# Advanced ParFlow Short Course
# CLM Overview

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# Common Land Model

## Part 1: Introduction


Slides from:

Jennifer Jefferson &

Reed Maxwell

# General Information

# Where did CLM originate?

(Common Land Model)

- Community effort to combine best pieces of existing modular land surface models

- 3 models
  1. Land Surface Model (LSM) Bonan (1996)
  2. Biosphere Atmosphere Transfer Scheme (BATS) Dickinson (1993)
  3. Chinese Academy of Sciences Institute of Atmospheric Physics LSM 1994 version (IAP94) Dai and Zeng (1997)

- Initial documentation in Dai et al. (2003)

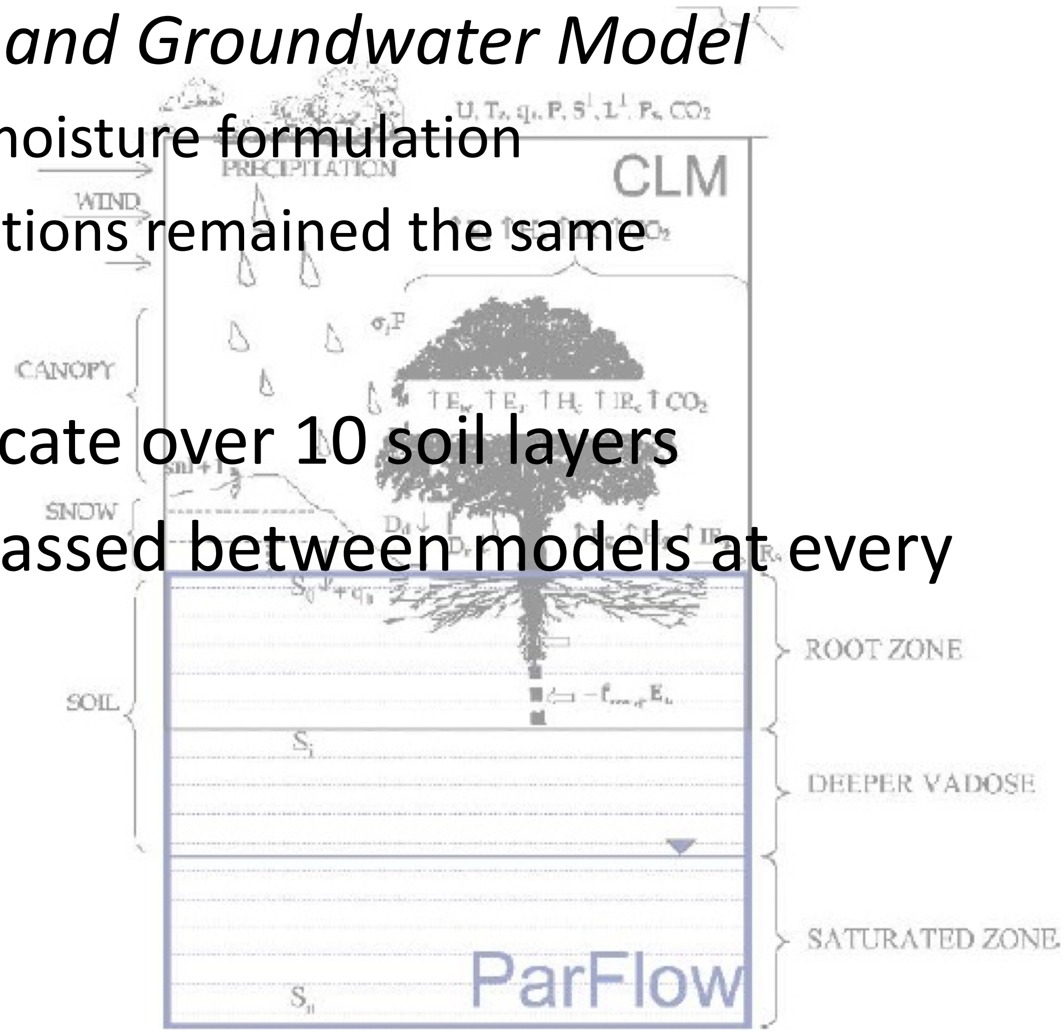
# Who maintains CLM today?

(Community Land Model)

- Name change from “Common” to “Community” occurred around 2002 with the release of CLMv2
- National Center for Atmospheric Research (NCAR)
- CLM is now the land surface component of the Community Earth System Model (CESM)
- CLM is housed within the Land Model working group led by Keith Oleson
- Current CLM version is 4.5
  - Technical Description of v4.5 contains a nice overview of the history of each CLM version
- [http://www.cesm.ucar.edu/models/clm/](http://www.cesm.ucar.edu/models/clm/)

# When was CLM first coupled to PF?

- Maxwell and Miller (2005) – *Development of a Coupled Land Surface and Groundwater Model*
  - PF replaced CLM soil moisture formulation
  - Surface (CLM) formulations remained the same
- ≈CLMv3
- PF and CLM communicate over 10 soil layers
- Fluxes and variables passed between models at every time step




For more applications/papers see Table 1.1 in ParFlow Manual

# What are *some* differences between PF-CLM and CLMv4.5?

- Soil resistance
  - PF-CLM incorporates soil moisture computed using 3D Richards equation
  - Choose between linear and cosine soil resistance factors to limit bare soil evaporation in PF-CLM
  - CLMv4.5 has vertical soil moisture transport (i.e, no lateral flow)

- Fractional vegetation coverage
  - PF-CLM is not setup to handle fractional vegetation (even if you put it in drv_vegm.dat this way)
  - CLMv4.5 tiles can have several land uses

- Leaf area index (LAI)
  - PF-CLM computes LAI at each time step using an empirical equation that depends on soil temperature
  - CLMv4.5 updates LAI daily based on interpolation of monthly MODIS LAI values
- ET adjustment factors
  - PF-CLM assumes C3 plants (unless manually changed)
  - CLMv4.5 includes additional factors to adjust photosynthesis rates/stomatal resistance (canopy scaling, nitrogen, day length)
- Irrigation through Water Allocation Model (WAM)

# PF-CLM Details

# How do I “turn-on” CLM in PF?

```
pfset Solver.LSM                                              CLM
pfset Solver.WriteSiloCLM                                True
pfset Solver.CLM.MetForcing                              1D
pfset Solver.CLM.MetFileName                             Tonzi_Sept2002_2003.txt
pfset Solver.CLM.MetFilePath                             ./

pfset Solver.PrintCLM                                    True

pfset Solver.PrintLSMSink                                False
pfset Solver.CLM.CLMDumpInterval                         1
pfset Solver.CLM.CLMFileDir                                   "output/"
pfset Solver.CLM.BinaryOutDir                                 False
pfset Solver.CLM.IstepStart                              1
pfset Solver.WriteCLMBinary                              False
pfset Solver.WriteSiloCLM                                     False

pfset Solver.CLM.EvapBeta                                Linear

pfset Solver.CLM.WriteLogs                               False
pfset Solver.CLM.WriteLastRST                            True
pfset Solver.CLM.DailyRST                                False
pfset Solver.CLM.SingleFile                              True
```

Optional CLM flags (ParFlow Manual 6.1.35)

