Goddard Institute for Space Studies at Columbia University in New York

Goddard Space Flight Center

The City University of New York

Harvard University

Ent: A Dynamic Global Terrestrial Ecosystem Model (DGTEM) for Coupling with GCMs

Nancy Y. Kiang, Igor Aleinov, David Rind (GISS)

Randal D. Koster (GSFC)

Paul R. Moorcroft (Harvard University)

Wenge Ni-Meister (GSFC and CUNY)

Postdocs: Pushker Kharecha (Columbia)

Yeonjoo Kim (Harvard)

NASA-MAP Science Team Meeting, March 7-9, 2007

Existing Coupled DGVM-GCM's

- IBIS-CCM3 (Foley, U. Wisc; NCAR)
- TRIFFID-HadCM3 (Cox, Hadley Ctr.)
- LPJ-Bern CC (Max Planck, Potsdam, Bern)
- LPJ-NCAR Community Climate Model (Bonan)
- ED-GFDL (Pacala, GFDL)

- In progress:
  MAPSS revision (Neilson, Oregon State U.)

Overview

1. Ent overview

2. Process coupling issues

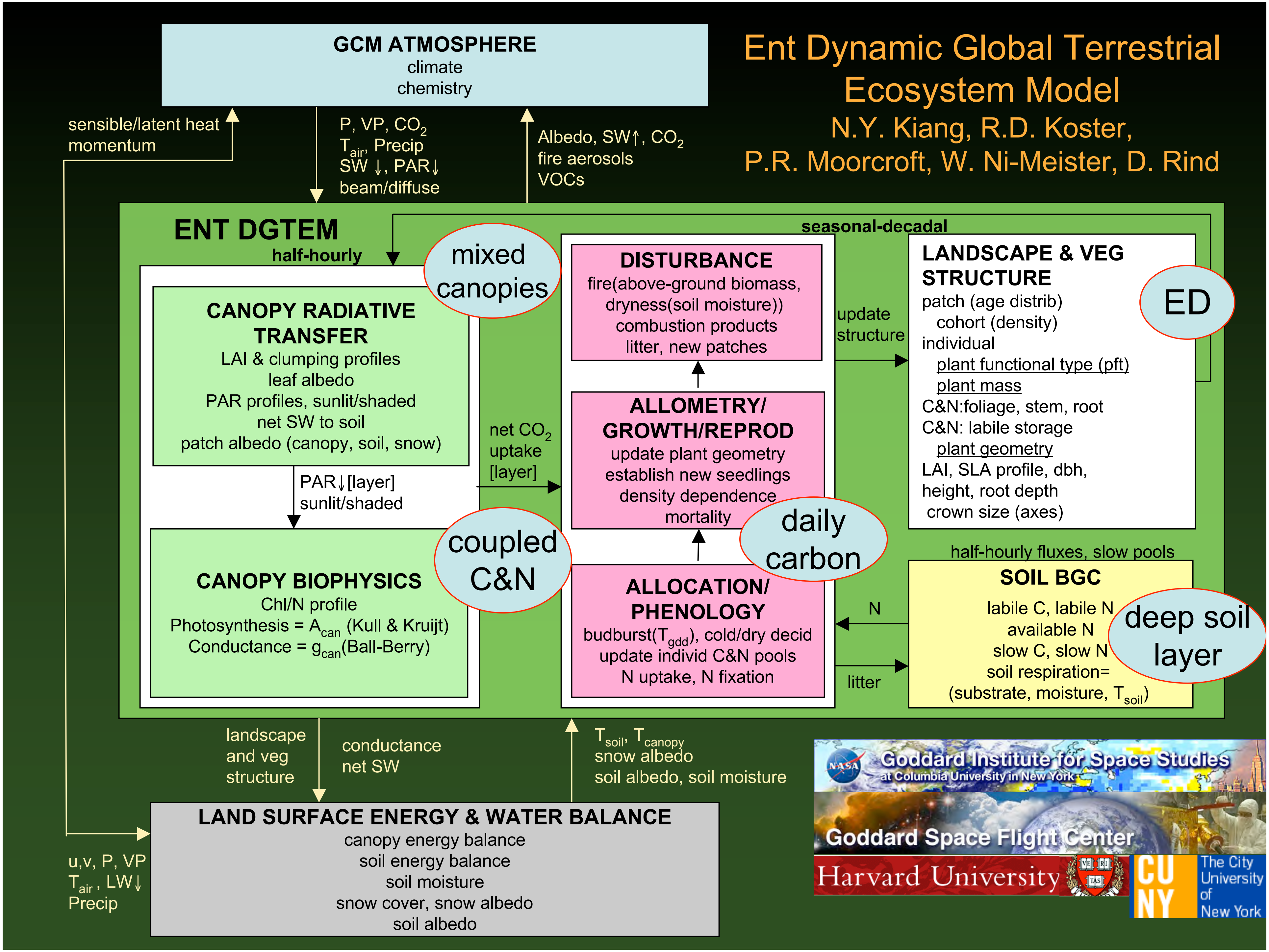
3. Model-to-model coupling issues

1. Ent overview

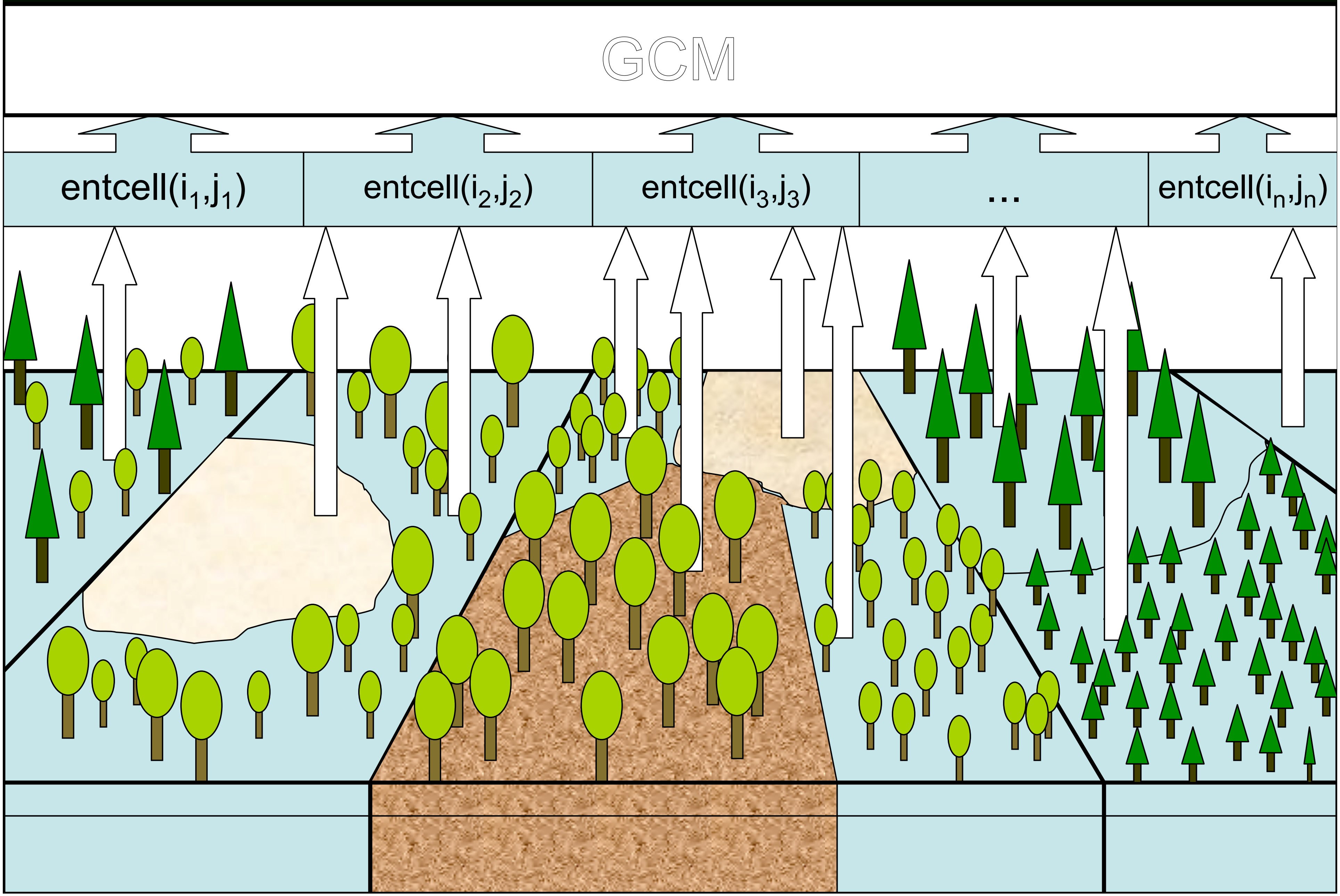
SCIENTIFIC COMMUNITY GOALS:

ENT will be a standalone set of modules that can be used by the climate modeling community to couple with land hydrology models and atmospheric GCMs

Research questions:	GISS	GMAO	NAI	Science community
synoptic/seasonal weather evolution	☐	☒	☐	☒
data assimilation	☐	☒	☐	☒
vegetation phenology	☒	☒	☐	☒
global carbon budget	☒	☒	☐	☒
global change: past, present, and future	☒	☐	☐	☒
vegetation-climate feedbacks	☒	☒	☒	☒
astronomical biosignatures	☐	☐	☒	☒


Ent Dynamic Global Terrestrial Ecosystem Model
N.Y. Kiang, R.D. Koster,
P.R. Moorcroft, W. Ni-Meister, D. Rind
GCM ATMOSPHERE
climate
chemistry
sensible/latent heat
momentum
P, VP, CO_2
T_{air}, Precip
SW ↓, PAR↓
beam/diffuse
Albedo, SW↑, CO_2
fire aerosols
VOCs
ENT DGTEM
half-hourly
seasonal-decadal
mixed canopies
CANOPY RADIATIVE TRANSFER
LAI & clumping profiles
leaf albedo
PAR profiles, sunlit/shaded
net SW to soil
patch albedo (canopy, soil, snow)
PAR↓[layer]
sunlit/shaded
CANOPY BIOPHYSICS
Chl/N profile
Photosynthesis = A_{can} (Kull & Kruijt)
Conductance = g_{can}(Ball-Berry)
coupled C&N
net CO_2
uptake
[layer]
DISTURBANCE
fire(above-ground biomass,
dryness(soil moisture))
combustion products
litter, new patches
ALLOMETRY/ GROWTH/REPROD
update plant geometry
establish new seedlings
density dependence
mortality
daily carbon
ALLOCATION/ PHENOLOGY
budburst(T_{gdd}), cold/dry decid
update individ C&N pools
N uptake, N fixation
update
structure
LANDSCAPE & VEG STRUCTURE
patch (age distrib)
cohort (density)
individual
plant functional type (pft)
plant mass
C&N:foliage, stem, root
C&N: labile storage
plant geometry
LAI, SLA profile, dbh,
height, root depth
crown size (axes)
ED
half-hourly fluxes, slow pools
SOIL BGC
labile C, labile N
available N
slow C, slow N
soil respiration=
(substrate, moisture, T_{soil})
deep soil layer
N
litter
landscape
and veg
structure
conductance
net SW
T_{soil}, T_{canopy}
snow albedo
soil albedo, soil moisture
u,v, P, VP
T_{air} , LW↓
Precip
LAND SURFACE ENERGY & WATER BALANCE
canopy energy balance
soil energy balance
soil moisture
snow cover, snow albedo
soil albedo
Goddard Institute for Space Studies
at Columbia University in New York
Goddard Space Flight Center
Harvard University
CUNY
The City University of New York

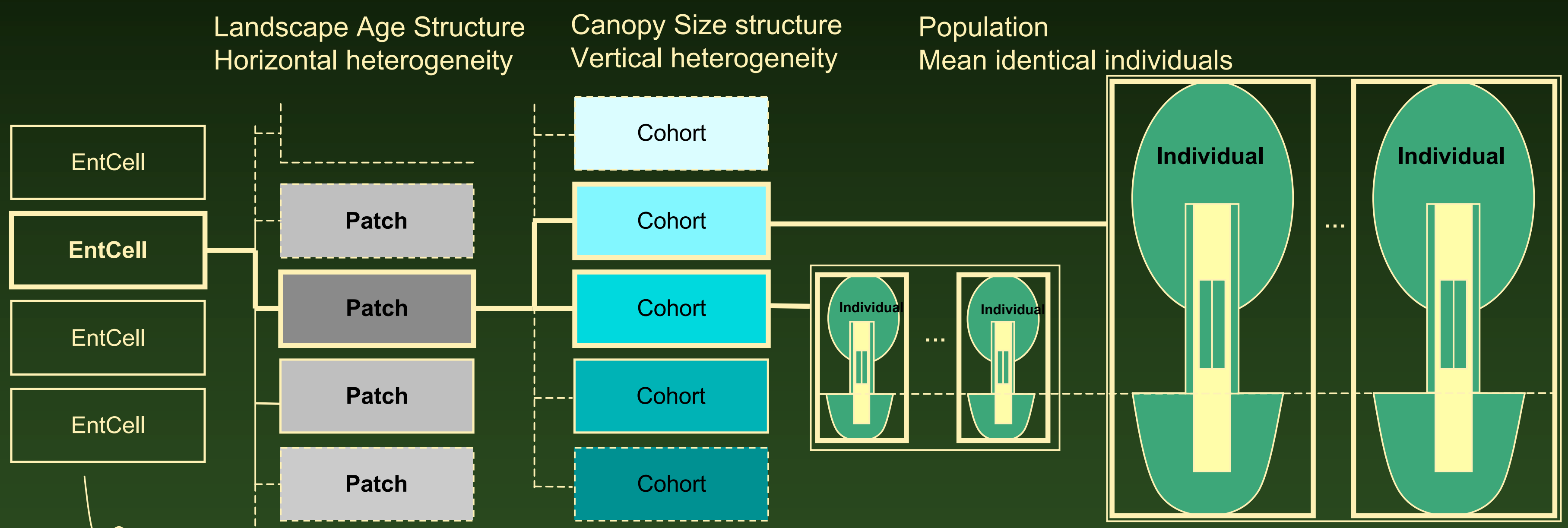
Ent subgrid heterogeneity and mixed canopies



