Terrestrial Water and Carbon Exchanges in Earth System Models

The “Missing” Seasonal Cycle

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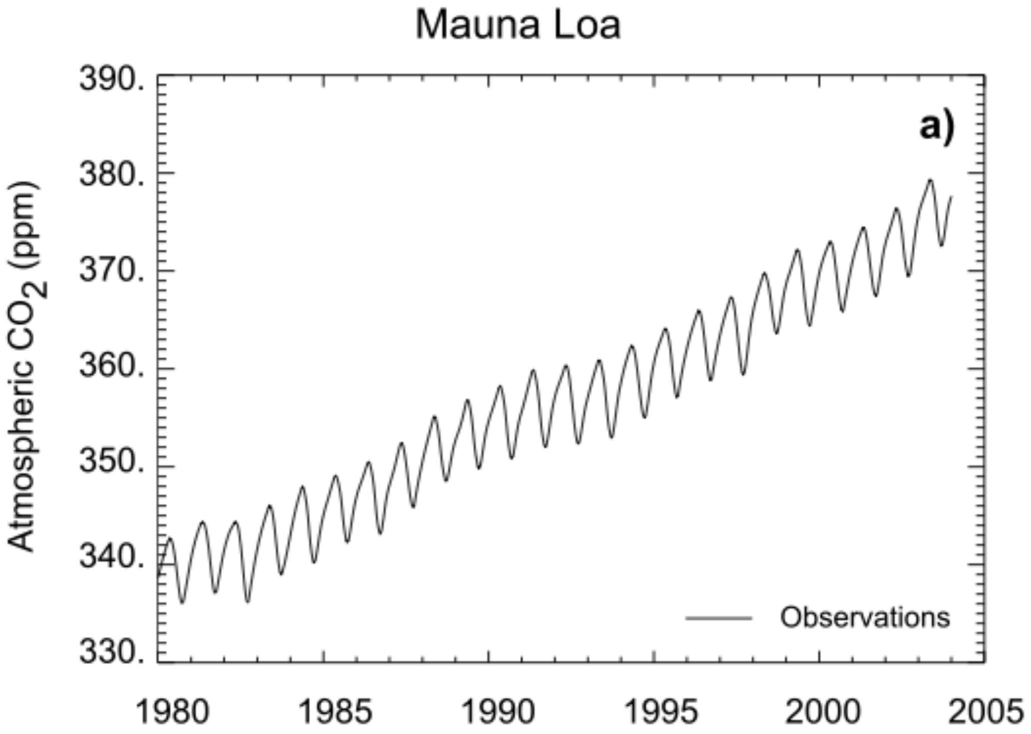
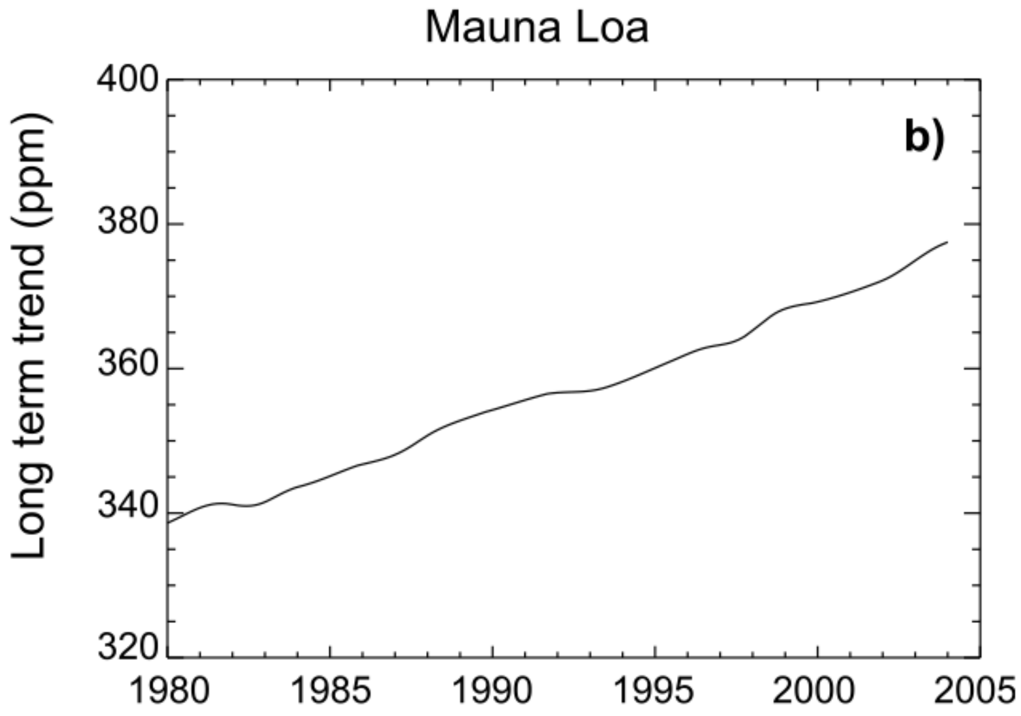
And many friends from NCAR, CSU, ORNL, ETHZ, FLUXNET and NASA/GSFC

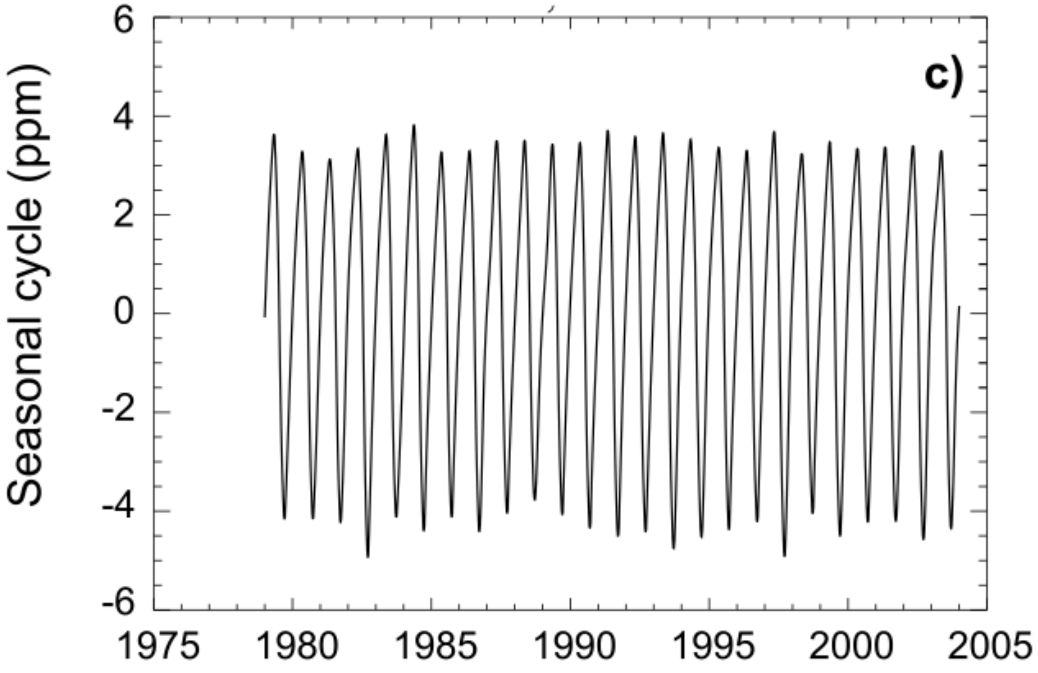
Carbon Cycle: across timescales



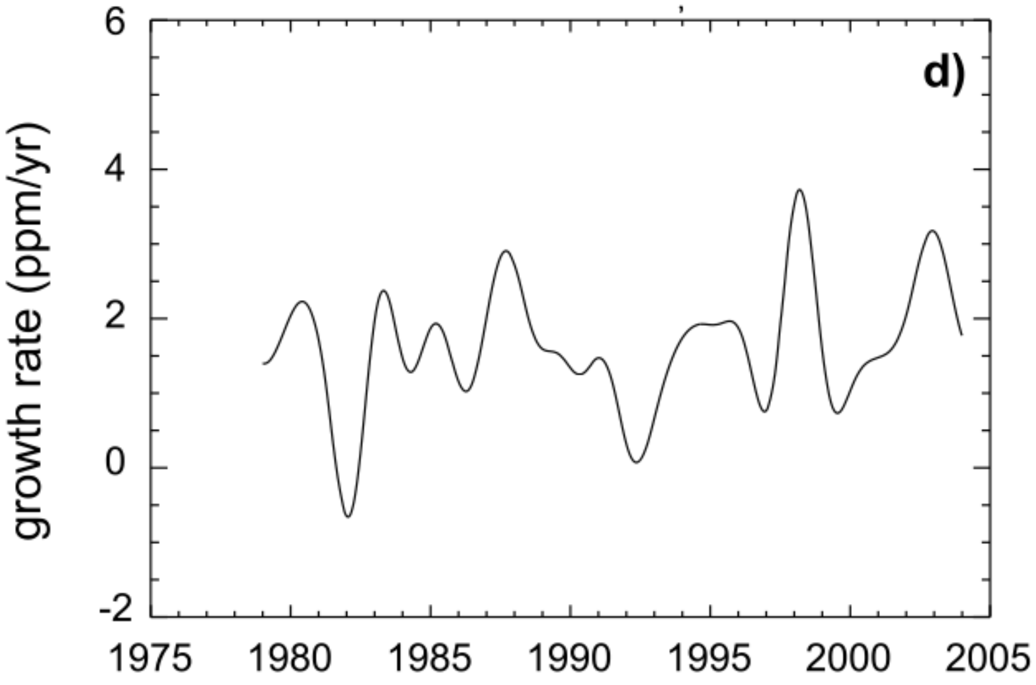
atmospheric carbon



long term trend



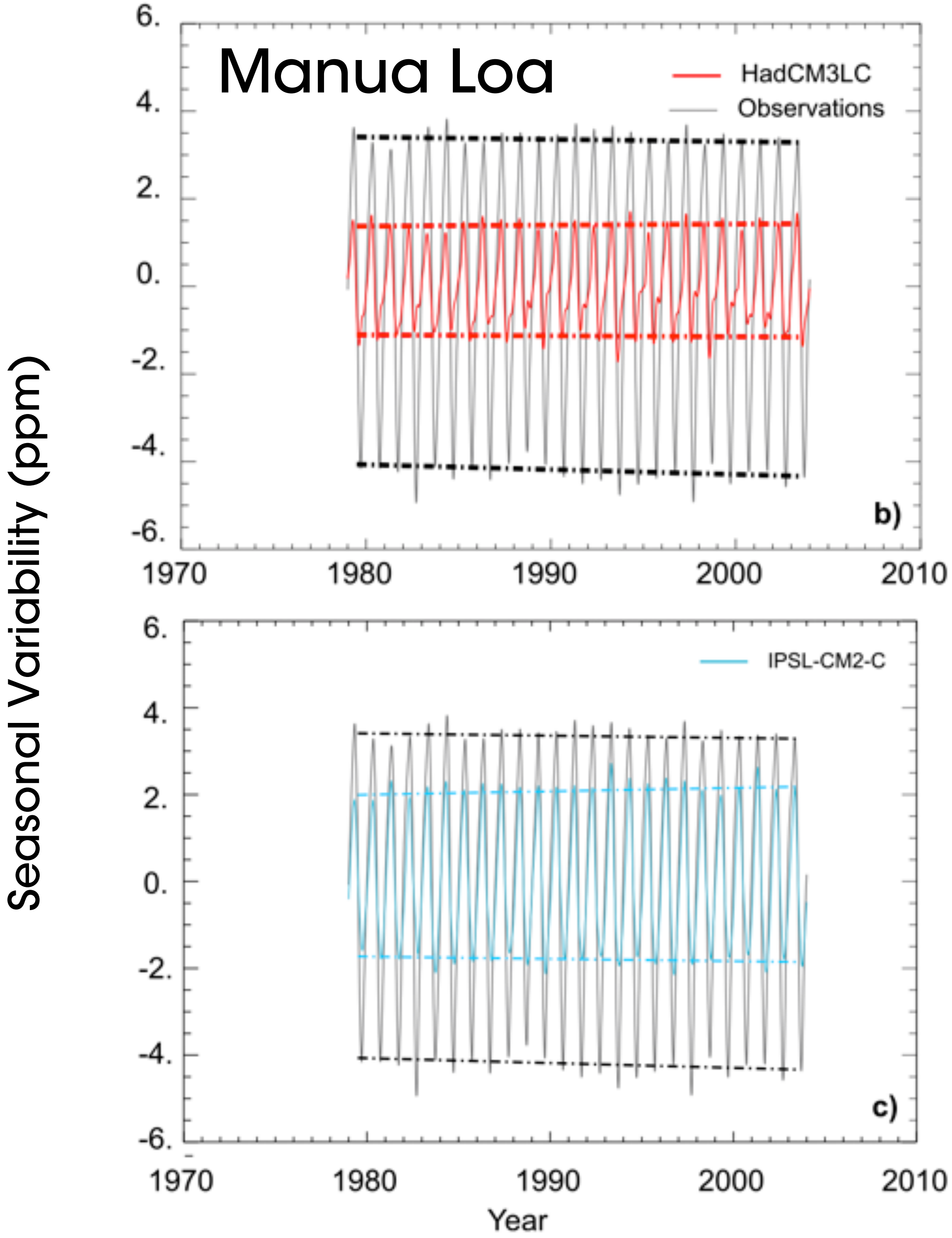
seasonal variability



interannual variability

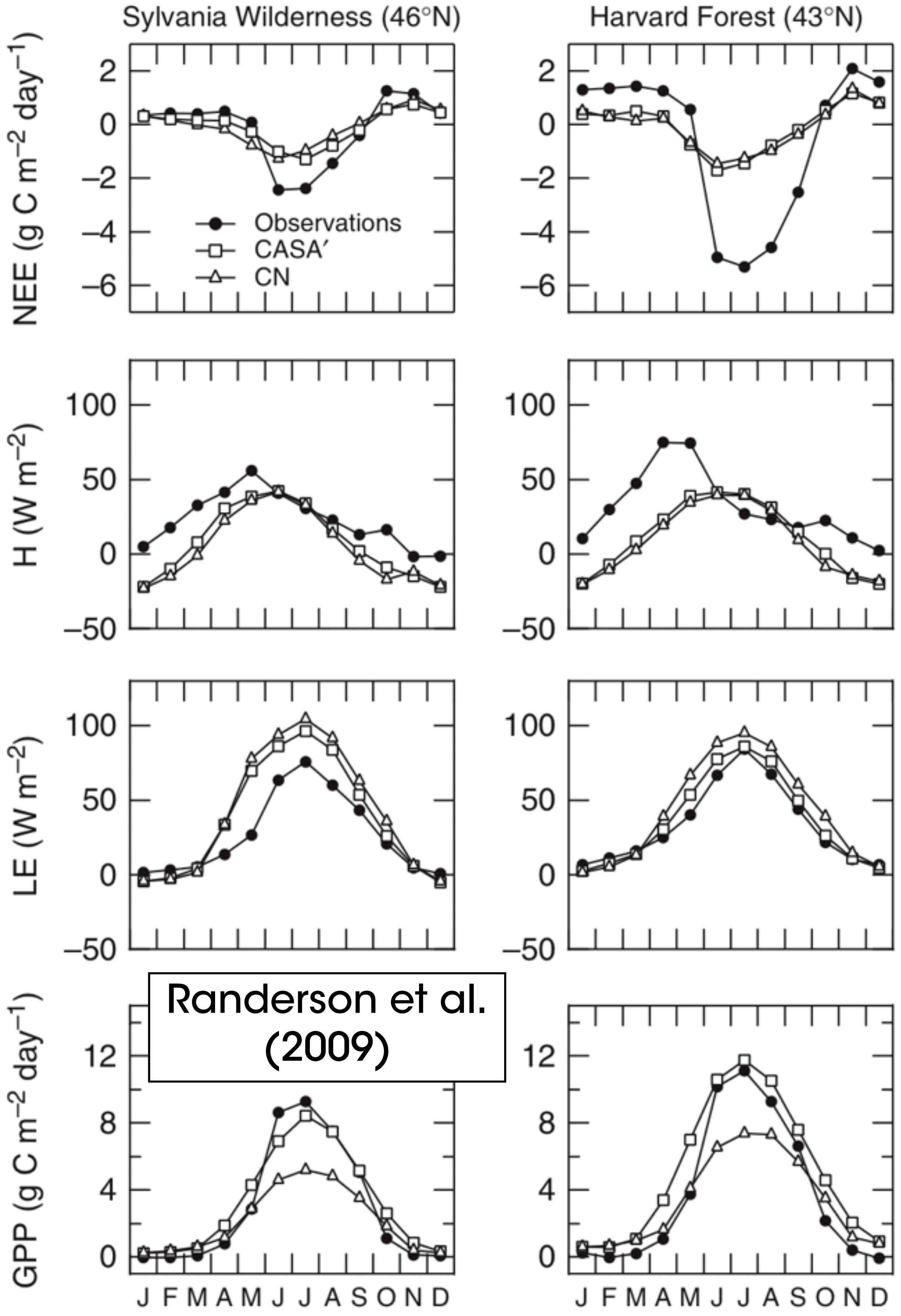
Cadule, Friedlingstein et al. (2010)

Carbon Cycle: seasonal variability



Cadule, Friedlingstein et al. (2010)