# What files do I need to run CLM?

^
(at a minimum)

1. drv_vegm.dat
2. drv_vegp.dat
3. drv_clmin.dat

4. Meteorological forcing file(s) – 1D or 3D
5. .tcl script

* Need pressure + .rst files + modifications to drv_vegp.dat and .tcl if restarting

# drv_vegm.dat

## (includes information for each tile in domain)

x, y coordinate for each tile in domain; coordinates for single column (1, 1) are shown

cosine of the zenith angle (light for photosynthesis/transpiration)
convert from GMT to local time

soil thermal properties

soil albedo calculation; scale of 1 (light) to 8 (dark)

```
x   y   lat      lon         sand  clay    color
        (Deg)    (Deg)       (%/100)       index
1    1  38.4316 -120.9660   0.16  0.265   2

fractional coverage of grid by vegetation class (Must/Should Add to 1.0)
1    2    3    4    5    6    7    8    9    10   11   12   13   14   15   16   17   18
0.0 0.0  0.0  1.0  0.0  0.0  0.0  0.0  0.0  0.0  0.0  0.0  0.0  0.0  0.0  0.0  0.0  0.0
```

Remember, PF-CLM does not have fractional coverage!

# Land Cover Types
## (i.e., vegetation class in drv_vegp.dat)

(IGBP = International Geosphere-Biosphere Programme)

```
!IGBP Land Cover Types (other classes can be used by changing this file)
!  1 evergreen needleleaf forests
!  2 evergreen broadleaf forests
!  3 deciduous needleleaf forests
!  4 deciduous broadleaf forests
!  5 mixed forests
!  6 closed shrublands
!  7 open shrublands
!  8 woody savannas
!  9 svannas
! 10 grasslands
! 11 permanent wetlands
! 12 croplands
! 13 urban and built-up lands
! 14 cropland / natural vegetation mosaics
! 15 snow and ice
! 16 barren or sparsely vegetated
! 17 water bodies
! 18 bare soil
```

# drv_vegp.dat

## (specifies vegetation parameter values)

```
lai               Maximum leaf area index [-]
6.00 6.00 6.00 6.00 6.00 6.00 6.00 6.00 6.00 2.00 6.00 6.00 5.00 6.00 0.00 6.00 0.00 0.00
!
lai0              Minimum leaf area index [-]
5.00 5.00 1.00 1.00 3.00 2.00 1.00 2.00 1.00 0.50 0.50 0.50 1.00 2.00 0.00 0.50 0.00 0.00
```

lai properties that correspond to 10. grasslands

- (maximum) leaf area index (-)
- (minimum) leaf area index (-)
- stem area index (-)
- aerodynamic roughness length (m)
- displacement height (m)
- leaf dimension (m)
- fitted numerical index of rooting distribution (-)
- fitted numerical index of rooting distribution (-)
- leaf reflectance – visible light (-)
- leaf reflectance – near infrared light (-)
- stem reflectance – visible light (-)
- stem reflectance – near infrared light (-)
- leaf transmittance – visible light (-)
- leaf transmittance – near infrared light (-)
- stem transmittance – visible light (-)
- stem transmittance – near infrared light (-)
- leaf/stem orientation index (-)
- btran exponent (-)

# drv_clmin.dat

## (includes timing information and additional parameters)

- Make sure times are entered in GMT and correspond to times in the forcing file
- Change name of output file prefixes, if desired

```
outf1d        stomataSA.output.txt                  CLM output file
poutf1d       stomataSA.para.out.dat                CLM 1D Parameter Output File
rstf          stomataSA.rst.                        CLM active restart file
```

- Update lines in this file if restarting simulation (from 2 to 1)

```
startcode     2                                     1=restart file,2=defined
clm_ic        2                                     1=restart file,2=defined
```

- Includes several other specified parameter values
  - Meteorological station heights
  - Roughness lengths
  - Finite difference parameters

# Meteorological Forcing File
## (Pg. 140 ParFlow Manual)

**DSWR:** Downward Visible or Short-Wave radiation $[W/m^2]$.

**DLWR:** Downward Infa-Red or Long-Wave radiation $[W/m^2]$

**APCP:** Precipitation rate $[mm/s]$

**Temp:** Air temperature $[K]$

**UGRD:** West-to-East or U-component of wind $[m/s]$

**VGRD:** South-to-North or V-component of wind $[m/s]$

**Press:** Atmospheric Pressure $[pa]$

**SPFH:** Water-vapor specific humidity $[kg/kg]$

- Columns must be in this order and have these units
- 1D – .txt file with single column for each variable and each row is one timestep
- 3D - .pfb files, one for each variable and multiple time steps

# Where does PF call CLM?

from solver_richards.c

```
CALL_CLM_LSM(pp,sp,et,ms,po_dat,dz_dat,istep,cdt,t,start_time,
               dx,dy,dz,ix,iy,nx,ny,nz,nx_f,ny_f,nz_f,nz_rz,ip,p,q,r,gnx, gny,rank,
               sw_data,lw_data,prcp_data,tas_data,u_data,v_data,patm_data,qatm_data,
                 eflx_lh,eflx_lwrad,eflx_sh,eflx_grnd,qflx_tot,qflx_grnd,
               qflx_soi,qflx_eveg,qflx_tveg,qflx_in,swe,t_g,t_soi,
                 public_xtra -> clm_dump_interval,
                 public_xtra -> clm_1d_out,
                 public_xtra -> clm_file_dir,
                 clm_file_dir_length,
                 public_xtra -> clm_bin_out_dir,
                 public_xtra -> write_CLM_binary,
                 public_xtra -> clm_beta_function,
                 public_xtra -> clm_veg_function,
                 public_xtra -> clm_veg_wilting,
                 public_xtra -> clm_veg_fieldc,
                 public_xtra -> clm_res_sat,
                 public_xtra -> clm_irr_type,
                 public_xtra -> clm_irr_cycle,
                 public_xtra -> clm_irr_rate,
                 public_xtra -> clm_irr_start,
                 public_xtra -> clm_irr_stop,
                 public_xtra -> clm_irr_threshold,
                 qirr, qirr_inst, iflag,
                 public_xtra -> clm_irr_thresholdtype,
                 soi_z,clm_next,clm_write_logs,clm_last_rst,clm_daily_rst);
```

all of these variables get passed from PF to CLM

# What happens in CLM?

A lot of calculations!