ED Size- and Age-Structured Approach to Gap or Patch Dynamics

(Moorcroft, et.al., 2001) Not spatially explicit

- discretization of size- and age -structured partial differential equations



- Aging
- Disturbance

- Growth
- Mortality

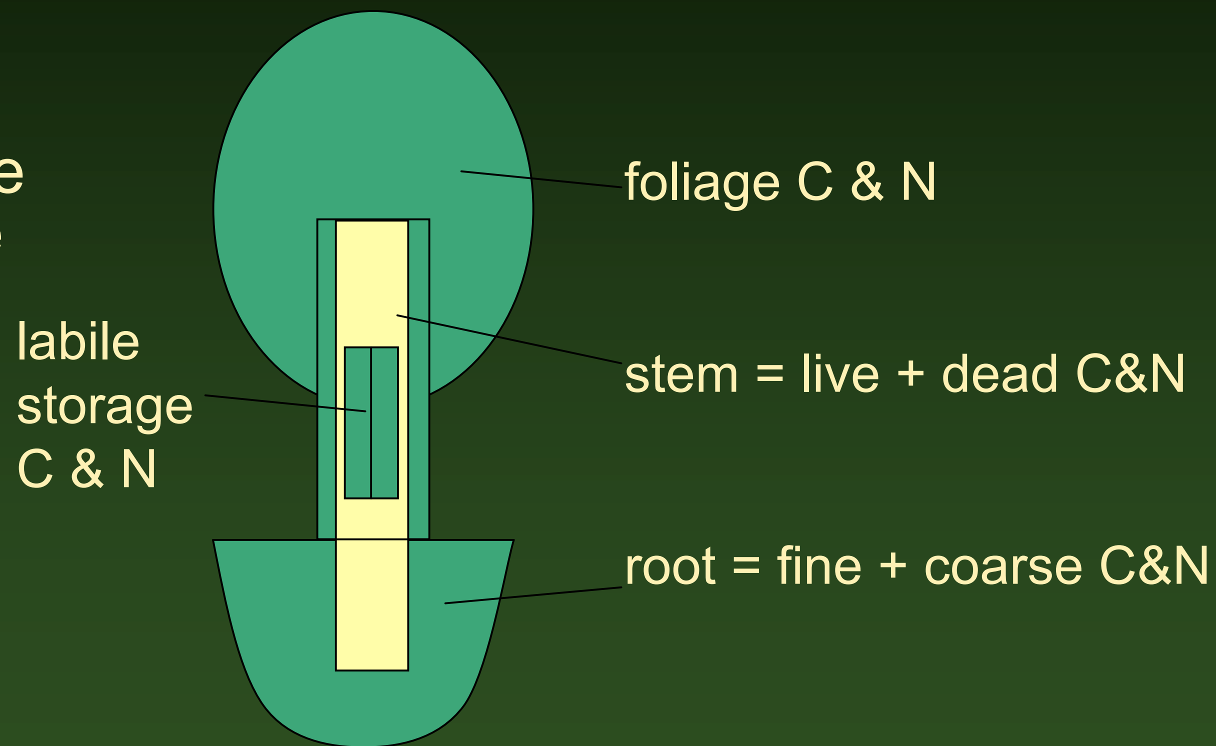
Grid cell or
Catchment zone

Individual tree: C & N pools

Geometry: ellipsoid crowns

Pools: C & N

- active tissue
- dead tissue



- Fixed allometry for computational limits.

Ent “Core” Plant Functional Types (PFTs):

- growth form, phenology, photosynthetic pathway, early/late sucessional

  1-2: evergreen broadleaf, early and late successional
  3-4: evergreen needleleaf, early and late successional
  5-6: cold deciduous broadleaf, early and late successional
  7: drought deciduous broadleaf
  8: cold adapted shrub
  9: arid adapted shrub
  10: C3 grass
  11: C4 grass
  12: arctic C3 grass
  13: C4 crops

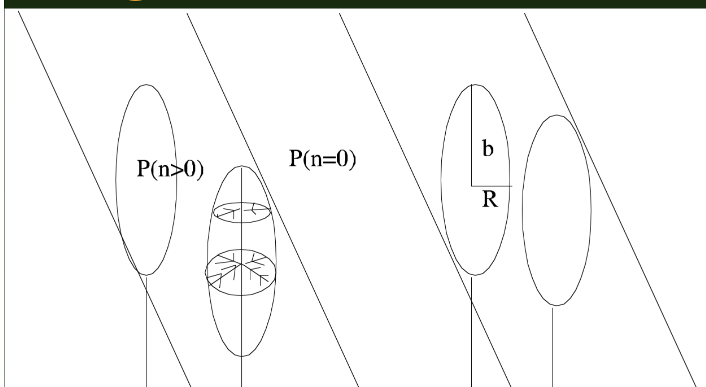
  - Based on Reich, et.al. (1999) data on specific leaf area/nitrogen/leaf longevity relations.

  - PFTs can be customized (e.g. GISS vegetation types also supported).

Ent recent progress

computationally simple

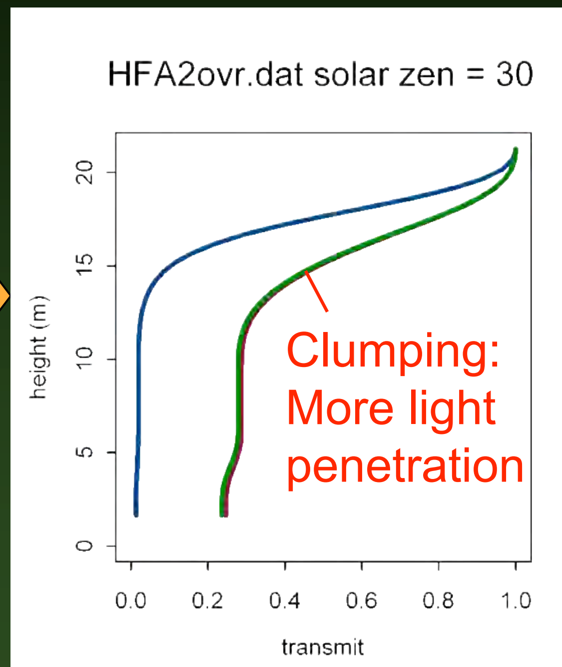
Canopy radiative transfer for mixed and changing vegetation structure



3D GORT geometry
(Ni, et.al., 1999)
ellipsoid crowns

Clumped Beer's law

f(ellipticity, foliage density)



How to get clumping factor?

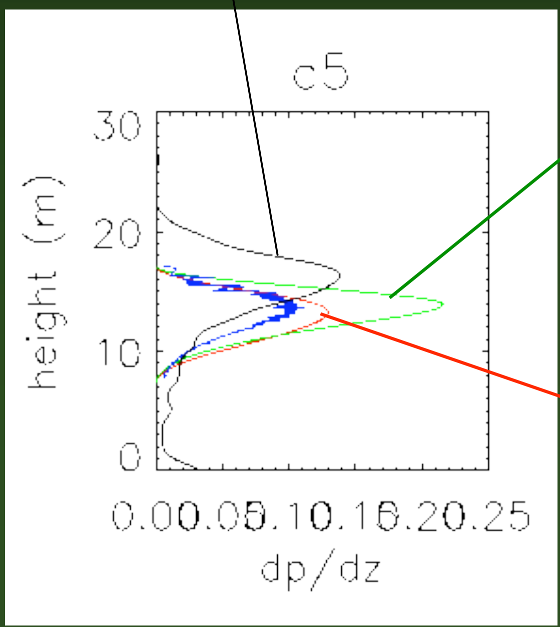
- Canopy albedo
- Vertical profiles
- Sunlit/shaded leaf area fractions
- Transmittance to ground

Ent canopy radiative transfer

Field tests at Harvard Forest (temperate broadleaf deciduous)

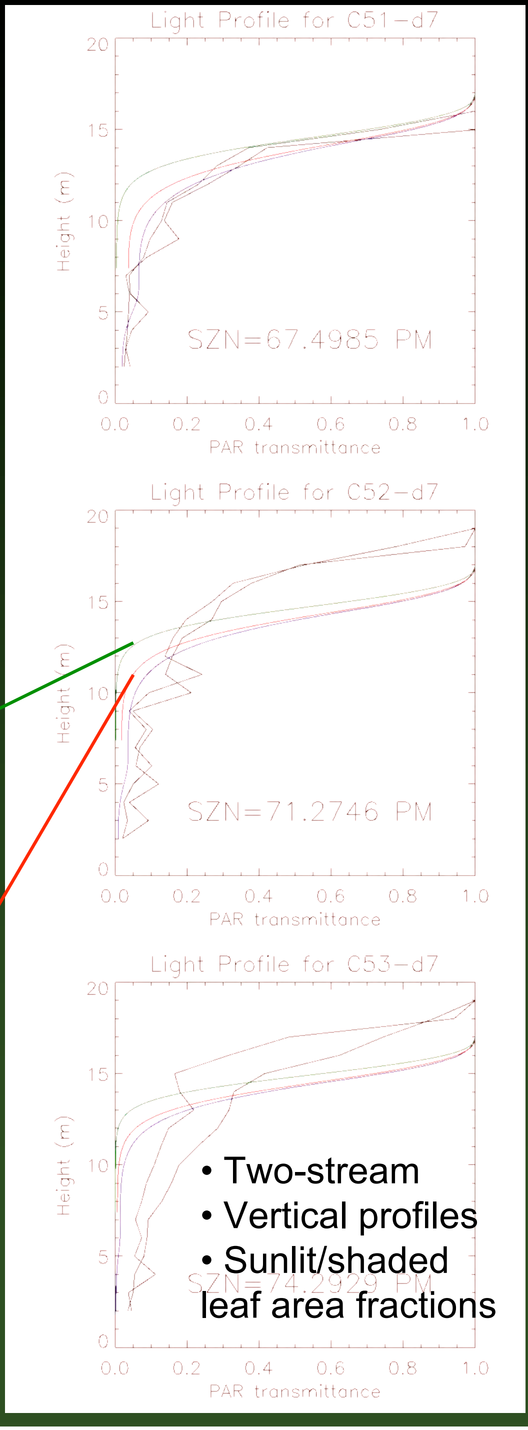
- Beer's Law
- 3D GORT overclumped
- Analytical clump factor
- LIDAR - Harvard Forest
- Balloon profile - " "

LIDAR closest to clump factor model
(but height parametrization may be off for forest plot)



Beer's law is too opaque

Analytically derived clumping factor is intermediate between Beer's and over-clumped 3D GORT



Ent Canopy Radiative Transfer

Analytical Model for Clumping Factor

(based on Li and Strahler, 1988)

Beer's Law with clumping factor, γ

$$\tau_s(h) = \exp\left(\frac{-\gamma G L(h)}{\cos\theta}\right)$$

τ_s: penetration function (fraction) for beam radiation

G: leaf orientation function

see poster

Clumping factor, γ

Non-overlapping cr

$$\gamma = \frac{3}{4\Gamma R}\left(1 - \frac{1-(2\Gamma R+1)e^{-2\Gamma R}}{2(\Gamma R)^2}\right)$$

ctor

$\gamma=1$, no clumping, leaves random

$\gamma<1$, clumped

$\gamma>1$, uniform/dispersed

where:

$$\Gamma R = GFaR\left(\frac{1+\tan^2\theta}{1+\left(\frac{b}{R}\right)^2\tan^2\theta}\right)^{\frac{1}{2}} = \frac{3GLAI}{4\lambda\pi R^2}\left(\frac{1+\tan^2\theta}{1+\left(\frac{b}{R}\right)^2\tan^2\theta}\right)^{\frac{1}{2}}$$

θ= solar zenith angle, Fa = foliage area volume density,
R = crown radius, b/R = crown ellipticity, λ = tree density