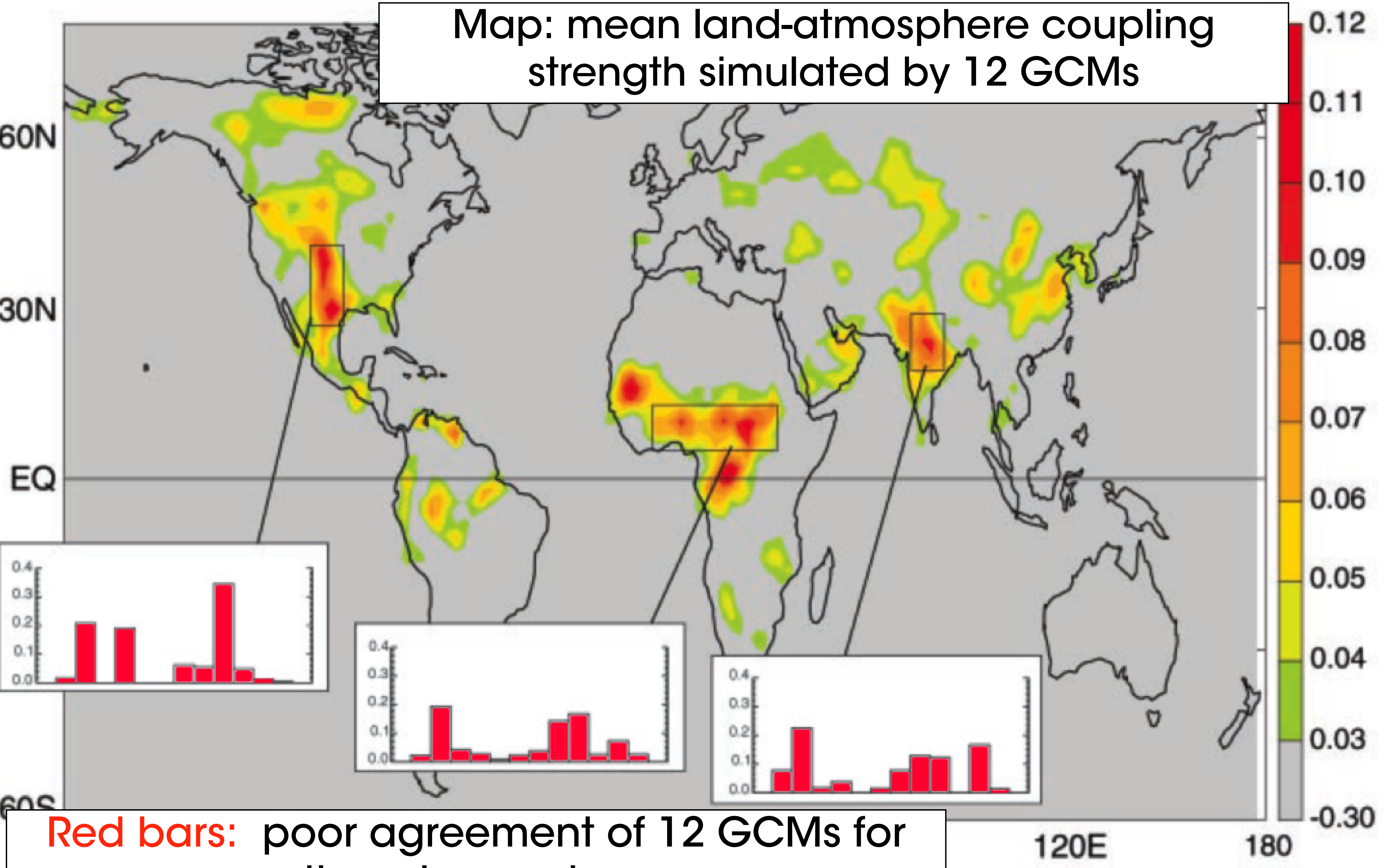
Atmosphere



Randerson et al. (2009)

Terrestrial

Water Cycle: land-atmosphere coupling



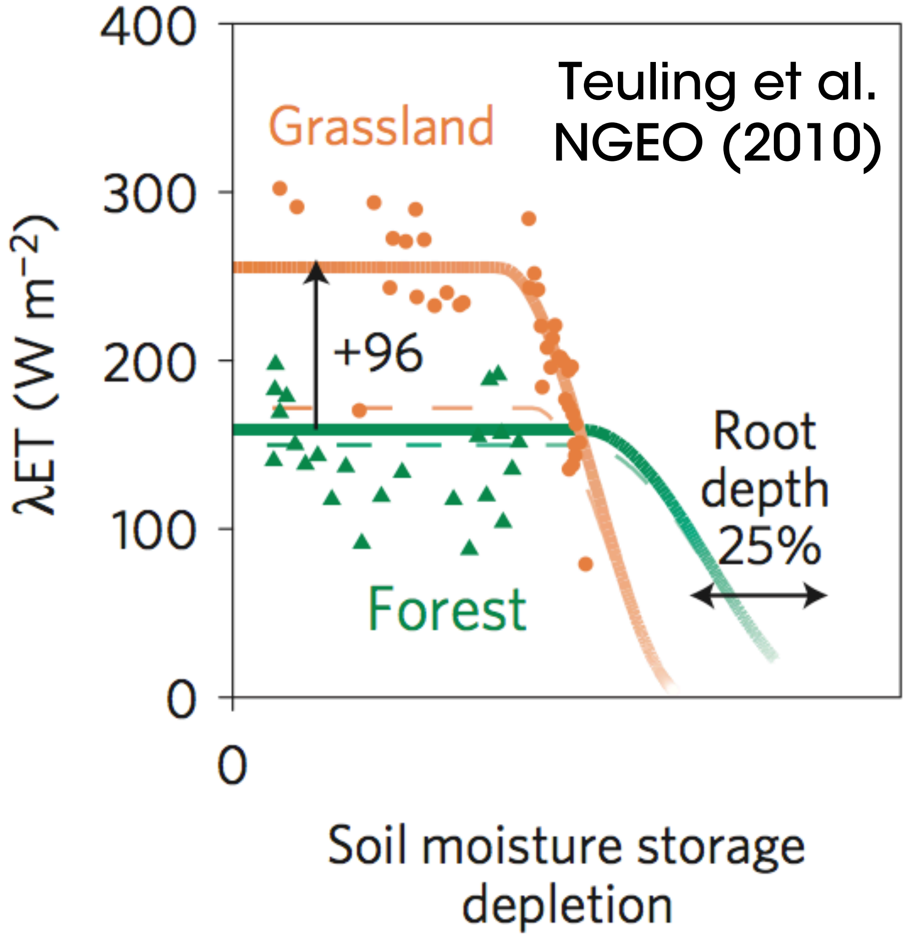
Map: mean land-atmosphere coupling strength simulated by 12 GCMs

Red bars: poor agreement of 12 GCMs for three key regions

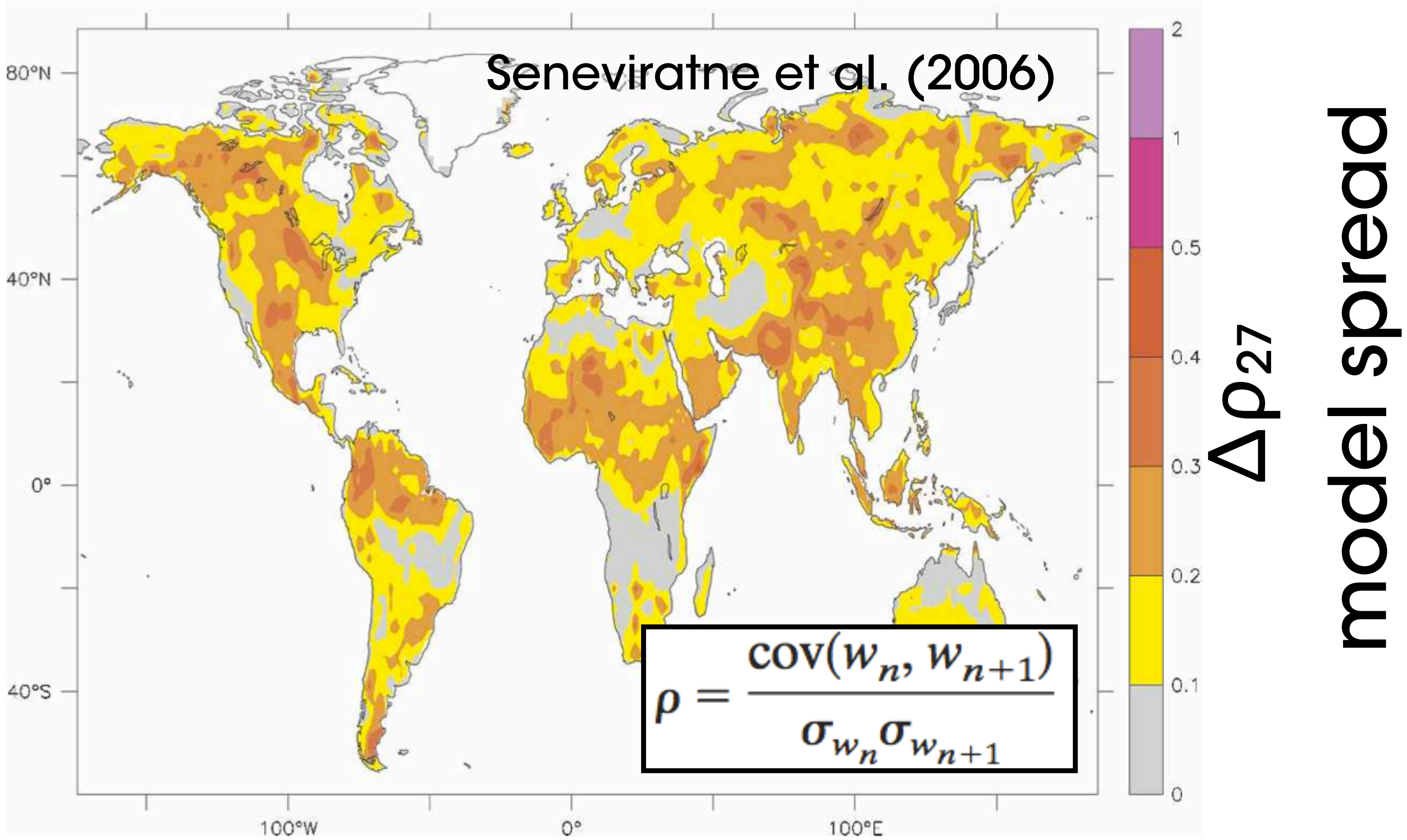
Koster et al. (2004)

Water Cycle: soil moisture memory

OBS

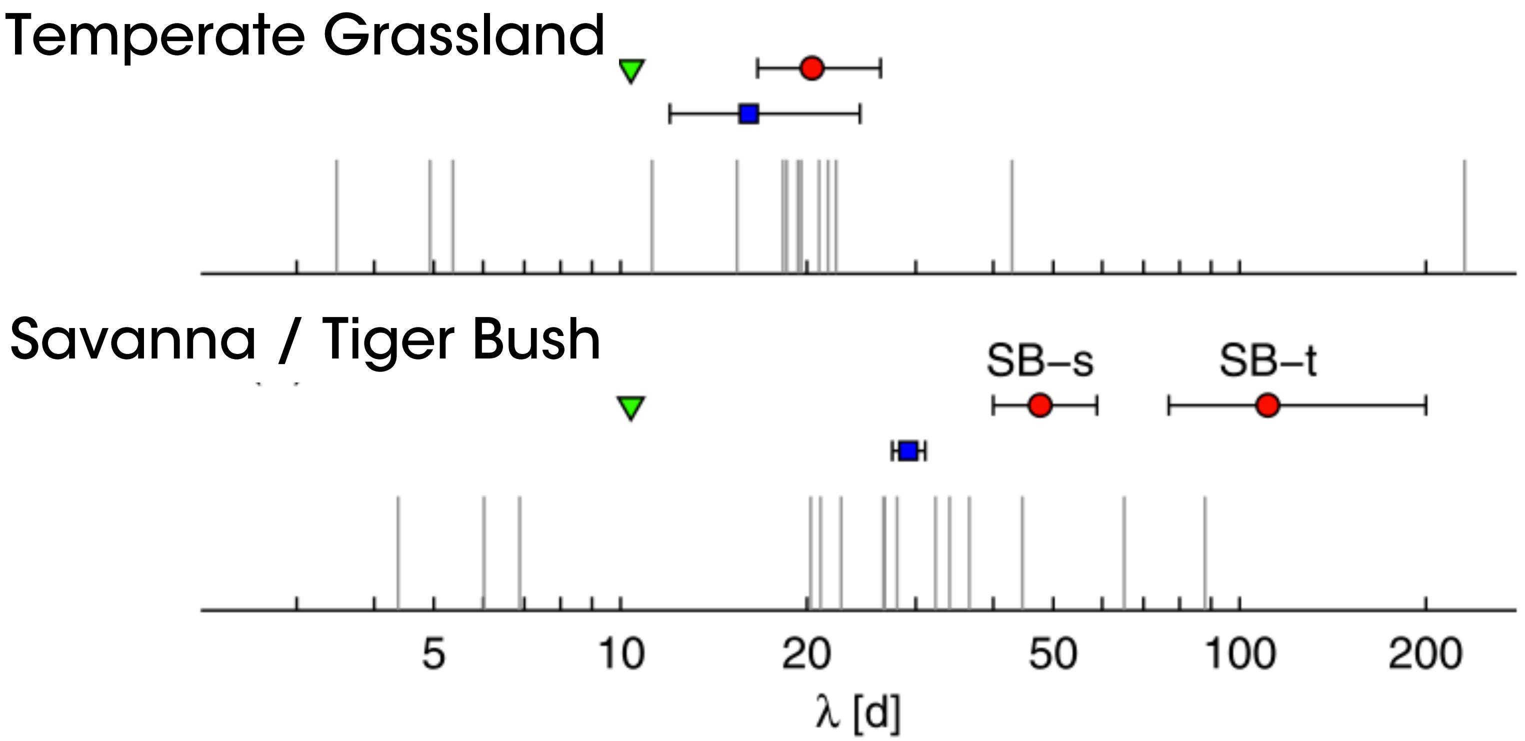


MODELS



$$\rho = \frac{\mathrm{cov}(w_n, w_{n+1})}{\sigma_{w_n}\sigma_{w_{n+1}}}$$

OBS+MODELS

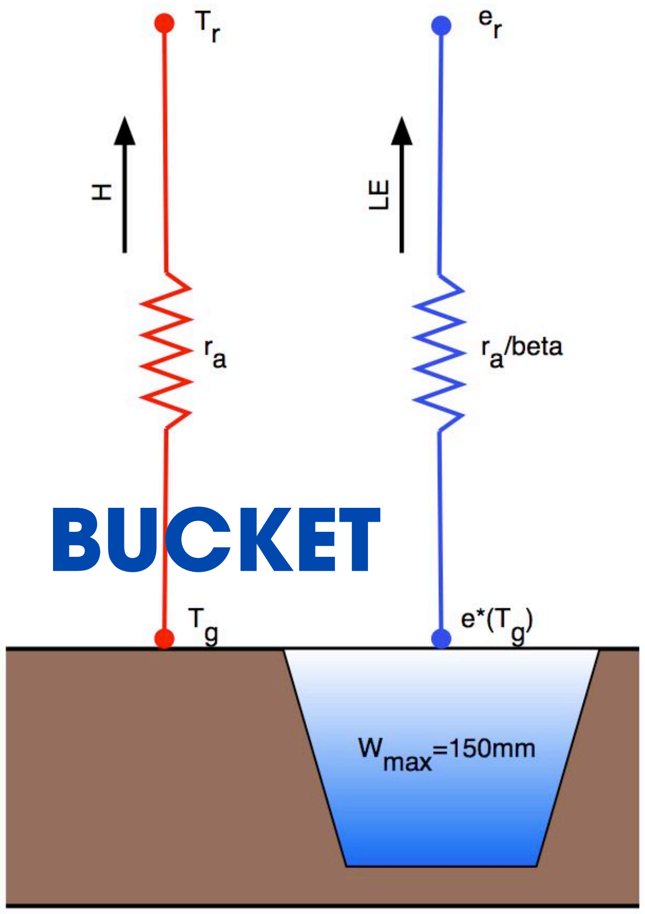


$$ET(t) = ET_0 \exp\left(-\frac{t - t_0}{\lambda}\right)$$

red dots: observed memory
black bars: modeled memory

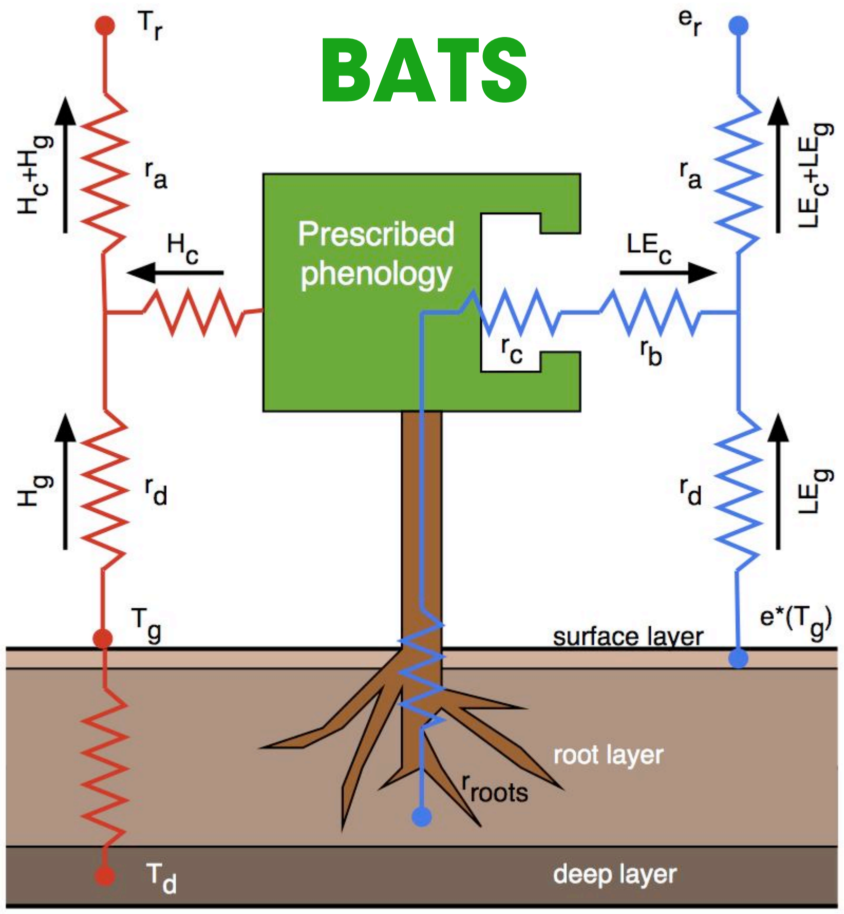
Teuling et al. (2006)

