy) = 1._r8/(csoilcn*uuc(p))
else
   rah(p,below_canopy) = 1._r8/(csoilcn*uaf(p))
endif
```

CLM5/6 canopy physics: under-canopy turbulence

2025: CLM6

- Conceptual framework is unchanged over 40+ years
- C_s and u change as needed for a particular model configuration
- uuc changes fluxes in a way unrelated to the storage of heat in biomass. It changes the under-canopy turbulence.



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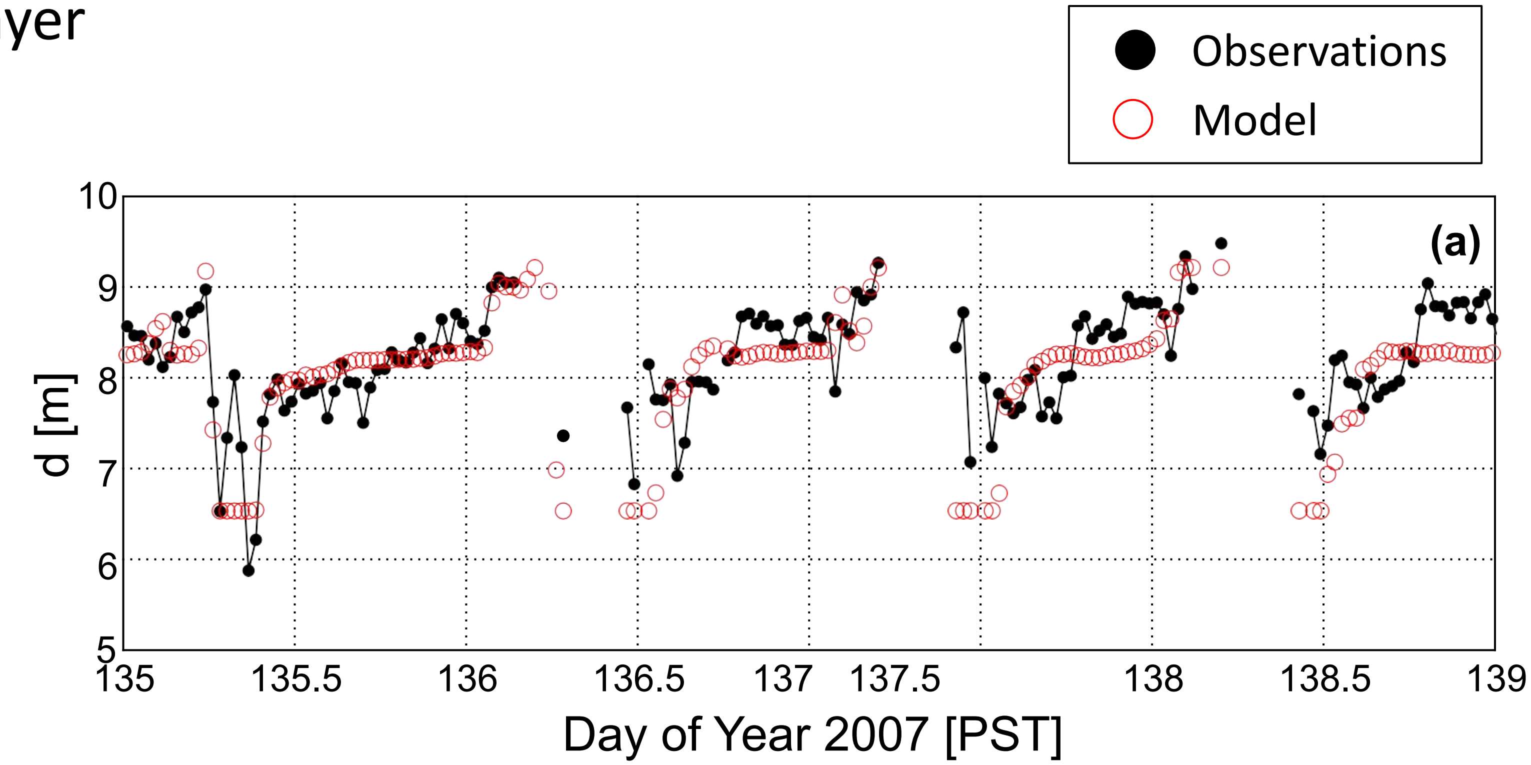
```

Canopy turbulence: z_0 & d

- z_0 is an empirical parameter used in MOST
- Multilayer canopy replaces z_0 with observable canopy-imposed parameters (e.g., leaf drag coefficient)
- *d* emerges from roughness sublayer theory and depends on flow
- Varies by 3 m in a 10-m canopy!



Bonan, Burns & Patton (unpublished)

CLM5/6 canopy physics

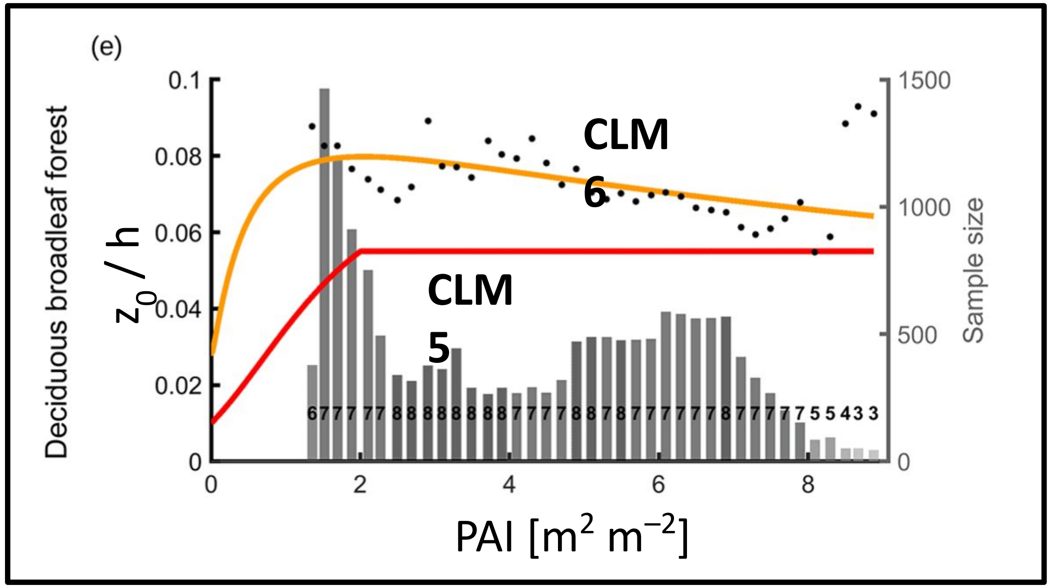
Roughness length (z_0) and displacement height (*d*)