Ent phenology and growth

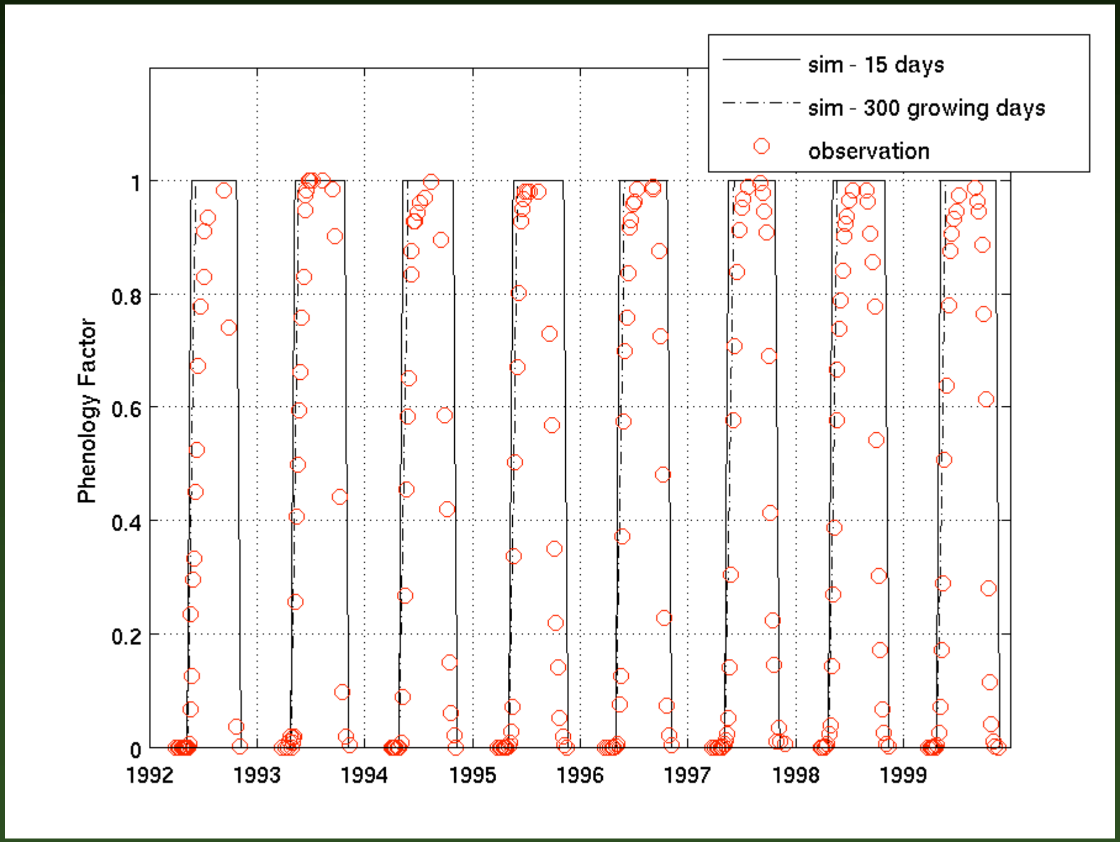
Daily Time Step

Allocation and Growth:

• Controlled by phenology and static allometry.

• Consistent with ellipsoid crowns of radiative transfer scheme

• N uptake/allocation: vertically stratified photosynthetic activity by cohort.



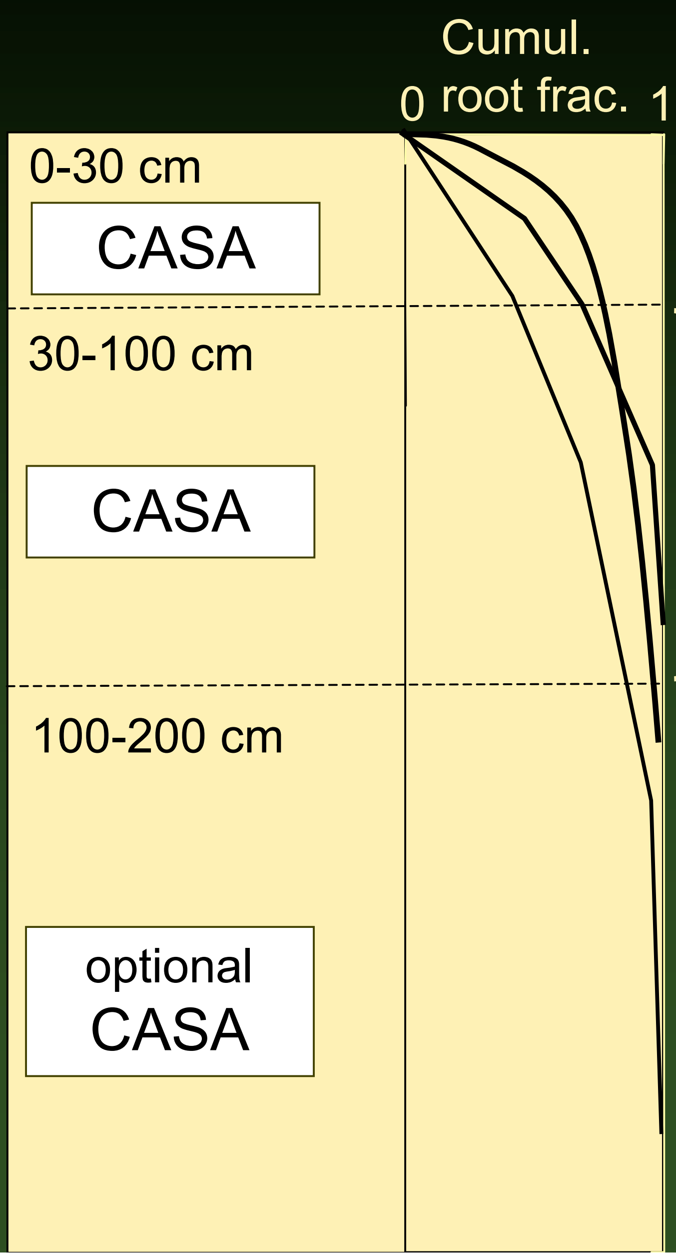
preliminary result
Harvard Forest

Phenology:

1. Leaf flush: Botta et al. (2000)
   - growing degree days, chilling days
   - 10-day running avg air temperature
2. Leaf drop: White et al. (1997)
   - day length
   - 10-day running avg. soil temperature
3. Drought-deciduous:
   - Relative extractable water content
   - 10-day running avg. soil moisture

Ent Soil Biogeochemistry:
CASA with deep layers

see poster



Most respiration fluxes to the atmosphere
(Existing models)

Storage pool due to deep roots
(Ent addition)

Additional deep storage.
Optional dynamics given computational limits.

CASA soil model: Potter et al. (1993, 1997, 1999)

Ent-CASA soil biogeochemistry

preliminary spin-up results for grassland

- 400-year spin-up of soil carbon
- Forcing values from the Ponca, OK, FLUXNET winter wheat site
- Two soil respiration parameterizations: 1) CASA[1], 2) Del Grosso[2]

kg-C/m^2 by layer	400-yr spin-up		Field site data				Global datasets	
	CASA[1]	Del Grosso[2]	Ponca[3] winter wheat	Tonzi[4] annual grassland	Idaho[5] C3 grassland	FIFE[6] C4 grassland	Post[7] temp. thorn steppe	ISRIC /WISE[8] cambisols
0-30 cm	3.77 (1%)	1.20 (3%)	4.79 (1.2%)	4.4 (0.92%)	(1.8%) top 10 cm	8.2 (2.2%)	7.6±6.8	5
30-100 cm	1.07 (0.1%)	0.36 (0.04%)	8.68 (0.8%)	n/a	n/a	2.6 (0.6%)		10

[1]Potter et al. (1993,1997,1999)
[2]Del Grosso et al. (2005) Biogeoch. 73:71-91
[3]FLUXNET site page [http://www.fluxnet.ornl.gov/fluxnet]
[4]Xu et al. (2004) GBC 18: Art. No. GB4002
[5]M. Myklebust, Utah St. Univ.
[6]Huemmrich F. & E. Levine (1994) Soil Survey Reference (FIFE). [http://www.daac.ornl.gov]
[7]Post et al. (1985) Nature 317. Zinke et al. (1986).
[8]Batjes, N. (1996) Eur. J. Soil Sci. 47(2):151-163.

2. Process coupling issues:

time scales

layering schemes

biogeochemistry

Ent process time scales

“slow” soil respires at time step

“Seasonal” updated daily

Irregular change rather than exact intervals

Time step: ~hourly fluxes

- CO_2:
  - Photosynthesis and plant respiration
  - Soil respiration
- H_2O:
  - Transpiration (land model: evaporation)
- C & N pools:
  - Photosynthesis inputs to labile carbon pool
  - Soil organic matter turnover

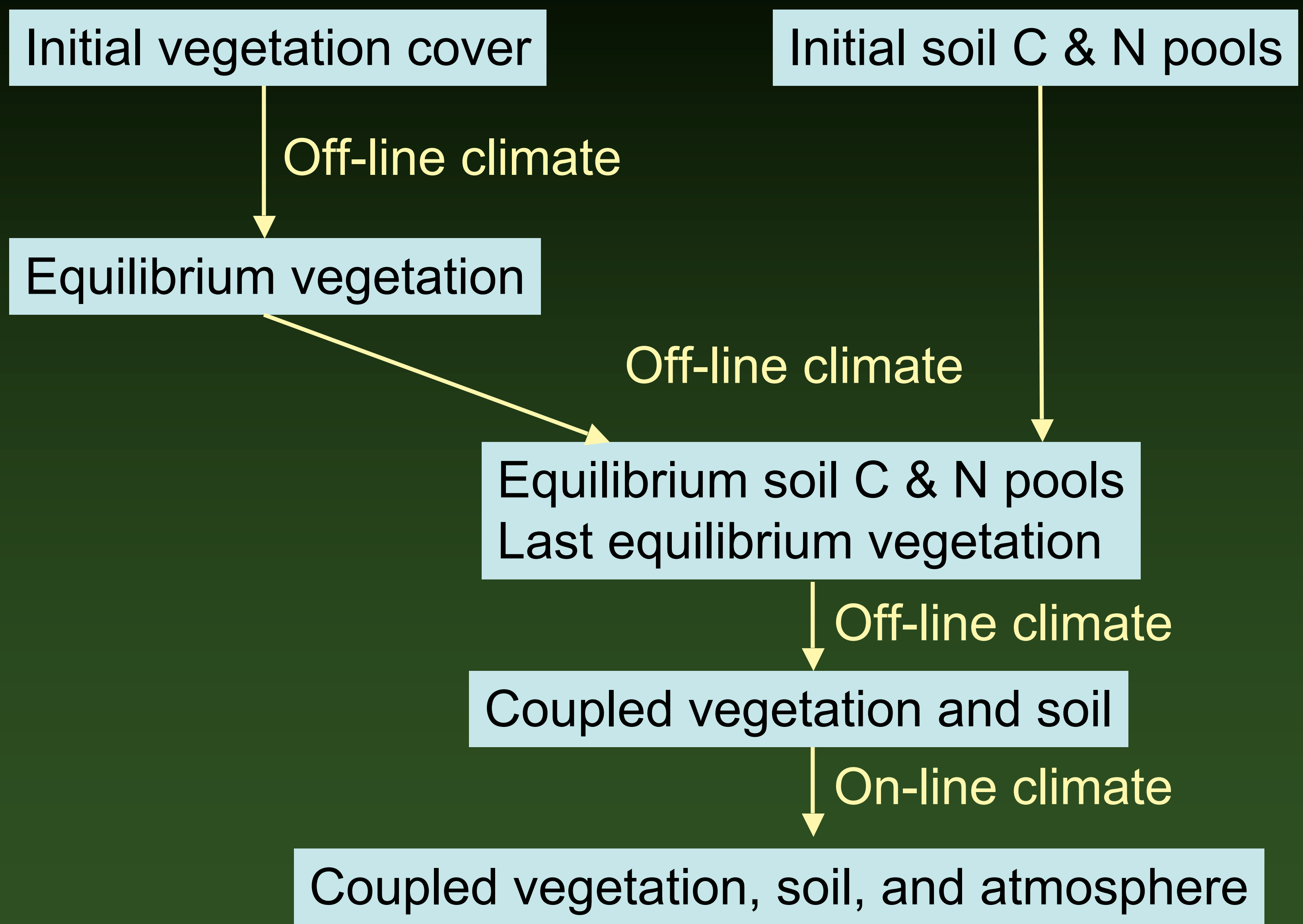
Daily: phenology, growth, disturbance probability

- C & N pools:
  - All plant pools, LAI
  - N uptake
  - Litterfall
  - Fuel build-up

Intermittent: community dynamics, disturbance

- Community change:
  mortality, establishment, reproduction
- Vegetation cover change: mortality, disturbance