3+ Generations of LSM's



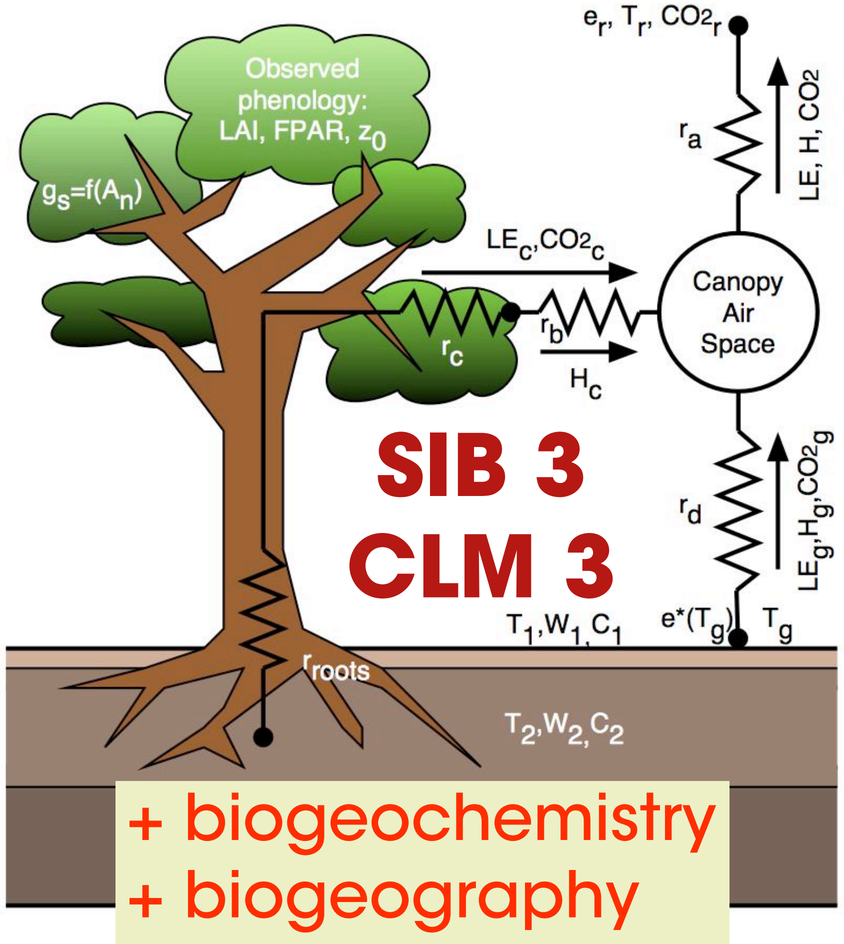
surface radiation balance

Manabe 1969



biophysical control of transpiration

Dickinson 1986
Jarvis 1976
Deardroff 1978



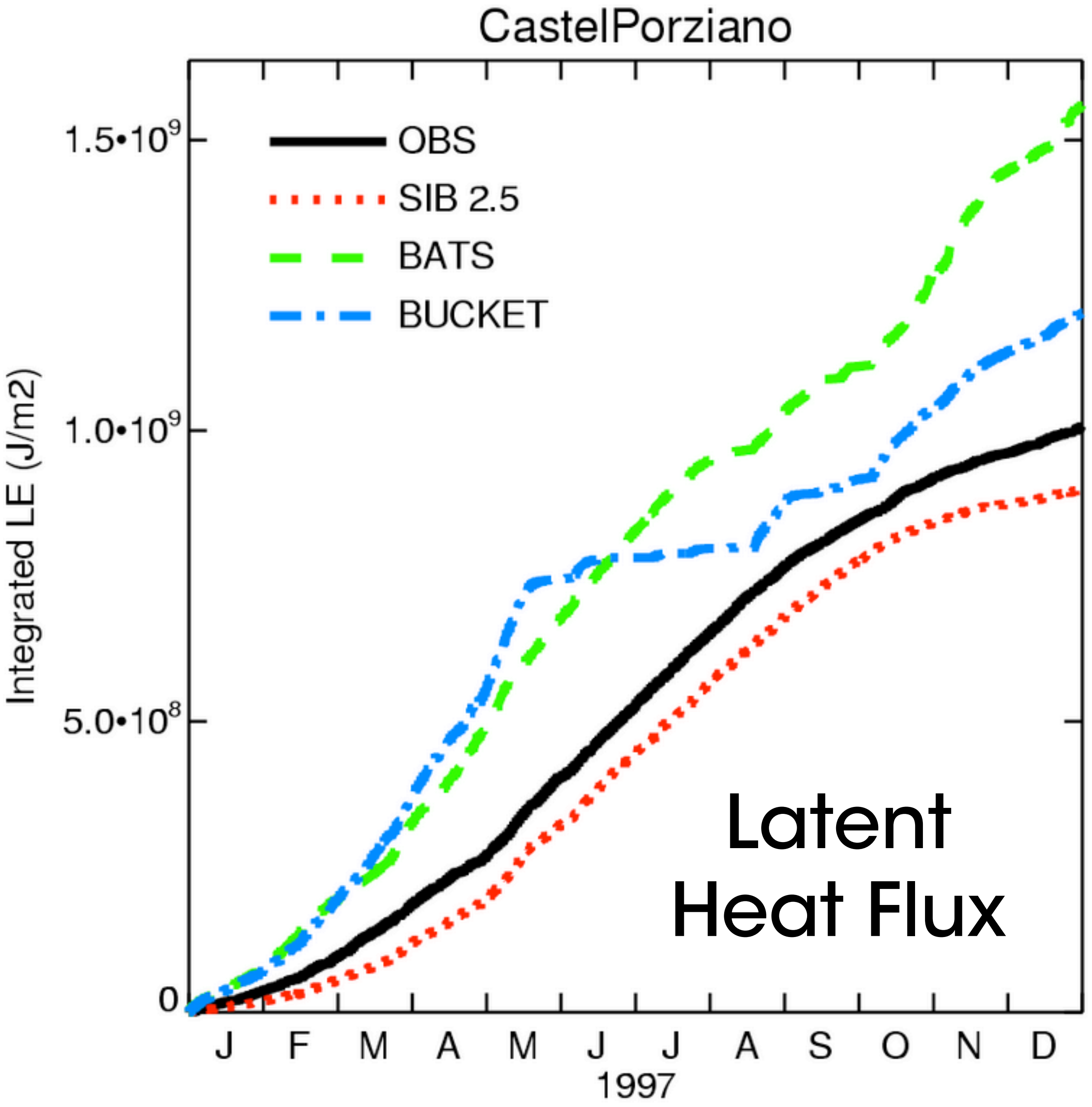
+ biogeochemistry
+ biogeography

biochemical control of transpiration

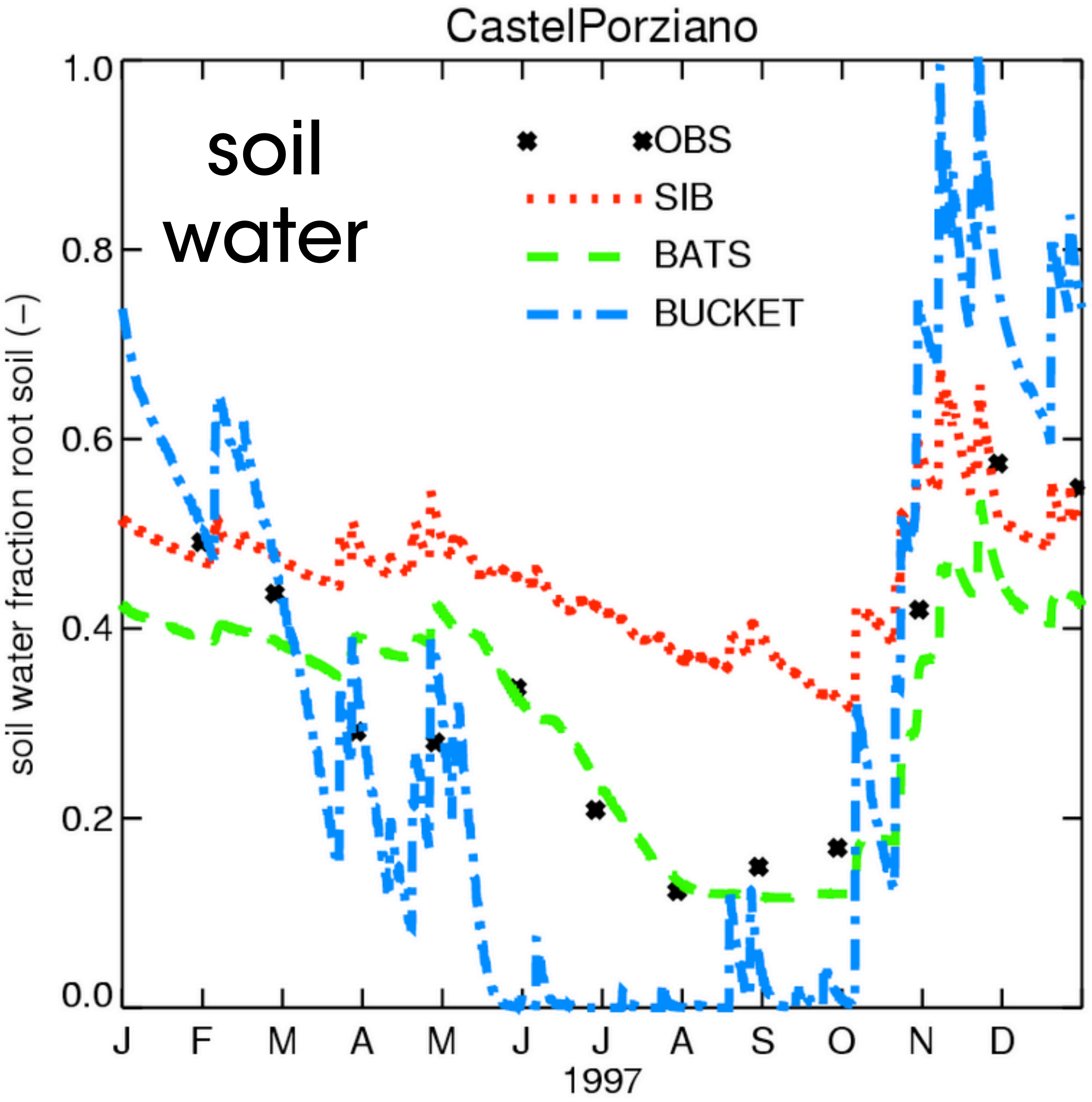
Sellers et al. 1996
Farquhar 1980
Collatz 1991

3+ Generations of LSM’s

In order to calculate land E+W fluxes a land surface model needs to realistically represent biophysics, biochemistry, soil hydrology and SL aerodynamics.



Latent Heat Flux



soil water

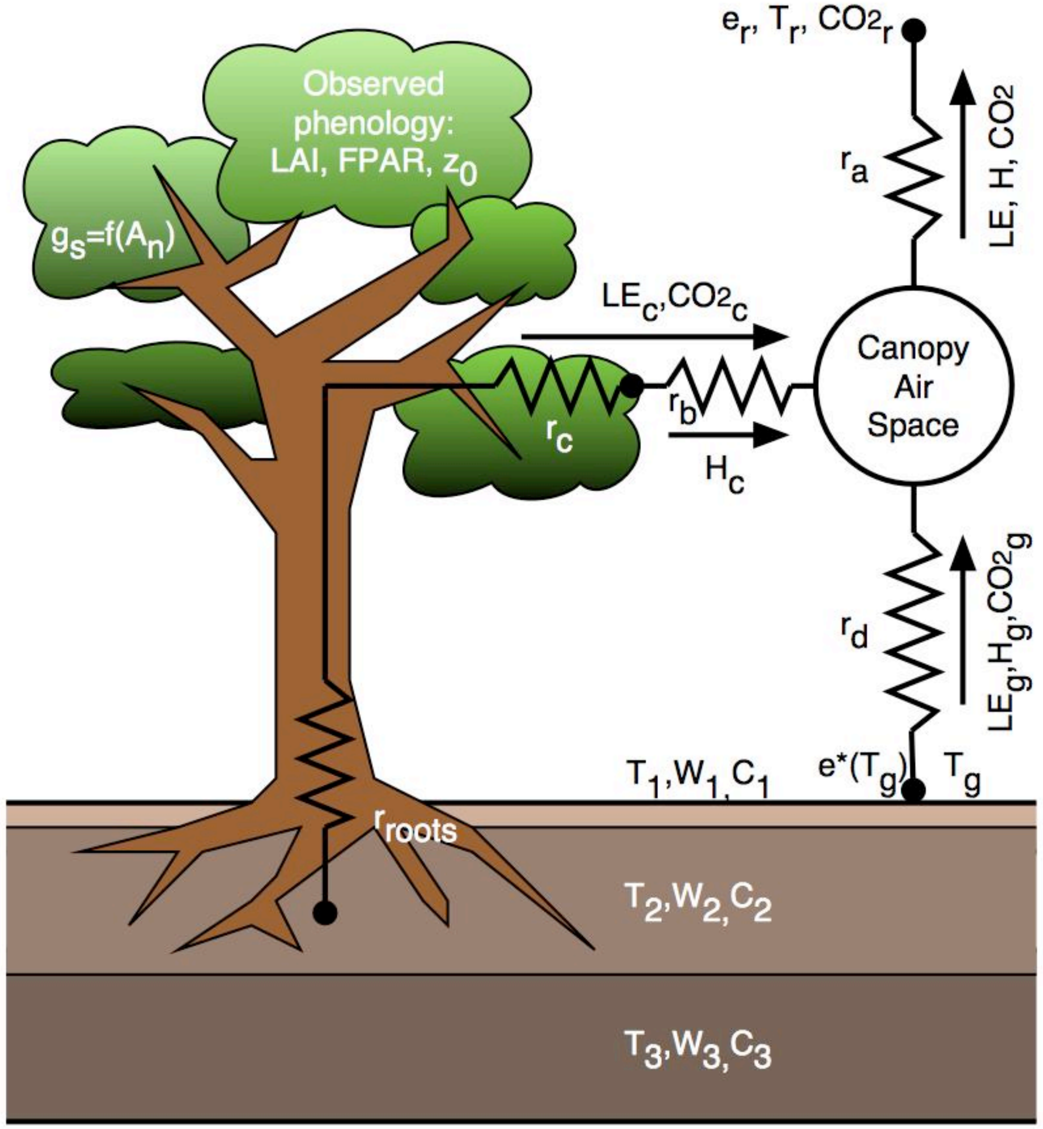
Stöckli & Vidale (2005), Theor. & Appl. Climatology

LSM Processes & Parameters

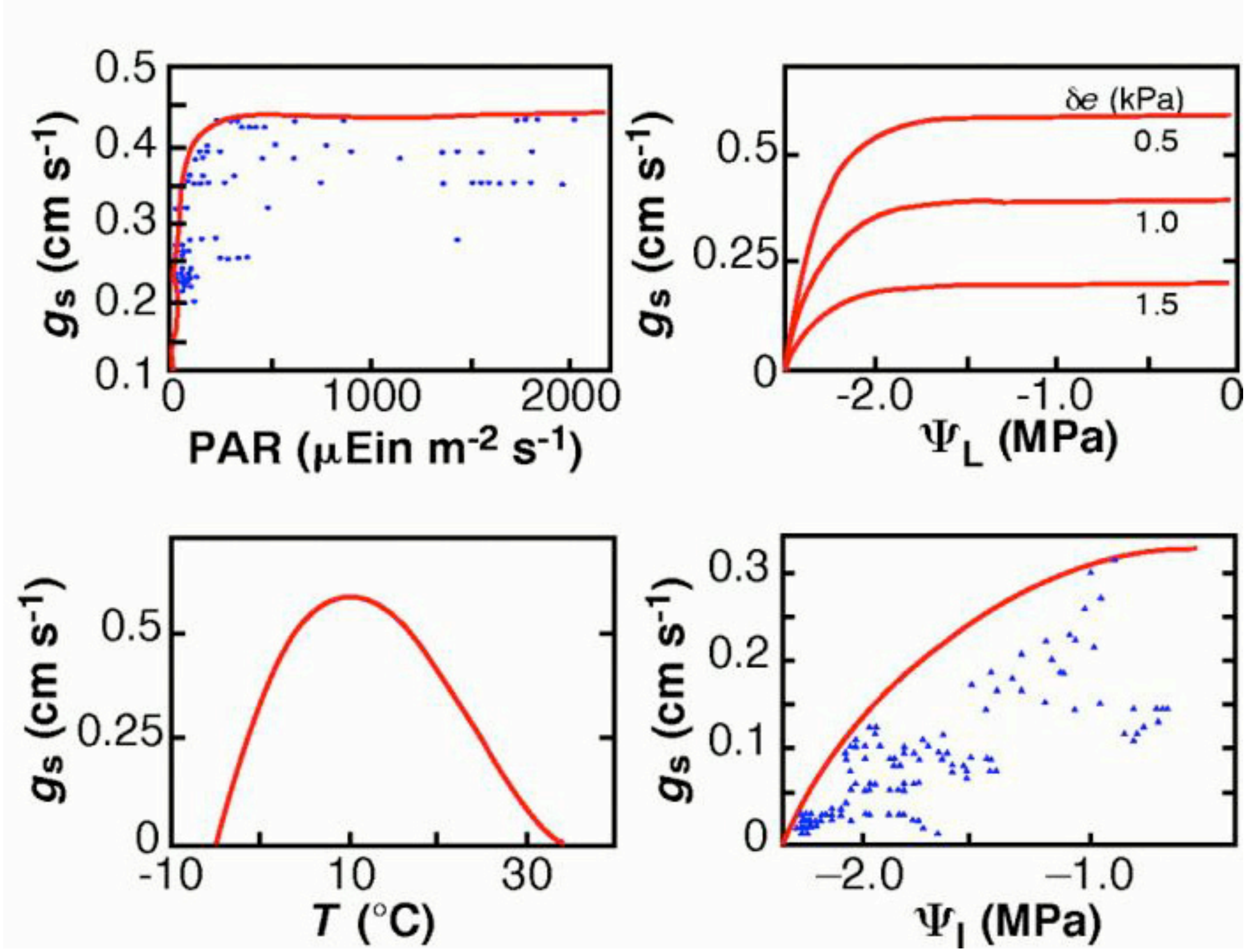
- multiple soil layers, resistances, radiative transfer
- most mechanistic models include semi-empirical parameterizations, e.g. A-gs, Farquhar (1980):

$$g_s = m \frac{A_n}{c_s} h_s p + b \qquad g_s = f(PAR, \delta e, T, \Psi_l)$$

a) mechanistic formulations



b) parameterizations



Sellers 1997

LSM Parameters

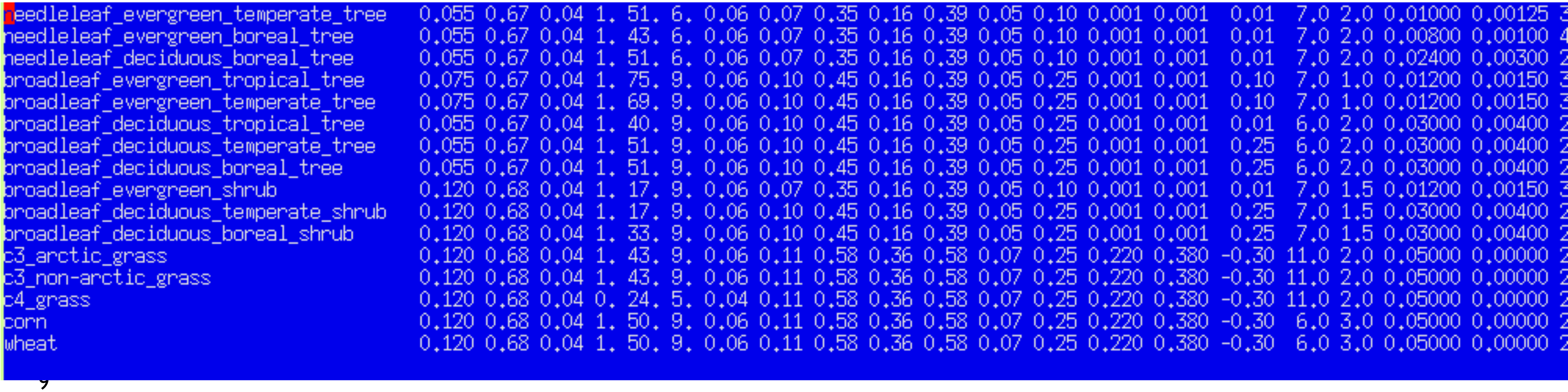
History

- From field work over the past 30-50 years
- Gathered from literature or other models
- Classified by Plant Functional Type or LCC

