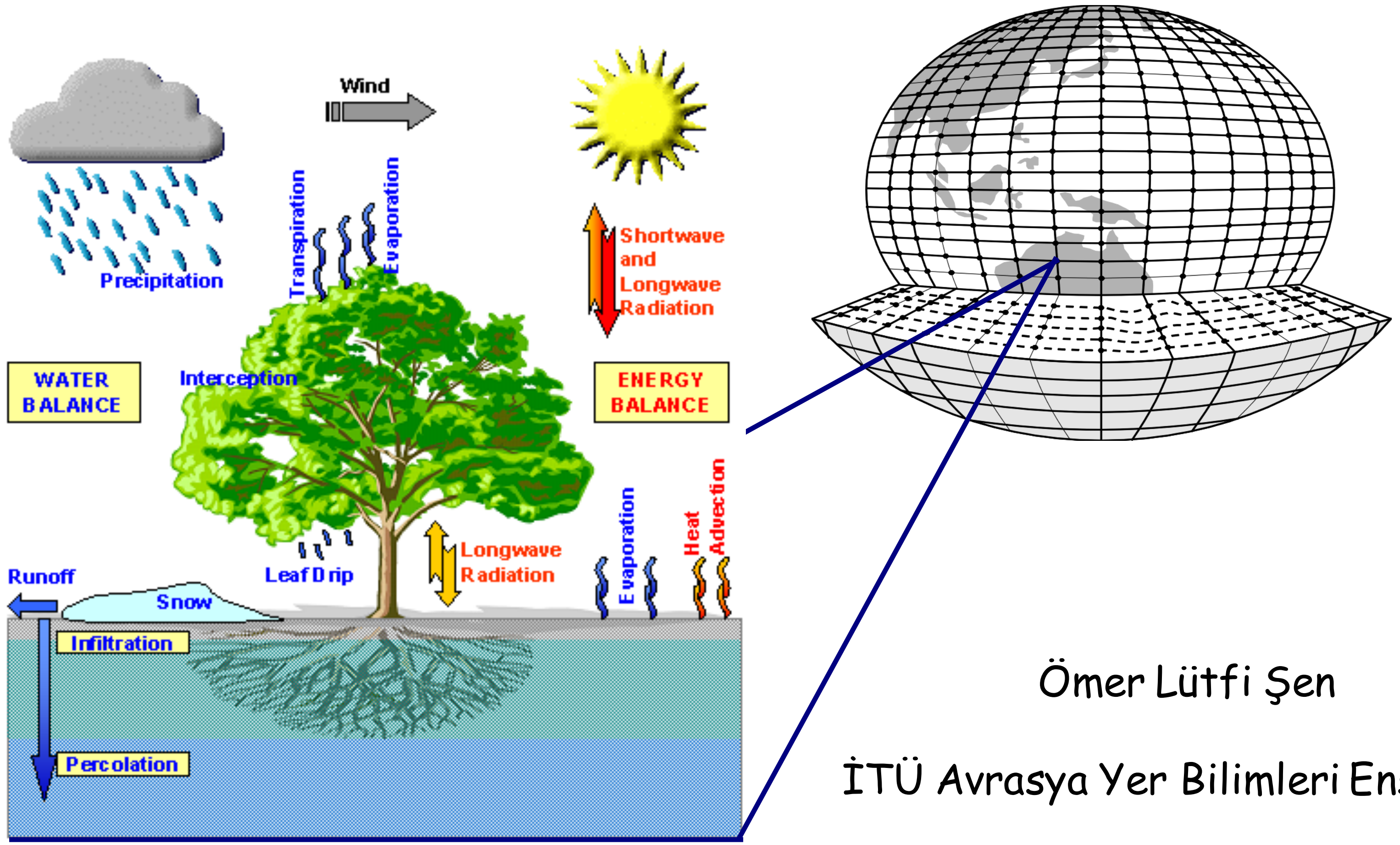
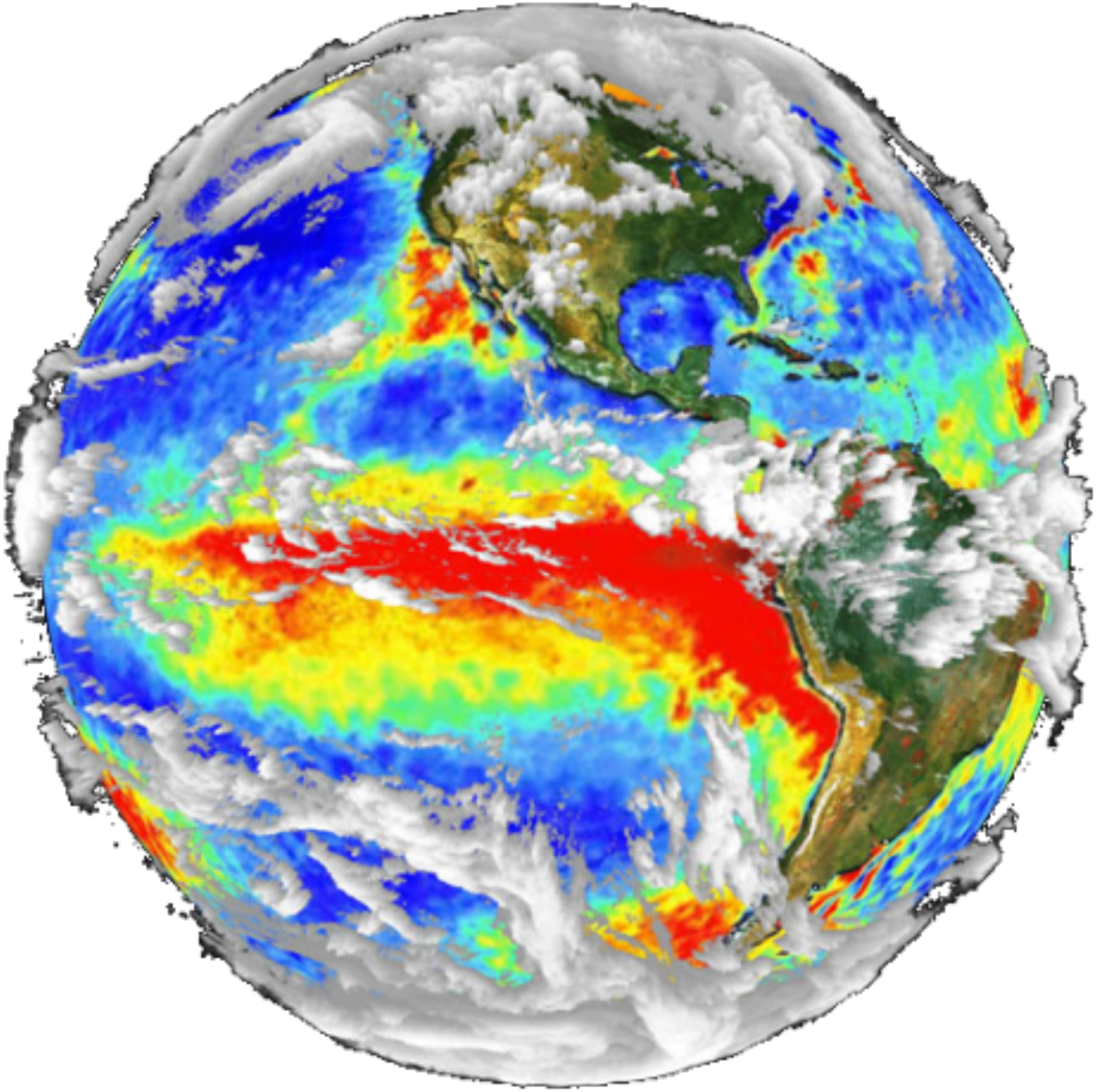
The interface between land and atmosphere and its representation in climate models