Ent process time scales: spin-ups

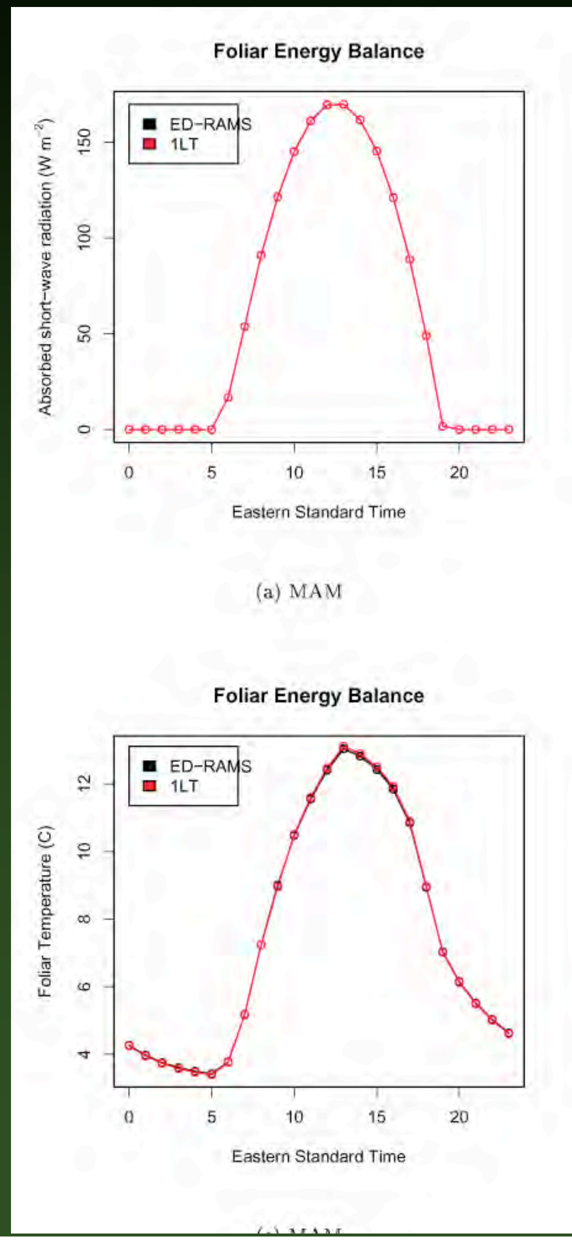


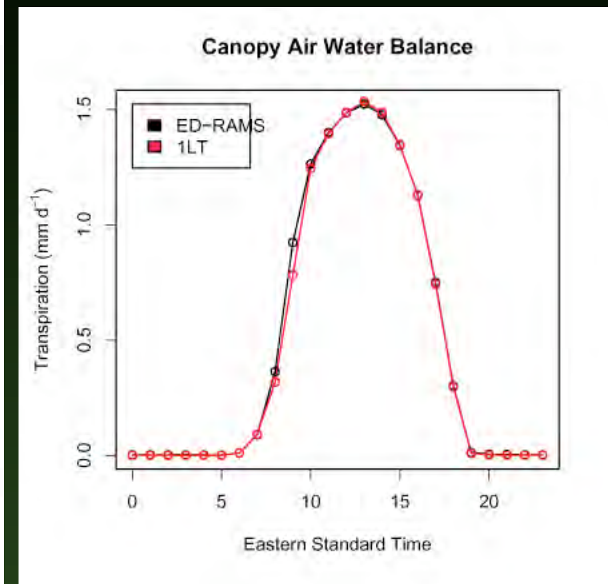
Canopy layering for energy, CO_2, and H_2O fluxes

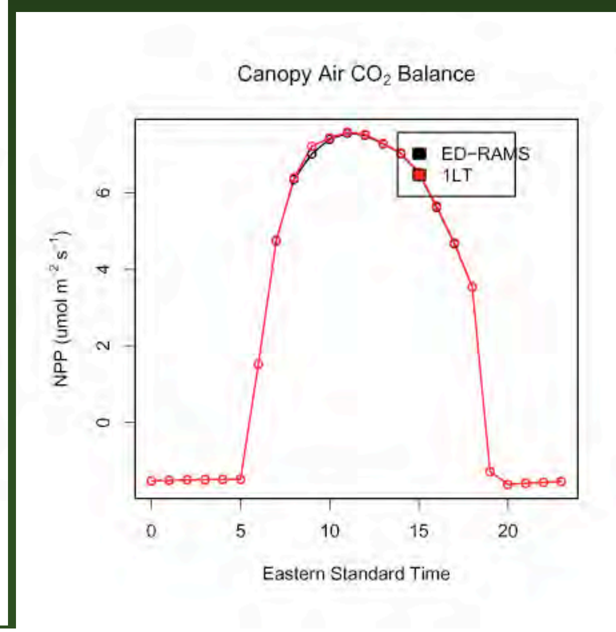
black line:

ED-RAMS:

multi-layer canopy







Conclusion:

red line:

1LT:

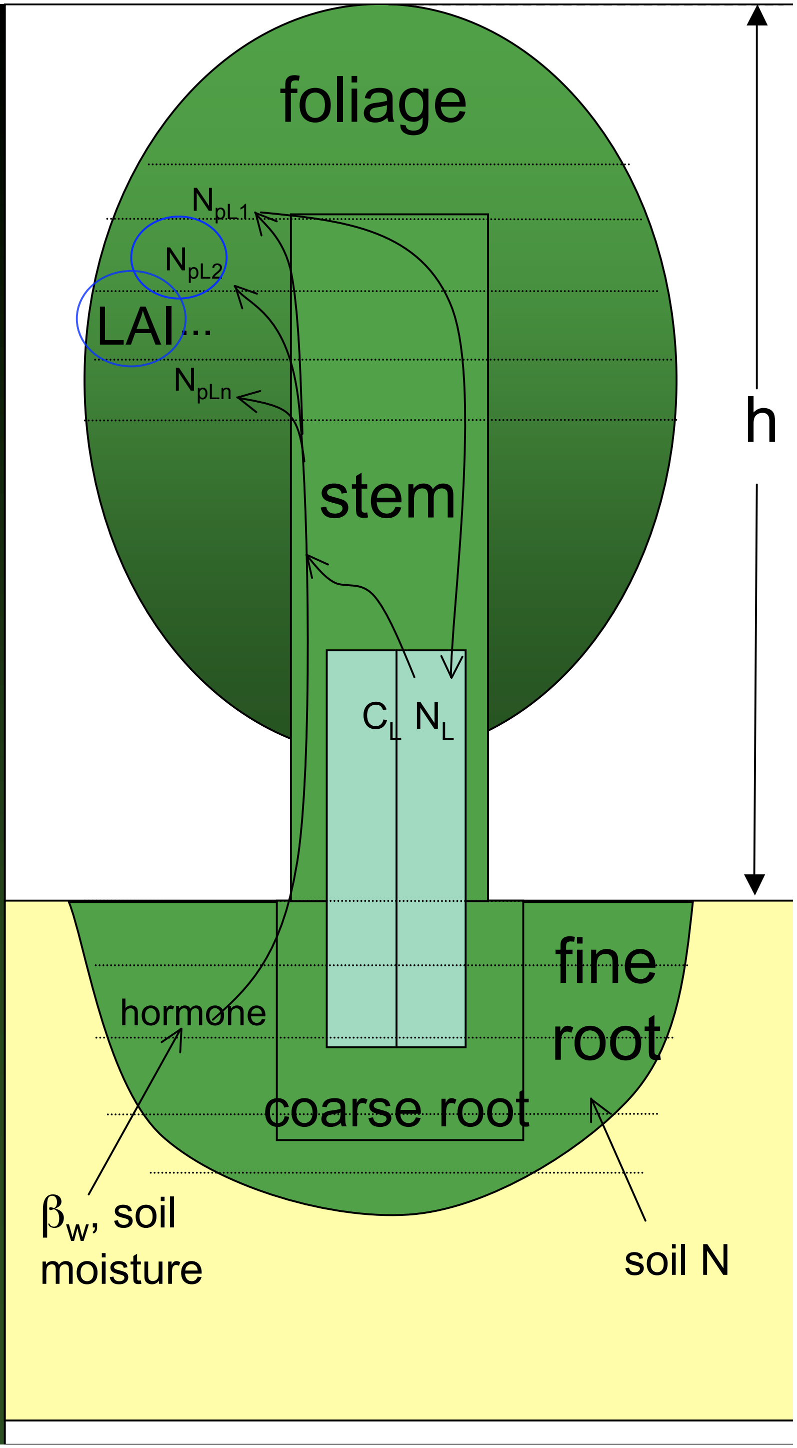
- single-layer temperature
- multi-layer radiative transfer/ photosynthesis

Canopy and Soil layering and C & N coupling

Allocation of foliage N ideally: Stratified by light profile/activity

- Photosynthetic N should be vertically stratified by light profile/activity.

Soil biogeochemistry layering: pools vs. fluxes



Canopy and Soil layering and C & N coupling

Allocation of foliage N ideally: Stratified by light profile/activity

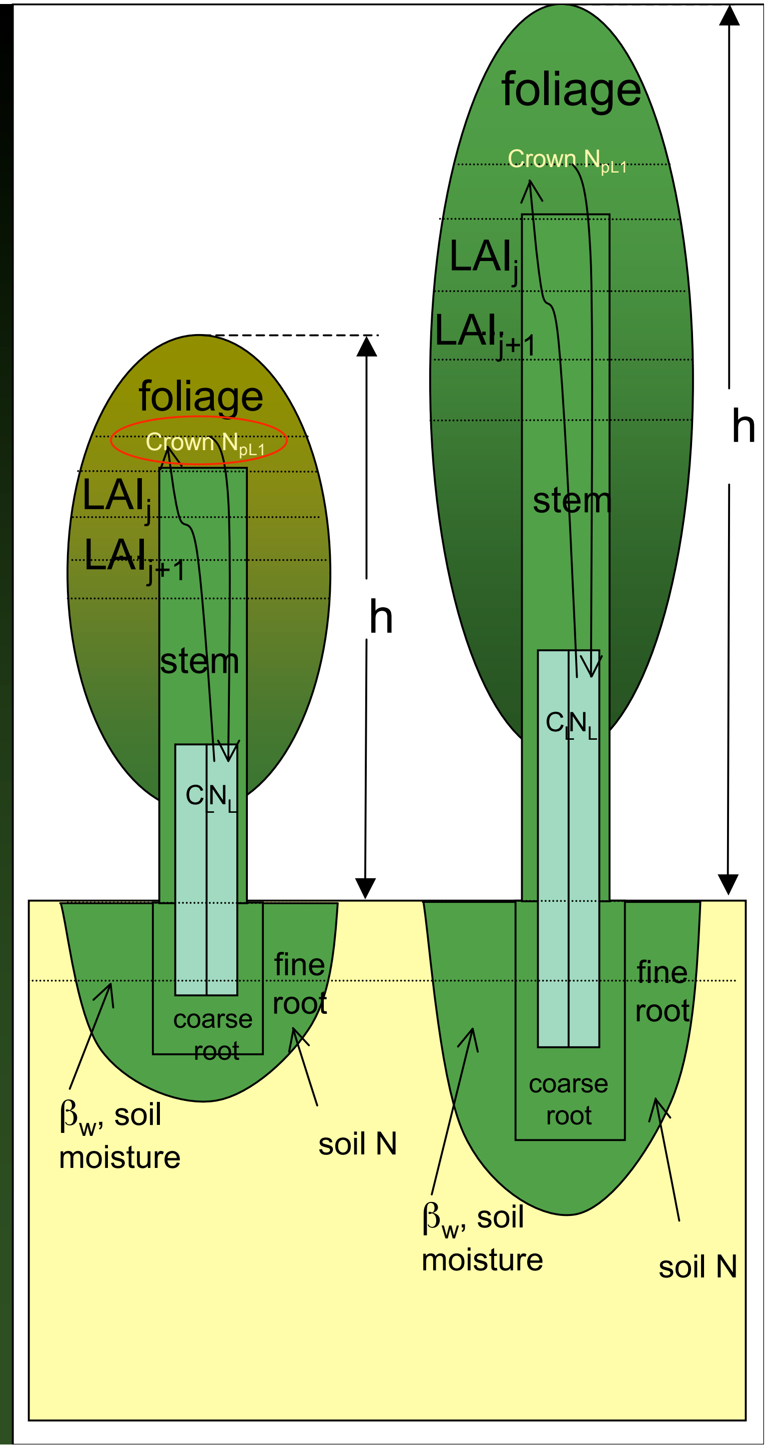
- Photosynthetic N should be vertically stratified by light profile/activity.