Issues:

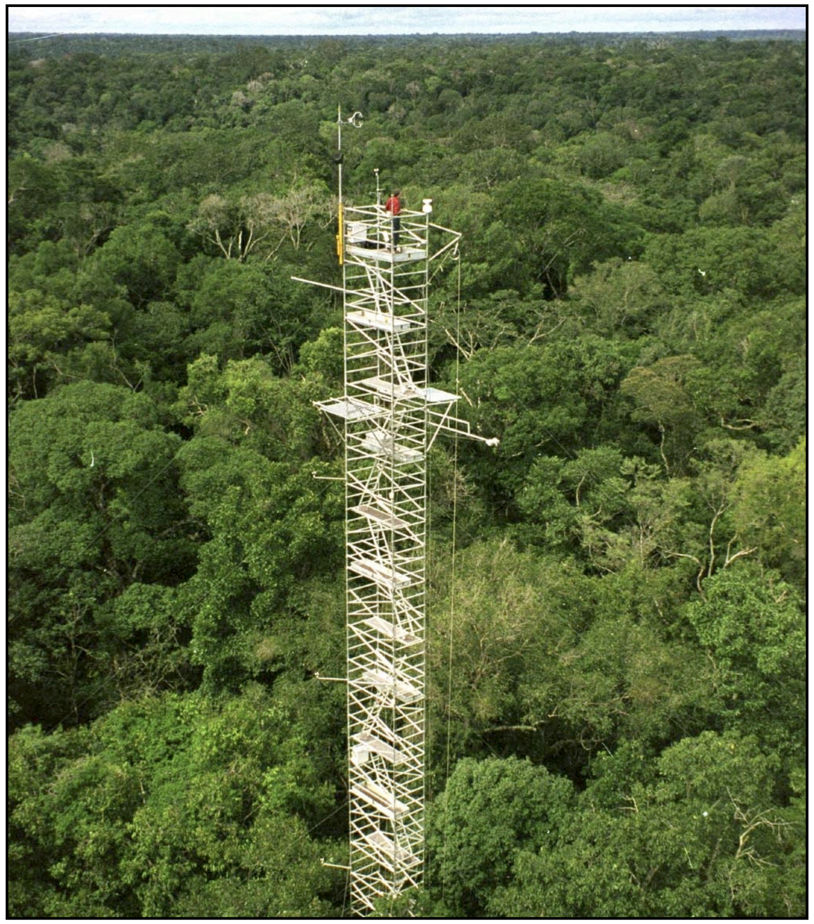
- Scalability: leaf to canopy to landscape?
- Variability: are parameters time-dependent?
- Diversity: more than 20 classes needed?

Example: CLM 3.5 PFT-dependent plant physiology parameters (2007)



```
needleleaf_evergreen_temperate_tree    0.055 0.67 0.04 1. 51. 6. 0.06 0.07 0.35 0.16 0.39 0.05 0.10 0.001 0.001  0.01  7.0 2.0 0.01000 0.00125 3
needleleaf_evergreen_boreal_tree       0.055 0.67 0.04 1. 43. 6. 0.06 0.07 0.35 0.16 0.39 0.05 0.10 0.001 0.001  0.01  7.0 2.0 0.00800 0.00100 4
needleleaf_deciduous_boreal_tree       0.055 0.67 0.04 1. 51. 6. 0.06 0.07 0.35 0.16 0.39 0.05 0.10 0.001 0.001  0.01  7.0 2.0 0.02400 0.00300 2
broadleaf_evergreen_tropical_tree      0.075 0.67 0.04 1. 75. 9. 0.06 0.10 0.45 0.16 0.39 0.05 0.25 0.001 0.001  0.10  7.0 1.0 0.01200 0.00150 3
broadleaf_evergreen_temperate_tree     0.075 0.67 0.04 1. 69. 9. 0.06 0.10 0.45 0.16 0.39 0.05 0.25 0.001 0.001  0.10  7.0 1.0 0.01200 0.00150 3
broadleaf_deciduous_tropical_tree      0.055 0.67 0.04 1. 40. 9. 0.06 0.10 0.45 0.16 0.39 0.05 0.25 0.001 0.001  0.01  6.0 2.0 0.03000 0.00400 2
broadleaf_deciduous_temperate_tree     0.055 0.67 0.04 1. 51. 9. 0.06 0.10 0.45 0.16 0.39 0.05 0.25 0.001 0.001  0.25  6.0 2.0 0.03000 0.00400 2
broadleaf_deciduous_boreal_tree        0.055 0.67 0.04 1. 51. 9. 0.06 0.10 0.45 0.16 0.39 0.05 0.25 0.001 0.001  0.25  6.0 2.0 0.03000 0.00400 2
broadleaf_evergreen_shrub              0.120 0.68 0.04 1. 17. 9. 0.06 0.07 0.35 0.16 0.39 0.05 0.10 0.001 0.001  0.01  7.0 1.5 0.01200 0.00150 3
broadleaf_deciduous_temperate_shrub    0.120 0.68 0.04 1. 17. 9. 0.06 0.10 0.45 0.16 0.39 0.05 0.25 0.001 0.001  0.25  7.0 1.5 0.03000 0.00400 2
broadleaf_deciduous_boreal_shrub       0.120 0.68 0.04 1. 33. 9. 0.06 0.10 0.45 0.16 0.39 0.05 0.25 0.001 0.001  0.25  7.0 1.5 0.03000 0.00400 2
c3_arctic_grass                        0.120 0.68 0.04 1. 43. 9. 0.06 0.11 0.58 0.36 0.58 0.07 0.25 0.220 0.380 -0.30 11.0 2.0 0.05000 0.00000 2
c3_non-arctic_grass                    0.120 0.68 0.04 1. 43. 9. 0.06 0.11 0.58 0.36 0.58 0.07 0.25 0.220 0.380 -0.30 11.0 2.0 0.05000 0.00000 2
c4_grass                               0.120 0.68 0.04 0. 24. 5. 0.04 0.11 0.58 0.36 0.58 0.07 0.25 0.220 0.380 -0.30 11.0 2.0 0.05000 0.00000 2
corn                                   0.120 0.68 0.04 1. 50. 9. 0.06 0.11 0.58 0.36 0.58 0.07 0.25 0.220 0.380 -0.30  6.0 3.0 0.05000 0.00000 2
wheat                                  0.120 0.68 0.04 1. 50. 9. 0.06 0.11 0.58 0.36 0.58 0.07 0.25 0.220 0.380 -0.30  6.0 3.0 0.05000 0.00000 2
```

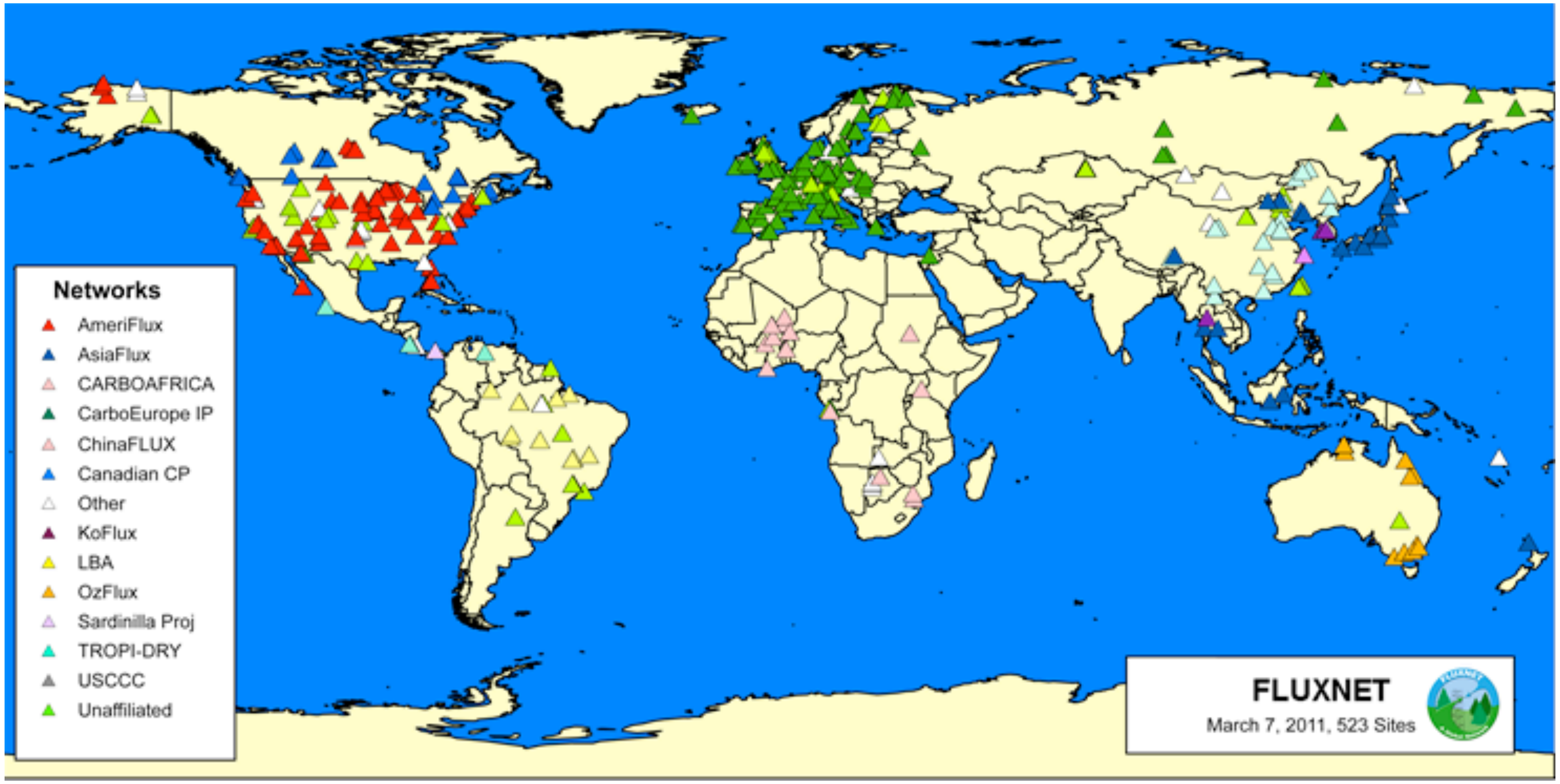
Local-Scale Observations



turbulent fluxes

soil processes

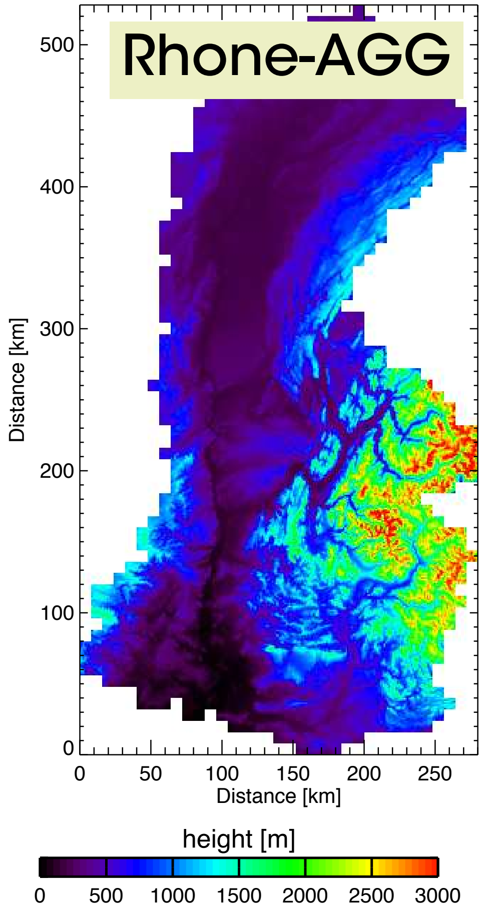
FLUXNET (Baldocchi et al. 2001)

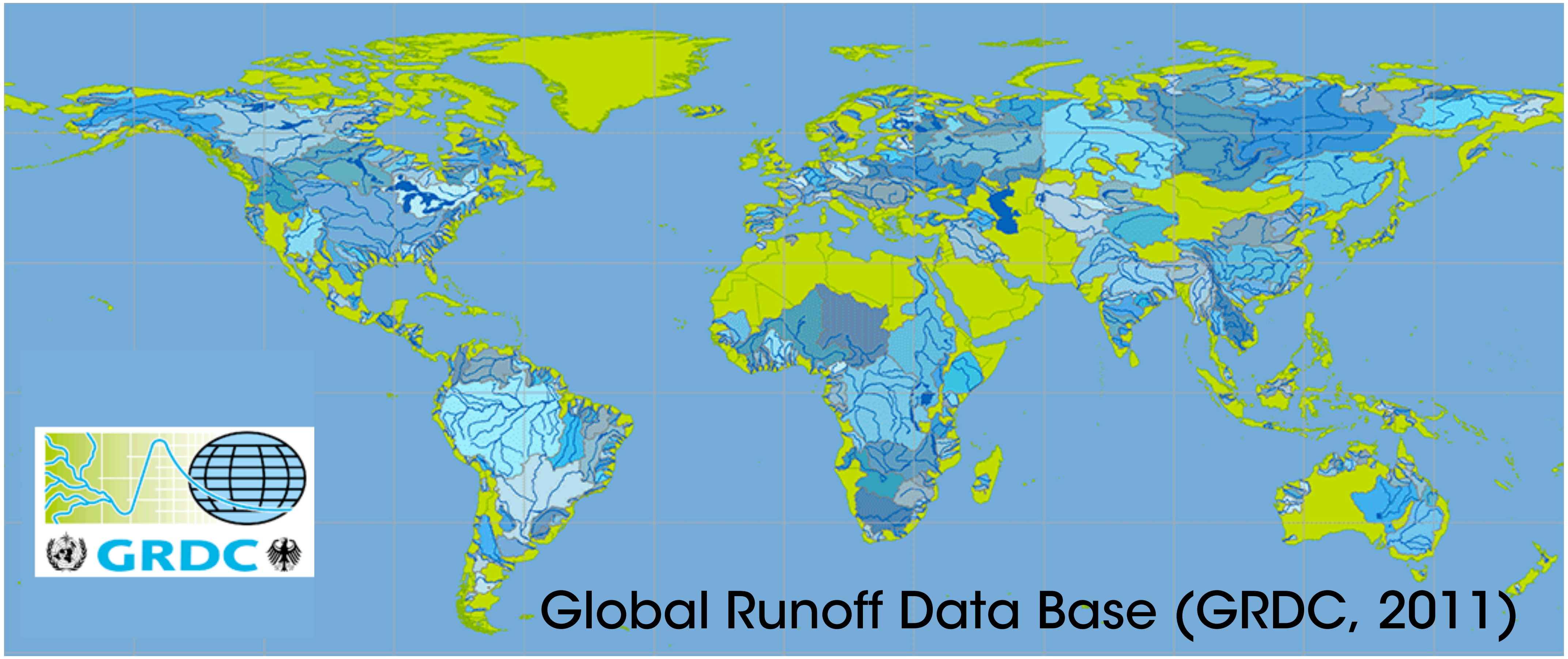


FLUXNET (500+ sites by 2011)

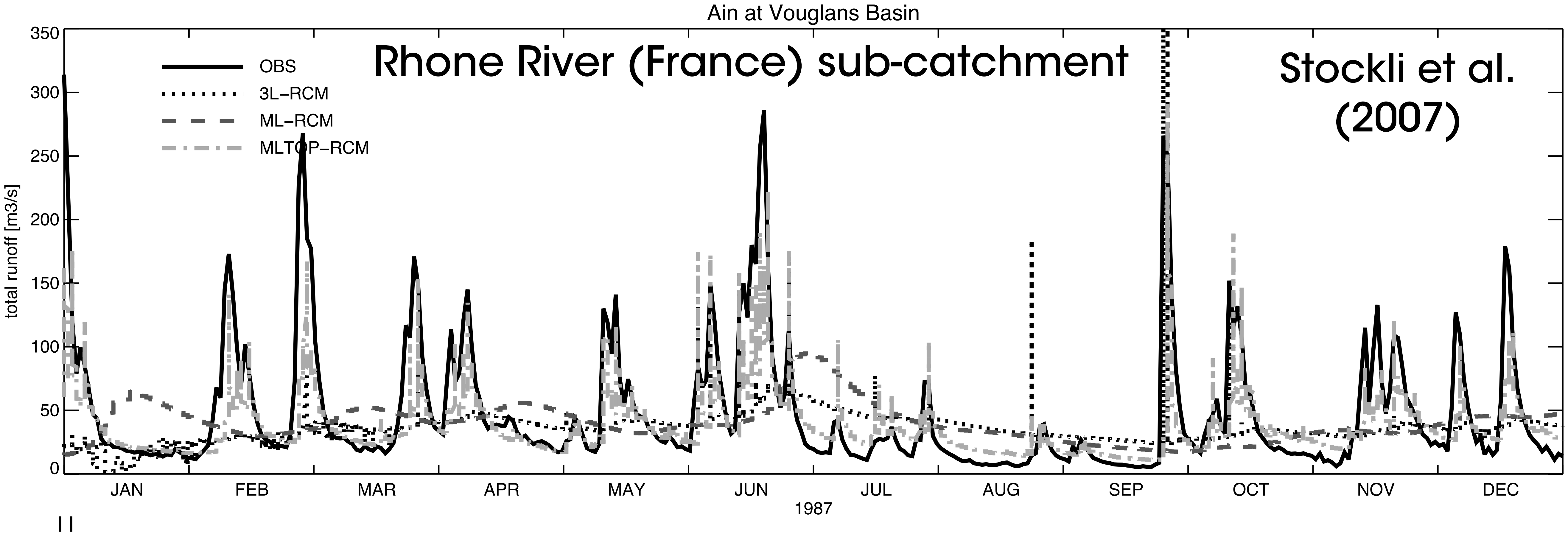
- wide range of climatic zones
- meteorological states
- R, H, LE and CO_2 fluxes
- soil moisture & soil temperature