Treated as canopy parameters: vary with *h* and *PAI*

CLM5: Zeng & Wang (2007)

CLM6: Meier et al. (2022) ⟶ Raupach (1994) fitted to FLUXNET data

FATES: passes z_0 and *d* to CLM: f(h)
& CLM6 adjusts for PAI using
Zeng & Wang (2007) as in CLM5



Meier et al. (2022) Geosci. Model Dev., 15, 2365–2393

CLM5/6 canopy physics

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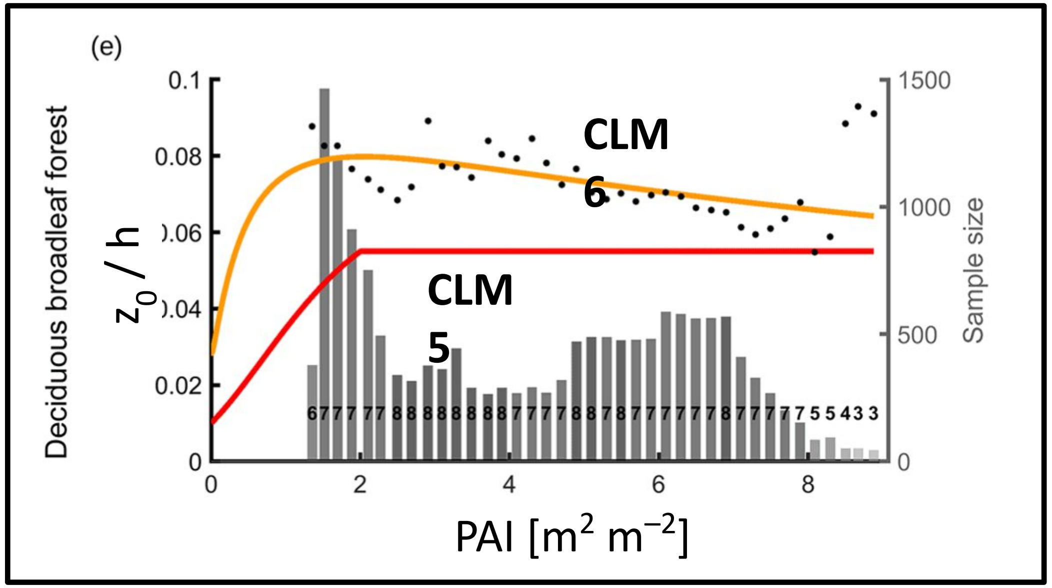
Technical debt:
5 subroutines in 4 modules
6 variables in two data types



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CLM5/6 and FATES treat z_0 and d as canopy structural parameters not as turbulent flow parameters

Leads to scientific debt in how z_0 and d are used throughout CLM, e.g.

forc_hgt = $z_{atm} + z_0 + d$

Technical debt:
5 subroutines in 4 modules
6 variables in two data types

Canopy physics: a complex system of equations

Fluxes depend on canopy states but canopy states depend on fluxes:

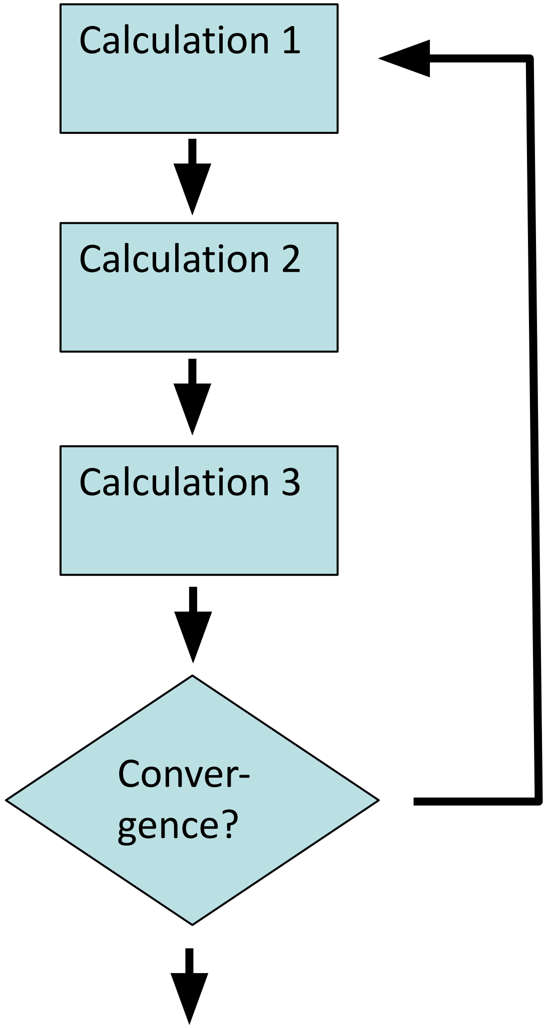
- $g_s = f(T_{leaf})$ and $T_{leaf} = f(g_s)$
- $L = f(H, \lambda E)$ and $H = f(L)$, $\lambda E = f(L)$

The physiological state of a plant community substantially influences the microclimate within it; in turn, the microclimate influences the physiological state, so that neither is independent of the other.

Finnigan & Raupach (1987) in *Stomatal Function*
(Zeiger, Farquhar & Cowan, eds.; Stanford Univ. Press)