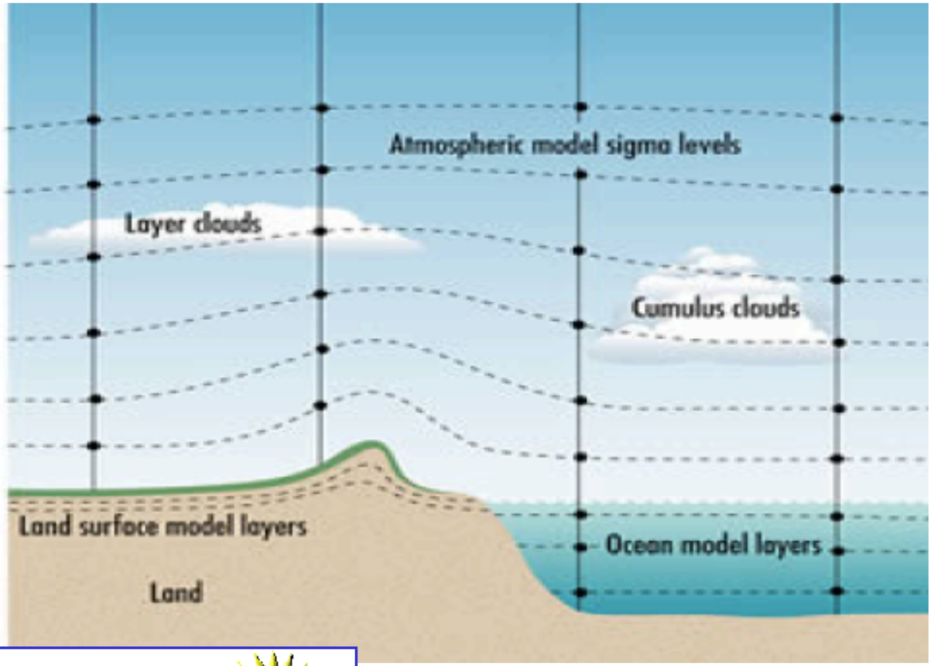
Ömer Lütfi Şen

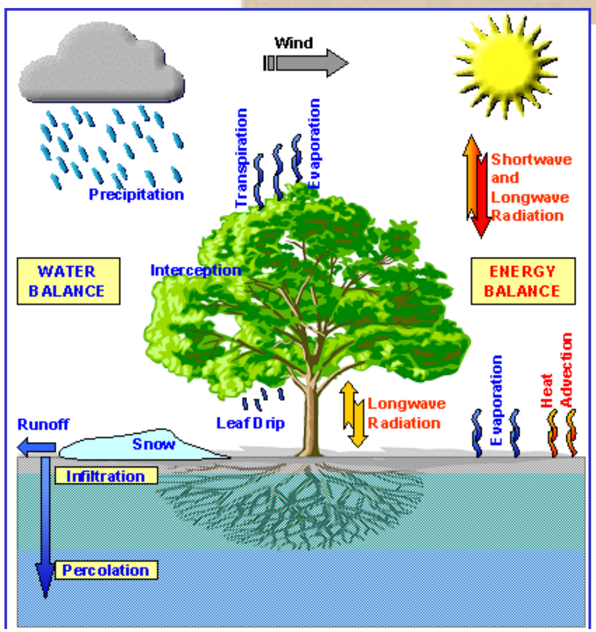
İTÜ Avrasya Yer Bilimleri Enstitüsü

Land surface is important!



Climate models comprise land surface models





Role of land surface models in climate models

- Provides the boundary conditions at the land-atmosphere interface
  - e.g. albedo, surface temperature, surface fluxes
- Partitions available energy at the surface into sensible and latent heat flux components
- Partitions rainfall into runoff and evaporation
  - Evaporation provides surface-atmosphere moisture flux
  - River runoff provides freshwater input to the oceans
- Provides the carbon fluxes at the surface (photosynthesis, respiration)
- Updates state variables which affect surface fluxes
  - e.g. snow cover, soil moisture, soil temperature, vegetation cover, leaf area index

- LSM cost is actually not that high (~10% of full coupled model)

http://www.cgd.ucar.edu/staff/bonan/seminars/ASPJun06.pdf

Role of land surface models in climate models

The land-surface model solves (at each timestep)

- **Surface energy balance** (and other energy balances, e.g. in canopy, snow, soil)
  - $S^{\downarrow} + L^{\downarrow} = S^{\uparrow} + L^{\uparrow} + \lambda E + H + G$
    - $S^{\downarrow}$, $S^{\uparrow}$ are down(up)welling solar radiation
    - $L^{\downarrow}$, $L^{\uparrow}$ are down(up)welling longwave radiation
    - λ is latent heat of vaporization, E is evaporation
    - H is sensible heat flux
    - G is ground heat flux

- **Surface water balance** (and other water balances such as snow and soil water)
  - $P = E_S + E_T + E_C + R_{Surf} + R_{Sub\text{-}Surf} + \Delta SM / \Delta t$
    - P is rainfall
    - E_S is soil evaporation, E_T is transpiration, E_C is canopy evaporation
    - R_{Surf} is surface runoff, $R_{Sub\text{-}Surf}$ is sub-surface runoff
    - $\Delta SM / \Delta t$ is the change in soil moisture over a timestep

- **Carbon balance** (and plant and soil carbon pools)
  - $NPP = GPP - Ra = (\Delta C_f + \Delta C_s + \Delta C_r) / \Delta t$
  - $NEP = NPP - Rh$
  - $NBP = NEP - Combustion$
    - NPP is net primary production, GPP is gross primary production
    - Ra is autotrophic (plant) respiration, Rh is heterotrophic (soil) respiration
    - ΔC_f, ΔC_s, ΔC_r are foliage, stem, and root carbon pools
    - NEP is net ecosystem production, NBP is net biome production
    - Combustion is carbon loss during fire

http://www.cgd.ucar.edu/staff/bonan/seminars/ASPJun06.pdf

Surface energy balance and surface temperature

Surface energy balance

$$(S\downarrow - S\uparrow) + \varepsilon L\downarrow = L\uparrow[T_s] + H[T_s] + \lambda E[T_s] + G[T_s]$$

$$L\uparrow = \varepsilon\sigma(T_s + 273.15)^4 + (1-\varepsilon)L\downarrow$$

$$H = -\rho C_p \frac{(T_a - T_s)}{r_{aH}}$$

$$\lambda E = -\frac{\rho C_p}{\gamma}\frac{(e_a - e_*[T_s])}{r_{aW}}$$

$$G = k\frac{(T_s - T_{soil})}{\Delta z}$$

Atmospheric forcing

$S\downarrow$ - incoming solar radiation

$L\downarrow$ - incoming longwave radiation

T_a – air temperature

e_a – vapor pressure

Surface properties

$S\uparrow$ - reflected solar radiation (albedo)

ε - emissivity

raH – aerodynamic resistance (roughness length)

raW – aerodynamic resistance (roughness length)

T_{soil} – soil temperature

k – thermal conductivity

Δz – soil depth

With atmospheric forcing and surface properties specified, solve for temperature T_s that balances the energy budget

http://www.cgd.ucar.edu/staff/bonan/seminars/ASPJun06.pdf

Energy, Water and Carbon Link at surface

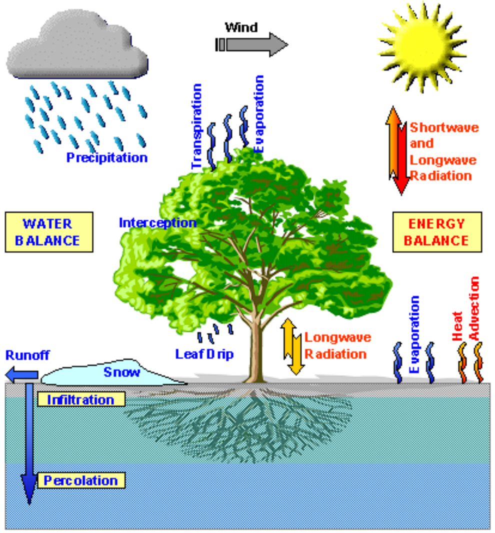
$$L\uparrow = \varepsilon\sigma T_s^4$$

$$H = \frac{T_s - T_r}{\boxed{r_a}}\rho c_p$$

$$R_n = S\downarrow(1-\alpha) + L\downarrow - \boxed{L\uparrow}$$

$$r_a = \frac{\ln[(z_u - d)/z_{0m}]\ln[(z_e - d)/z_{0v}]}{(0.41)^2 U_z}$$

$$R_n = G + H + \lambda E$$



$$\lambda E = \left(\frac{e^*(T_s) - e_r}{\boxed{r_c} + r_a}\right)\frac{\rho c_p}{\gamma}$$

$$G = -K\frac{dT_s}{dz}$$

$$r_c = \boxed{r_s} / LAI$$

$$r_s = r_{s\min} \times R_f \times S_f \times M_f \times V_f$$

or

$$A_n = \min(A_c, A_L, A_S) - R_d$$

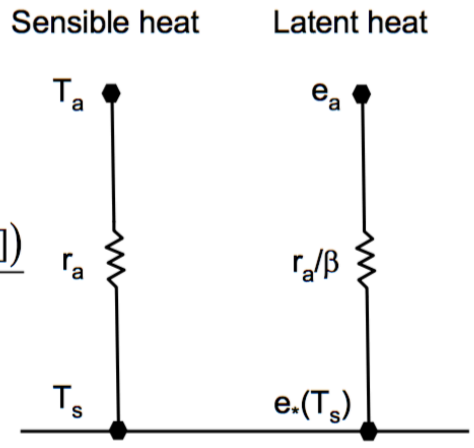
$$m\frac{A_n h_s}{C_s}p + b = r_s^{-1}$$