Catchment-Scale Observations





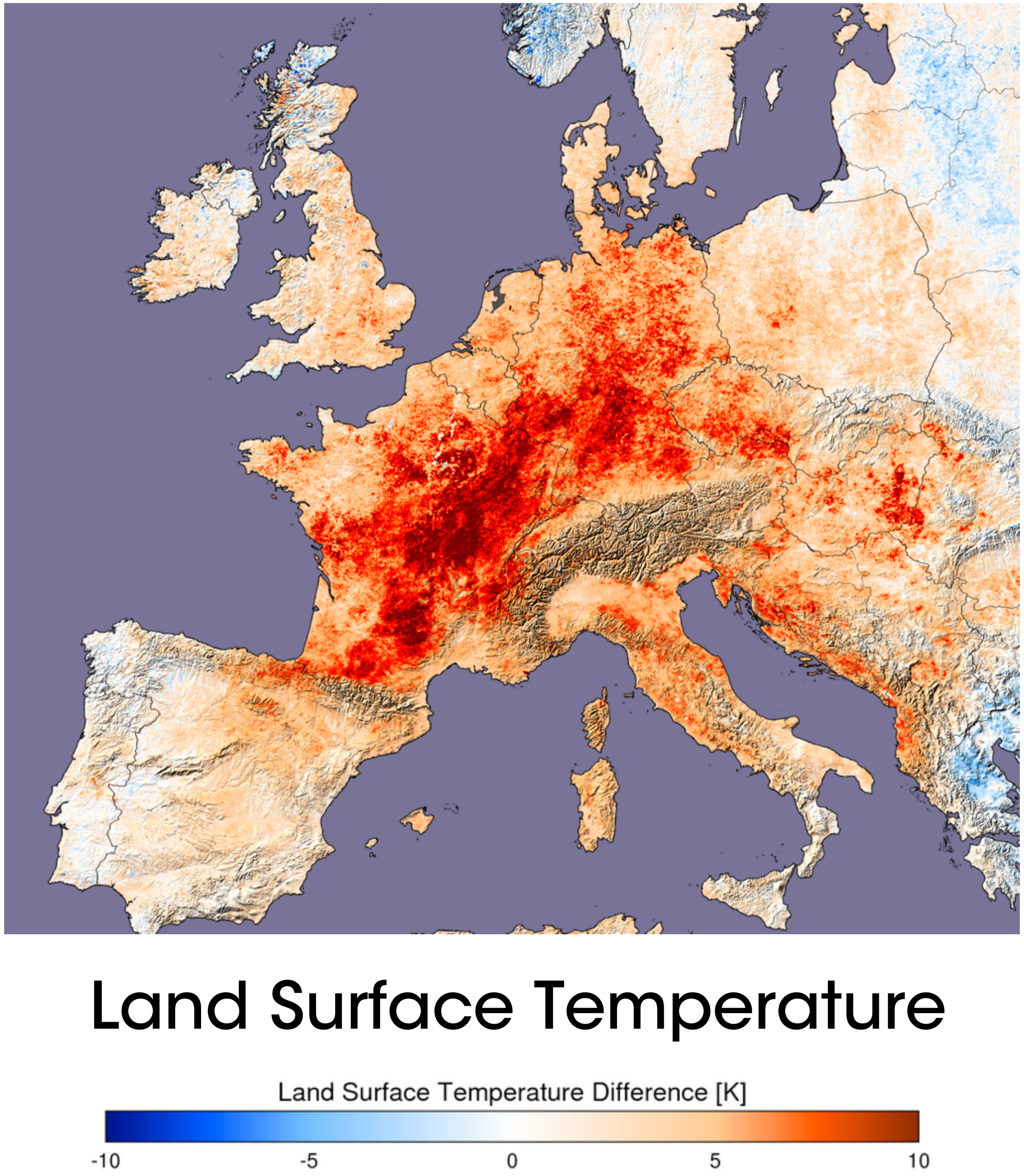
Global Runoff Data Base (GRDC, 2011)



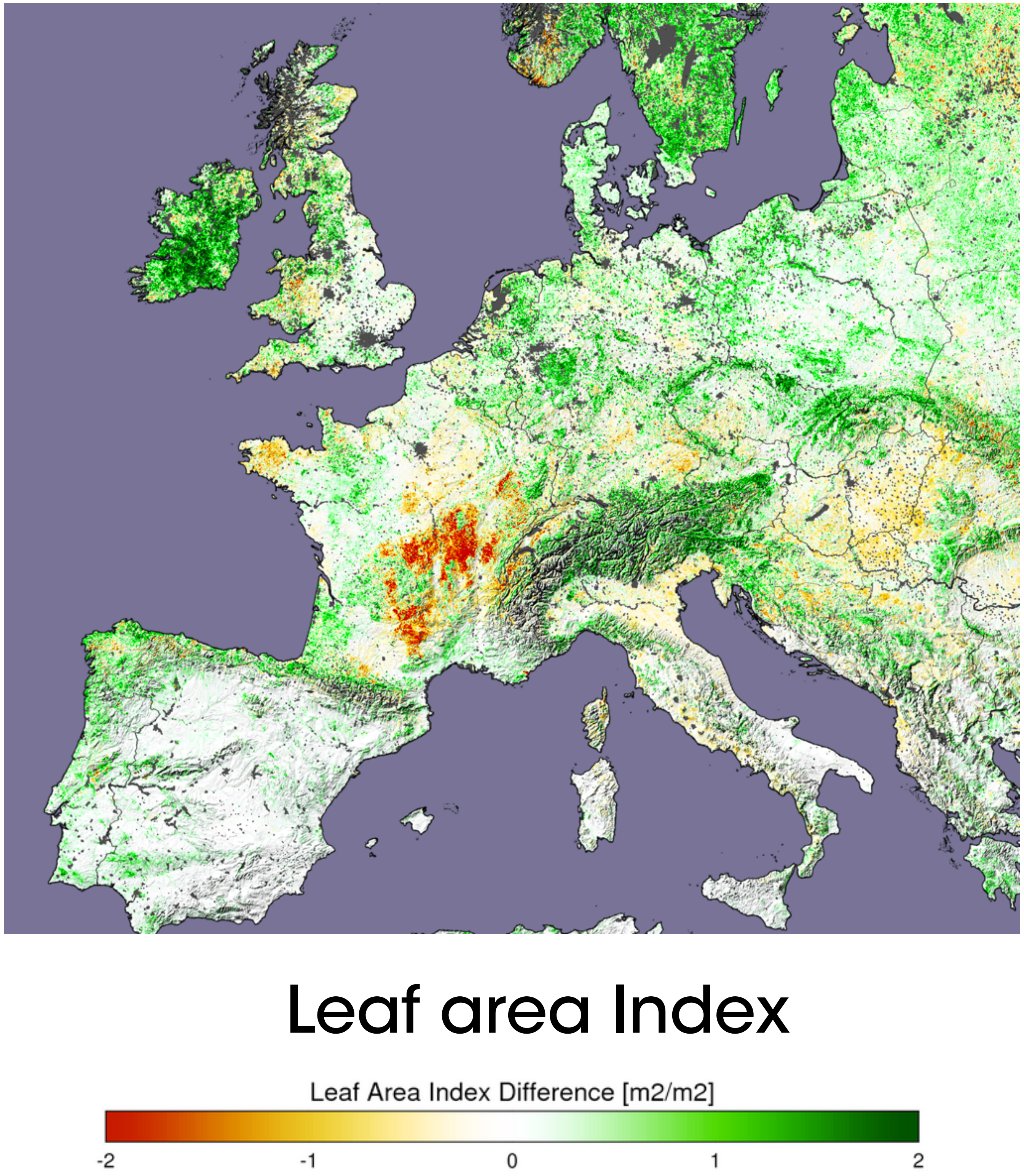
Rhone River (France) sub-catchment

Stockli et al. (2007)

Global-Scale Observations



Land Surface Temperature

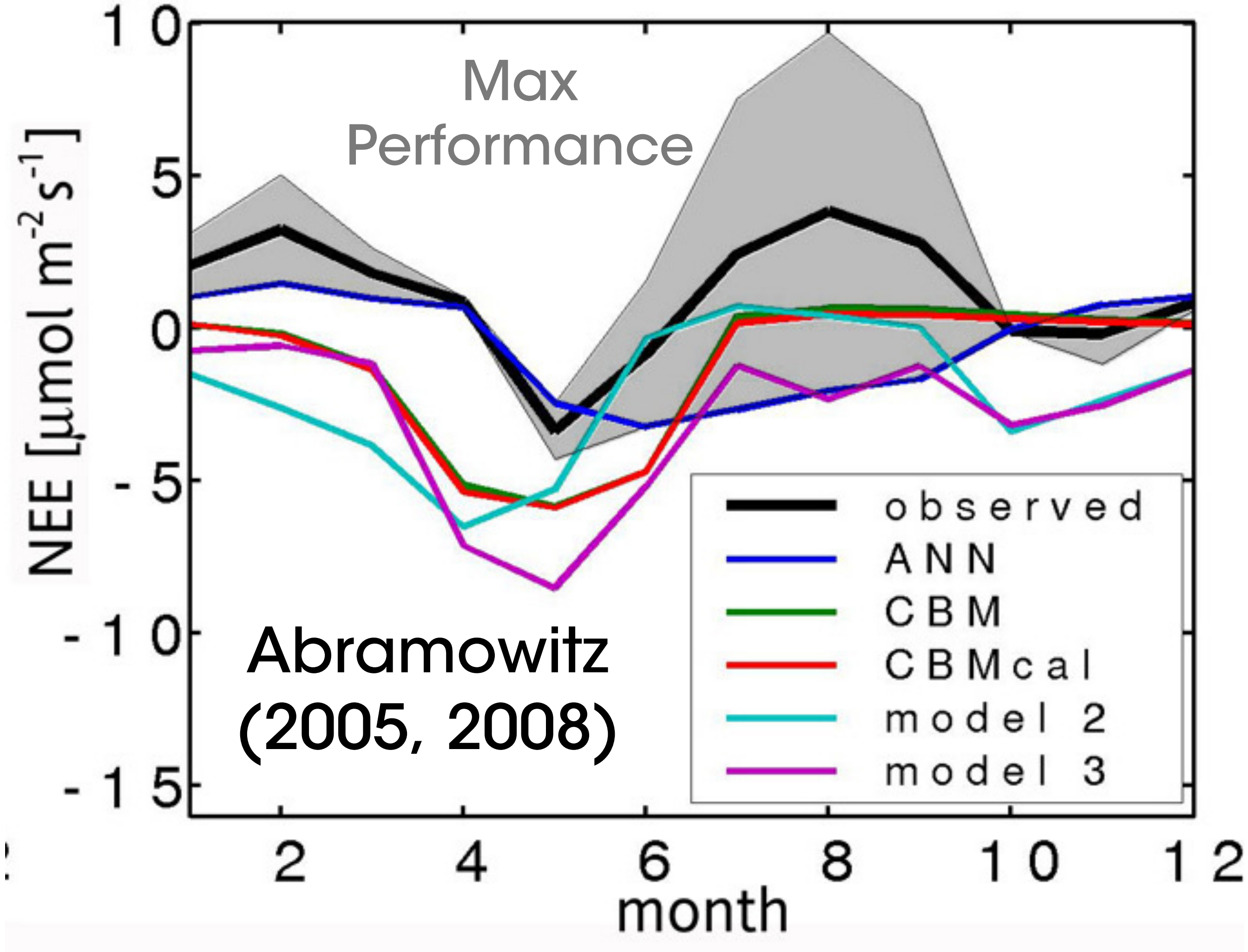


Leaf area Index

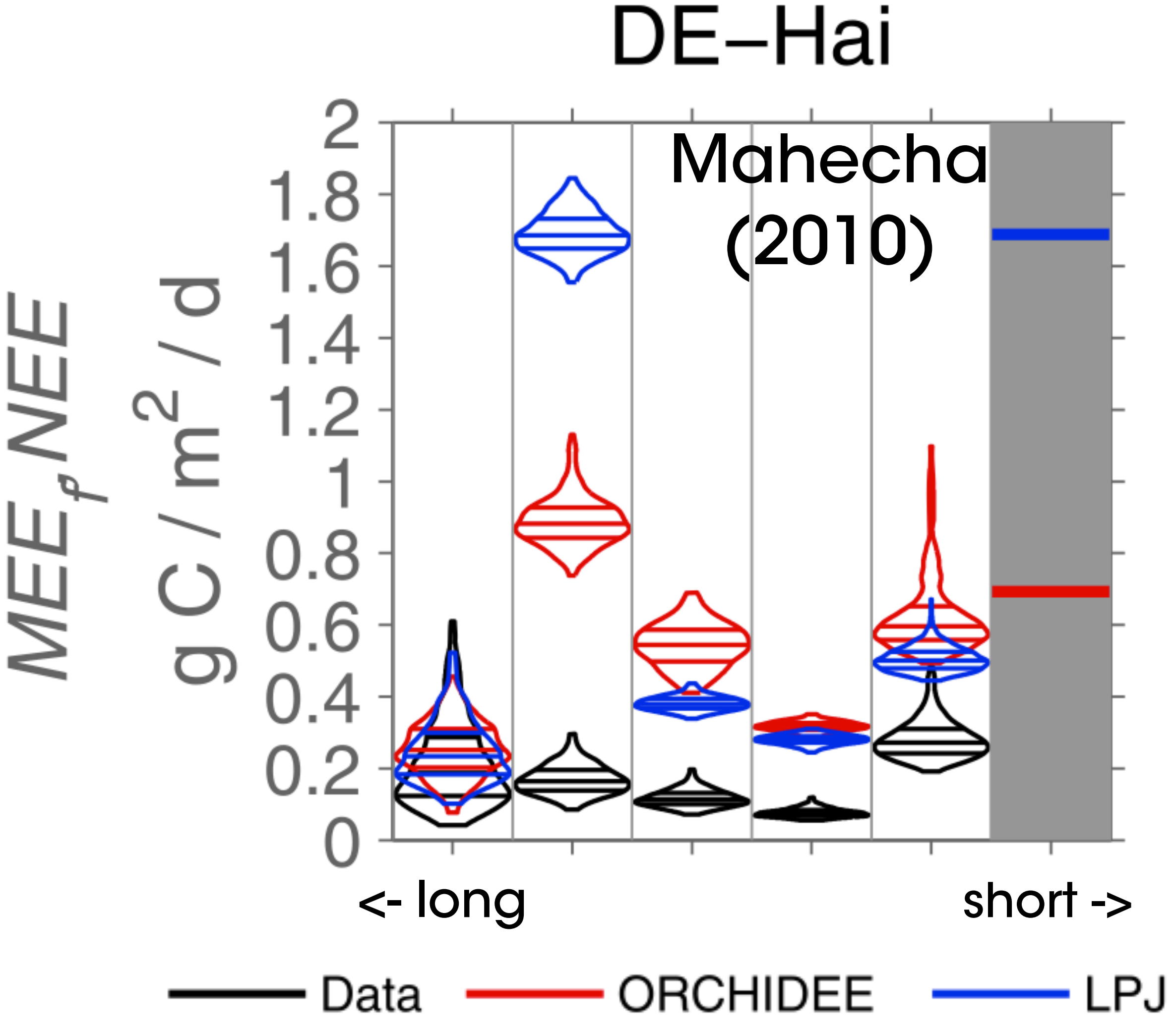
MODIS/TERRA satellite data from July & August 2003 versus 2000-2007

Image: Stöckli et al. (2004), in Allen&Lord (2004) Nature, 432: 551-552

How to benchmark LSM's



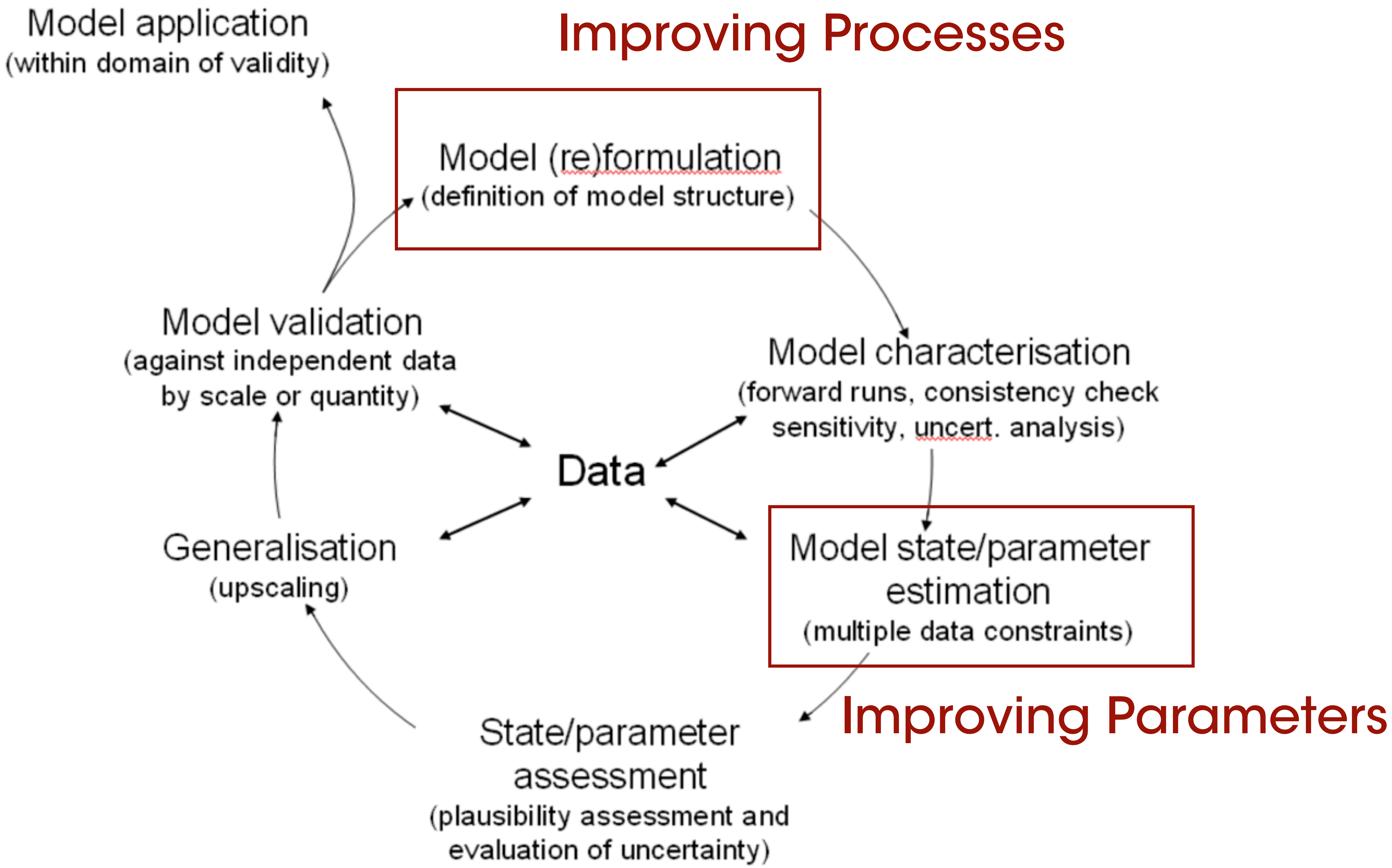
Abramowitz (2005, 2008)



Mahecha (2010)

- **Test against Maximum achievable performance**
  - ignore long-term "hidden" biospheric states
  - LSM's under-utilize meteorological information
- **Decompose analysis into time scales**
  - high-freq: turbulence scheme issues
  - long-term: ill-defined biogeochemical states

How to improve LSM's?