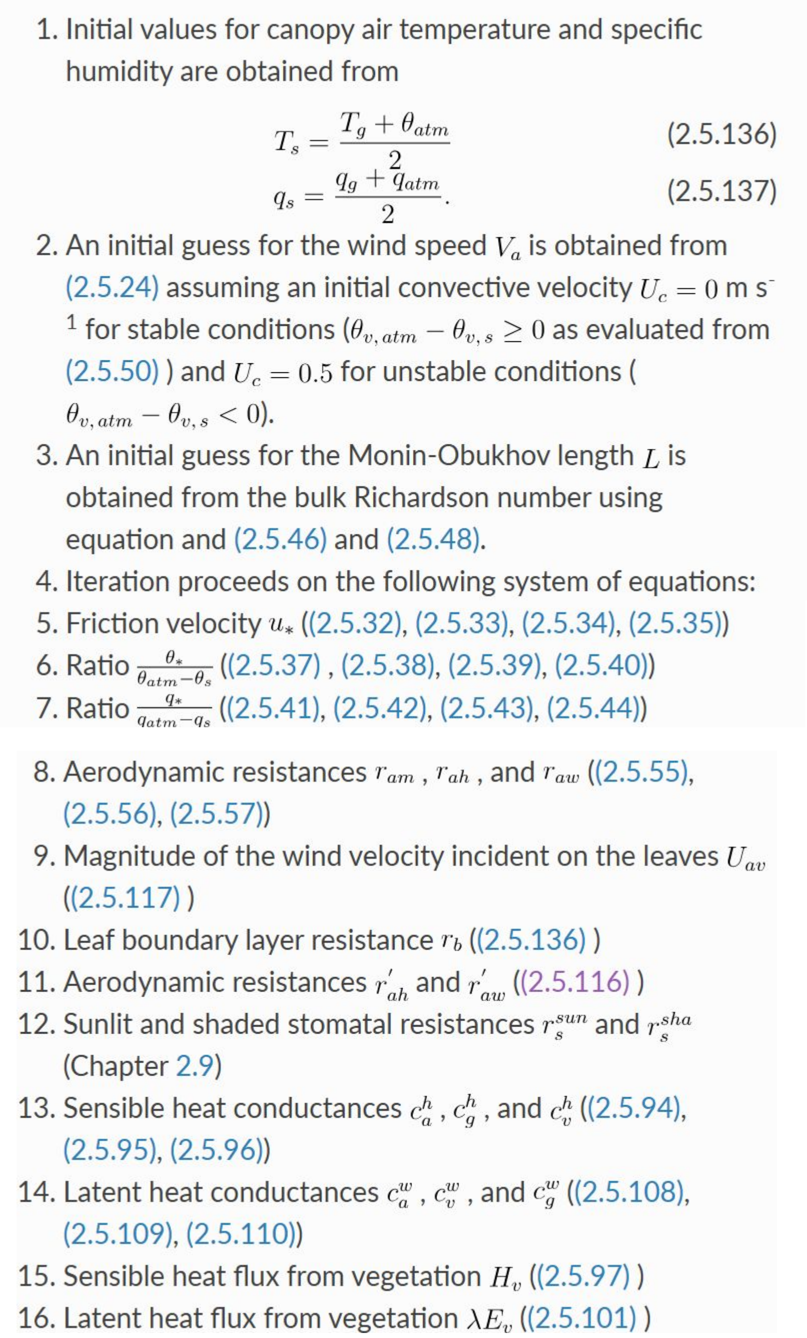
CLM5/6 canopy physics: a deep dive

CLM5/6 use a multistep iterative solution for fluxes/temperature



Up to 40 iterations (standard)
and 3 iterations (fast)

37 step solution



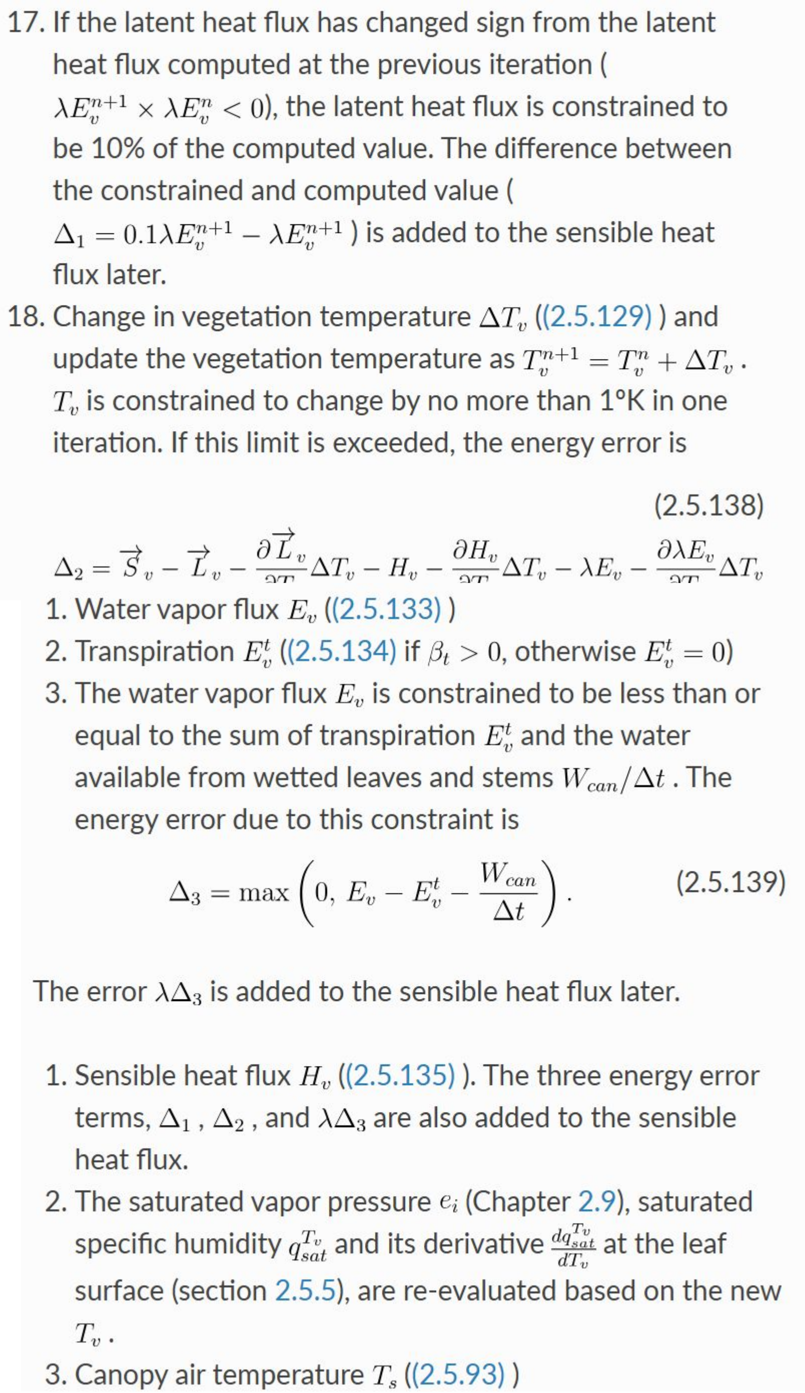
1. Initial values for canopy air temperature and specific humidity are obtained from