➡ See the PF-CLM flowchart

http://parflow.blogspot.com/2015/10/clm-modules.html

# Variables in CLM

- Global variables
  – clm%zlnd
  – See clmtype.F90

- Local variables
  – efpot
  – See individual modules

- Constant values
  – Gravity = 9.8616
  – See clm_varcon.F90

# What information is output from CLM?

(Order of information obtained from solver_richards.c)

single file output layer

```
1. eflx_lh_tot                  ! latent heat flux from canopy height to atmosphere [W/2]
2. eflx_lwrad_out               ! outgoing long-wave radiation from ground+canopy
3. eflx_sh_tot                  ! sensible heat from canopy height to atmosphere [W/m2]
4. eflx_soil_grnd               ! ground heat flux [W/m2]
5. qflx_evap_tot                ! evapotranspiration from canopy height to atmosphere [mm/s]
6. qflx_evap_grnd               ! ground surface evaporation rate (mm h2o/s)
7. qflx_evap_soi                ! evaporation heat flux from ground [mm/s]
8. qflx_evap_veg                ! evaporation+transpiration from leaves [mm/s]
9. qflx_tran_veg                ! transpiration rate [mm/s]
10. qflx_infl                   ! infiltration (mm H2O /s)
11. swe_out                     ! snow water equivalent
12. t_grnd                      ! ground temperature (K)

13. qflx_qirr                   ! qflx_surf directed to irrig (mm H2O/s);irrigation applied at
                         surface [mm/s](added to rain or throughfall, depending)
OR
13. qflx_qirr_inst(nlevsoi)     !irrigation applied by 'instant' method [mm/s] (added to pf_flux)

14-23. tsoil                    ! soil temperature for each soil layer; assuming 10 soil layers
```

# How is this information output from CLM?

- Binary format
  - convert from .pfb to .silo to view
  - convert from .pfb to .si to read in tabular format
  - use pfb reader to read into R/Matlab

- Single file output = 1 file for each time step that contains all variables on previous slide

  ```
  pfset Solver.CLM.SingleFile                True
  ```

  Output files would be titled as follows:

  ```
  runnamethatyoupick.out.clm_output.00001.C.pfb
  runnamethatyoupick.out.clm_output.00002.C.pfb
  ...
  ```

- Non-single file output = 1 file for each time step for each variable

# Common Land Model

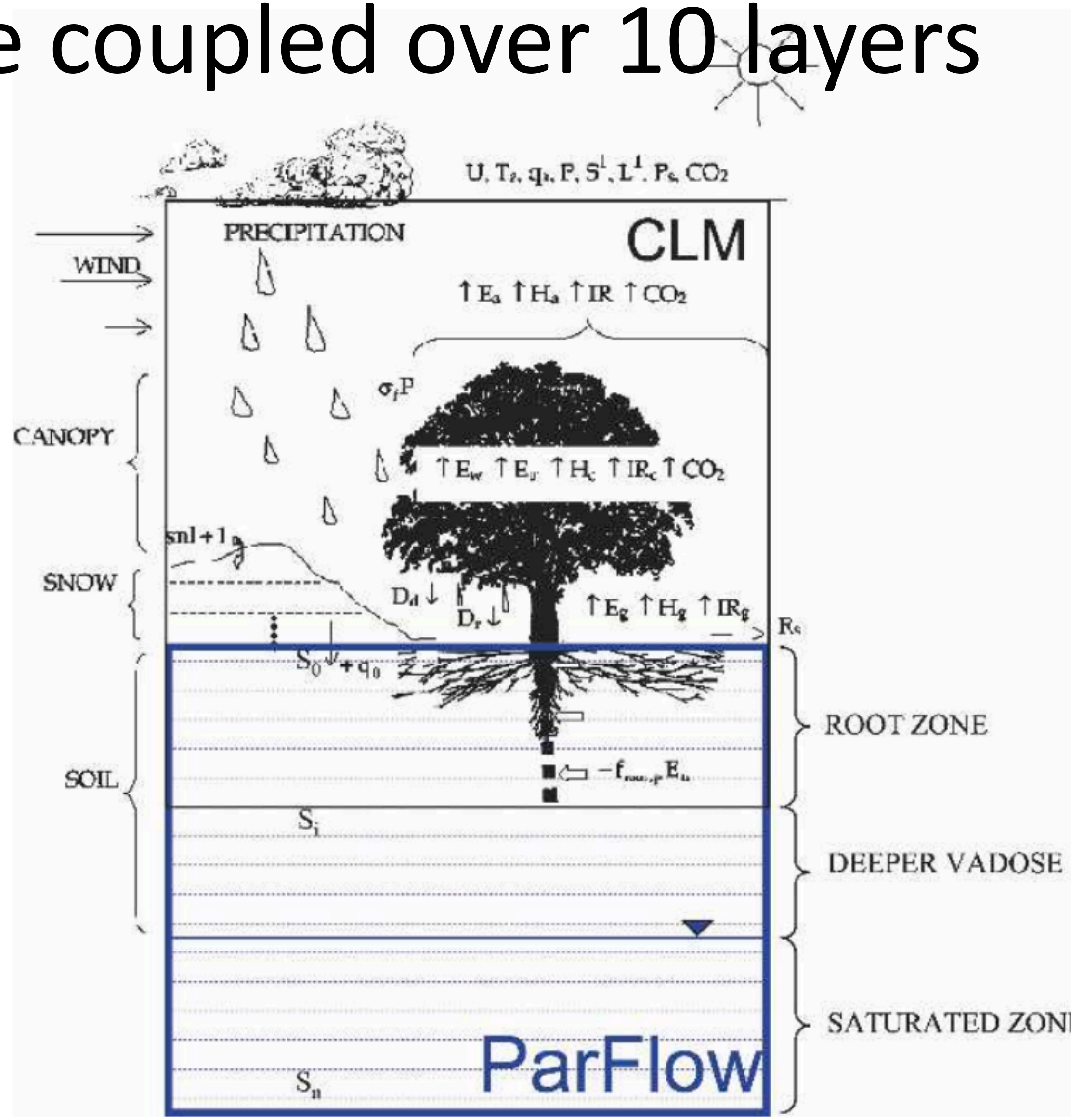
## Part 2: Evaporation and Transpiration

Slides from: Jennifer Jefferson

# PF and CLM are coupled over 10 layers

***Process:***

1. Soil moisture is calculated in ParFlow over entire domain
2. Soil moisture from (10) uppermost layers passed to CLM and are used to calculate infiltration, **evaporation** and **transpiration**
3. These quantities are then passed back to ParFlow and treated as fluxes in/out of domain




*Maxwell and Miller, 2005*
*Kollet and Maxwell, 2008*

# PF and CLM Coupled Through Source/Sink Term ($q_s$)

$z$ = 0

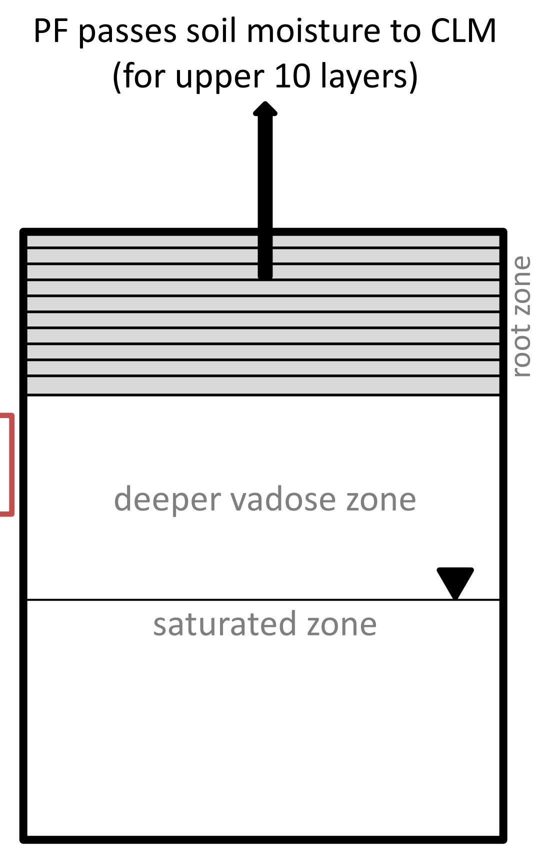
land surface (overland flow equation)

subsurface (Richards equation)