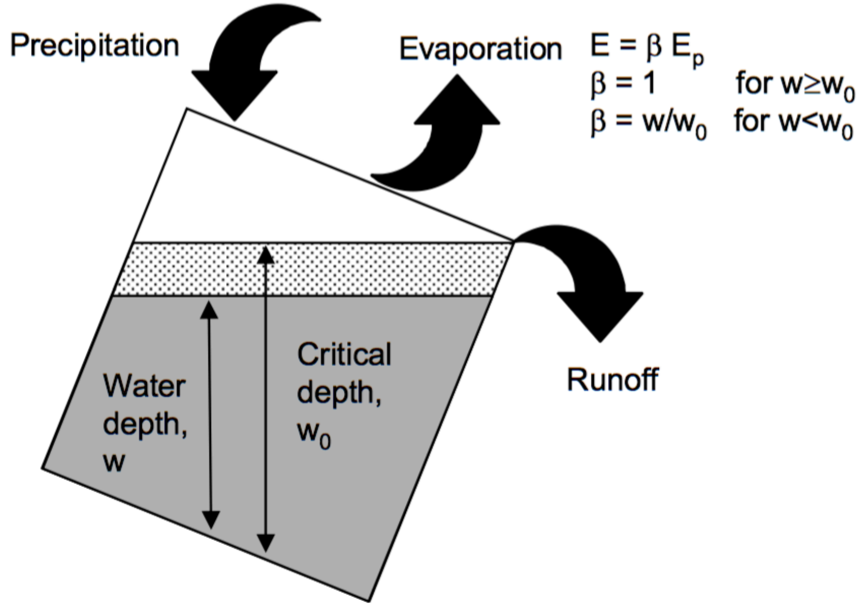
$$RO = P - E - I$$

First-generation land surface models

$$H = -\rho C_p \frac{(T_a - T_s)}{r_a}$$

$$\lambda E = -\frac{\rho C_p}{\gamma} \frac{(e_a - e_*[T_s])}{r_a / \beta}$$





Simple energy balance model: $(1-r)S\downarrow + \varepsilon L\downarrow = L\uparrow[T_s] + H[T_s] + \lambda E[T_s]$

Prescribed surface albedo

Bulk parameterizations of sensible and latent heat flux

No influence of vegetation on surface fluxes

Prescribed soil wetness factor β or calculated wetness from bucket model

No soil heat storage

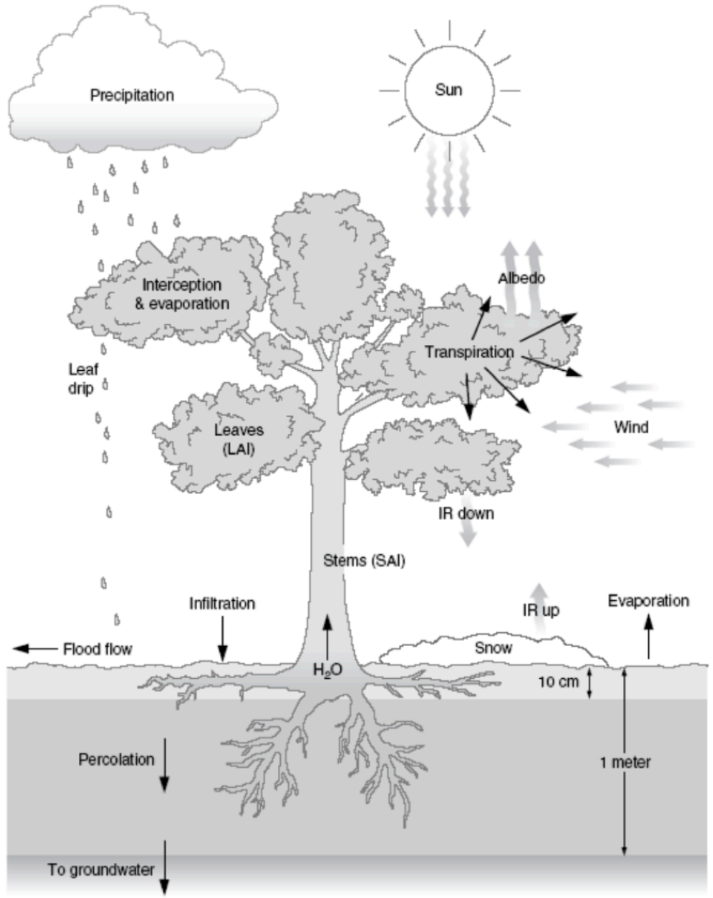
Manabe (1969) Monthly Weather Review 97:739-774
Williamson et al. (1987) NCAR/TN-285+STR

http://www.cgd.ucar.edu/staff/bonan/seminars/ASPJun06.pdf

Second-generation land surface models

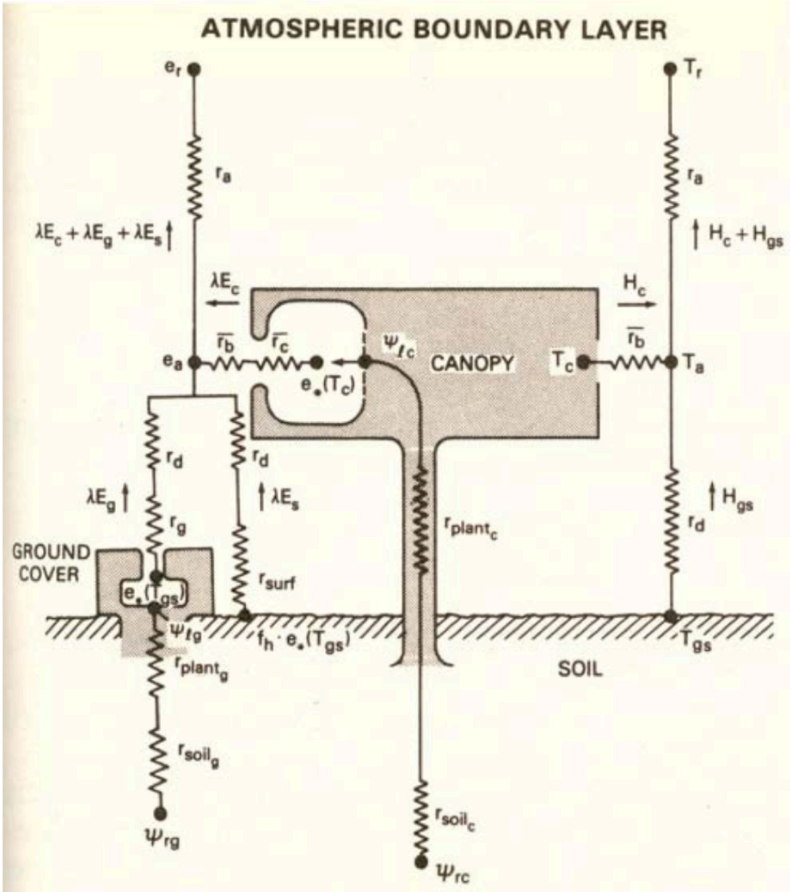
Vegetation and hydrologic cycle

Biosphere-Atmosphere Transfer Scheme (BATS)



Dickinson et al. (1986) NCAR/TN-275+STR

Simple Biosphere Model (SiB)