Model application
(within domain of validity)

Improving Processes

Model (re)formulation
(definition of model structure)

Model validation
(against independent data
by scale or quantity)

Model characterisation
(forward runs, consistency check
sensitivity, uncert. analysis)

Data

Generalisation
(upscaling)

Model state/parameter
estimation
(multiple data constraints)

Improving Parameters

State/parameter
assessment
(plausibility assessment and
evaluation of uncertainty)

M. Williams et al. (2009)

①

Improving mechanistic processes in a land model by use of FLUXNET observations

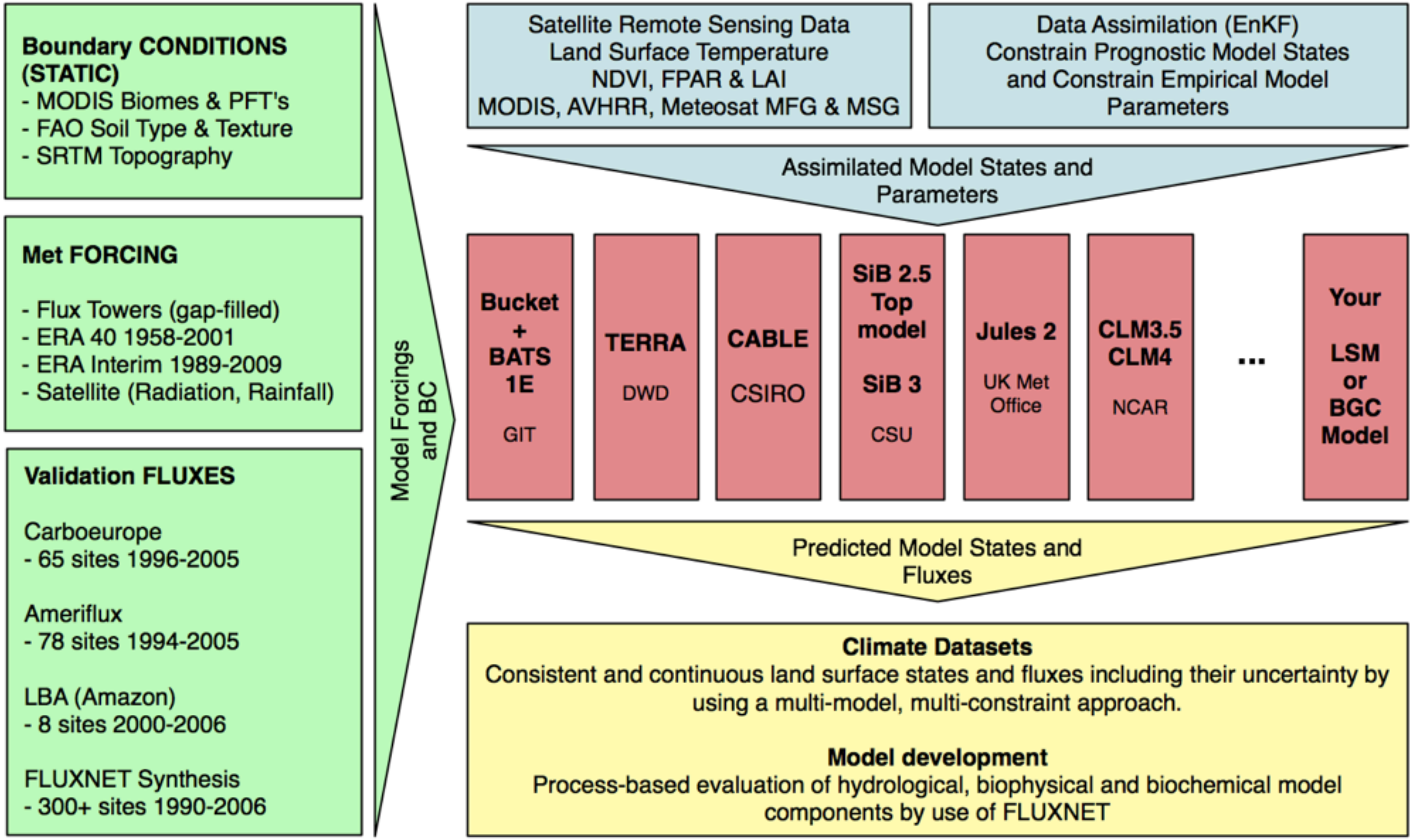
Stöckli, R., Lawrence, D. M., Niu, G.-Y., Oleson, K. W., Thornton, P. E., Yang, Z.-L., Bonan, G. B., Denning, A. S., and Running, S. W. (2008). The use of FLUXNET in the community land model development. J. Geophysical Research-Biogeosciences, 113(G01025):doi: 10.1029/2007JG000562.

Oleson, K. W., Niu, G.-Y., Yang, Z.-L., Lawrence, D. M., Thornton, P. E., Lawrence, P. J., Stöckli, R., Dickinson, R. E., Bonan, G. B., and Levis, S. (2008). Improvements to the community land model and their impact on the hydrological cycle. J. Geophysical Research-Biogeosciences, 113(G01021):doi:10.1029/2007JG000563.

The Model Farm

A Satellite- and Model-based Reanalysis of Land Surface Radiation, Heat, Water and Carbon Fluxes

Reto Stöckli (reto.stoeckli@meteoswiss.ch)



Boundary CONDITIONS (STATIC)
- MODIS Biomes & PFT's
- FAO Soil Type & Texture
- SRTM Topography

Met FORCING

- Flux Towers (gap-filled)
- ERA 40 1958-2001
- ERA Interim 1989-2009
- Satellite (Radiation, Rainfall)

Validation FLUXES

Carboeurope
- 65 sites 1996-2005

Ameriflux
- 78 sites 1994-2005

LBA (Amazon)
- 8 sites 2000-2006

FLUXNET Synthesis
- 300+ sites 1990-2006

Model Forcings and BC

Satellite Remote Sensing Data
Land Surface Temperature
NDVI, FPAR & LAI
MODIS, AVHRR, Meteosat MFG & MSG

Data Assimilation (EnKF)
Constrain Prognostic Model States and Constrain Empirical Model Parameters

Assimilated Model States and Parameters

Bucket + BATS 1E
GIT

TERRA
DWD

CABLE
CSIRO

SiB 2.5 Top model
SiB 3
CSU

Jules 2
UK Met Office

CLM3.5
CLM4
NCAR

...

Your LSM or BGC Model

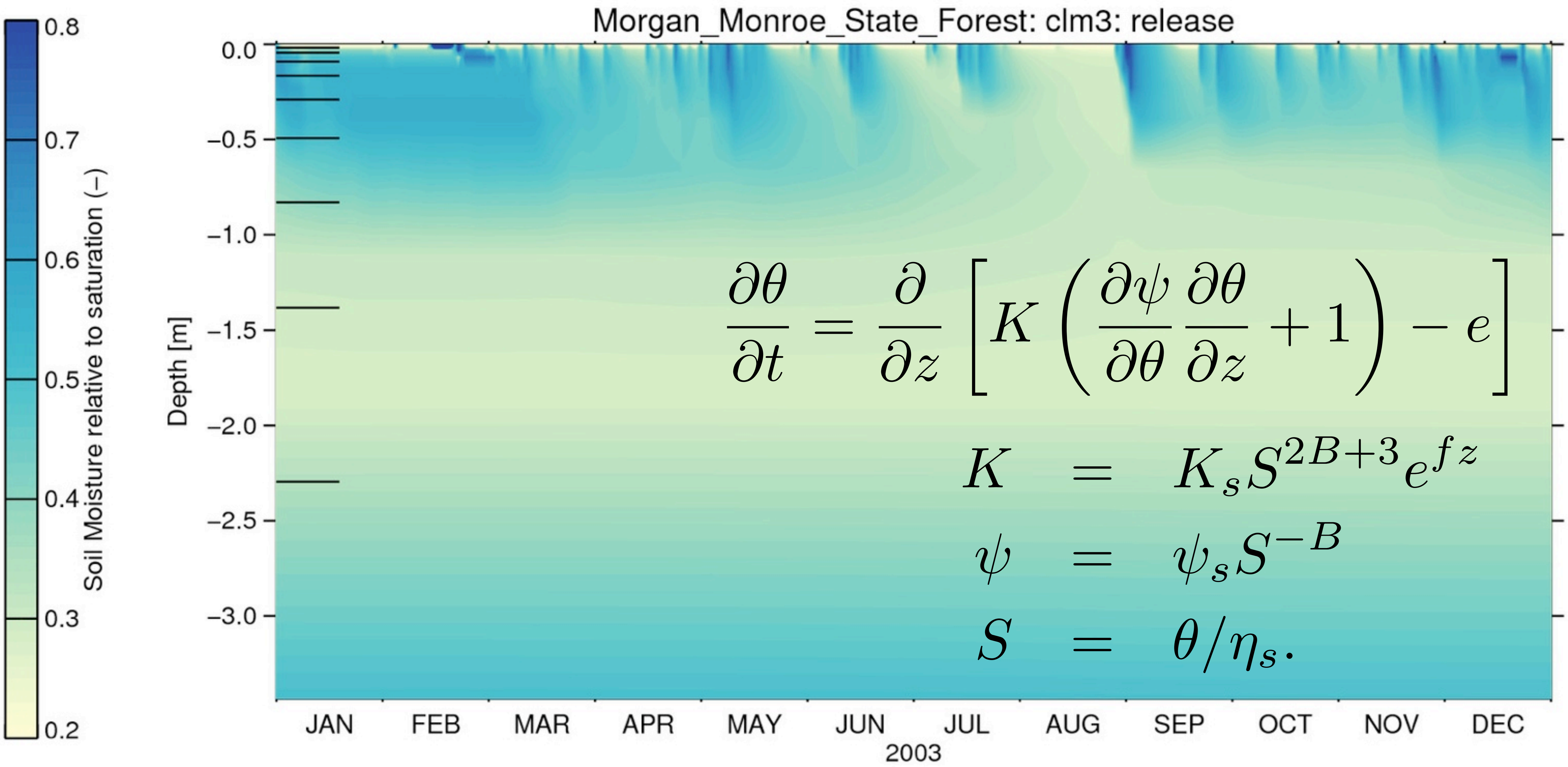
Predicted Model States and Fluxes

Climate Datasets
Consistent and continuous land surface states and fluxes including their uncertainty by using a multi-model, multi-constraint approach.

Model development
Process-based evaluation of hydrological, biophysical and biochemical model components by use of FLUXNET

The Model Farm is open source code (GNU General Public License). Some of the models and data underly individual license schemes

Model development: better physics?



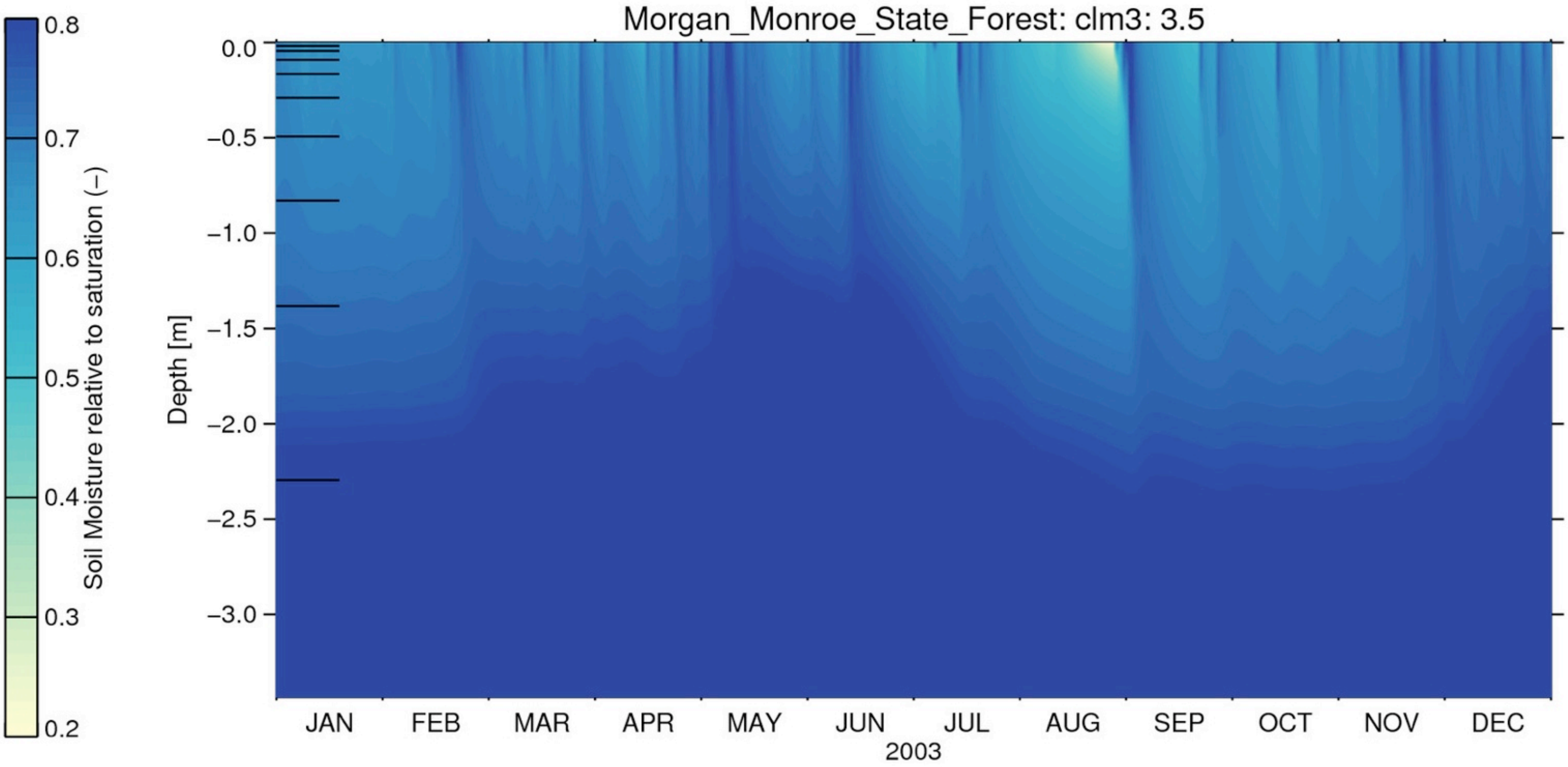
$$\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial z}\left[K\left(\frac{\partial \psi}{\partial \theta}\frac{\partial \theta}{\partial z} + 1\right) - e\right]$$

$$\begin{aligned} K &= K_s S^{2B+3} e^{fz} \\ \psi &= \psi_s S^{-B} \\ S &= \theta/\eta_s. \end{aligned}$$

Community Land Model 3.0

- dry soil layers inhibit infiltration
- decoupling of upper from lower soil layers