Compromise: stratify N by cohort, partition tall cohorts, photosynthesis still by layers

- Photosynthesis (Kull & Kruijt, 1999)
- Stomatal conductance (Ball-Berry, 1987)

Soil biogeochemistry layering: pools vs. fluxes

- 0-30 cm: respiration fluxes
- 30-100 cm: deep storage



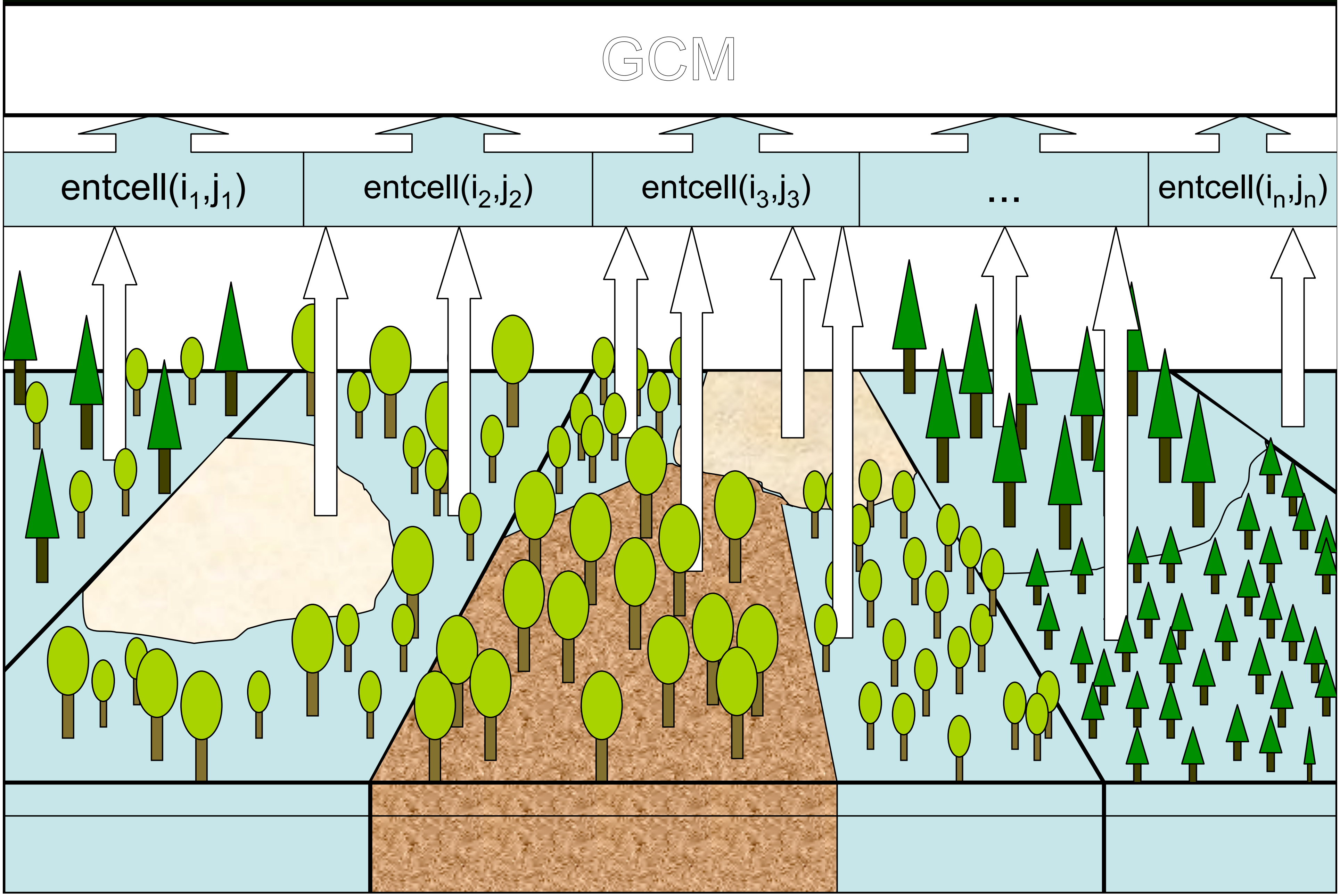
3. Model-to-model coupling:

subgrid heterogeneity

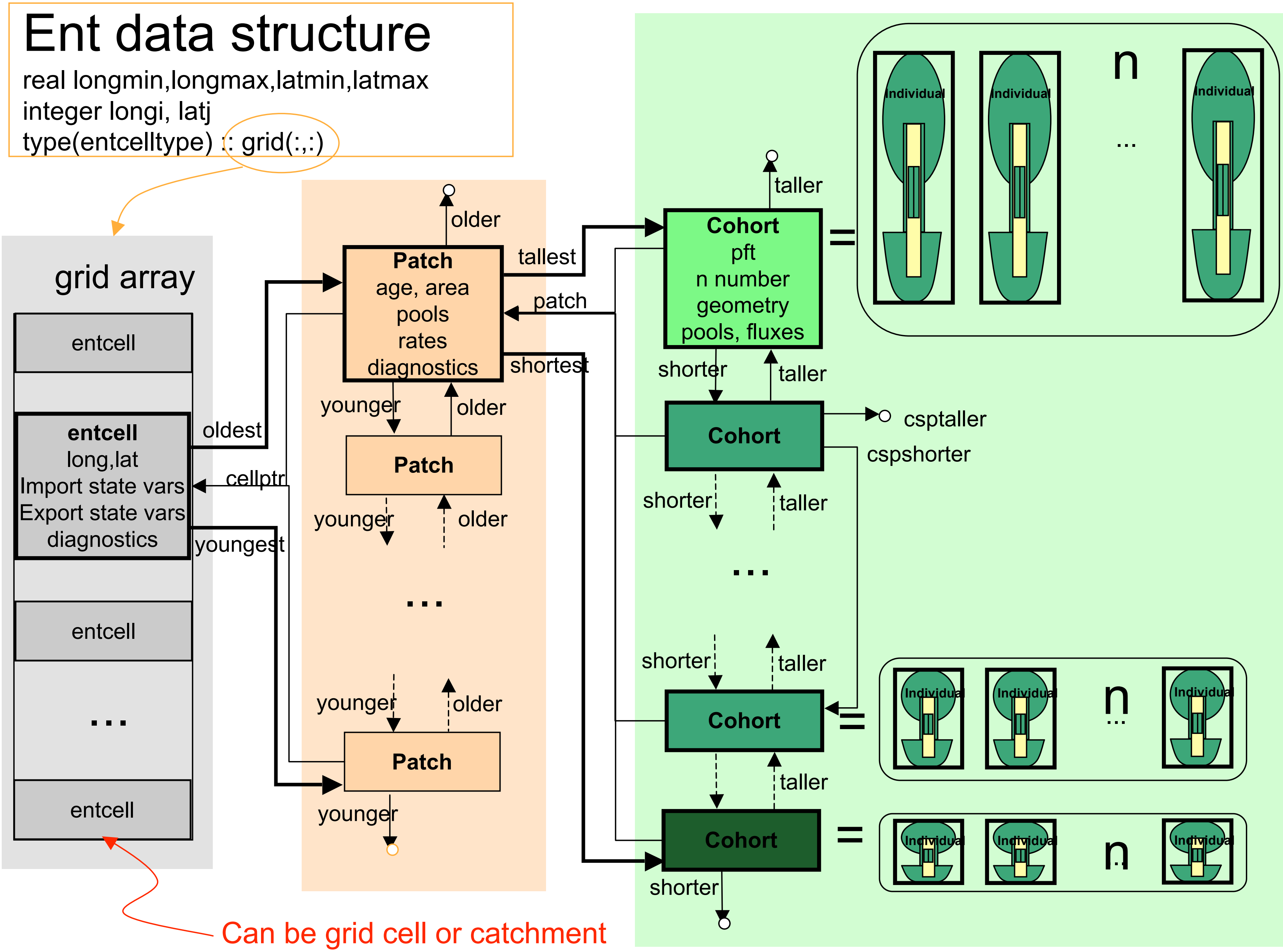
computational constraints

GISS GCM, GEOS-5 GCM

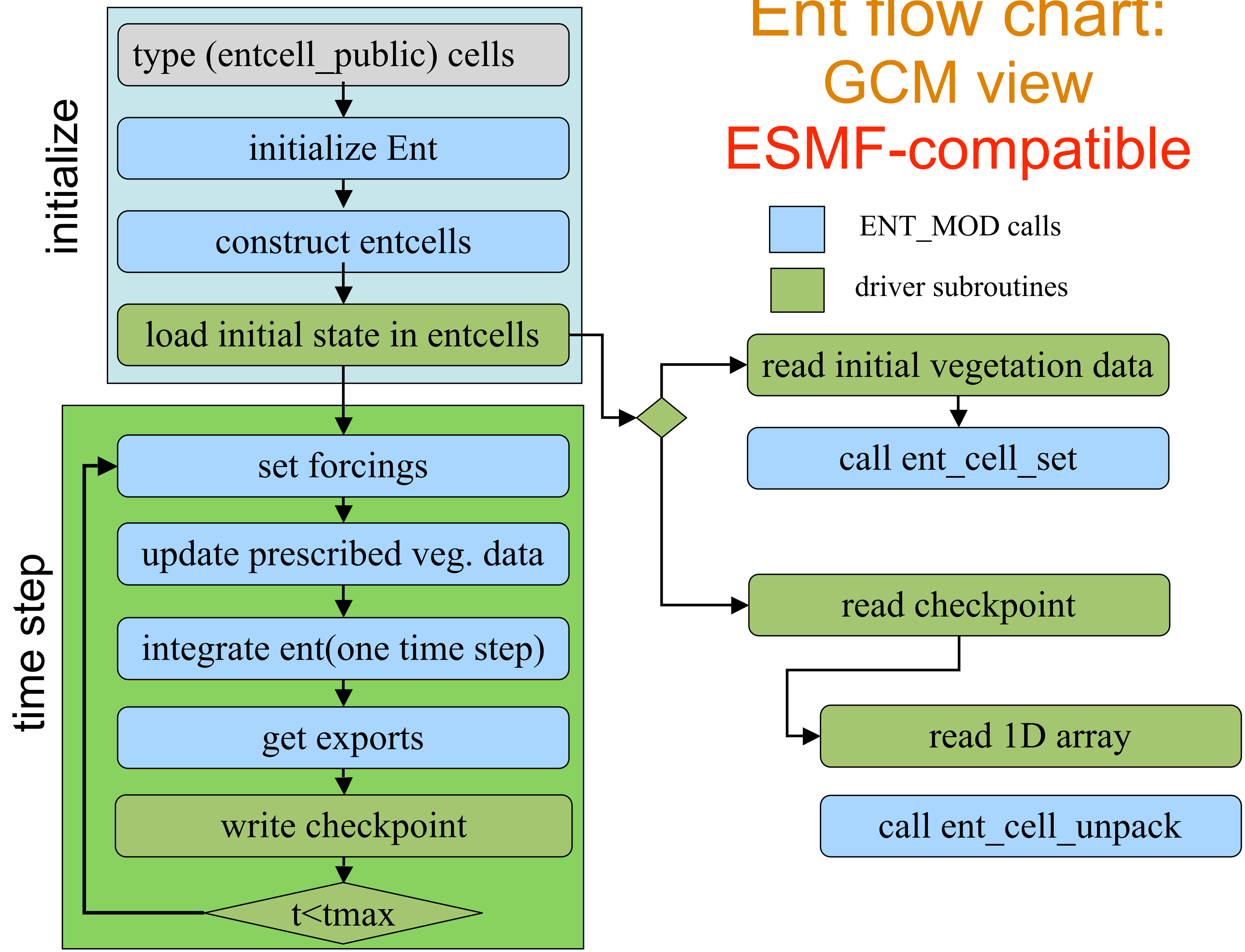
Ent subgrid fluxes and GCM coupling



General GCM coupling protocols, utilities


Ent data structure
real longmin,longmax,latmin,latmax
integer longi, latj
type(entcelltype) :: grid(:,:)
grid array
entcell
entcell
long,lat
Import state vars
Export state vars
diagnostics
entcell
...
entcell
oldest
cellptr
youngest
older
Patch
age, area
pools
rates
diagnostics
younger
older
Patch
younger
older
...
younger
older
Patch
younger
tallest
patch
shortest
taller
Cohort
pft
n number
geometry
pools, fluxes
=
Individual
Individual
n
...
Individual
shorter
taller
Cohort
csptaller
cspshorter
shorter
taller
...
shorter
taller
Cohort
=
Individual
Individual
n
...
Individual
taller
Cohort
=
Individual
Individual
n
Individual
shorter
Can be grid cell or catchment

Ent flow chart: GCM view ESMF-compatible



Interface between Ent and GCM: ent_mod

• Fortran 90 module which provides interface between Ent and GCM. All procedures listed below are Fortran 90 interfaces which work with 0, 1, and 2-dimensional arrays of entcells. So one can easily combine them into an ESMF component.

skip

Derived types:

type encellty... u...

General model c...

ent_initialize(do_soilresp,...)

Constructor:

ent_cell_construct(cells)

ent_cell_destruct(cells)

ent_cell_set(cells,...)

ent_cell_nullify(cells)

T... ste... ...es:

e... et_... ng... ls,...)

e... es... _... pdate(cells,...)

e... st... (cells, dt)

ent_get_exports(cells,...)