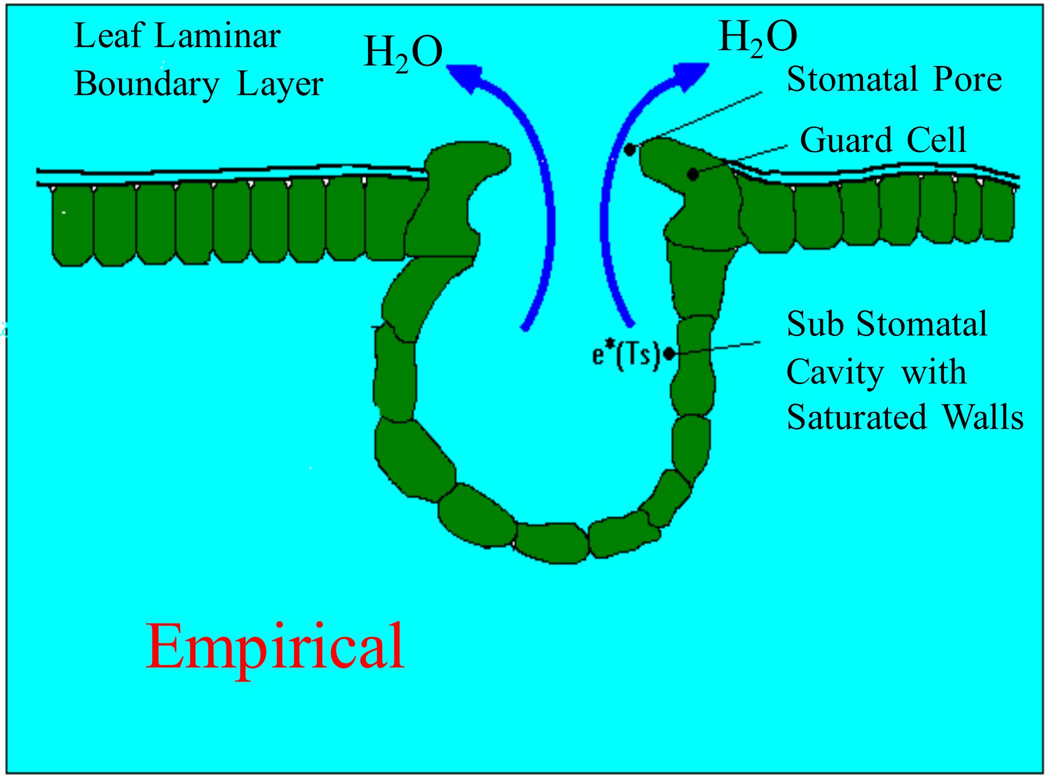


Sellers et al. (1986) J Atmos Sci 43:505-531

http://www.cgd.ucar.edu/staff/bonan/seminars/ASPJun06.pdf

Canopy resistance in second-generation models

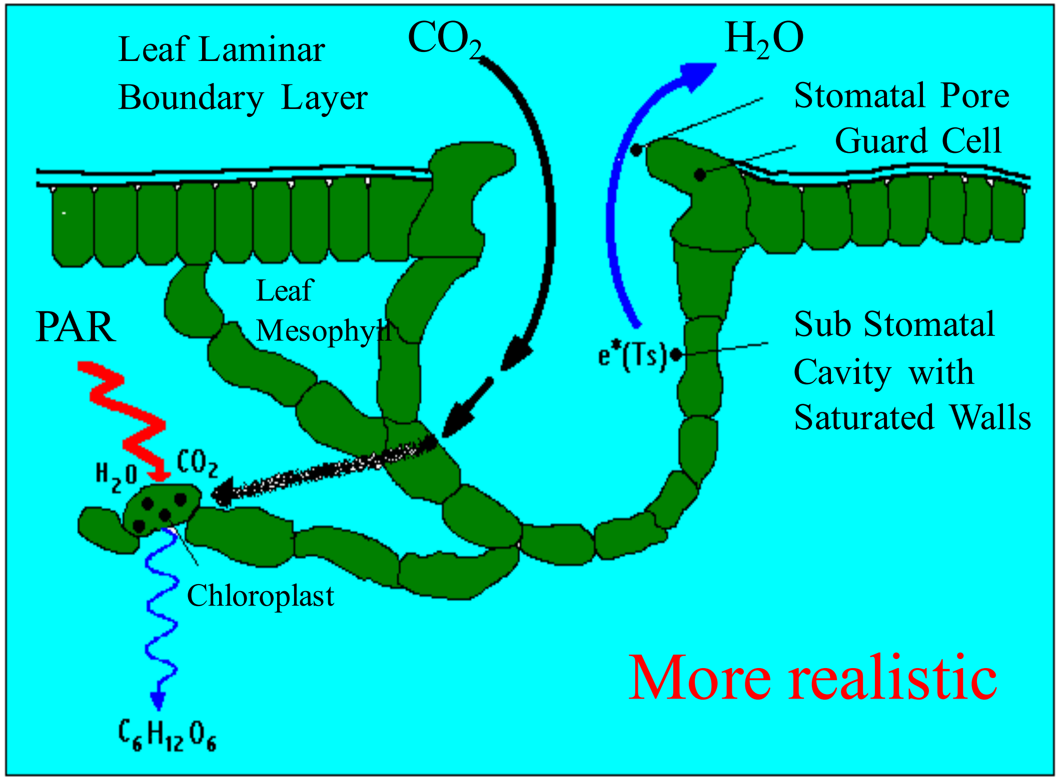
- ***"Jarvis-Stewart" type:***
  - A minimum canopy resistance is scaled by "stress functions" of
    - radiation
    - vapor pressure deficit
    - temperature
    - soil moisture
  - "stress functions" are empirical equations to give values between 0 and 1.
- ***BATS and SiB use this***



$$r_s = r_{s\min} \times R_f \times S_f \times M_f \times V_f$$

Third-generation models and canopy resistance

- ***"Ball-Berry" type:***
  - Carbon uptake is calculated based on the concepts of Farquhar et al. (1978)
  - Assimilation is then linked to conductance (inverse of resistance) via a semi-empirical relationship
- ***BATS2 and SiB2 use this***