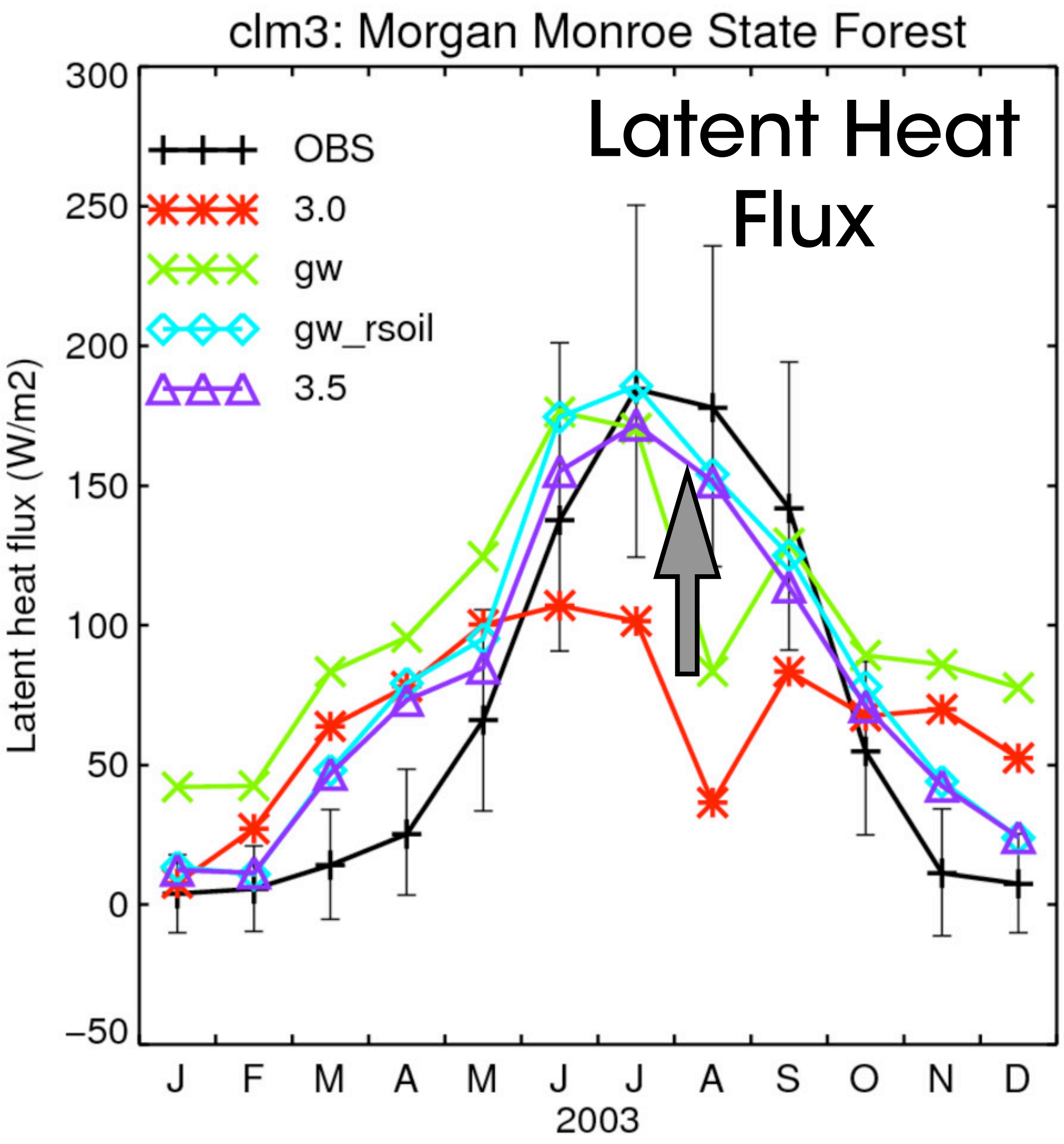
E.g.: addition of ground water storage



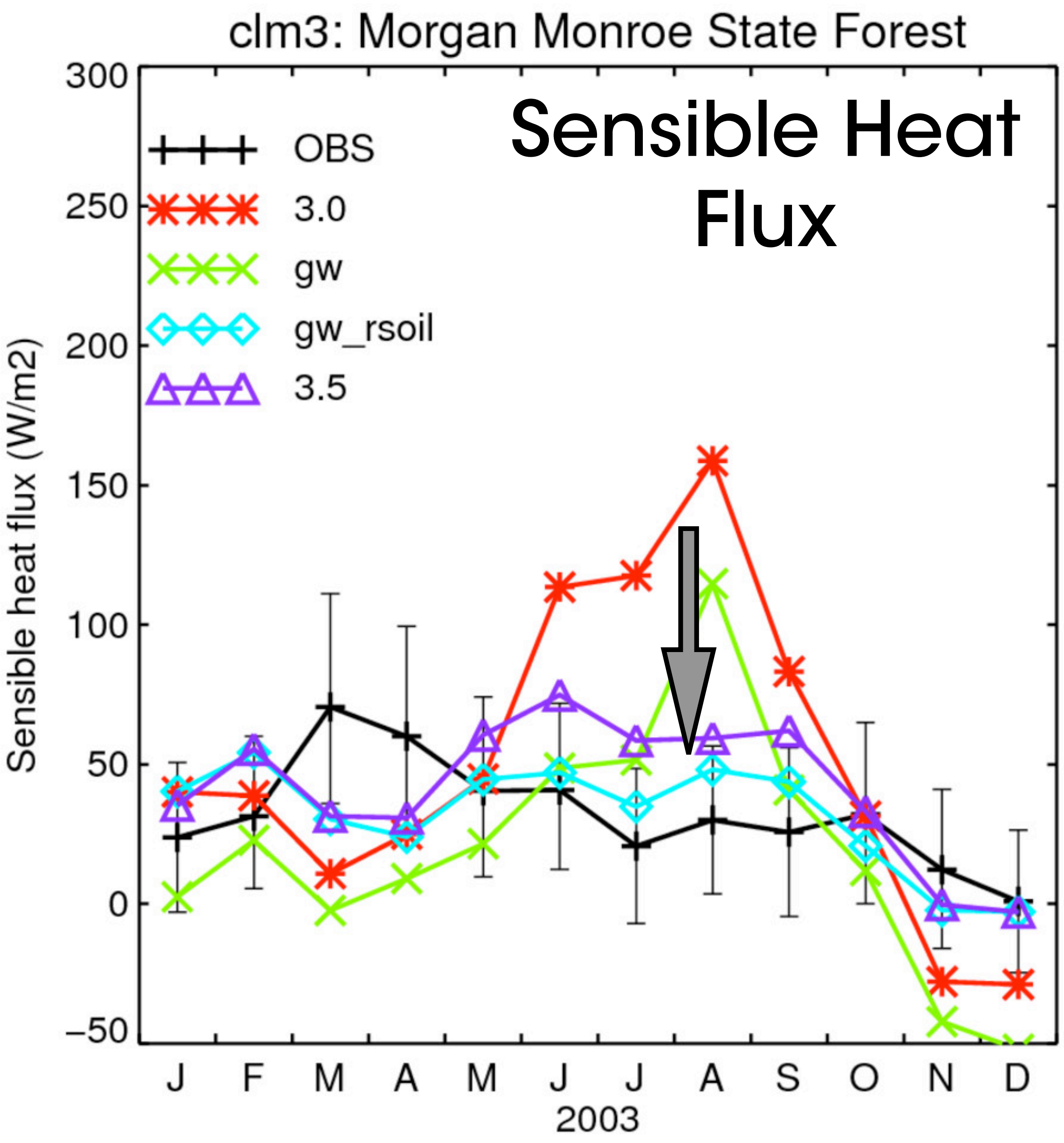
Community Land Model 3.5

- ground water storage becomes effective
- realistic physics -> stable numeric solution

Morgan Monroe State Forest (temperate)


clm3: Morgan Monroe State Forest

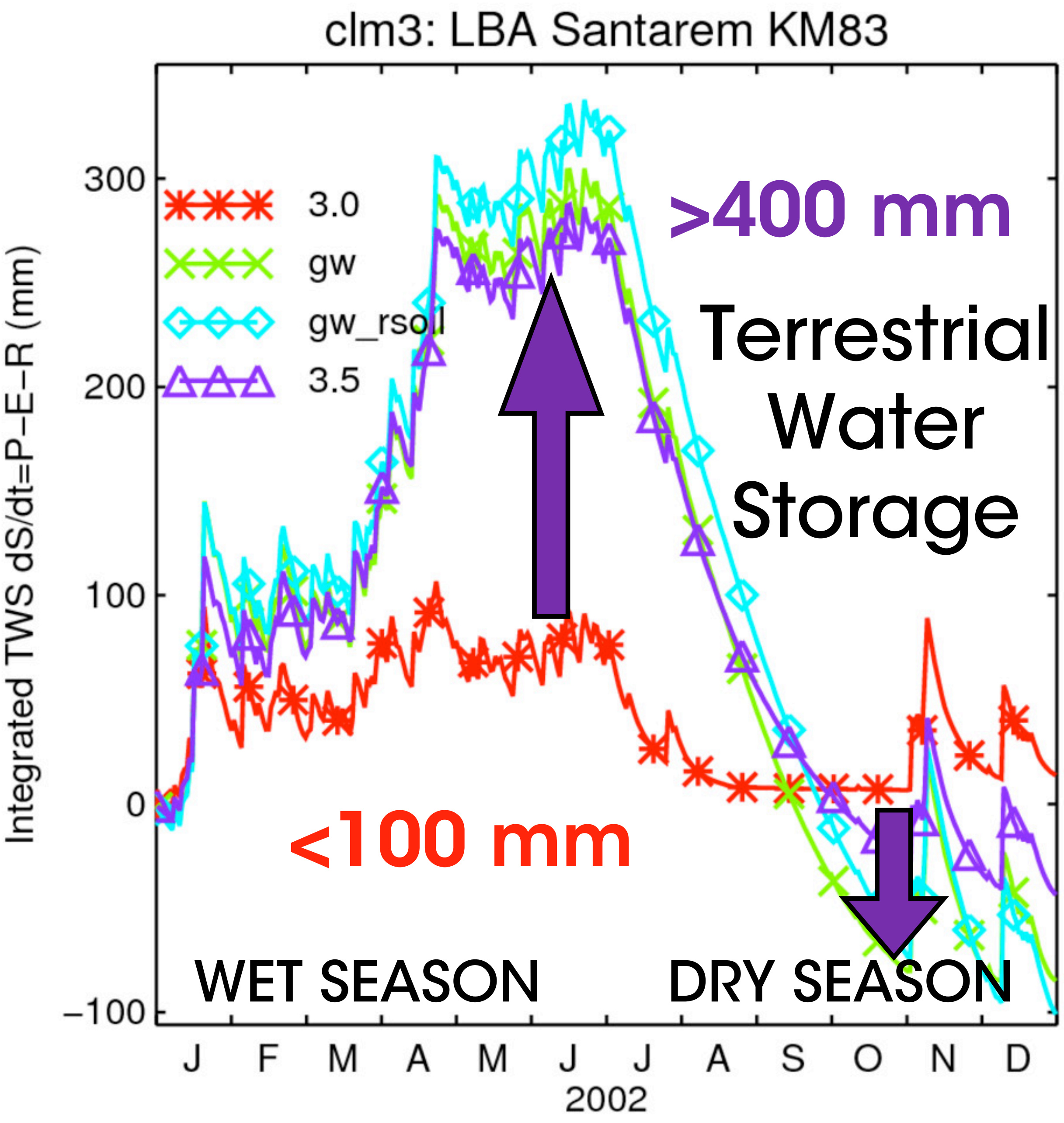
Latent Heat Flux

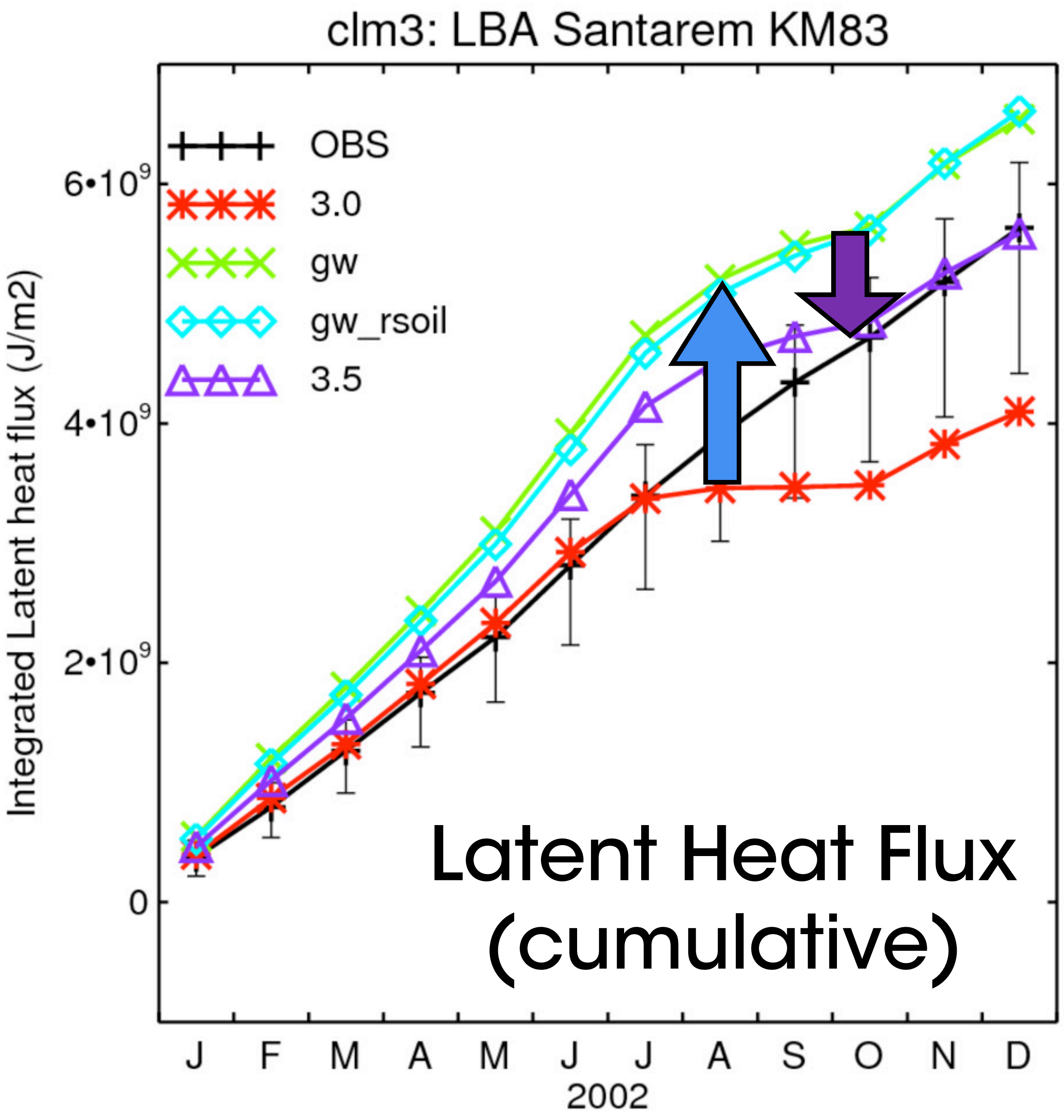

clm3: Morgan Monroe State Forest

Sensible Heat Flux

- CLM 3.0: depressed LE and exaggerated H
- Add ground water: exaggerated spring LE
- CLM 3.5: Modify bare soil resistance

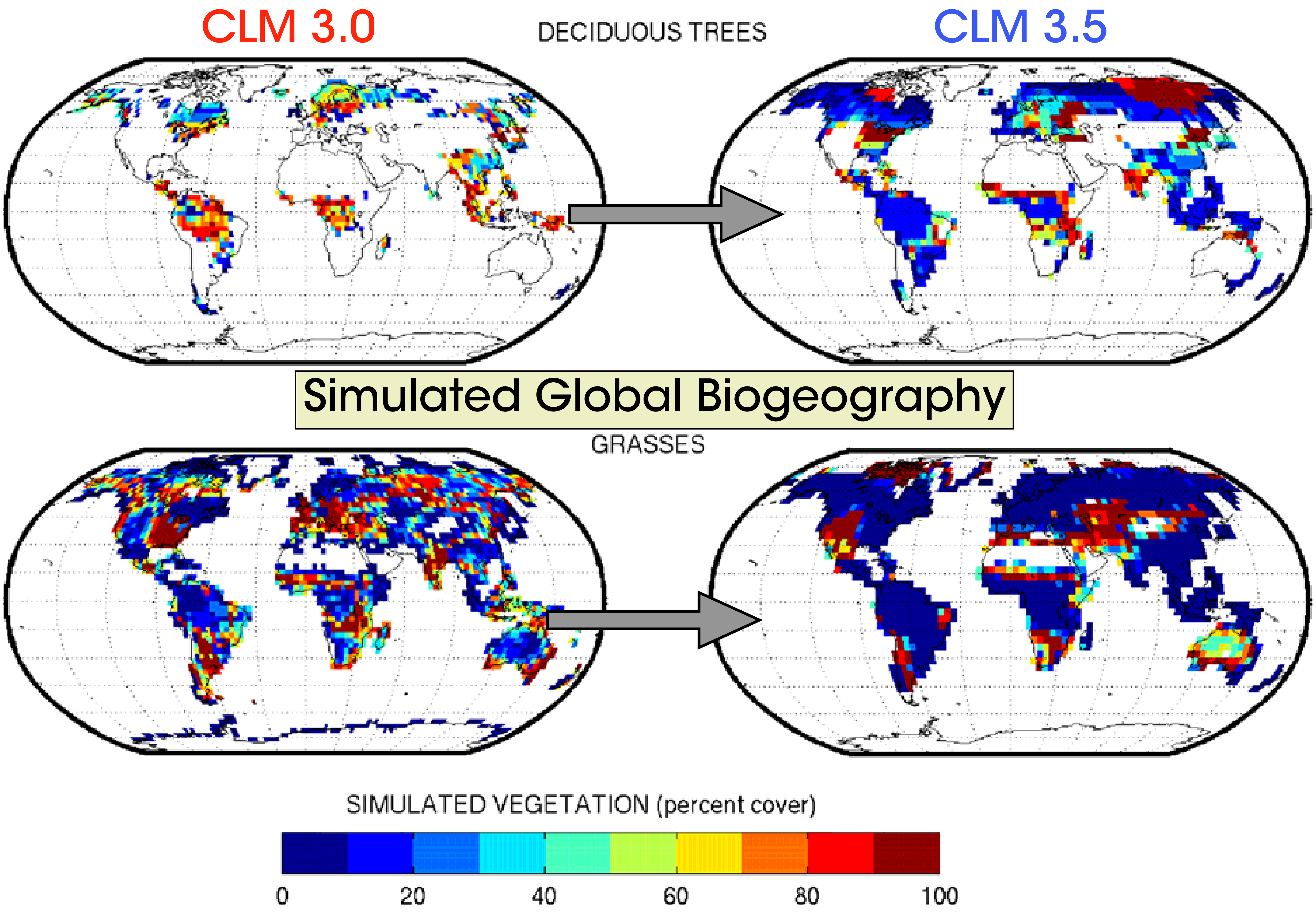
Santarem KM83 (tropical, broadleaf)





- High dynamics of terrestrial water storage needed for seasonally-dry ecosystems
- However: now we have to decrease Vc_{max} !