$z$ = - value

$$S_s S(\psi)\frac{\partial \psi}{dt} + \phi \frac{\partial S(\psi)}{dt} = \nabla \cdot \left[ k(x) k_r(\psi) \nabla (\psi - z) \right] \boxed{+ q_s}$$

$$q_s = \boxed{ET(S(\psi))} + q_{infl}$$



# What if my PF model does not have 10 layers?

ParFlow Manual – Pg. 146

*integer* **Solver.CLM.RootZoneNZ** [10]

This key sets the number of soil layers the ParFlow expects from CLM. It will allocate and format all the arrays for passing variables to and from CLM accordingly. Note that this does not set the soil layers in CLM to do that the user needs to change the value of the parameter **nlevsoi** in the file **clm_varpar.F90** in the *PARFLOW_DIR*\pfsimulator\clm directory to reflect the desired numnber of soil layers and recompile. Most likely the key Solver.CLM.SoiLayer, described below, will also need to be changed.

Example Useage:

```
pfset Solver.CLM.RootZoneNZ      4
```

Also change nlevsoi in clm_varpar.F90 (and recompile):

```
integer, parameter :: nlevsoi     =  10   !number of soil levels
```

*integer* **Solver.CLM.SoiLayer** [7]

This key sets the soil layer, and thus the soil depth, that CLM uses for the seasonal temperature adjustment for all leaf and stem area indices.

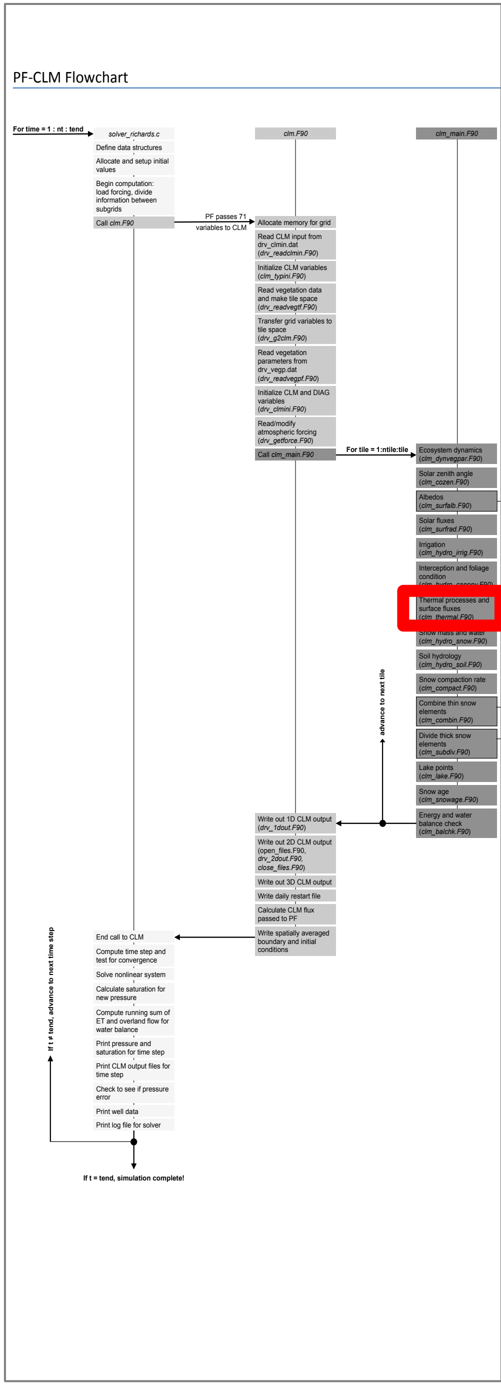
Example Useage:

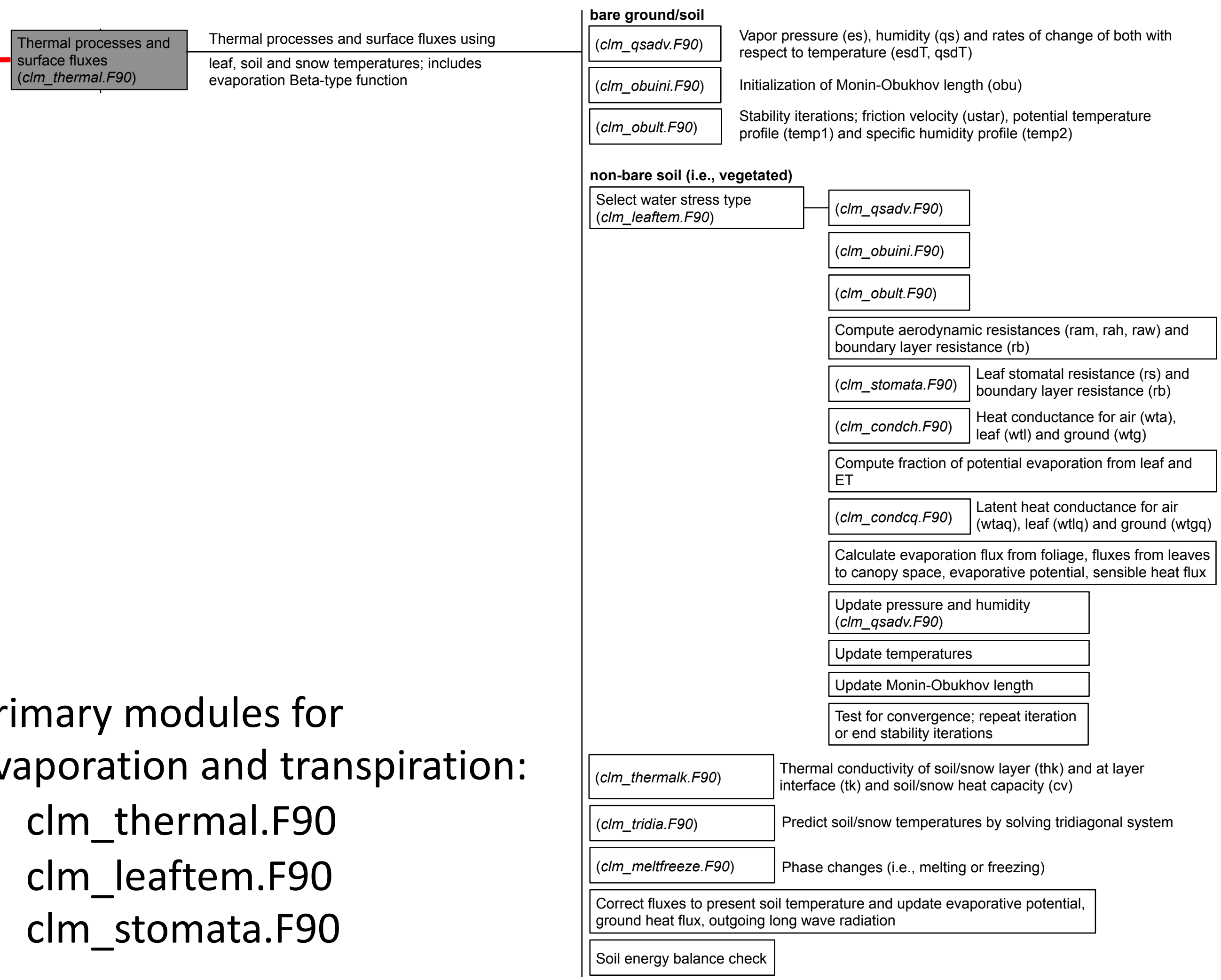
```
pfset Solver.CLM.SoiLayer      4
```