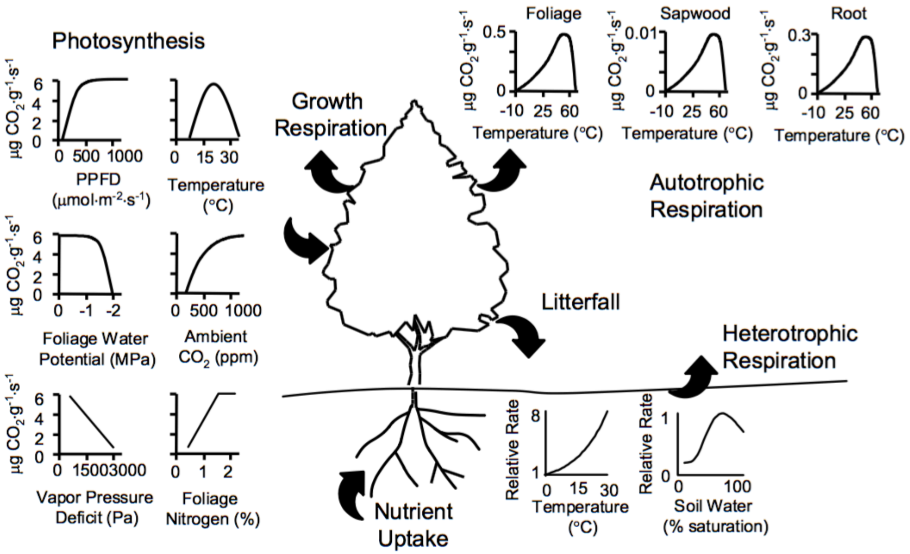


$$m\frac{A_n h_s}{C_s}p + b = r_s^{-1}$$

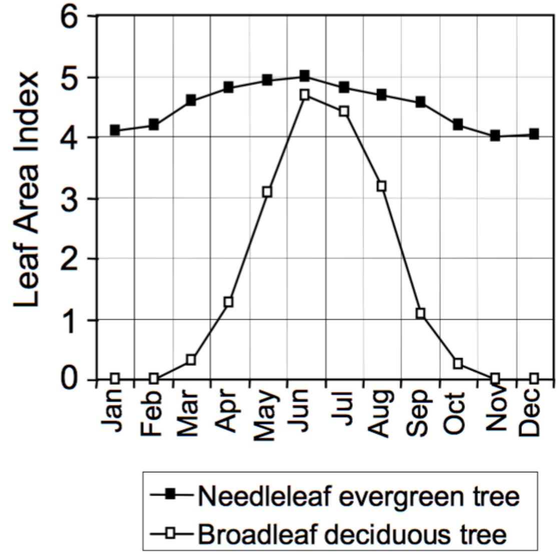
Fourth-generation land surface models

Dynamic vegetation

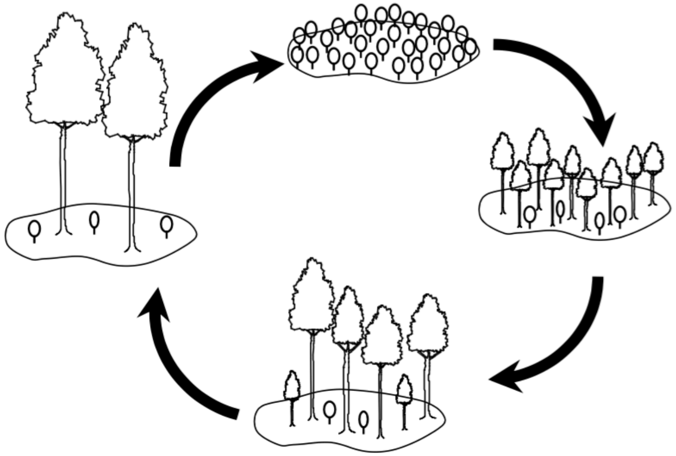
Ecosystem carbon balance



Leaf phenology



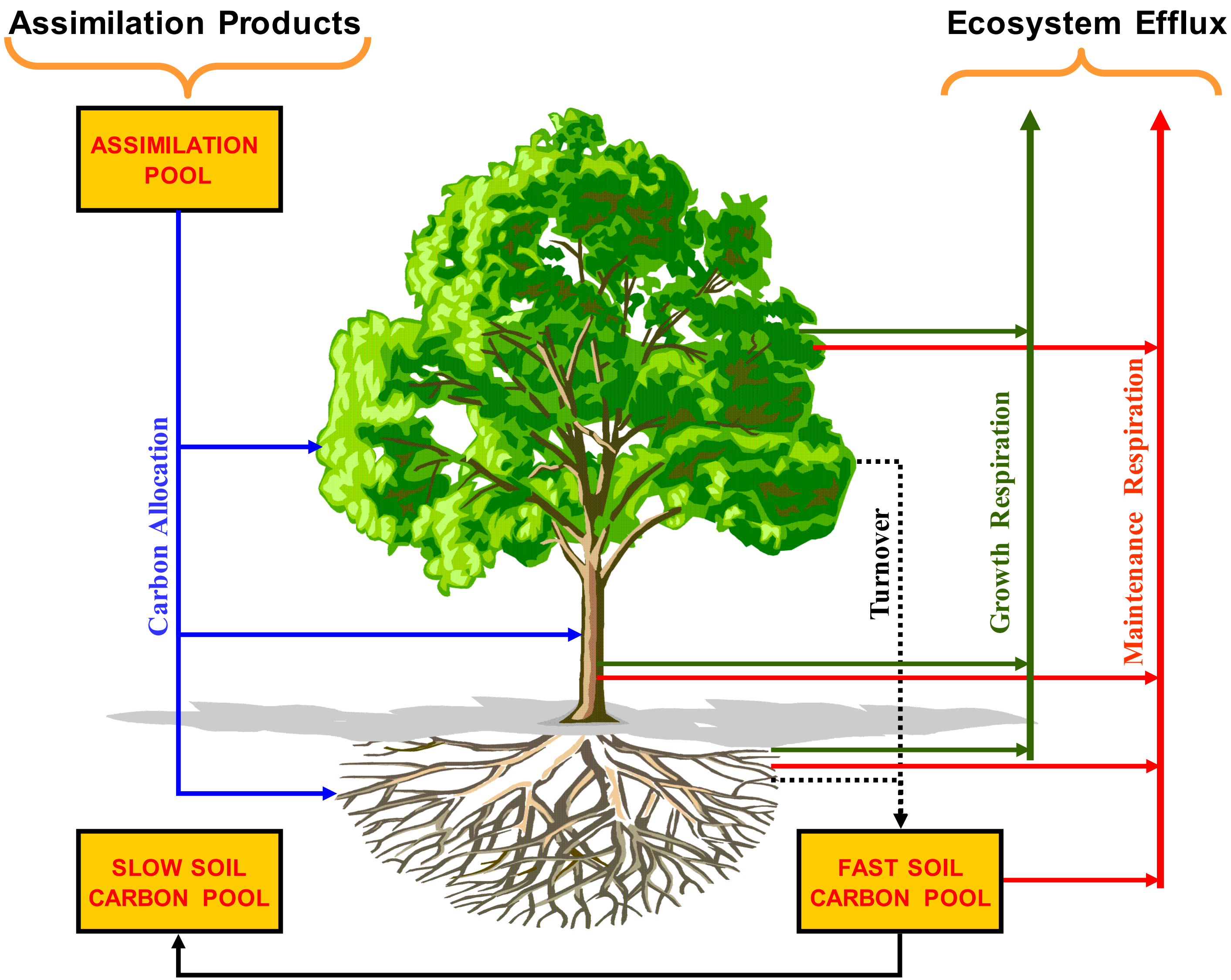
Vegetation dynamics



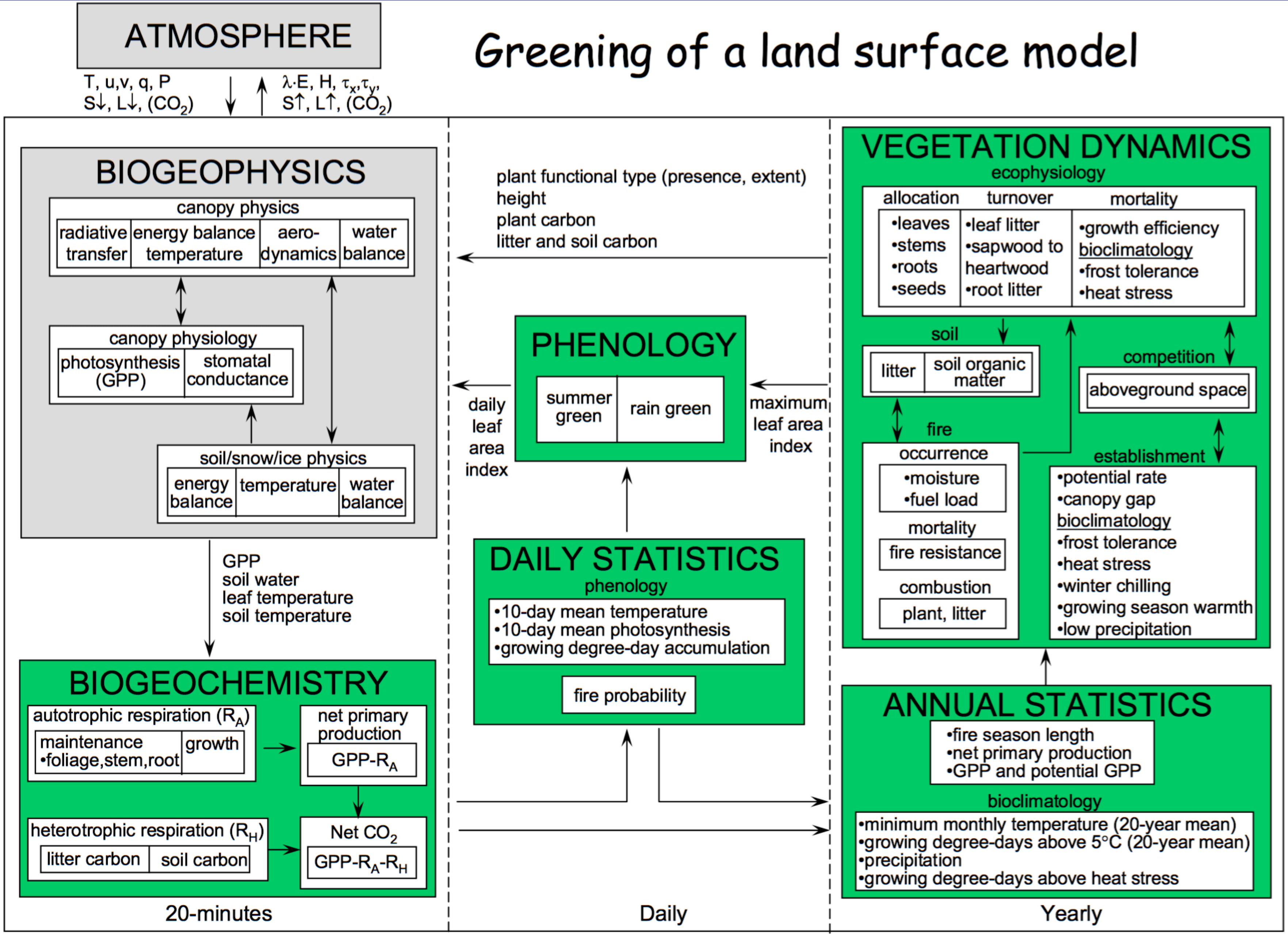
Foley et al. (1996) GBC 10:603-628
Levis et al. (1999) JGR 104D:31191-31198
Levis et al. (2000) J Climate 13:1313-1325
Cox et al. (2000) Nature 408:184-187