$$T_s = \frac{T_g + \theta_{atm}}{2} \qquad (2.5.136)$$

$$q_s = \frac{q_g + q_{atm}}{2}. \qquad (2.5.137)$$

2. An initial guess for the wind speed V_a is obtained from (2.5.24) assuming an initial convective velocity $U_c = 0$ m s⁻ ^{1} for stable conditions ($\theta_{v,atm} - \theta_{v,s} \geq 0$ as evaluated from (2.5.50)) and $U_c = 0.5$ for unstable conditions ($\theta_{v,atm} - \theta_{v,s} < 0$).
3. An initial guess for the Monin-Obukhov length L is obtained from the bulk Richardson number using equation and (2.5.46) and (2.5.48).
4. Iteration proceeds on the following system of equations:
5. Friction velocity u_* ((2.5.32), (2.5.33), (2.5.34), (2.5.35))
6. Ratio $\frac{\theta_*}{\theta_{atm}-\theta_s}$ ((2.5.37) , (2.5.38), (2.5.39), (2.5.40))
7. Ratio $\frac{q_*}{q_{atm}-q_s}$ ((2.5.41), (2.5.42), (2.5.43), (2.5.44))

8. Aerodynamic resistances r_{am} , r_{ah} , and r_{aw} ((2.5.55), (2.5.56), (2.5.57))
9. Magnitude of the wind velocity incident on the leaves U_{av} ((2.5.117))
10. Leaf boundary layer resistance r_b ((2.5.136))
11. Aerodynamic resistances r'_{ah} and r'_{aw} ((2.5.116))
12. Sunlit and shaded stomatal resistances r_s^{sun} and r_s^{sha} (Chapter 2.9)
13. Sensible heat conductances c_a^h , c_g^h , and c_v^h ((2.5.94), (2.5.95), (2.5.96))
14. Latent heat conductances c_a^w , c_v^w , and c_g^w ((2.5.108), (2.5.109), (2.5.110))
15. Sensible heat flux from vegetation H_v ((2.5.97))
16. Latent heat flux from vegetation λE_v ((2.5.101))



17. If the latent heat flux has changed sign from the latent heat flux computed at the previous iteration ($\lambda E_v^{n+1} \times \lambda E_v^n < 0$), the latent heat flux is constrained to be 10% of the computed value. The difference between the constrained and computed value ($\Delta_1 = 0.1\lambda E_v^{n+1} - \lambda E_v^{n+1}$) is added to the sensible heat flux later.
18. Change in vegetation temperature ΔT_v ((2.5.129)) and update the vegetation temperature as $T_v^{n+1} = T_v^n + \Delta T_v$. T_v is constrained to change by no more than 1°K in one iteration. If this limit is exceeded, the energy error is

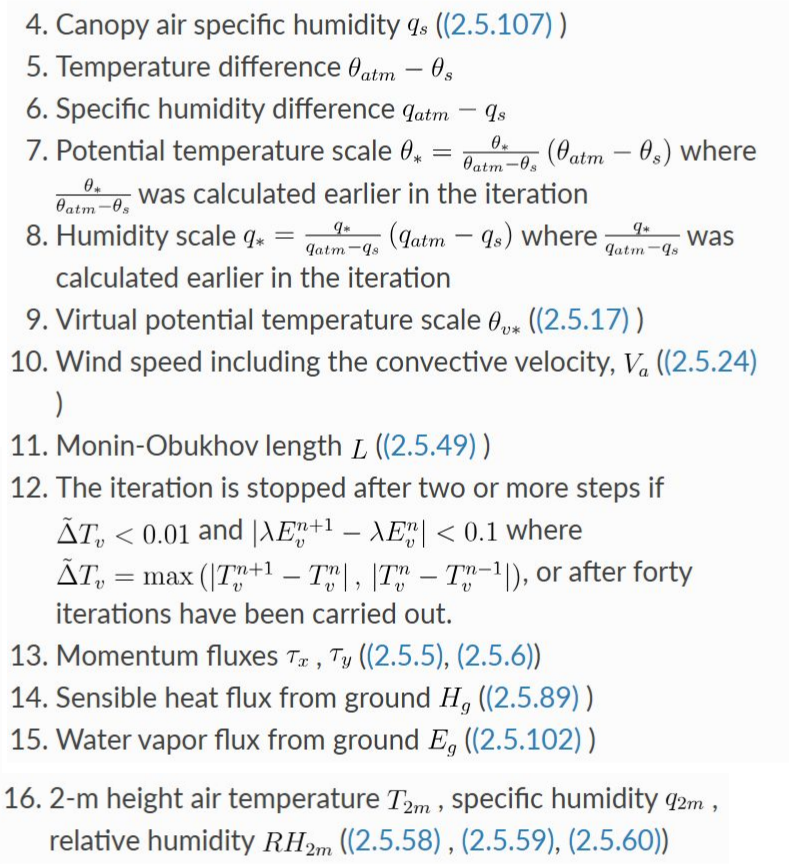
$$\Delta_2 = \overrightarrow{S}_v - \overrightarrow{L}_v - \frac{\partial \overrightarrow{L}_v}{\partial T_v}\Delta T_v - H_v - \frac{\partial H_v}{\partial T_v}\Delta T_v - \lambda E_v - \frac{\partial \lambda E_v}{\partial T_v}\Delta T_v \qquad (2.5.138)$$

1. Water vapor flux E_v ((2.5.133))
2. Transpiration E_v^t ((2.5.134) if $\beta_t > 0$, otherwise $E_v^t = 0$)
3. The water vapor flux E_v is constrained to be less than or equal to the sum of transpiration E_v^t and the water available from wetted leaves and stems $W_{can}/\Delta t$. The energy error due to this constraint is

$$\Delta_3 = \max\left(0,\ E_v - E_v^t - \frac{W_{can}}{\Delta t}\right). \qquad (2.5.139)$$

The error $\lambda\Delta_3$ is added to the sensible heat flux later.