LAI calculation in clm_dynvegpar.F90:

```
!seasb     = max(dble(0.), dble(1.) - dble(0.0016)*max(298.-clm%t_soisno(7),dble(0.0))**2)
seasb     = max(dble(0.), dble(1.) - dble(0.0016)*max(298.-
clm%t_soisno(clm%soi_z),dble(0.0))**2) ! NBE: Added variable to set layer #
clm%tlai  = clm%maxlai + (clm%minlai-clm%maxlai)*(1.-seasb)
```

# Energy Fluxes are Computed in clm_thermal.F90




Primary modules for evaporation and transpiration:

- clm_thermal.F90
- clm_leaftem.F90
- clm_stomata.F90

# Evaporation requires water [mass] and wind + atmosphere [transfer]

Input forcing data:

| time | sw rad | lw rad | precip | air temp | e-w wind | n-s wind | air press | spec hum |
|---|---|---|---|---|---|---|---|---|
| 1 | 163.5920000 | 304.31000000 | 0.00000644 | 288.39000000 | 0.37000000 | 1.05000000 | 68118.20000000 | 0.00595840 |
| 2 | 58.64000000 | 304.28000000 | 0.00000000 | 286.76000000 | 1.05000000 | 0.76000000 | 68076.00000000 | 0.00608740 |
| 3 | 0.00000000 | 304.25000000 | 0.00000022 | 285.13000000 | 1.73000000 | 0.47000000 | 68033.20000000 | 0.00621600 |

air density

wind speed

specific humidity of atmosphere

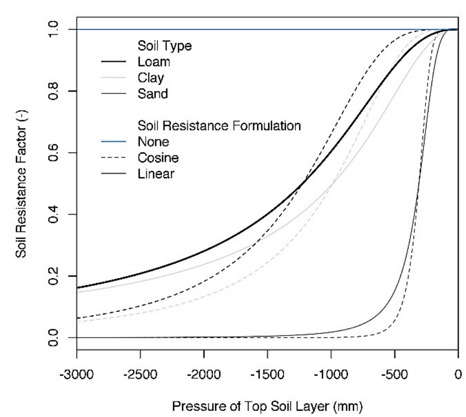
$$E_{gr} = \rho\, C_E\, \beta u\, (q_g - q_a)$$

specific humidity of ground

$$q_q = R_{h,g} q_{sat}$$

$$= \left[ (1 - S_{CV}) e^{\frac{p_1 g}{R T_g}} + S_{CV} \right] q_{sat}$$

soil resistance factor




mass transfer coefficient
(stability factors and roughness lengths)

$$C_E = \frac{\kappa^2}{\left[ \ln\left( \frac{z_u - d}{z_{0m}} \right) + \psi(\zeta) + \ldots \right] \left[ \ln\left( \frac{z_{sh} - d}{z_{0q}} \right) + \psi(\zeta) + \ldots \right]}$$

# Soil Resistance Factor

```
pfset Solver.CLM.EvapBeta      Linear
```

3 options available

1. None

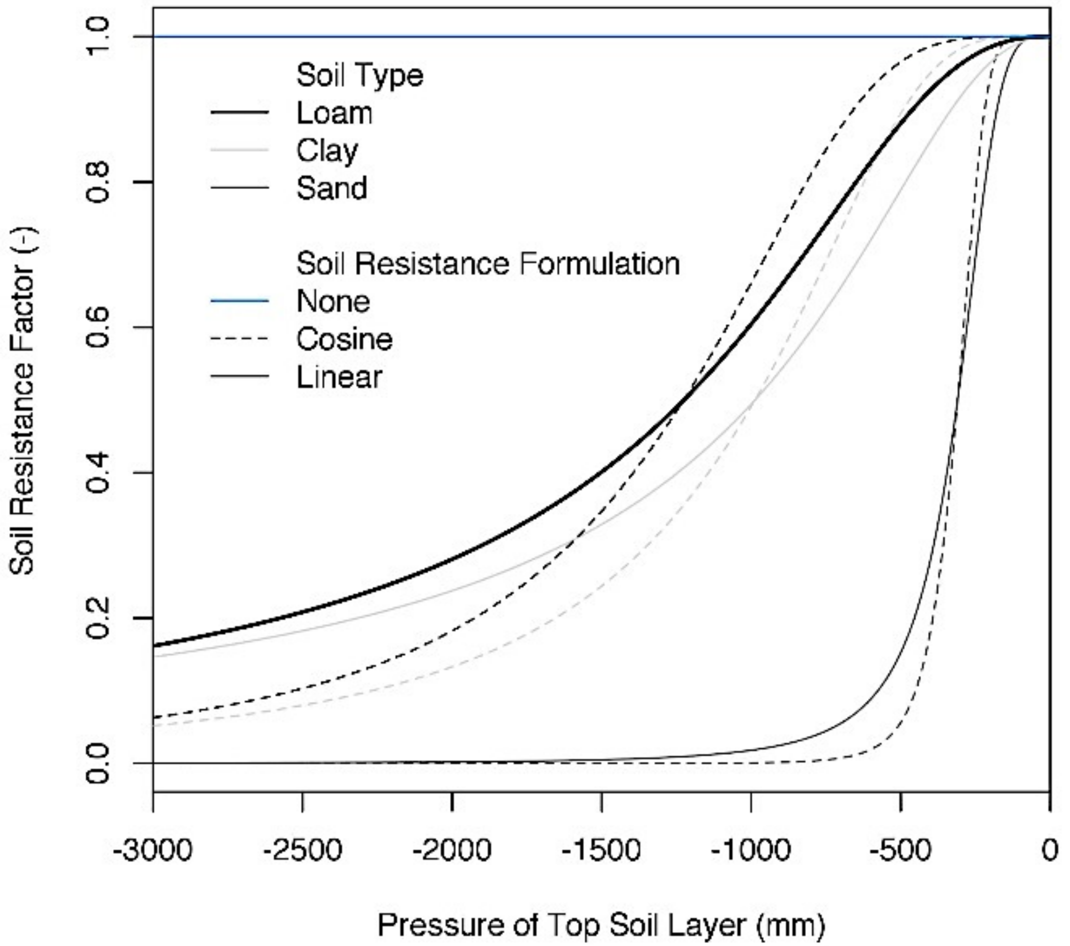
$$\beta = 1$$

1. Linear

$$\beta = \frac{\phi S - \phi S_{res}}{\phi - \phi S_{res}}$$

2. Cosine

$$\beta = \frac{1}{2}\left(1 - \cos\left(\frac{\phi S - \phi S_{res}}{\phi - \phi S_{res}}\right)\pi\right)$$