http://www.cgd.ucar.edu/staff/bonan/seminars/ASPJun06.pdf

Interactive Canopies for Climate Models



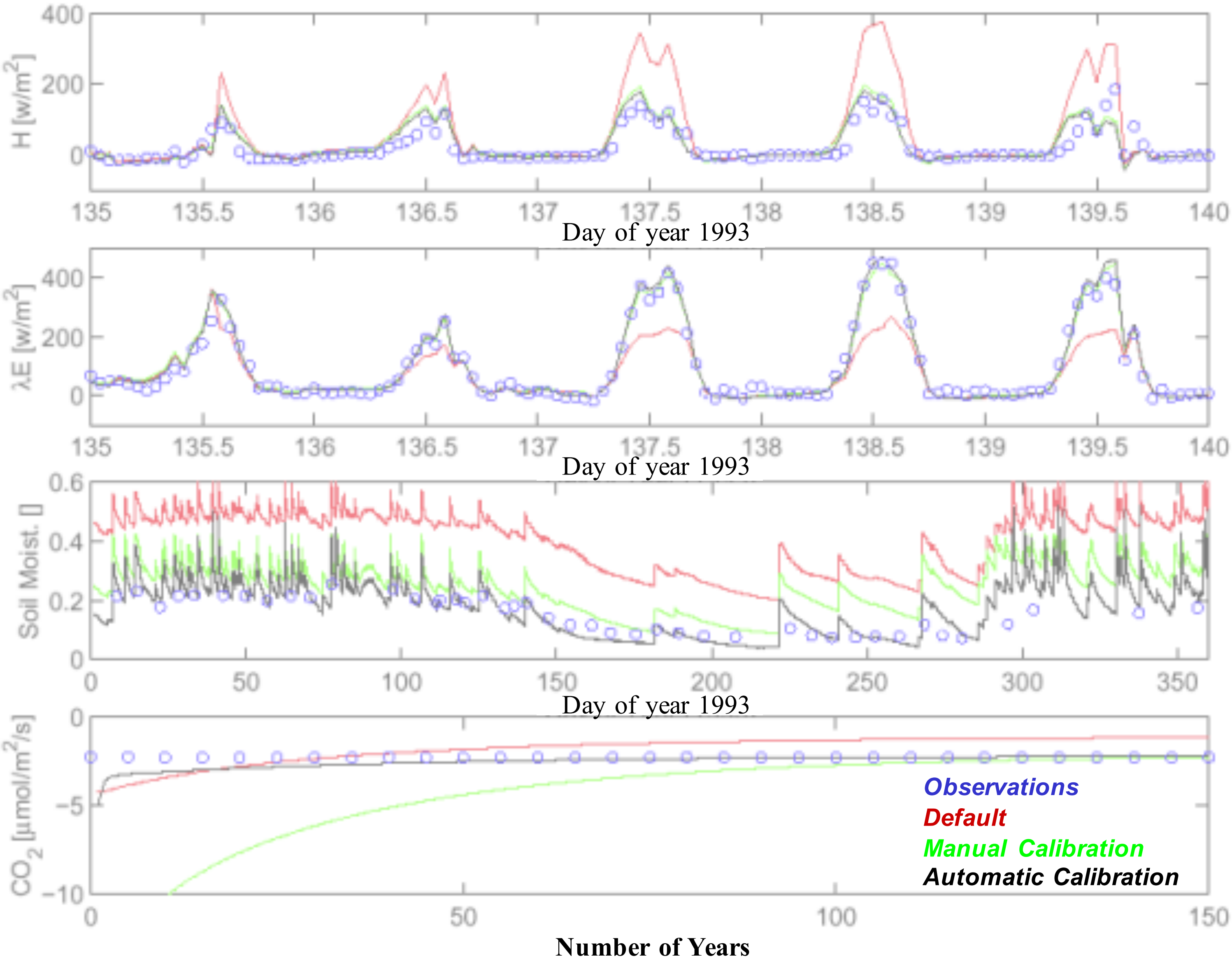
State-of-the-art land surface models



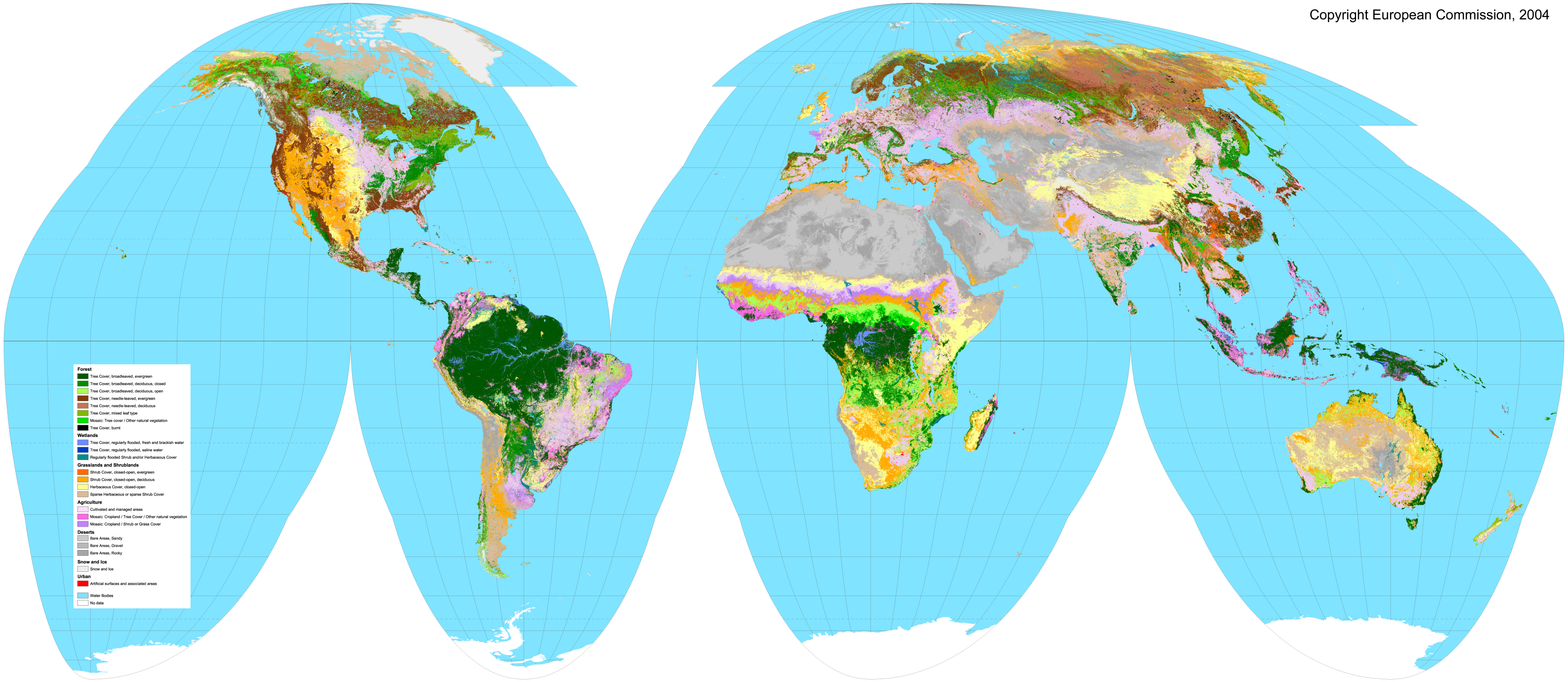
Bonan et al. (2003) Global Change Biology 9:1543-1566

http://www.cgd.ucar.edu/staff/bonan/seminars/ASPJun06.pdf

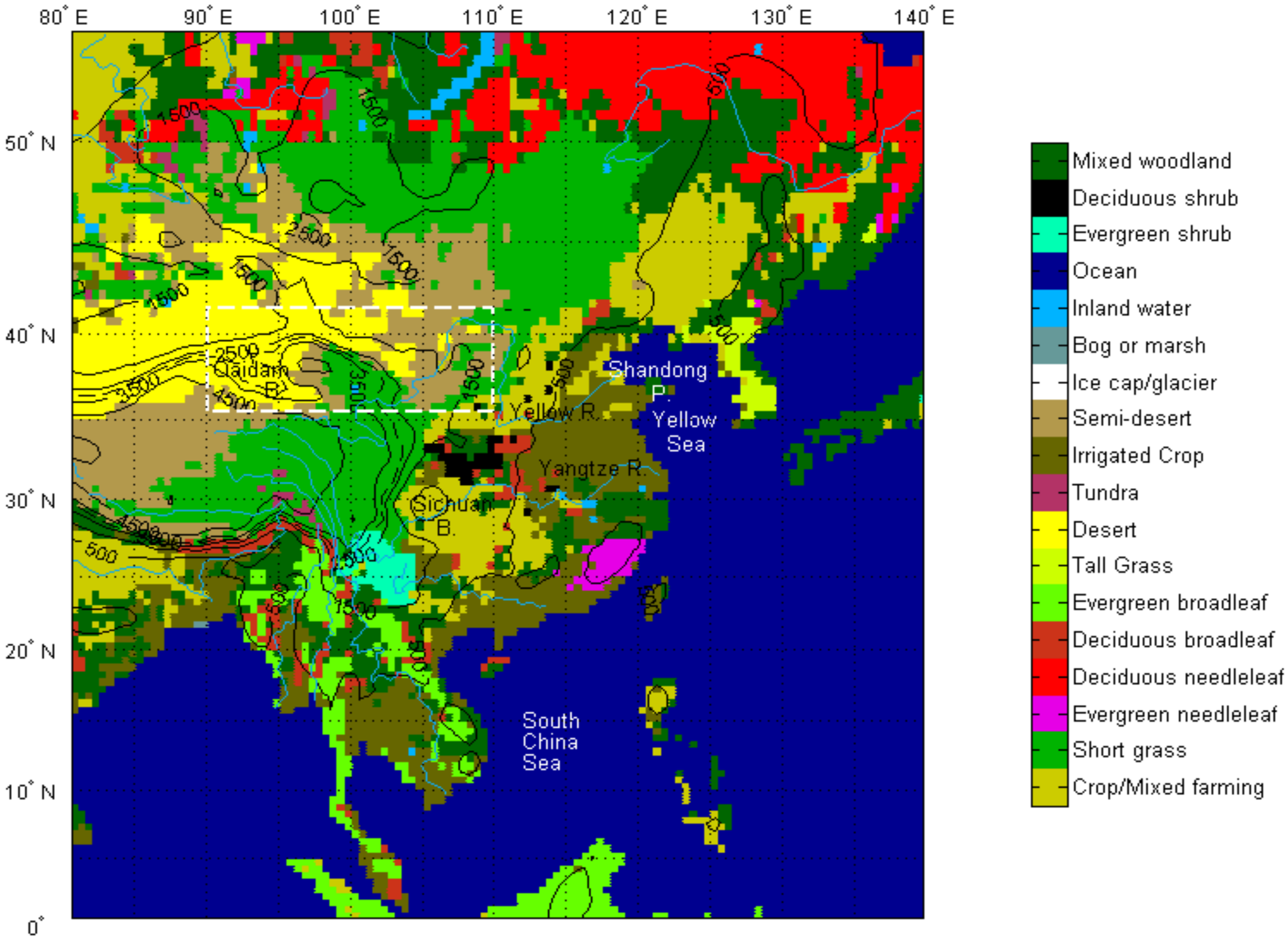
Model calibration for Reserva Jaru observations