I/O:

ent_cell_pack(buffer,cells)

ent_cell_unpack(buffer,cells)

Ent data structure utilities for GCM coupling

Supported utilities for GCM coupling:
- Initialization routines
- Time-stepping routines
- Packing and unpacking routines
  (used by GCM to save and restore the model state) :

```
subroutine ent_cell_pack(buffer, entcells)

subroutine ent_cell_unpack(buffer, entcells)
REAL*8, pointer :: buffer(:)
type(entcell_public) :: entcells(:)
```

ent_cell_pack: packs the contents of the entcell (or array of entcells) to a 1-dimensional array buffer(:).

ent_cell_unpack: unpacks buffer(:) into the entcell (or array of entcells)

Ent restart file size

<u>Regular grid (GISS GCM)</u>:

72x46 grid cells x (27-510 variables) * 8 (double precision)
* 0.25 land area fraction
= 0.2 - 4 MB

144x90 grid cells x (27-510 variables) * 8 (double precision)
= 1 - 13 MB

<u>Catchment arrays (GEOS-5 GCM)</u>:

70,000 catchments * 3 tiles * (27-510 variables) * 8 (double precision)
= 46 - 857 MB

GEOS-5
catchment model coupling

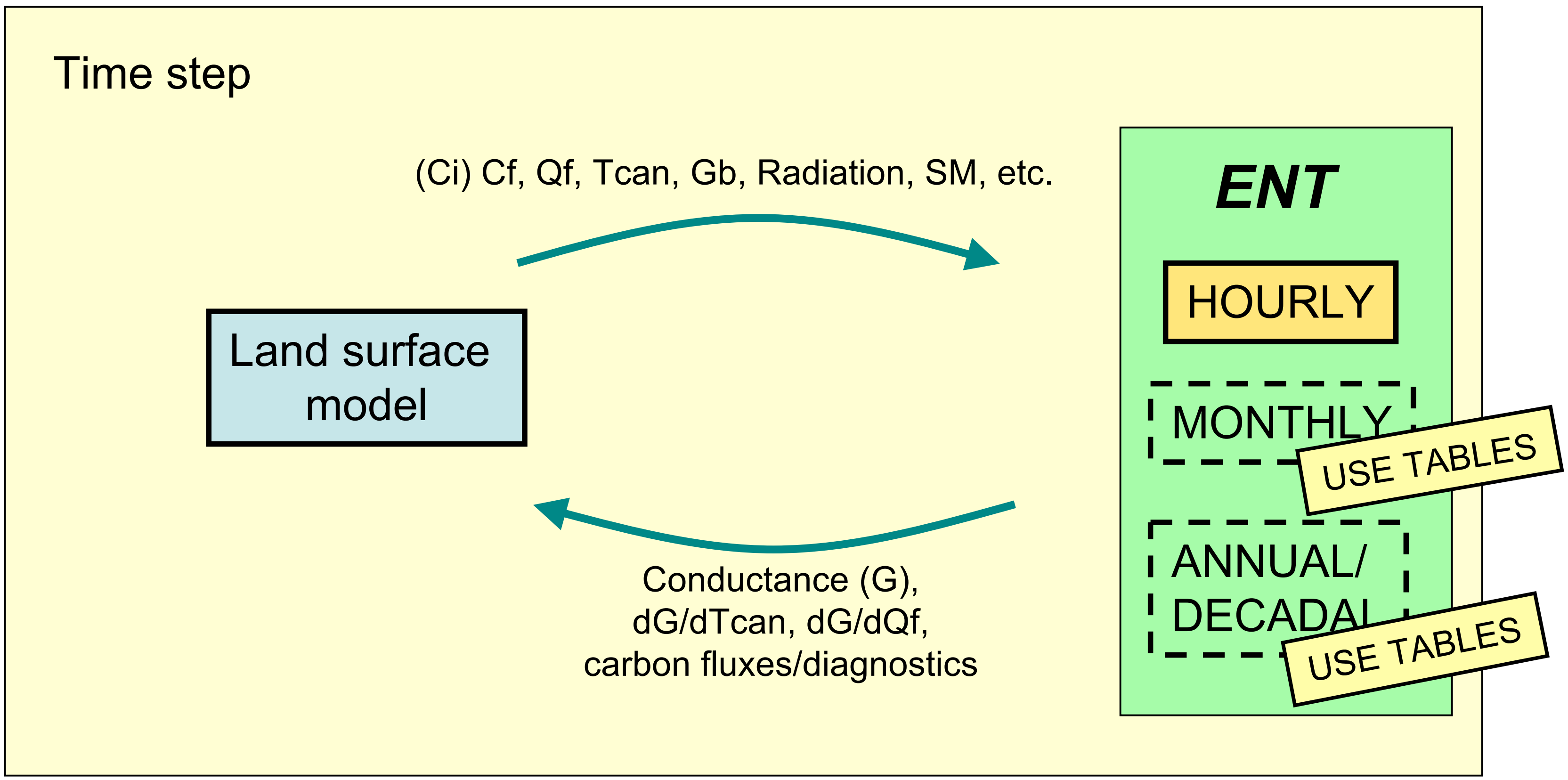
Ent – AGCM coupling issues

Ent operates at three different time scales:

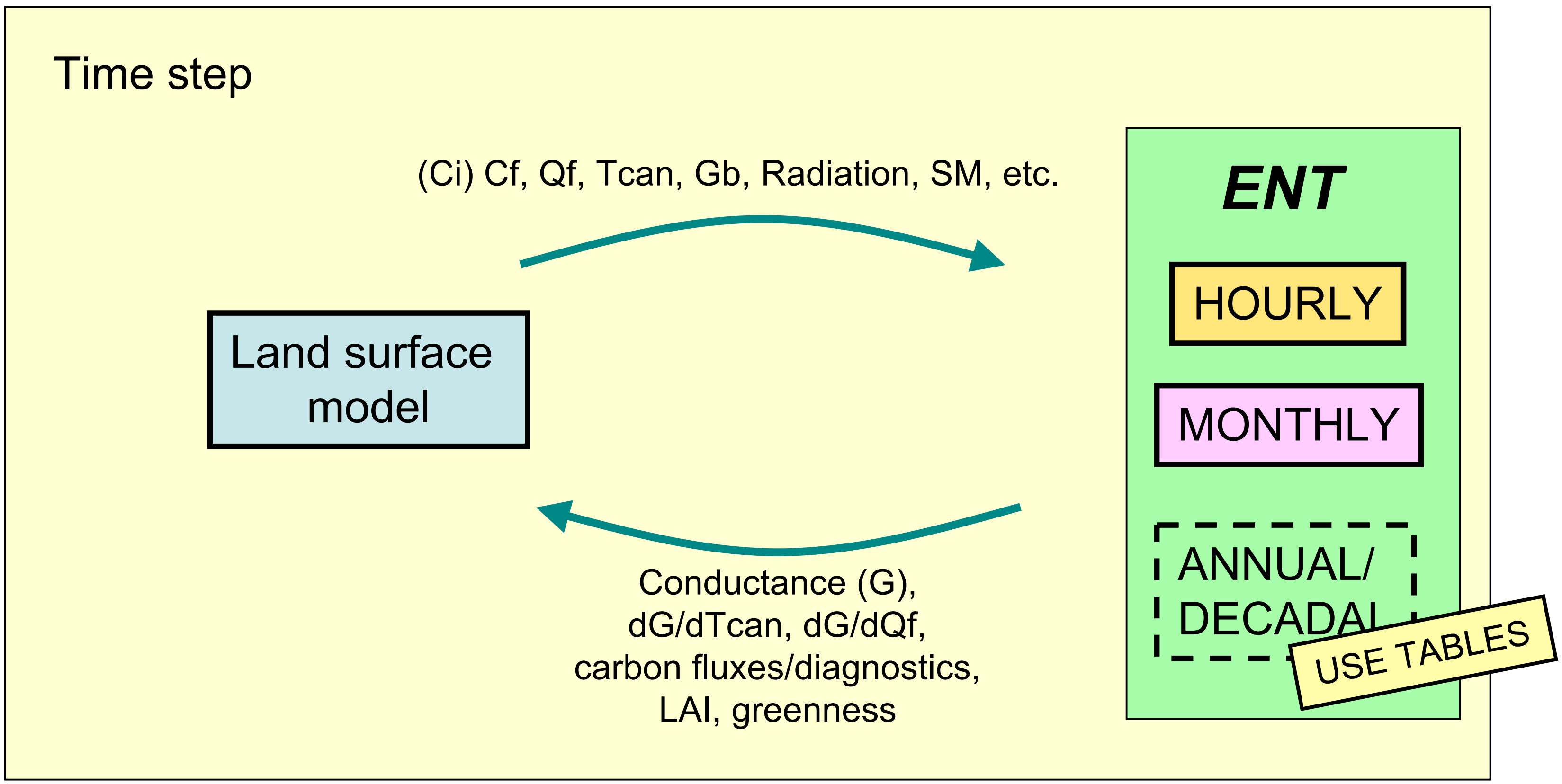
HOURLY	***MONTHLY***	***ANNUAL/DECADAL***
(e.g., photosynthesis-based conductance, carbon assimilation)	(phenology: LAI, greenness)	(vegetation growth, species transition, respiration, long-term carbon budgets)

Depending on the AGCM application, different parts of Ent will be utilized.

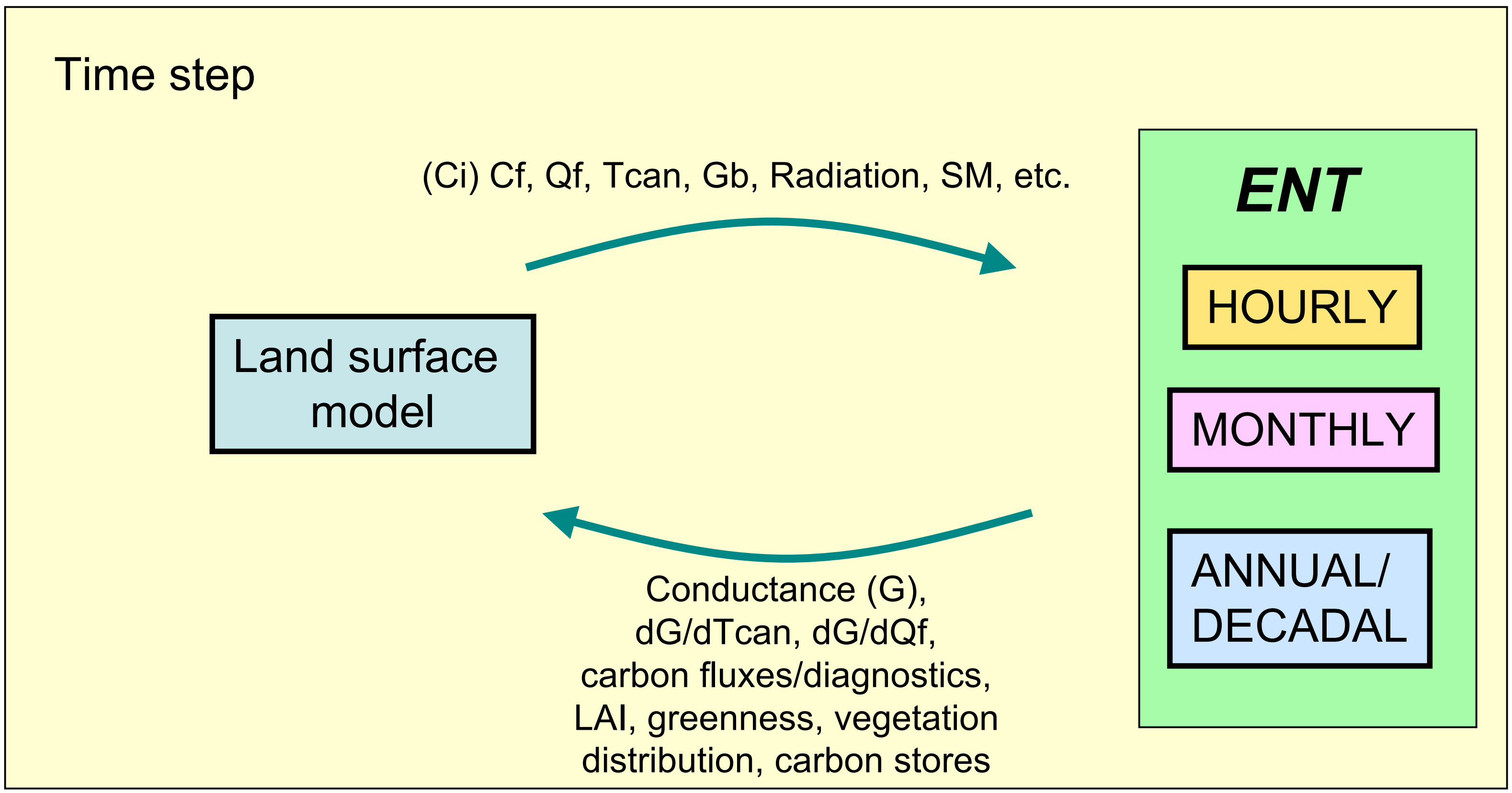
Example: For weather forecasts, use only the hourly physics.



Example: For seasonal weather forecasts, use the hourly physics and the monthly physics.



Example: For multi-decadal climate change runs, use all Ent components.