# Soil resistance limits bare soil evaporation, stomatal resistance limits transpiration

bare soil evaporation

$$E_{gr} = \rho\, C_E \beta u\, (q_g - q_a)$$

transpiration

$$E_{tr} = \rho\, \cancel{C_E}\, \cancel{\beta}\, \cancel{u}\, (q_{sat} - q_{af}) \left[ \frac{L_d r_b}{L_{AI}} \left( \frac{L_{AI,sun}}{r_b + \underline{r_{s,sun}}} + \frac{L_{AI,sha}}{r_b + \underline{r_{s,sha}}} \right) \right]$$

depend on photosynthesis

# Evapotranspiration Equation

(mass transfer/mean variables approach)

$$E_{veg} = \left\{ \left[ \frac{L_d r_b}{L_{AI}} \left( \frac{L_{AI,sun}}{r_b + r_{s,sun}} + \frac{L_{AI,sha}}{r_b + r_{s,sha}} \right) \right] + L_w \right\} \left[ \rho_a \frac{(L_{AI} + S_{AI})}{r_b} (q_{sat} - q_{af}) \right]$$

transpiration

canopy evaporation

**Components linked to meteorological forcing data:**

$\rho_a$ air density

obtain from air temperature and atmospheric pressure

$q_{sat}$ saturated specific humidity of foliage

$q_{af}$ air specific humidity within canopy space

depend on ground/air/leaf temperature and atmospheric pressure; obtain using a polynomial method

# Evapotranspiration Equation

(mass transfer/mean variables approach)

$$E_{veg} = \left\{ \left[ \frac{\cancel{L_d r_b}}{\cancel{L_{AI}}} \left( \frac{\cancel{L_{AI,sun}}}{r_b + r_{s,sun}} + \frac{\cancel{L_{AI,sha}}}{r_b + r_{s,sha}} \right) \right] + \cancel{L_w} \right\} \left[ \cancel{\rho_a} \frac{\cancel{(L_{AI} + S_{AI})}}{r_b} \cancel{(q_{sat} - q_{af})} \right]$$

**Component linked to meteorological forcing and atmospheric conditions:**

***$r_b$*** leaf boundary resistance

the “transfer” part of the formulation

function of wind speed, atmospheric stability and aerodynamic resistance to momentum transport

computed using Monin-Obukhov similarity theory

computationally expensive part of $E_{veg}$ (iterative calculation)

# Evapotranspiration Equation

(mass transfer/mean variables approach)

$$E_{veg} = \left\{ \left[ \frac{L_d r_b}{L_{AI}} \left( \frac{L_{AI,sun}}{r_b + r_{s,sun}} + \frac{L_{AI,sha}}{r_b + r_{s,sha}} \right) \right] + L_w \right\} \left[ \cancel{\rho_a} \frac{\left( L_{AI} + S_{AI} \right)}{r_b} \left( \cancel{q_{sat}} - \cancel{q_{af}} \right) \right]$$

**Components related to foliage:**

$L_{AI}$ Leaf Area Index; varies based on ground temperature

$S_{AI}$ Stem Area Index

$L_{AI,sun}$ sunlit **(sun)** fraction of the canopy

$L_{AI,sha}$ shaded **(sha)** fraction of the canopy

$L_w$ wet fraction of canopy; calculated from $w_{dew}$ and $w_{dmax}$

$w_{dew}$ – *canopy interception water store (mm)*

$w_{dmax}$ – *maximum water the canopy can hold (default 0.1 mm)*

$L_d$ *d*ry fraction of canopy

# Evapotranspiration Equation

(mass transfer/mean variables approach)

$$E_{veg} = \left\{ \left[ \cancel{\frac{L_d r_b}{L_{AI}}} \left( \frac{\cancel{L_{AI,sun}}}{\cancel{r_b} + r_{s,sun}} + \frac{\cancel{L_{AI,sha}}}{\cancel{r_b} + r_{s,sha}} \right) \right] + \cancel{L_w} \right\} \left[ \cancel{\rho_a} \frac{\cancel{(L_{AI} + S_{AI})}}{\cancel{r_b}} \left( \cancel{q_{sat}} - \cancel{q_{af}} \right) \right]$$

**One more component related to foliage:**

$r_s$ stomatal resistance

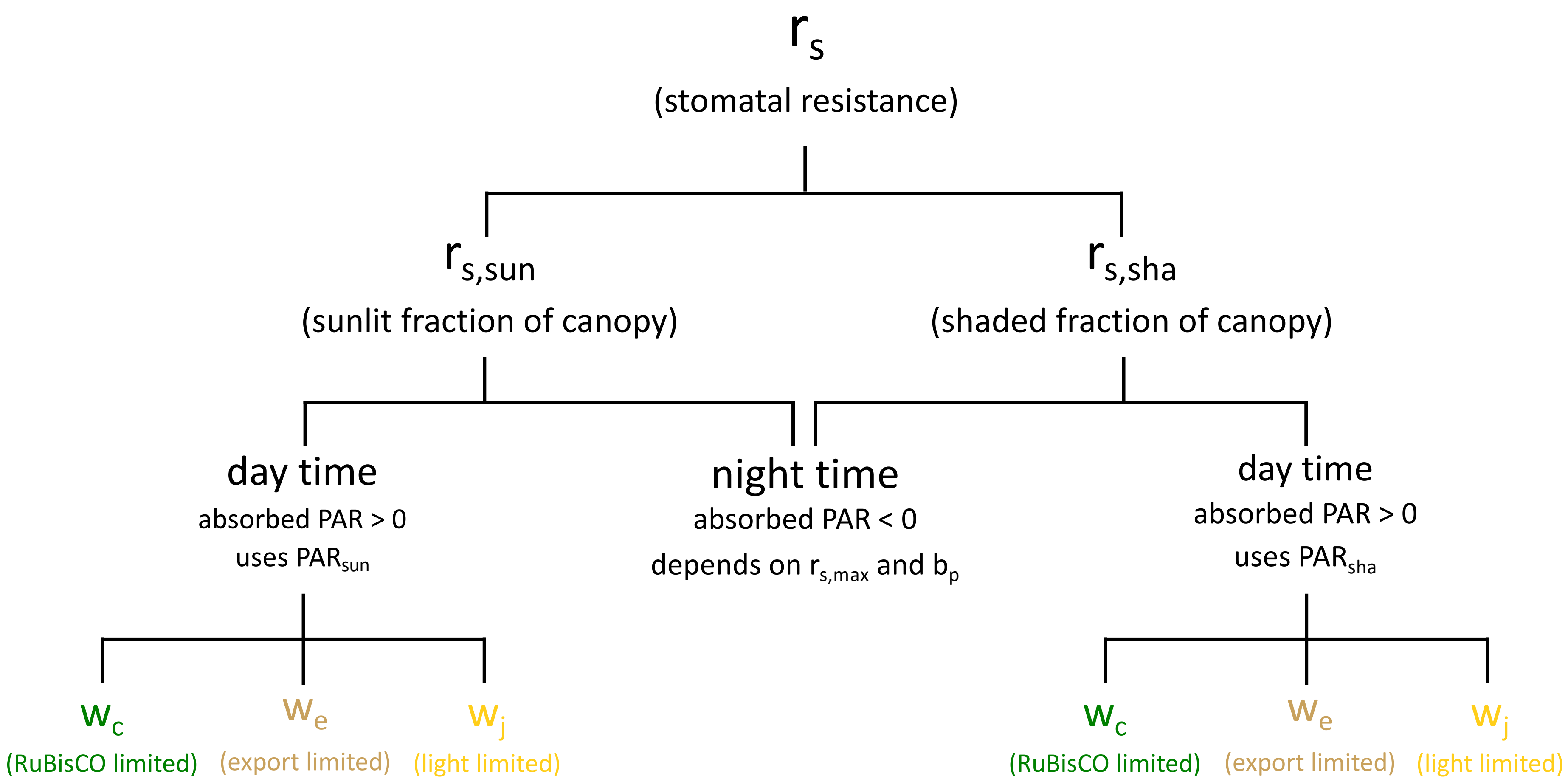
only parameter used to capture plant physiological processes in $E_{veg}$