LSMs require land cover maps for coupled use

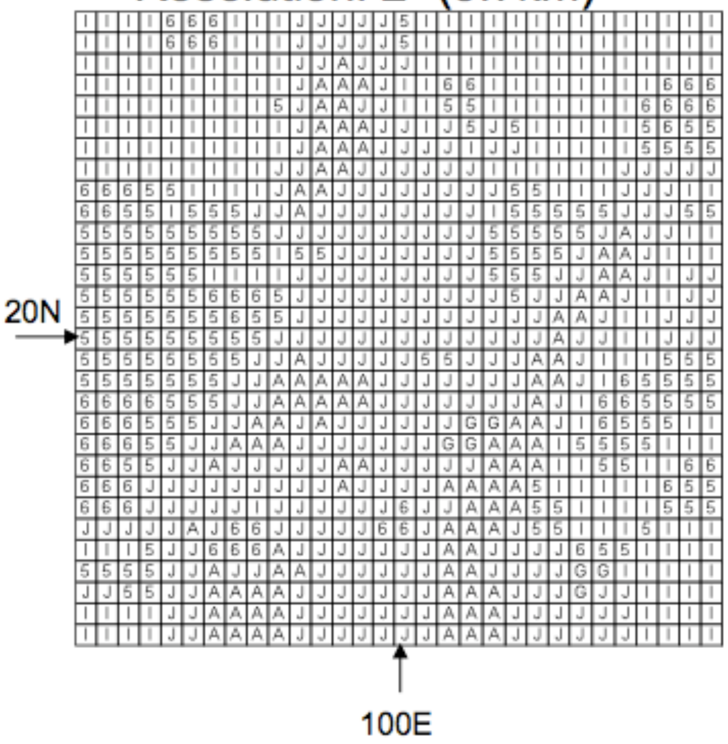


LSMs require land cover maps for coupled use



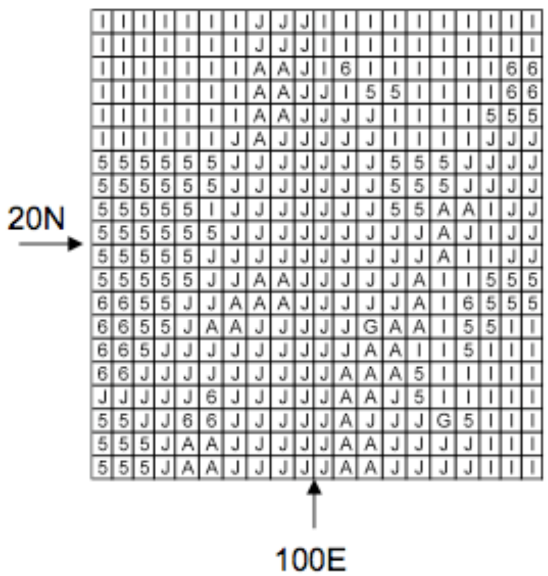
Land cover maps are produced through upscaling

Resolution: 2” (3.7km)

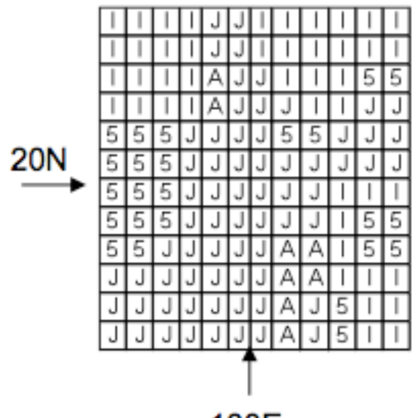


All for a 1ºx1º (111.2x111.2km) domain

Resolution: 3” (5.56 km)

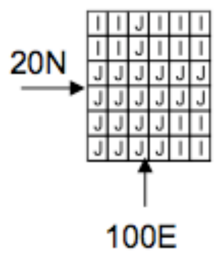


Resolution: 5” (9.3 km)

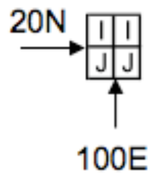


5 => Deciduous Broadleaf Tree
6 => Evergreen Broadleaf Tree
A => Irrigated Crop
G => Evergreen Shrub
I => Mixed woodland
J => Forest/Field Mosaic

Resolution: 10” (18.5 km)



Resolution: 30” (55.56 km)



Land Cover / Vegetation classes

Table 1: Land Cover/Vegetation classes

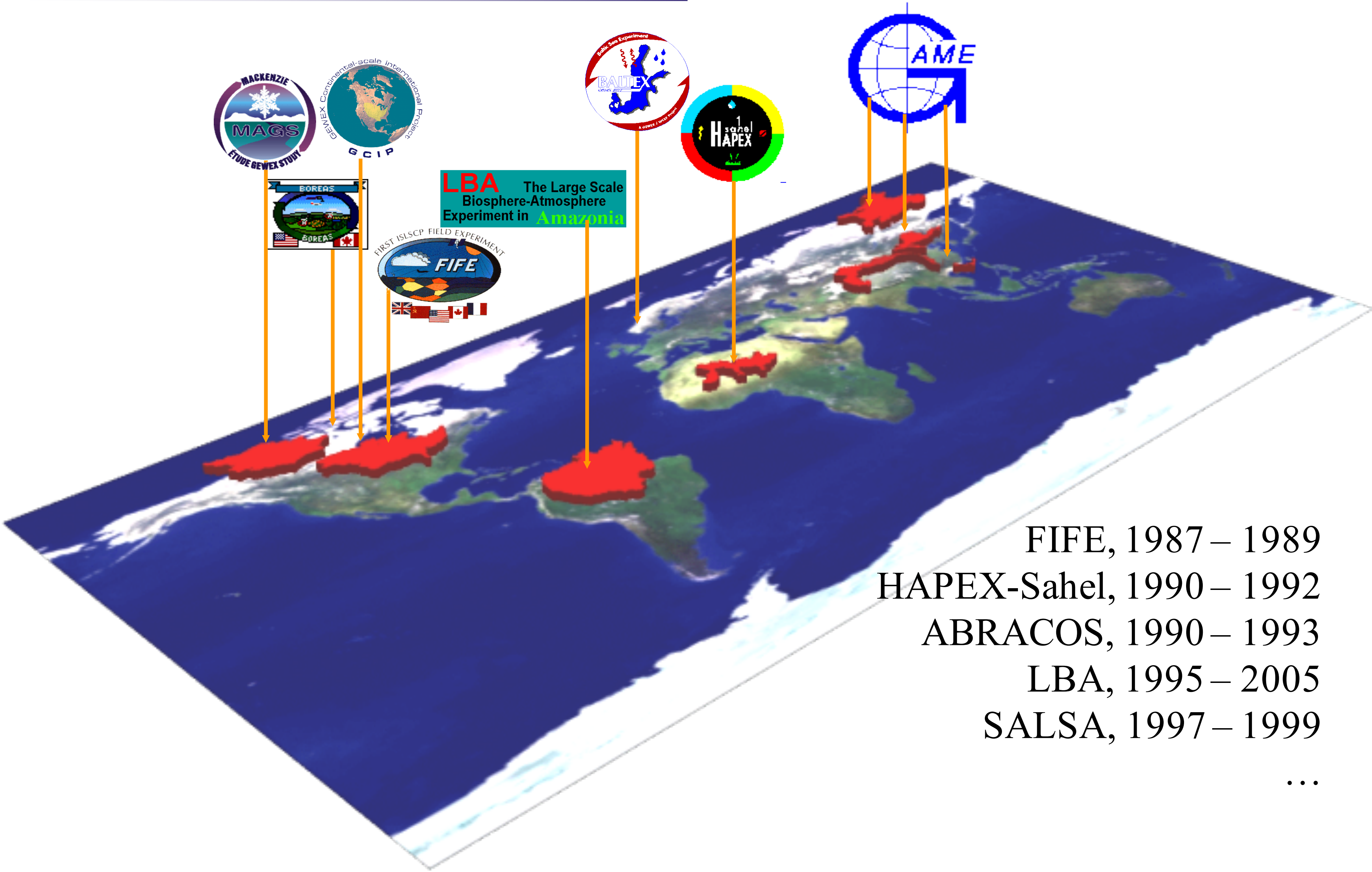
1.	Crop/mixed farming
2.	Short grass
3.	Evergreen needleleaf tree
4.	Deciduous needleleaf tree
5.	Deciduous broadleaf tree
6.	Evergreen broadleaf tree
7.	Tall grass
8.	Desert
9.	Tundra
10.	Irrigated Crop
11.	Semi-desert
12.	Ice cap/glacier
13.	Bog or marsh
14.	Inland water
15.	Ocean
16.	Evergreen shrub
17.	Deciduous shrub
18.	Mixed Woodland
19.	Forest/Field mosaic
20.	Water and Land mixture

BATS vegetation / land cover parameters

Table 2: BATS vegetation/land-cover

Parameter	Land Cover/Vegetation Type																			
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
Max fractional vegetation cover	0.85	0.80	0.80	0.80	0.80	0.90	0.80	0.00	0.60	0.80	0.35	0.00	0.80	0.00	0.00	0.80	0.80	0.80	0.80	0.80
Difference between max fractional vegetation cover and cover at 269 K	0.6	0.1	0.1	0.3	0.5	0.3	0.0	0.2	0.6	0.1	0.0	0.4	0.0	0.0	0.2	0.3	0.2	0.4	0.4	
Roughness length (m)	0.08	0.05	1.00	1.00	0.80	2.00	0.10	0.05	0.04	0.06	0.10	0.01	0.03	0.0004	0.0004	0.10	0.10	0.80	0.3	0.3
Displacement height (m)	0.0	0.0	9.0	9.0	0.0	18.0	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
Min stomatal resistence (s/m)	45	60	80	80	120	60	60	200	80	45	150	200	45	200	200	80	120	100	120	120
Max Leaf Area Index	6	2	6	6	6	6	6	0	6	6	6	0	6	0	0	6	6	6	6	6
Min Leaf Area Index	0.5	0.5	5	1	1	5	0.5	0	0.5	0.5	0.5	0	0.5	0	0	5	1	3	0.5	0.5
Stem (& dead matter) area index)	0.5	4.0	2.0	2.0	2.0	2.0	2.0	0.5	0.5	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0
Inverse square root of leaf dimension ($m^{-1/2}$)	10	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5
Light sensitivity factor (m^2 W^{-1})	0.02	0.02	0.06	0.06	0.06	0.06	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.06	0.02	0.02
Upper soil layer depth (mm)	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100
Root zone soil layer depth (mm)	1000	1000	1500	1500	2000	1500	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	2000	2000	2000
Depth of total soil (mm)	3000	3000	3000	3000	3000	3000	3000	3000	3000	3000	3000	3000	3000	3000	3000	3000	3000	3000	3000	3000
Soil texture type	6	6	6	6	7	8	6	3	6	6	5	12	6	6	6	6	5	6	6	0
Soil color type	5	3	4	4	4	4	4	1	3	3	2	1	5	5	5	4	3	4	4	0
Vegetation albedo for wavelengths $< 0.7\ \mu$ m	0.10	0.10	0.05	0.05	0.08	0.04	0.08	0.20	0.10	0.08	0.17	0.80	0.06	0.07	0.07	0.05	0.08	0.06	0.06	0.06
Vegetation albedo for wavelengths $> 0.7\ \mu$ m	0.30	0.30	0.23	0.23	0.28	0.20	0.30	0.40	0.30	0.28	0.34	0.60	0.18	0.20	0.20	0.23	0.28	0.24	0.18	0.18