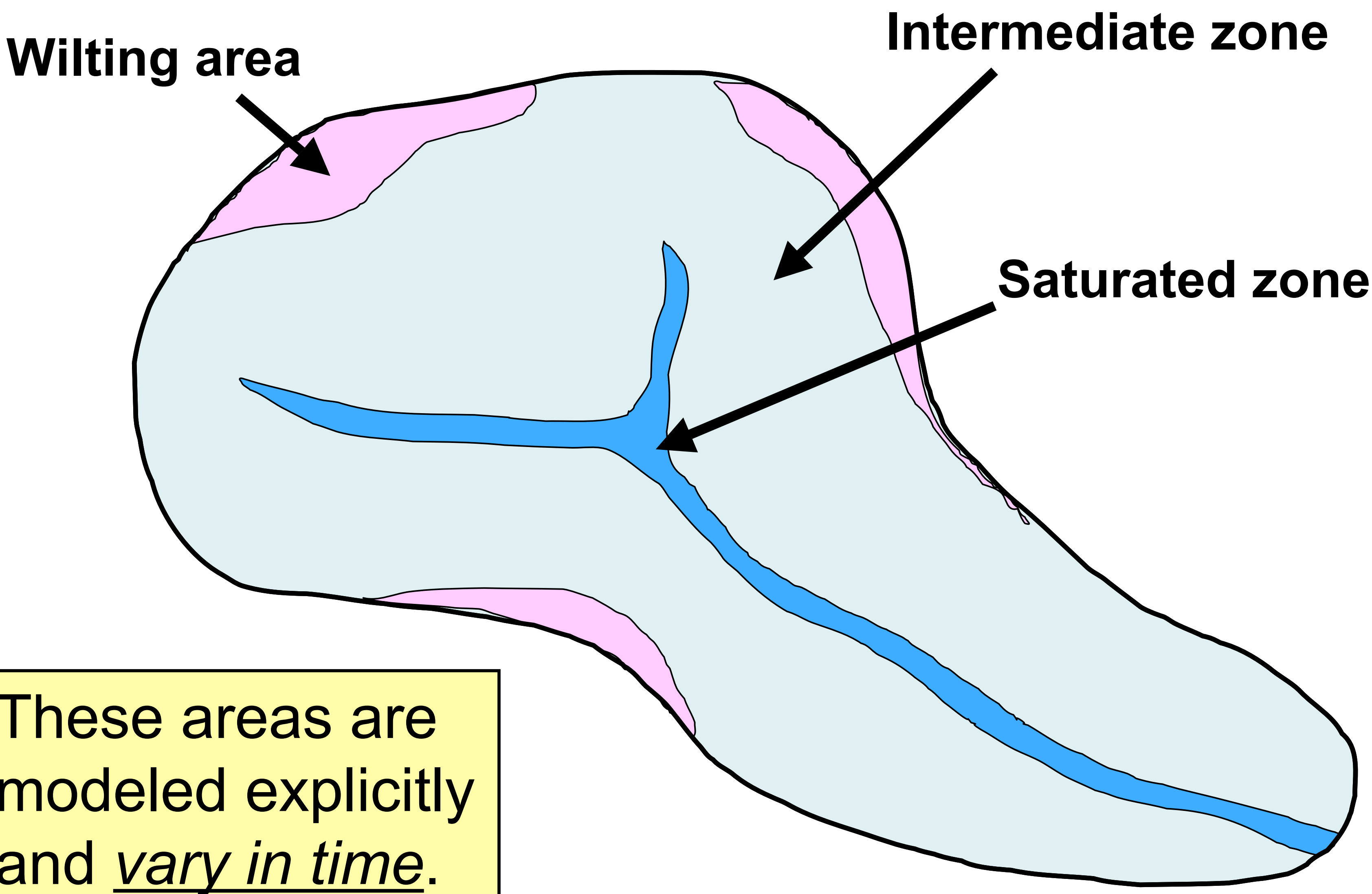
A clean separation of the different time-scale-based physics packages within Ent

⟹ greater efficiency of use.

(We rely here on the ESMF framework.)

Coupling Ent to the
GMAO Catchment Model Framework

Idealized picture of modeled catchment.

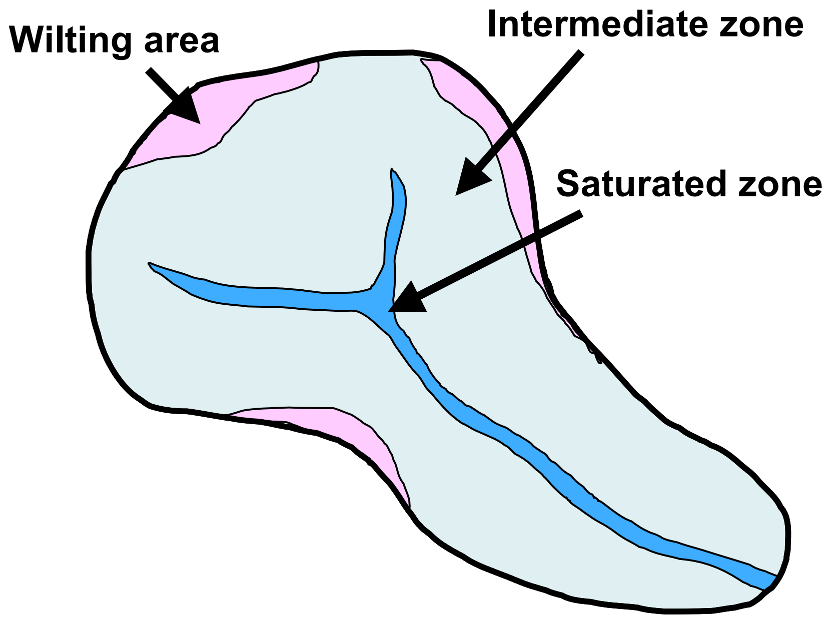


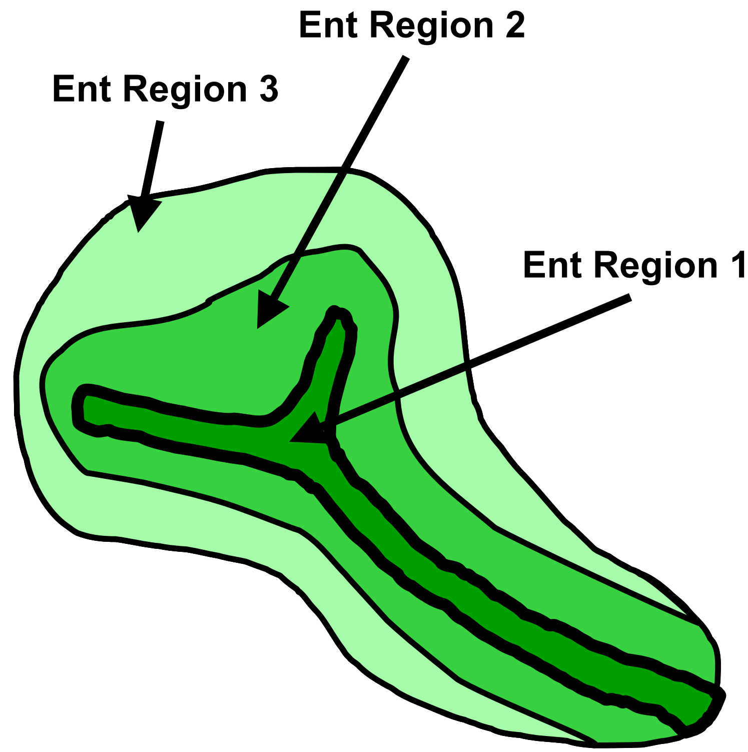
These areas are modeled explicitly and *vary in time*.

Combining the Catchment LSM's capabilities with Ent should allow the modeling of topographical impacts on vegetation.

Catchment photo

Breakdown of the catchment into three subregions, each holding an independent Ent module.