1. Sensible heat flux H_v ((2.5.135)). The three energy error terms, Δ_1 , Δ_2 , and $\lambda\Delta_3$ are also added to the sensible heat flux.
2. The saturated vapor pressure e_i (Chapter 2.9), saturated specific humidity $q_{sat}^{T_v}$ and its derivative $\frac{dq_{sat}^{T_v}}{dT_v}$ at the leaf surface (section 2.5.5), are re-evaluated based on the new T_v .
3. Canopy air temperature T_s ((2.5.93))



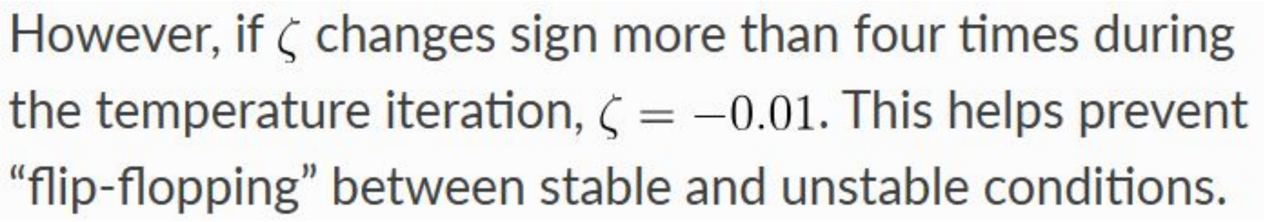
4. Canopy air specific humidity q_s ((2.5.107))
5. Temperature difference $\theta_{atm} - \theta_s$
6. Specific humidity difference $q_{atm} - q_s$
7. Potential temperature scale $\theta_* = \frac{\theta_*}{\theta_{atm}-\theta_s}(\theta_{atm} - \theta_s)$ where $\frac{\theta_*}{\theta_{atm}-\theta_s}$ was calculated earlier in the iteration
8. Humidity scale $q_* = \frac{q_*}{q_{atm}-q_s}(q_{atm} - q_s)$ where $\frac{q_*}{q_{atm}-q_s}$ was calculated earlier in the iteration
9. Virtual potential temperature scale θ_{v*} ((2.5.17))
10. Wind speed including the convective velocity, V_a ((2.5.24))
11. Monin-Obukhov length L ((2.5.49))
12. The iteration is stopped after two or more steps if $\tilde{\Delta}T_v < 0.01$ and $|\lambda E_v^{n+1} - \lambda E_v^n| < 0.1$ where $\tilde{\Delta}T_v = \max(|T_v^{n+1} - T_v^n|, |T_v^n - T_v^{n-1}|)$, or after forty iterations have been carried out.
13. Momentum fluxes τ_x , τ_y ((2.5.5), (2.5.6))
14. Sensible heat flux from ground H_g ((2.5.89))
15. Water vapor flux from ground E_g ((2.5.102))

16. 2-m height air temperature T_{2m} , specific humidity q_{2m} , relative humidity RH_{2m} ((2.5.58) , (2.5.59), (2.5.60))

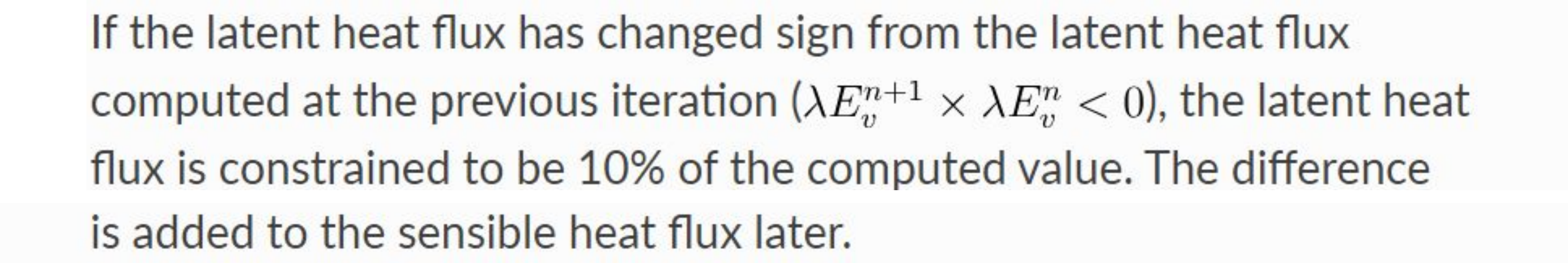
The end!

https://escomp.github.io/ctsm-docs/versions/release-clm5.0/html/tech_note/index.html

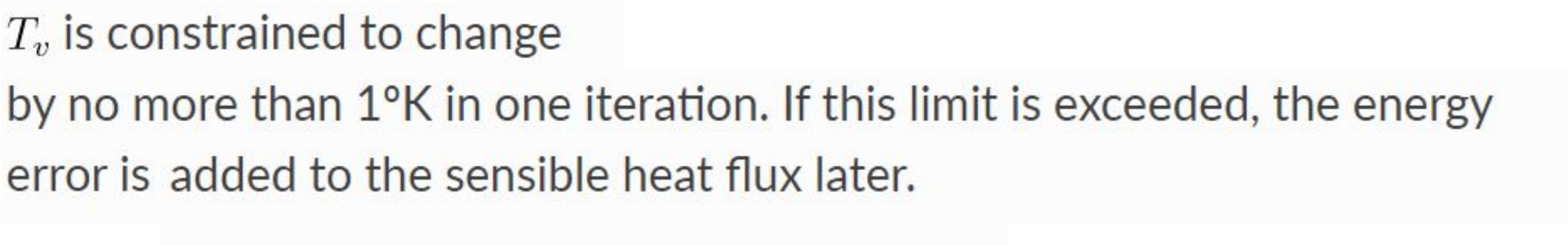
CLM5/6 canopy physics: a deep dive



However, if ζ changes sign more than four times during the temperature iteration, $\zeta = -0.01$. This helps prevent "flip-flopping" between stable and unstable conditions.



If the latent heat flux has changed sign from the latent heat flux computed at the previous iteration ($\lambda E_v^{n+1} \times \lambda E_v^n < 0$), the latent heat flux is constrained to be 10% of the computed value. The difference is added to the sensible heat flux later.



T_v is constrained to change
by no more than 1°K in one iteration. If this limit is exceeded, the energy error is added to the sensible heat flux later.