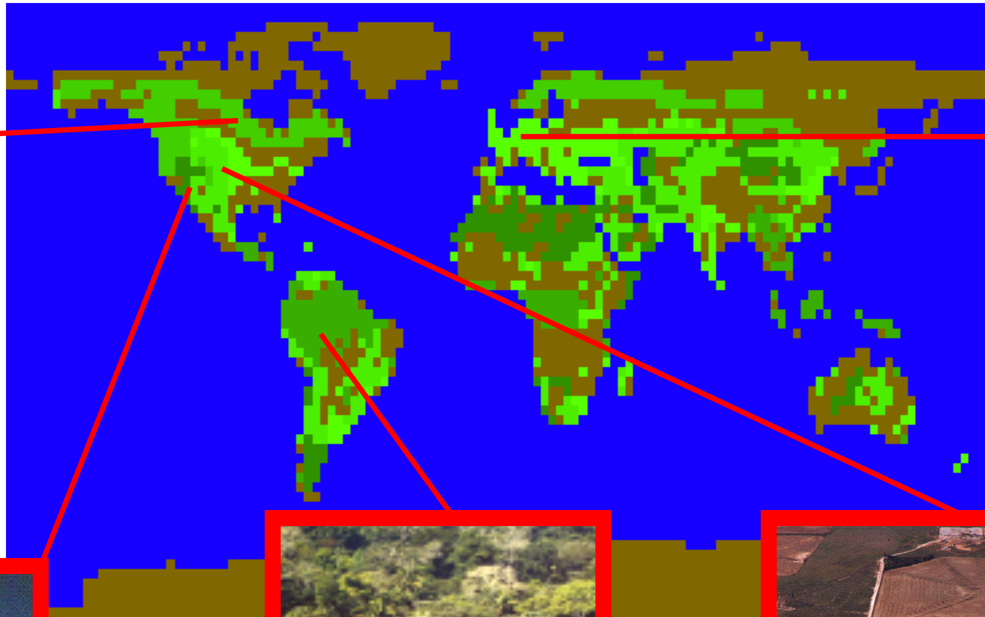
Field Experiments to collect LSM data



FIFE, 1987 – 1989
HAPEX-Sahel, 1990 – 1992
ABRACOS, 1990 – 1993
LBA, 1995 – 2005
SALSA, 1997 – 1999
…

CCM3-BATS calibration

BOREAS (NSA-OJP)
- Type: Evergreen Needleleaf
- Cover: 6.5%
- Precip: 242 mm
- Data : Jan 94 - Dec 96



Cabauw
- Type: Short Grass
- Cover: 16.6%
- Precip: 776 mm
- Data : Jan 87 - Dec 87

Tucson
- Type: Semi-Desert
- Cover: 9.2%
- Precip: 275 mm
- Data : May 93 - Jun 94

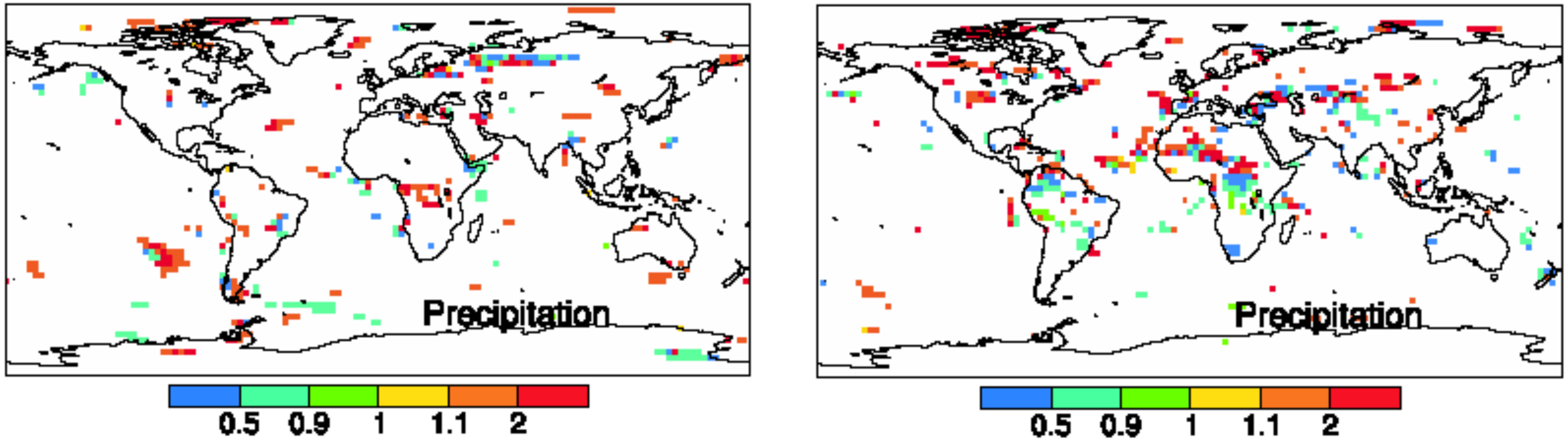
ABRACOS (Reserva Jaru)
- Type: Evergreen Broadleaf
- Cover: 9.7%
- Precip: 1600 mm
- Data : May 92 - Dec 93

ARM-CART (E13)
- Type: Mixed Crop / Farm Land
- Cover: 8.1%
- Precip: 600 mm
- Data : Apr 95 - Aug 95

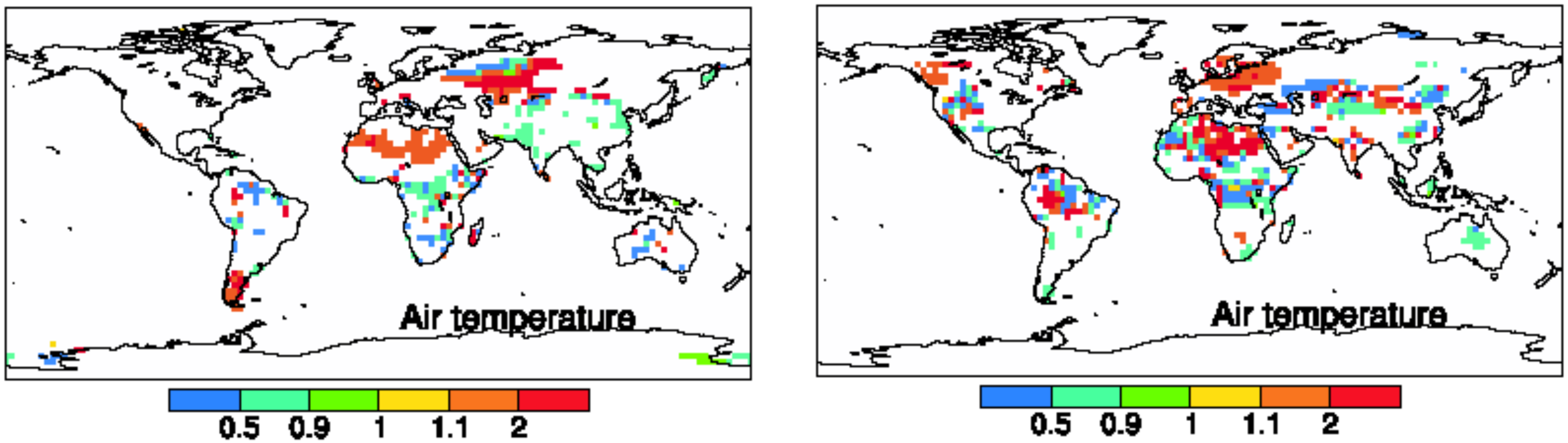
Sen et al. 2001, Q.J.R. Met. Soc. 127, 1199-1223.

CCM3-BATS improvement after parameter calibration

DJF JJA



$$idx = \sqrt{\frac{(Xdef - Xobs)^2}{(Xcal - Xobs)^2}}$$



Sen et al. 2001, Q.J.R. Met. Soc. 127, 1199-1223.