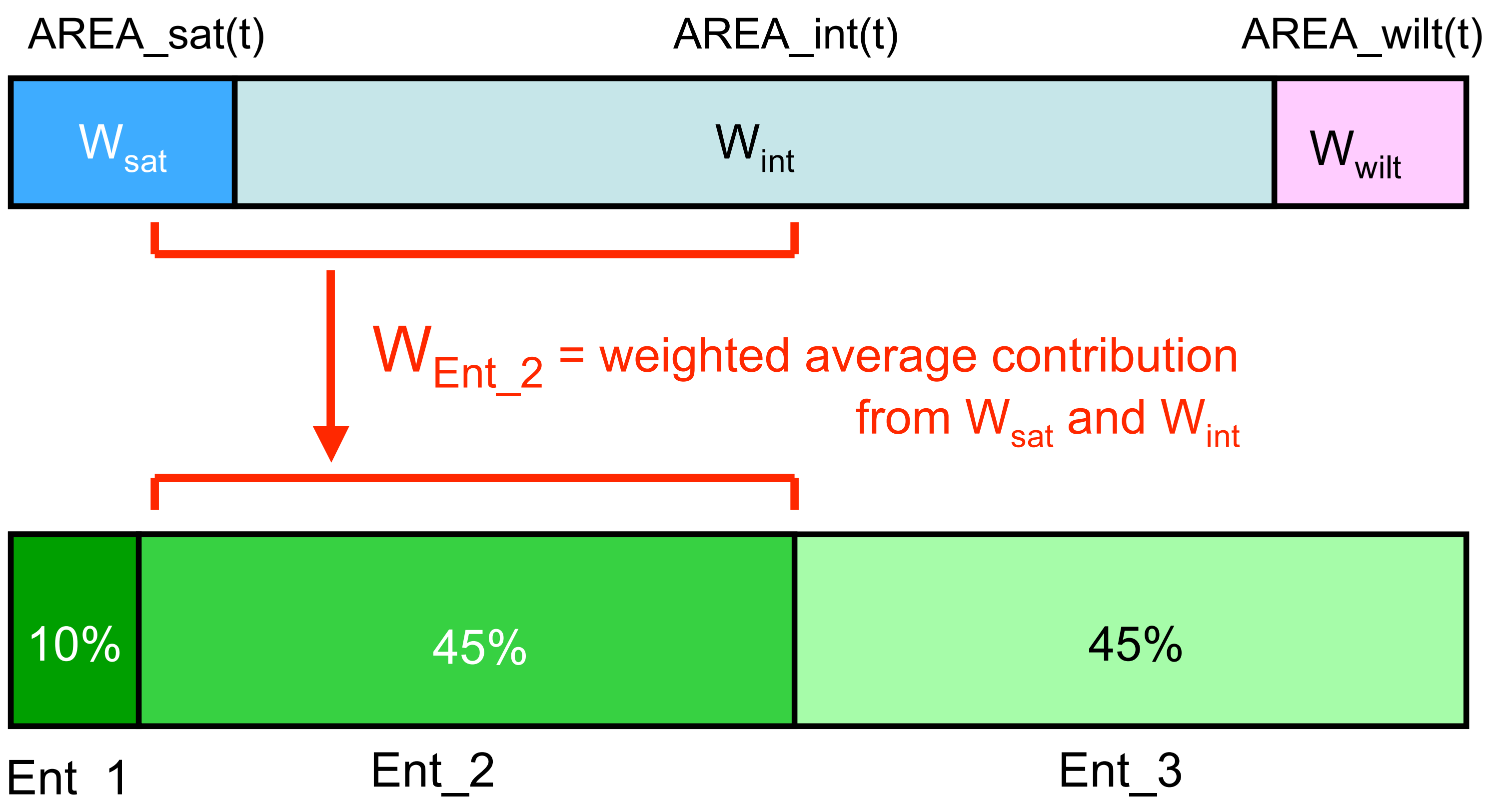




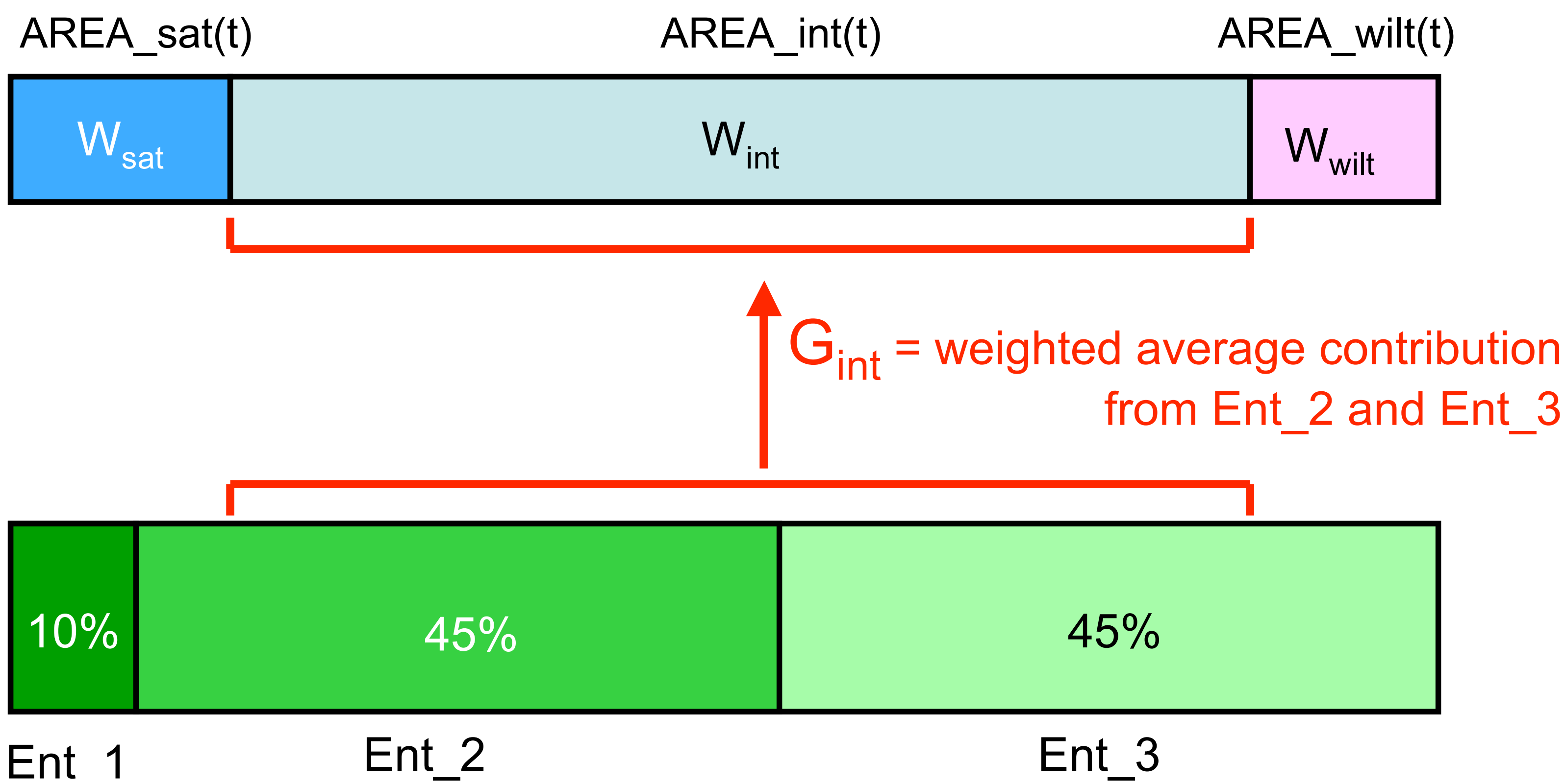
These areas vary in time

These areas *do not* vary in time

Transfer of a variable (e.g., root zone moisture, W) from the catchment model to Ent:



Return of information (e.g., canopy conductance, G) from Ent to the catchment model:



Ent status, discussion,etc.

PROCESS SUBMODELS

- Biophysics - Friend & Kiang (2005) biophysics currently being modified with Ball-Berry (1988) conductance scheme for vertical stratification between cohorts.
- Canopy radiative transfer - foliage clumping paper in prep.; testing required for albedo.
- Growth, phenology, soil biogeochemistry - in off-line development and testing with FLUXNET site data.
- Community dynamics - modules in place, testing in 2008.
- Scaling subgrid heterogeneity - new postdoc summer 2007

MODEL COUPLING

- Biophysics working in coupled mode with GISS GCM.
- Code structure compatible with ESMF, different land surface grid schemes (e.g. GMAO catchment hydrology).

Unknowns

- Sufficient subgrid heterogeneity of vegetation.
- Impact of subgrid water balances.
- Poorly known global soil carbon stocks and respiration rates.
- Phenological responses to immediate plant carbon balance.
- Shopping for more albedo + canopy structure data sets.

Acknowledgments

- Don Anderson
- NASA Earth Science, Modeling, Analysis & Prediction
  - GISS Global Model Development Grant (MAP/#)
  - Ent Dynamic Terrestrial Ecosystem Model Grant (MAP/04-116--0069)

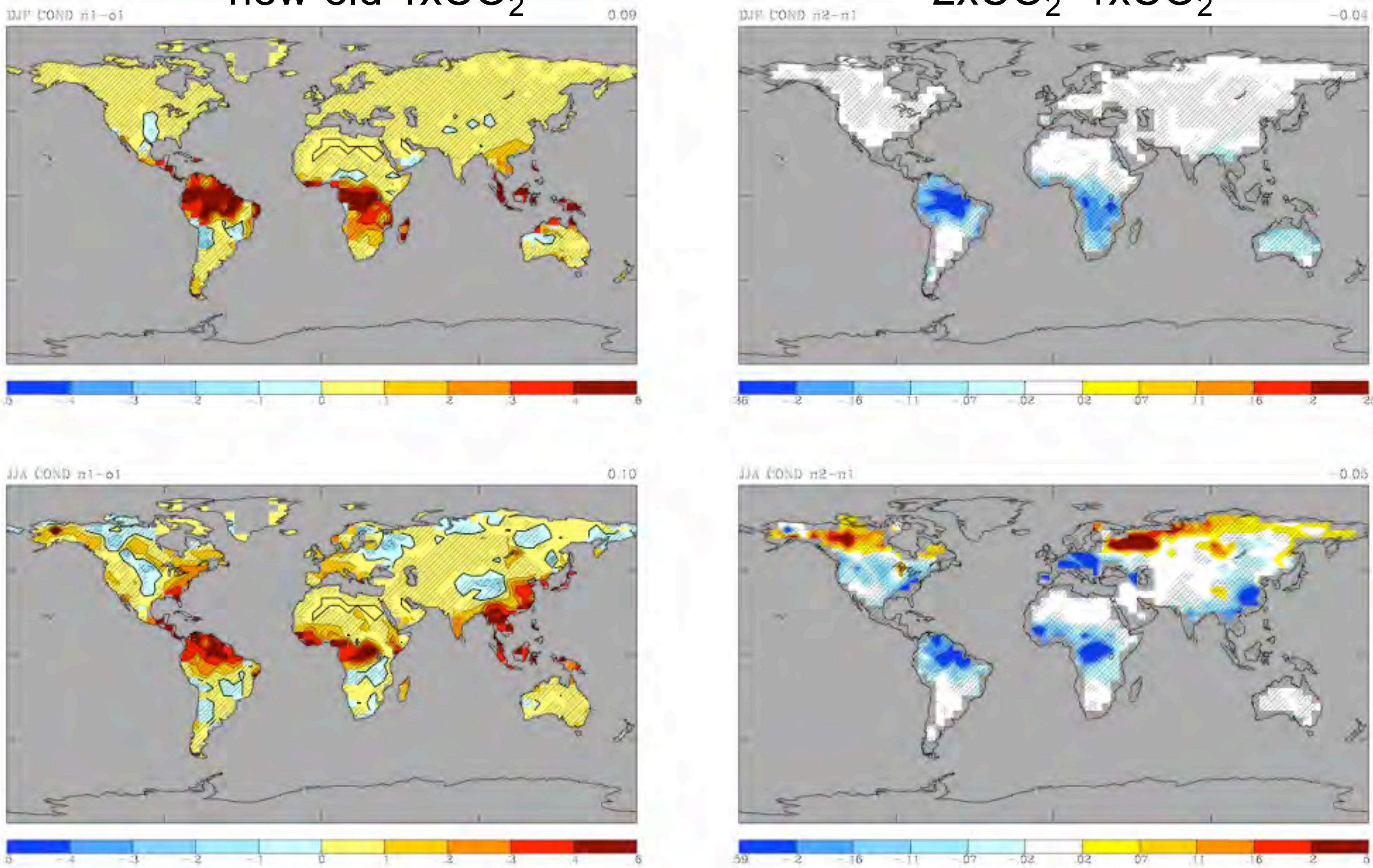
Old stuff in case anyone asks..

Conductance/Photosynthesis performance: Conductance

new-old $1xCO_2$ | $2xCO_2$ - $1xCO_2$

DJF

JJA



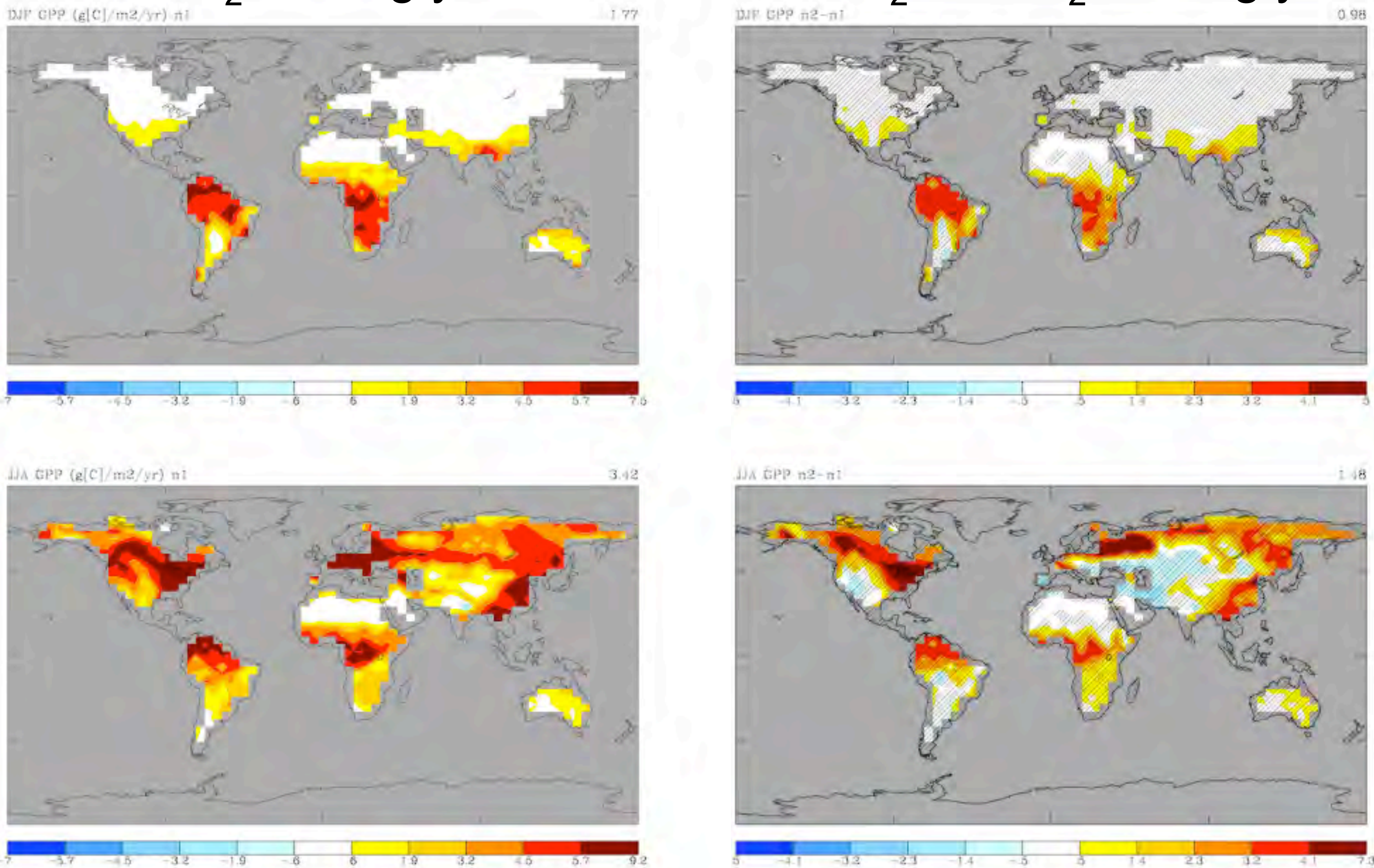
Conductance/Photosynthesis performance: GPP (net assimilation)

$1xCO_2$ 122 Pg/yr

$2xCO_2$ $-1xCO_2$ +57 Pg/yr

DJF

JJA



References

Collatz, G. J., J. T. Ball, C. Grivet and J. A. Berry (1991). "Physiological and environmental regulation of stomatal conductance, photosynthesis and transpiration: a model that includes a laminar boundary layer." Agricultural and Forest Meteorology 54: 107-136

Collatz, G. J., M. Ribas-Carbo and J. A. Berry (1992). "Coupled photosynthesis-stomatal conductance model for leaves of C4 plants." Australian Journal of Plant Physiology 19: 519-538.

Friend, A. D. and N. Y. Kiang (2005). "Land Surface Model Development for the GISS GCM: Effects of Improved Canopy Physiology on Simulated Climate." Journal of Climate 18(15): 2883-2902.

Kull, O. and B. Kruijt (1998). "Leaf photosynthetic light response: a mechanistic model for scaling photosynthesis to leaves and canopies." Functional Ecology 12: 767-777.

Moorcroft, P., G. C. Hurtt and S. W. Pacala (2001). "A method for scaling vegetation dynamics: The Ecosystem Demography Model (ED)." Ecological Monographs 71(4): 557-586.

Ni, W., X. Li, C. E. Woodcock, M. R. Caetano and A. H. Strahler (1999). "An analytical hybrid GORT model for bidirectional reflectance over discontinuous plant canopies." IEEE Transactions on Geoscience and Remote Sensing 37(2): 987-999.

Reich, P. B., D. S. Ellsworth, M. B. Walters, J. M. Vose, C. Gresham, J. C. Volin and W. D. Bowman (1999). "Generality of leaf trait relationships: a test across six biomes." Ecology 80(6): 1955-1969.