no universally accepted way to model $r_s$

- CLM uses the Ball-Berry method, but several other models are available and used in land surface models
- most methods are empirical and include many constants

another computationally expensive part of $E_{veg}$ (iterative calculation)

# $r_s$ is Computed for Sunlit and Shaded Fractions of the Canopy




PAR = photosynthetically active radiation; derived from shortwave radiation

# Vegetation Water Stress

```
pfset Solver.CLM.VegWaterStress        Saturation
```

- Computed using soil moisture information from each layer:

$$\beta_{veg} = \sum_{l=1}^{l=10} f_{root,l} \frac{\phi S_l - \phi S_{wp}}{\phi S_{fc} - \phi S_{wp}} = \sum_{l=1}^{l=10} f_{root,l} \beta_{t,S}$$

- Wilting point and field capacity can be specified using solver keys (ParFlow Manual, Page 144)

- Vegetation water stress is used in transpiration computation when photosynthesis is <u>not</u> limited by light (i.e., when photosynthesis rate is $w_e$ or $w_c$)

3 options available

1. None

$$\beta_{t,N} = 1$$

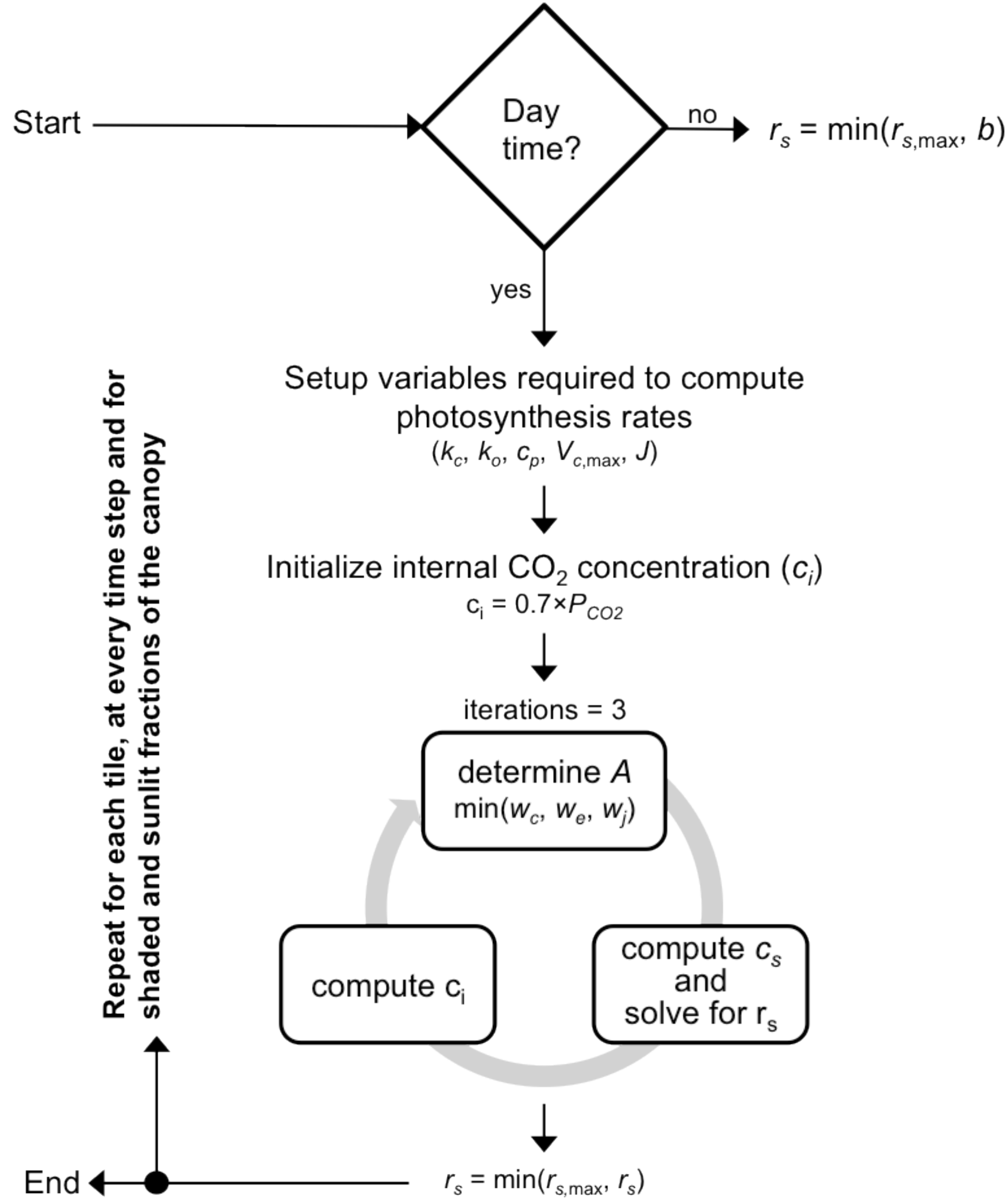
1. Saturation

$$\beta_{t,S} = \frac{\phi S_l - \phi S_{wp}}{\phi S_{fc} - \phi S_{wp}}$$

2. Pressure

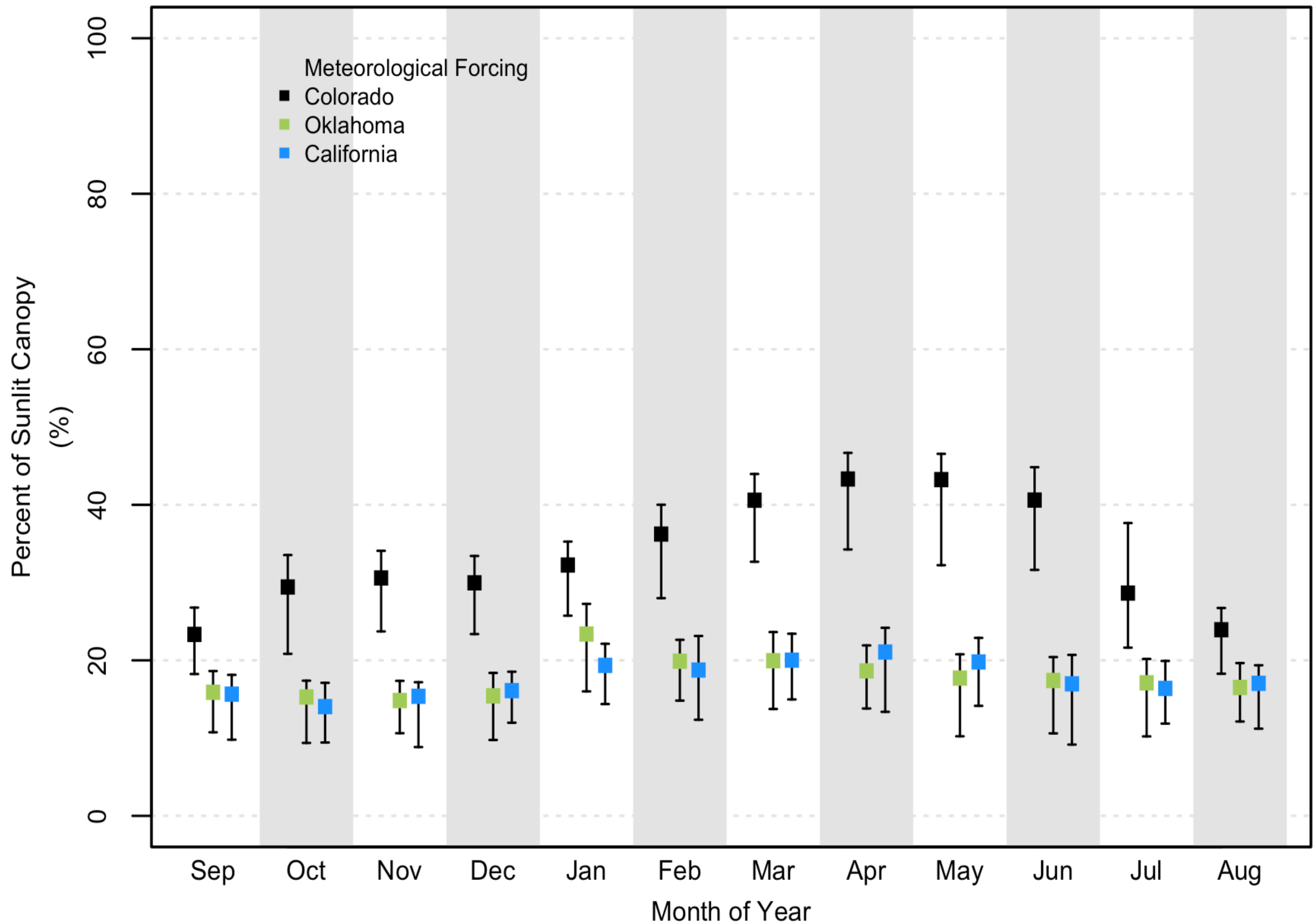
$$\beta_{t,P} = \frac{P_l - P_{wp}}{P_{fc} - P_{wp}}$$

# Another way to look at iterative nature of $r_s$ calculation

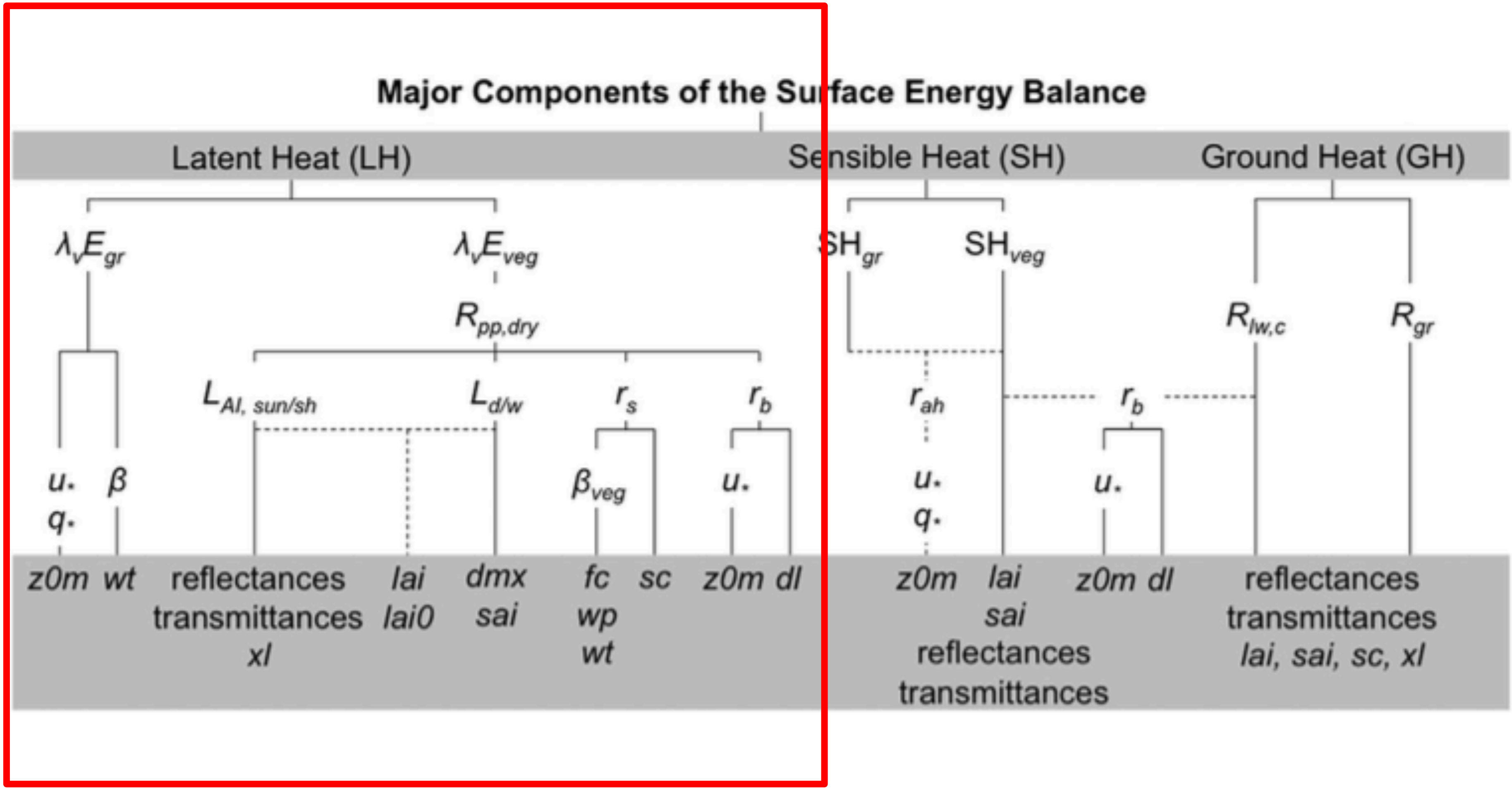


# Sunlit Fraction of Canopy

(from 300 single column realizations with varying stomatal resistance parameters)



# ET also Depends on Parameters from drv_vegp.dat




*Jefferson et al., 2015*