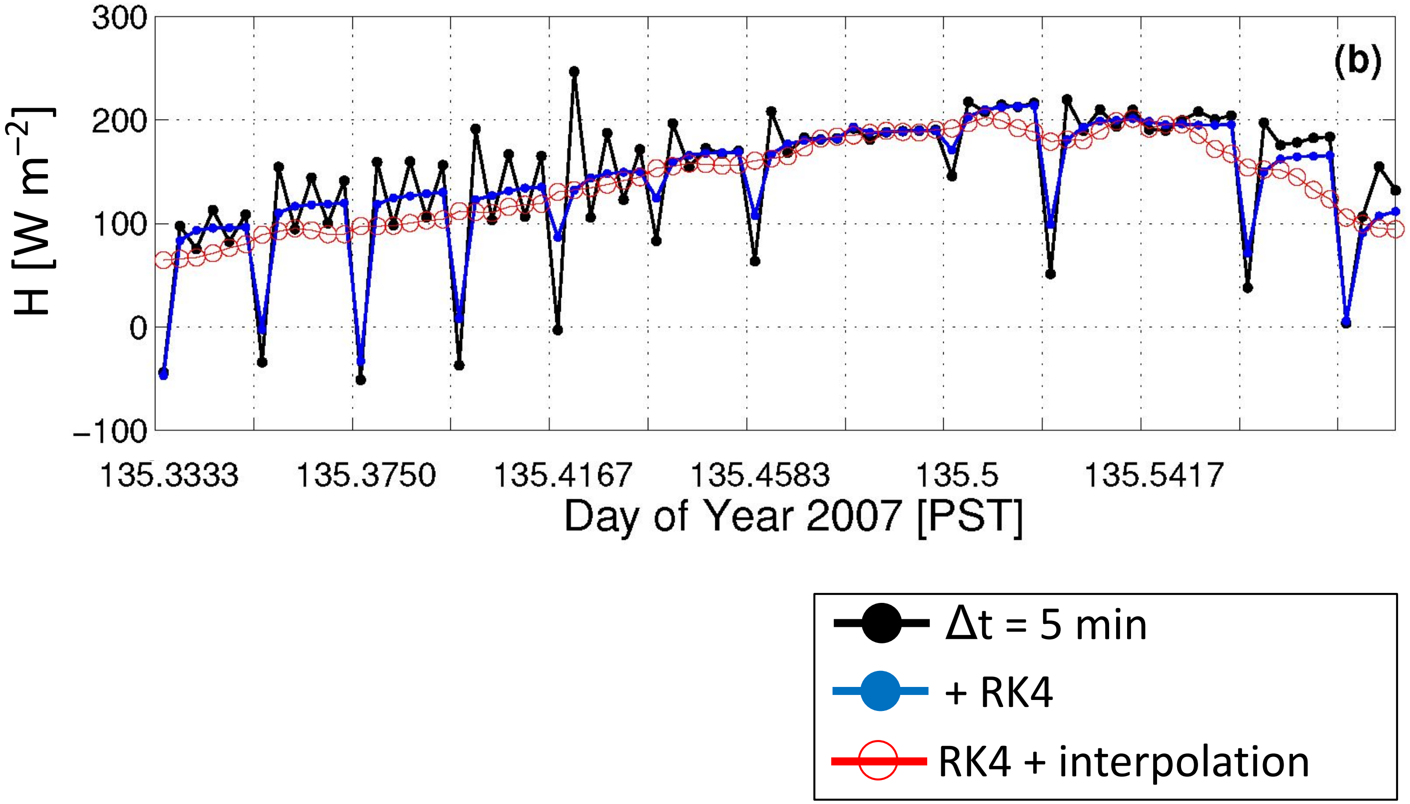
https://escomp.github.io/ctsm-docs/versions/release-clm5.0/html/tech_note/index.html

Numerical methods

CLM-ml v2:

- 5-min timestep instead of 30-min
- 4th-order Runge-Kutta (RK4)
- Interpolate 30-min forcing to 5-min

6-hour period from morning to mid-afternoon

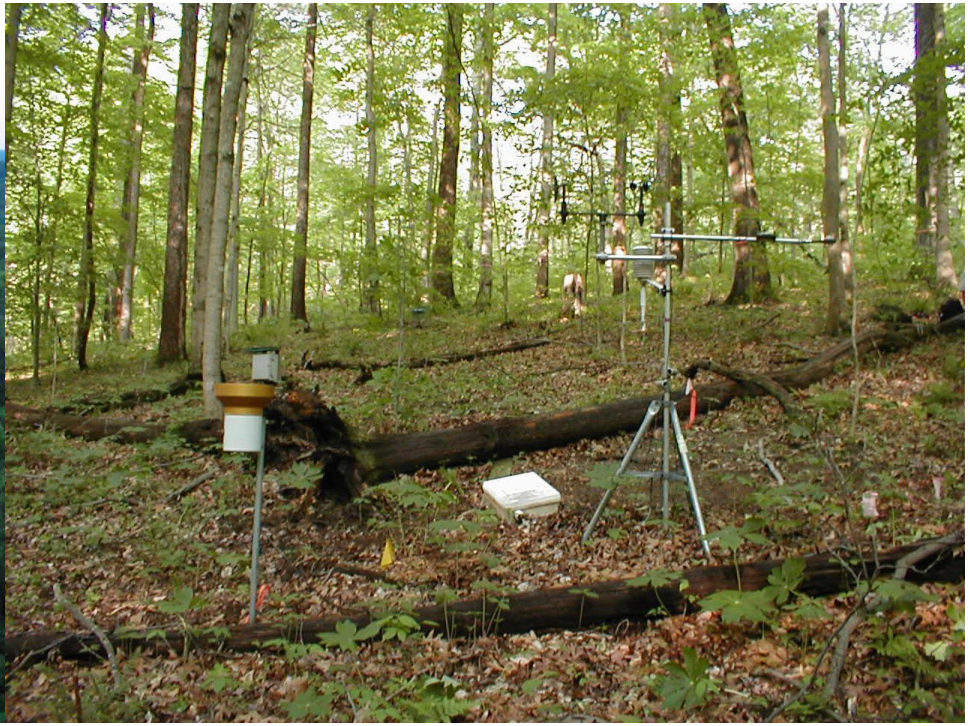


Advanced numerical methods can eliminate need for ad-hoc "fixes"

Bonan, Burns & Patton (unpublished)

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

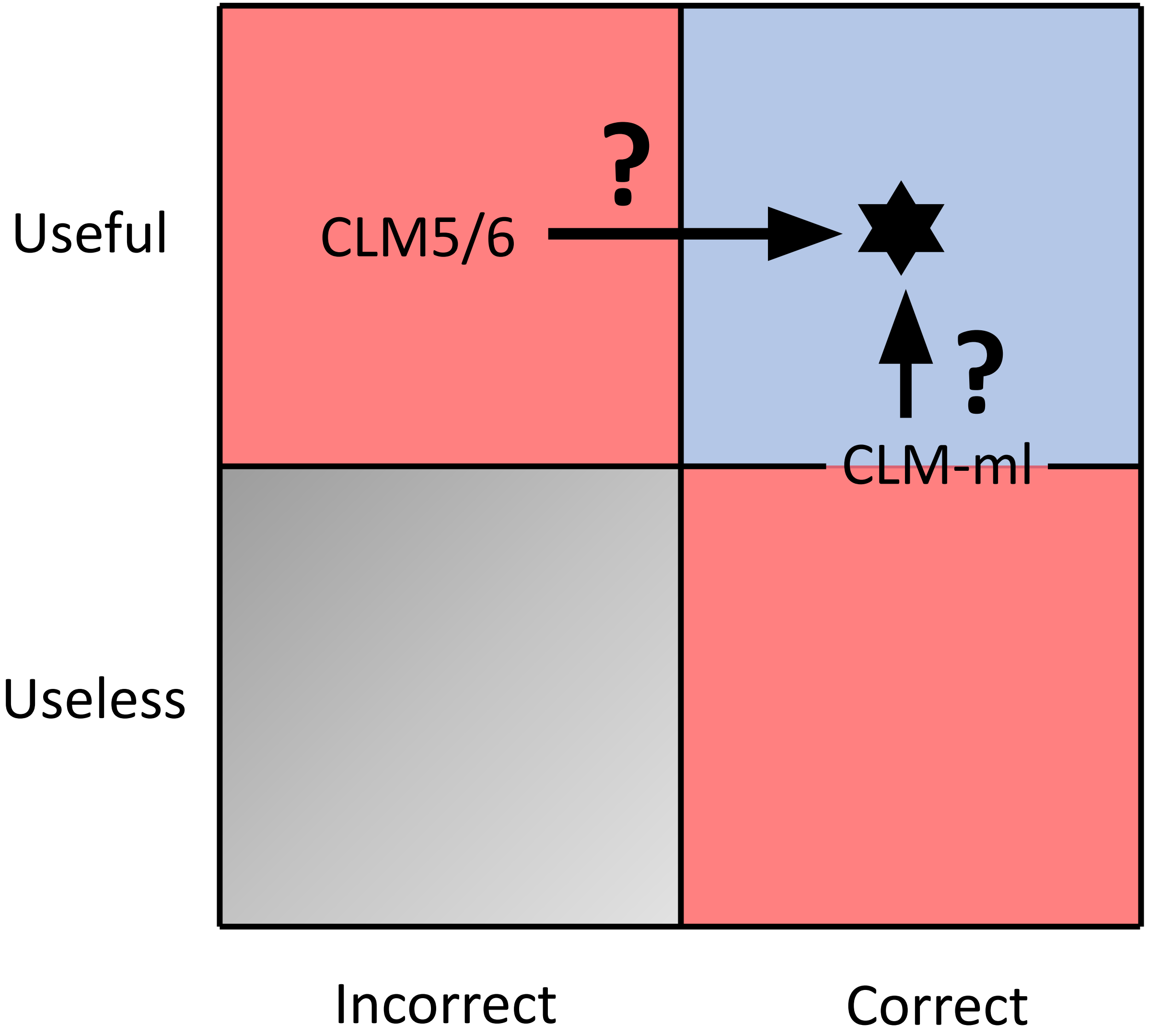
“incorrect but useful”

Multilayer canopy

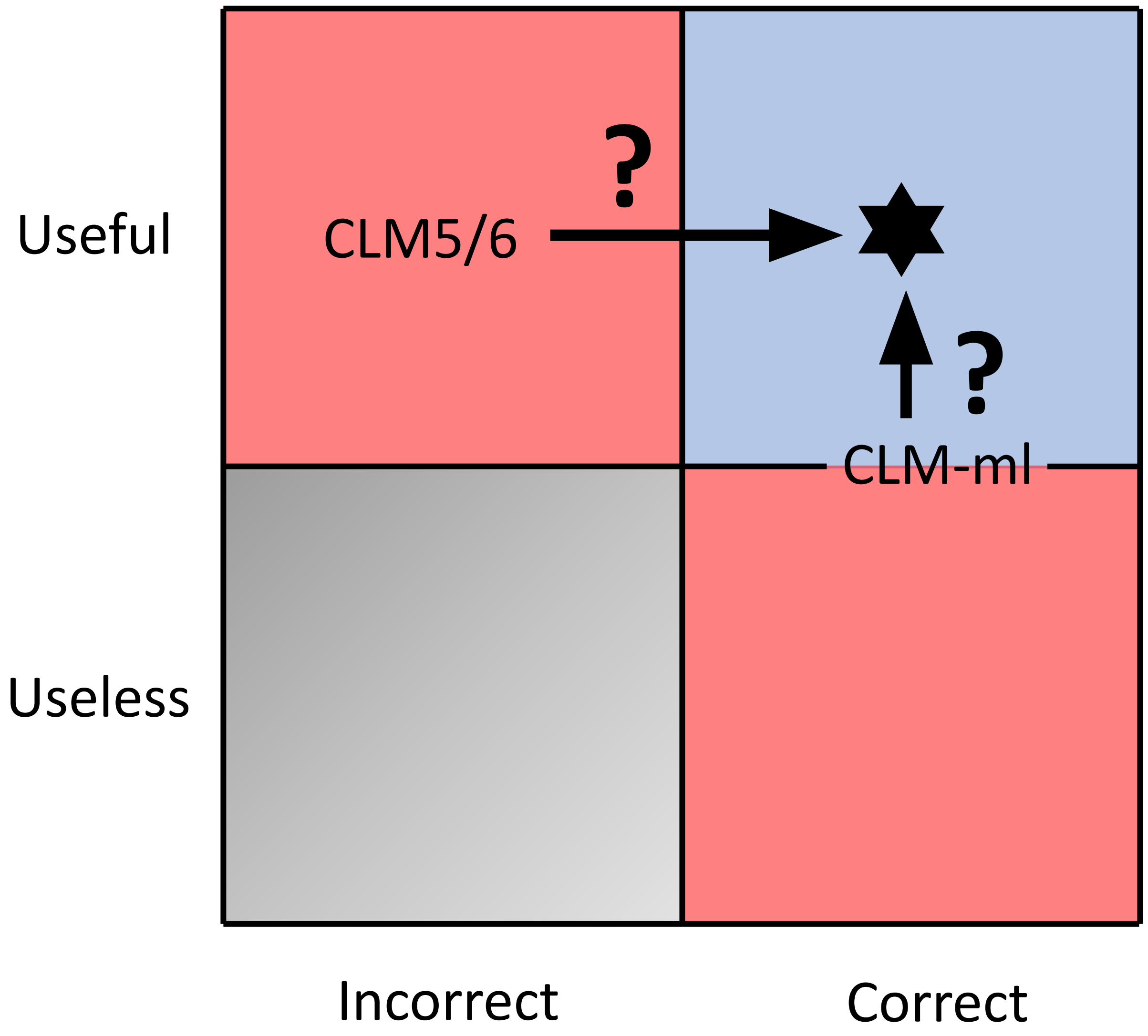
“correct but useless”

Raupach & Finnigan (1988) *Aust. J. Plant Physiol.*, 15, 705-716

Attaining the correct and useful model

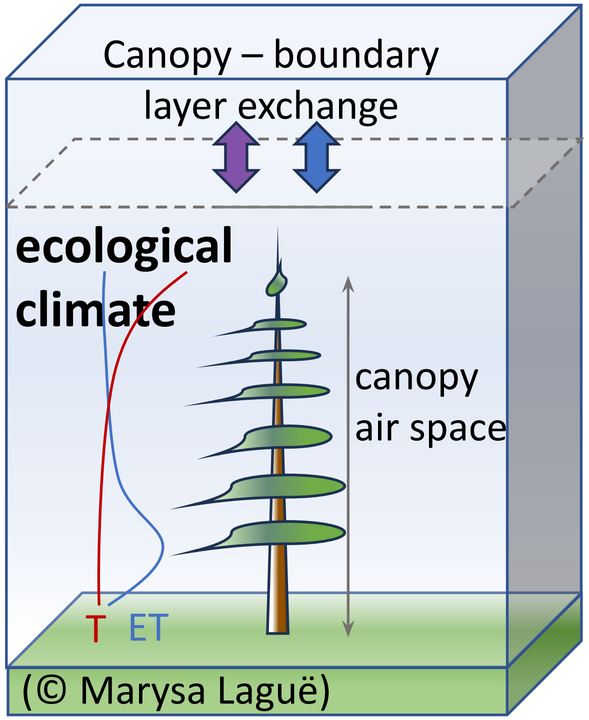


Attaining the correct and useful model



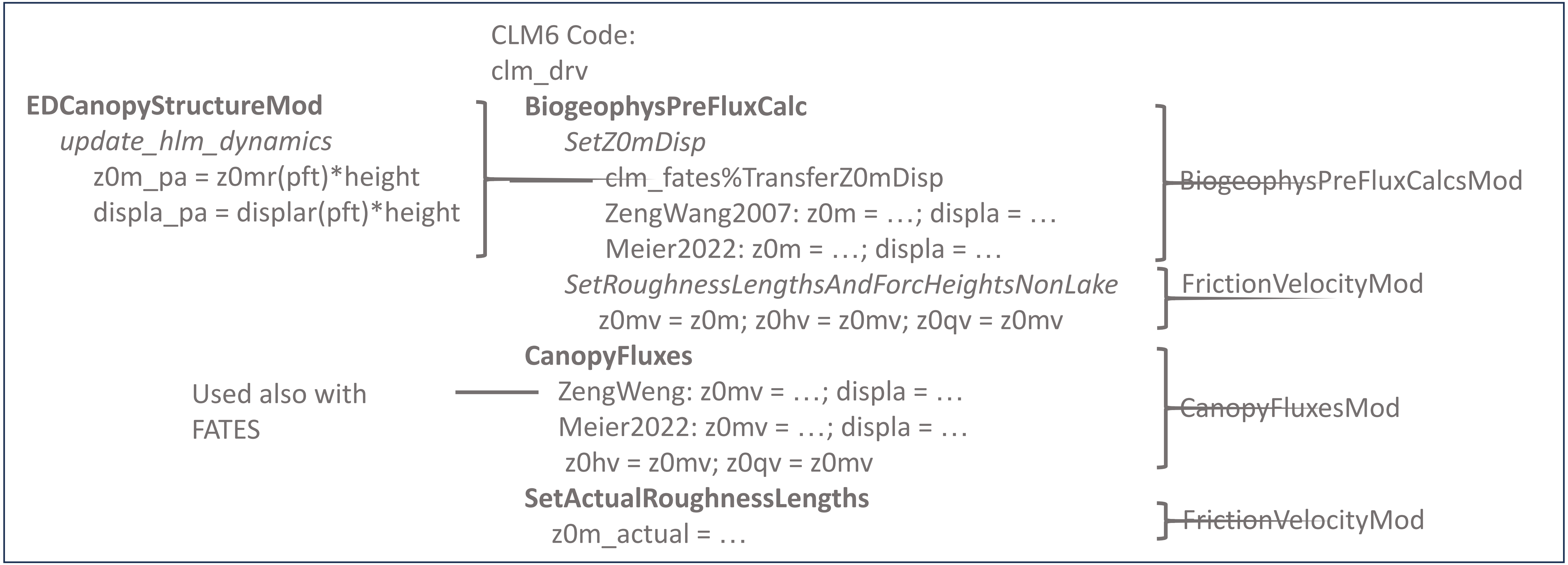
New science

- Directly observable (A_n, g_s, ψ_ℓ, T_ℓ, $\delta^{13}C$)
- Canopy chemistry (e.g., BVOCs, dry deposition)
- Forest microclimates (overstory, understory)
- Orphan air space



(© Marysa Laguë)

Technical debt



CLM6 Code:
clm_drv

EDCanopyStructureMod
update_hlm_dynamics
z0m_pa = z0mr(pft)*height
displa_pa = displar(pft)*height

BiogeophysPreFluxCalc
SetZ0mDisp
clm_fates%TransferZ0mDisp
ZengWang2007: z0m = …; displa = …
Meier2022: z0m = …; displa = …
SetRoughnessLengthsAndForcHeightsNonLake
z0mv = z0m; z0hv = z0mv; z0qv = z0mv

CanopyFluxes
ZengWeng: z0mv = …; displa = …
Meier2022: z0mv = …; displa = …
z0hv = z0mv; z0qv = z0mv

SetActualRoughnessLengths
z0m_actual = …

Used also with
FATES

BiogeophysPreFluxCalcsMod
FrictionVelocityMod
CanopyFluxesMod
FrictionVelocityMod

5 subroutines over 4 modules

6 variables over two data types

canopystate_type%z0m_patch
canopystate_type%displa_patch
frictionvel_type%z0mv_patch
frictionvel_type%z0hv_patch
frictionvel_type%z0qv_patch
frictionvel_type%z0m_actual_patch