Impact on global vegetation distribution



Simulated Global Biogeography

②

Improving empirical parameters in a phenology model by use of MODIS observations

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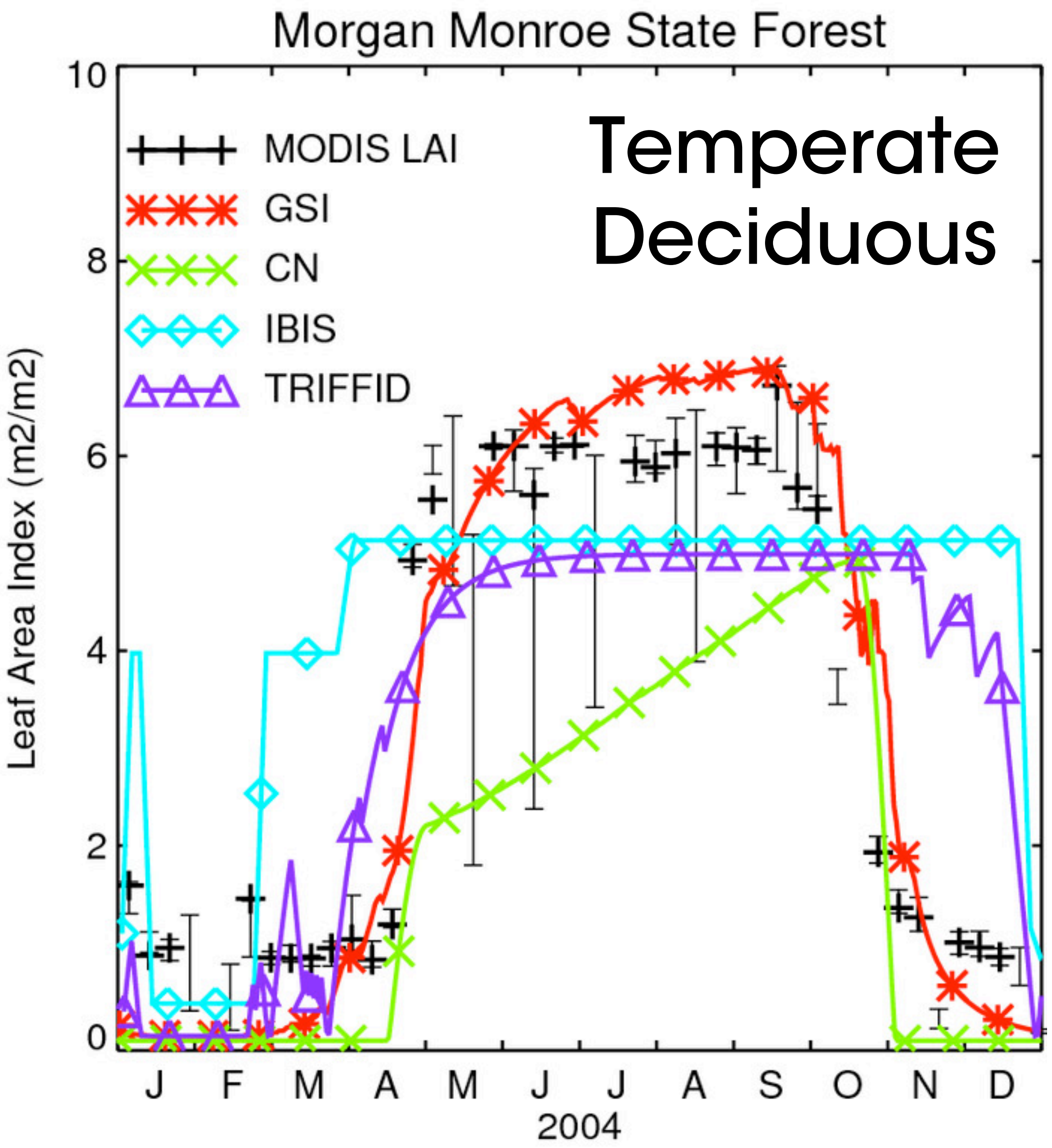
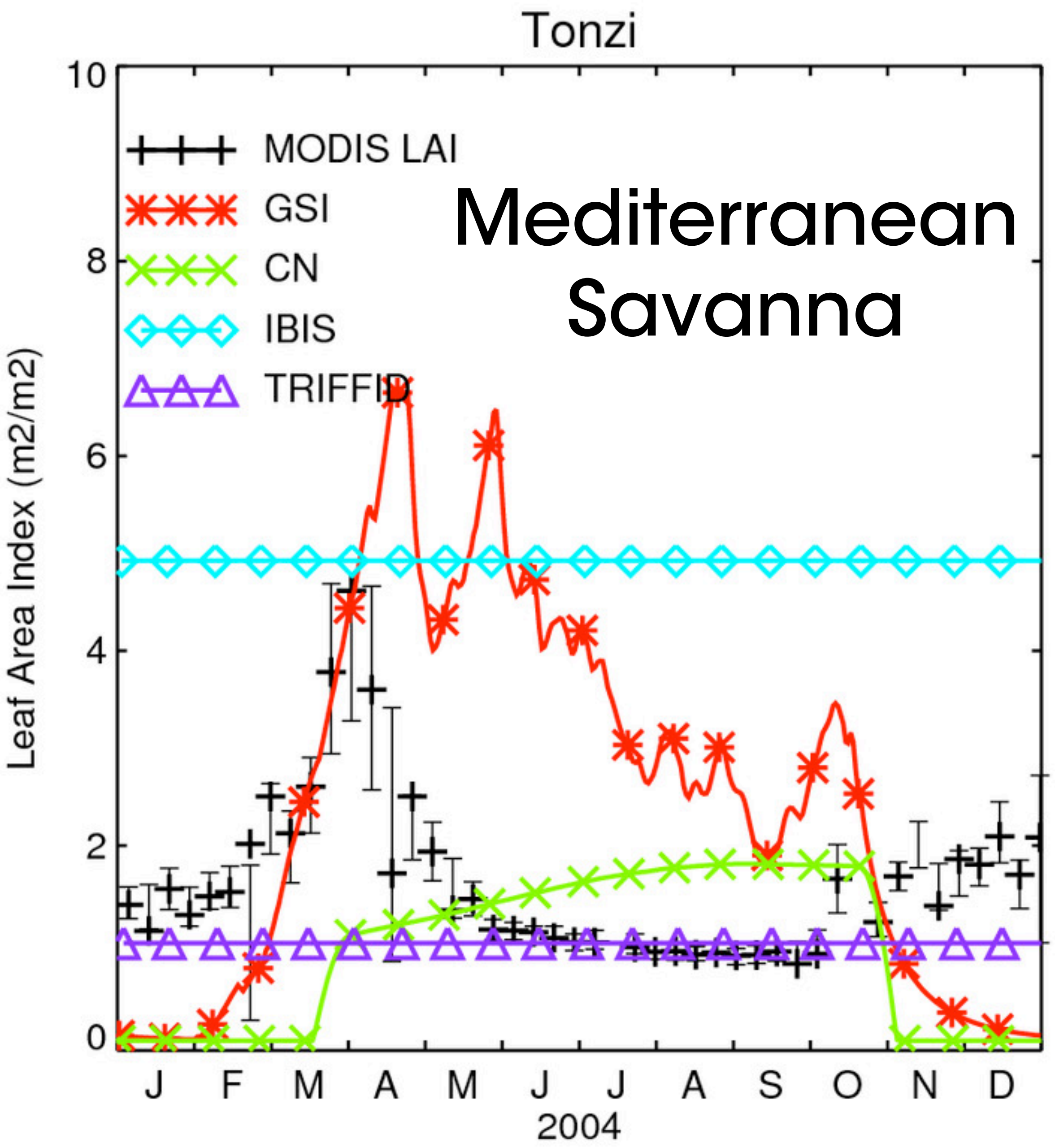
Stöckli, R., Rutishauser, T., Dragoni, D., Keefe, J. O., Thornton, P. E., Jolly, M., Lu, L., and Denning, A. S. (2008). Remote sensing data assimilation for a prognostic phenology model. J. Geophys. Res. - Biogeosciences.113 (G4), doi:10.1029/2008JG000781

Stöckli, R., T. Rutishauser, I. Baker, M. Liniger, and A. S. Denning (in press), A global reanalysis of vegetation phenology, J. Geophys. Res. - Biogeosciences, doi: 10.1029/2010JG001545

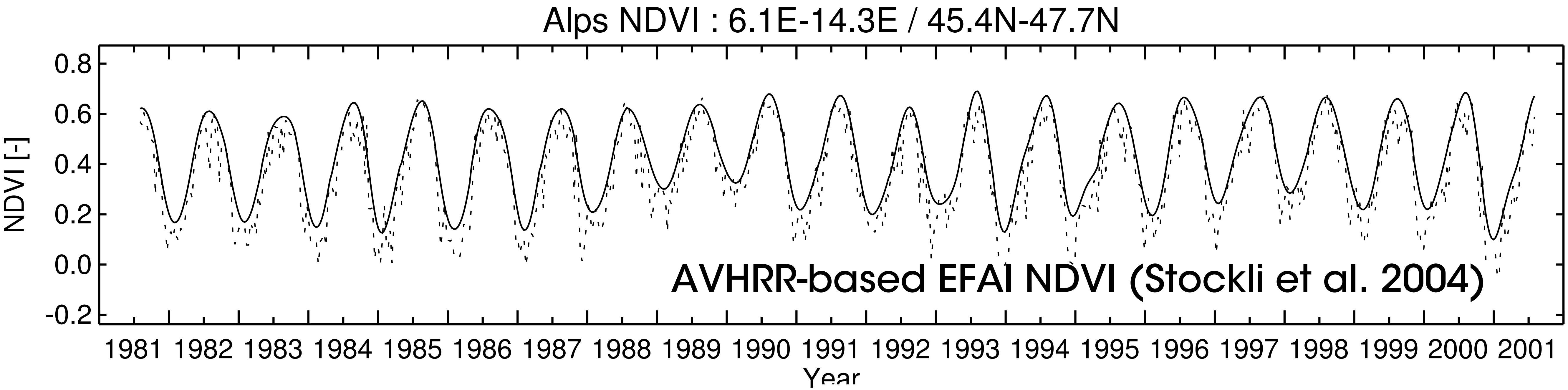
Model-based Phenology



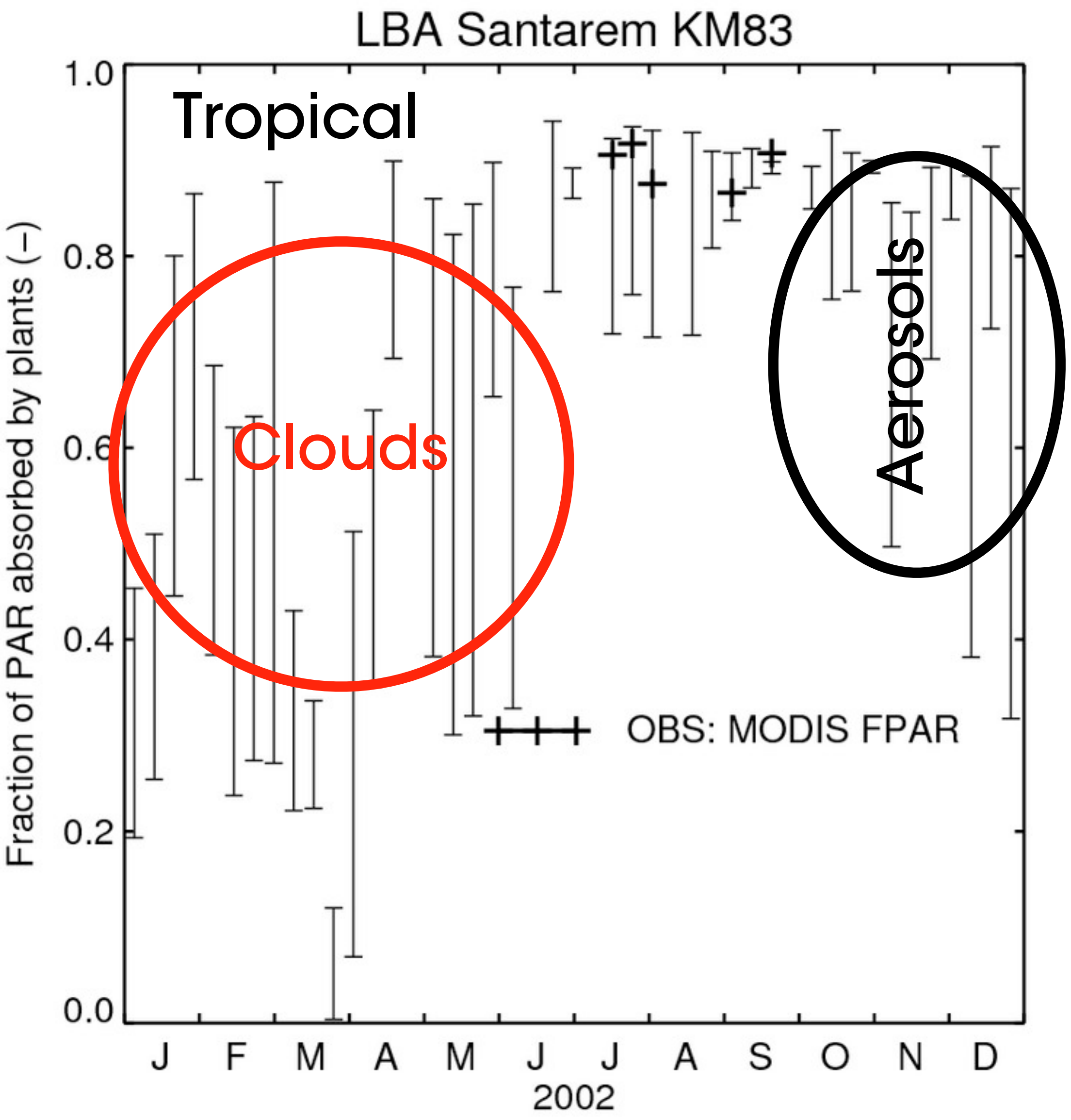


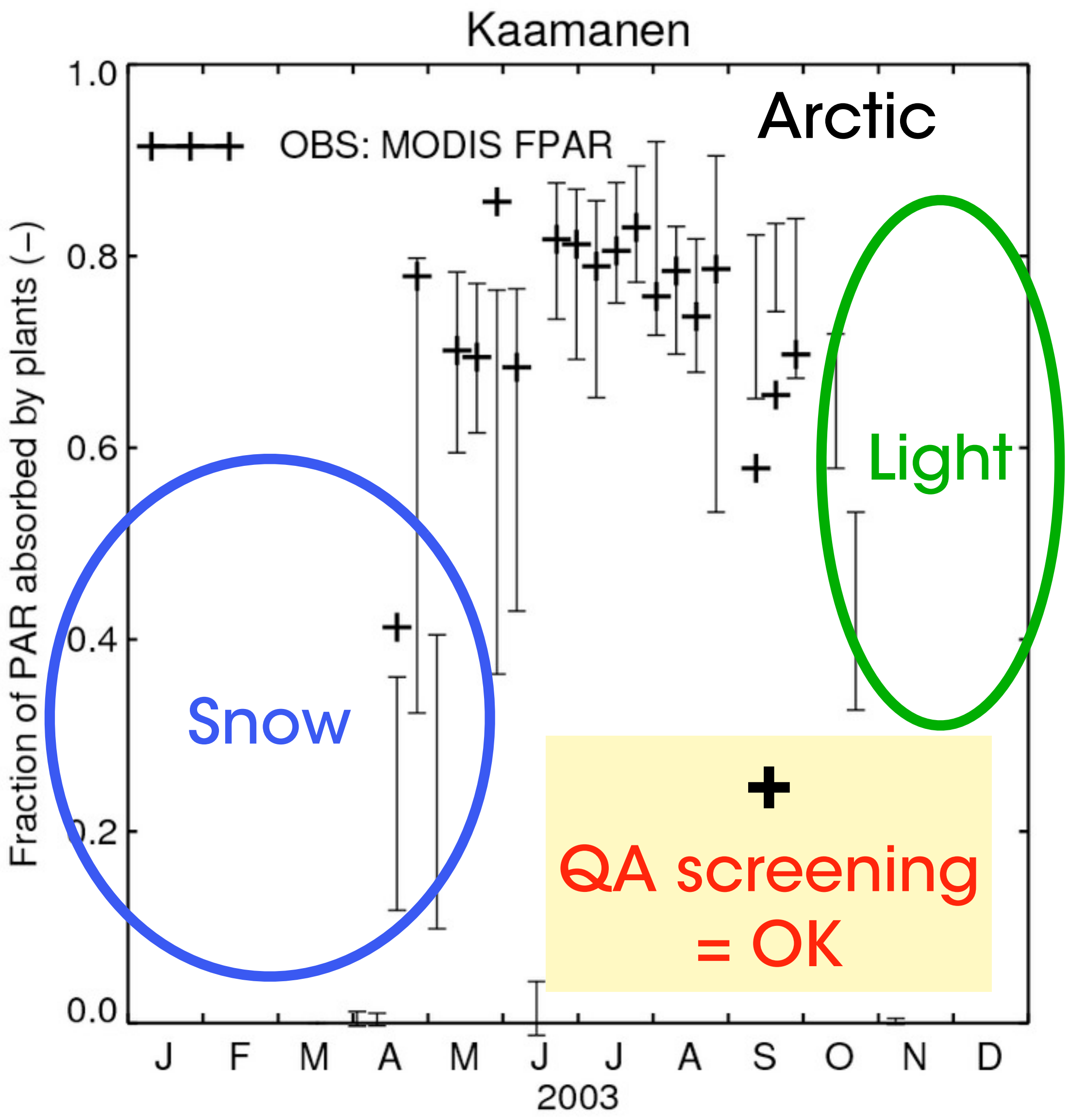
- few known “mechanistic” processes
- global-scale parameters: unknown
- no long term observational constraint for non-temperate PFT’s

Satellite-based Phenology



AVHRR-based EFAI NDVI (Stockli et al. 2004)





\+
QA screening
= OK

Data Assimilation: Best of both Worlds

$$\mathrm{GSI} = f(T) \cdot f(R) \cdot f(M)$$

GSI : phenological state (0 .. 1)
T : temperature, e.g. minimum daily (K)
R : light, e.g. global radiation (W/m2)
W : moisture, e.g. vapor pressure deficit (Pa)

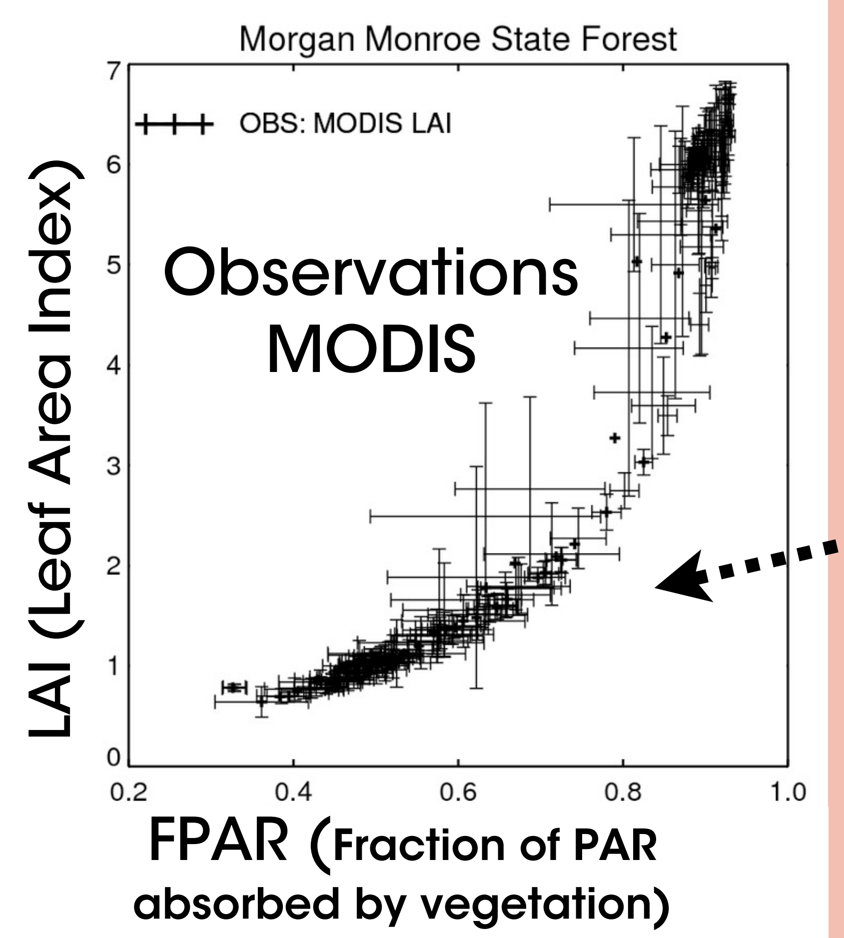
$$f(T) = \frac{T - T_{min}}{T_{max} - T_{min}}$$

$$f(R) = \frac{R - R_{min}}{R_{max} - R_{min}}$$

$$f(W) = 1 - \frac{W - W_{min}}{W_{max} - W_{min}}$$

Growing Season Index (GSI)
Jolly et al. (2005)

Ensemble Kalman Filter
(Evensen 2003)



Model States+Parameters:

$$\mathbf{A} = (\psi_1, \psi_2, ..., \psi_N) \in \Re^{n \times N}$$

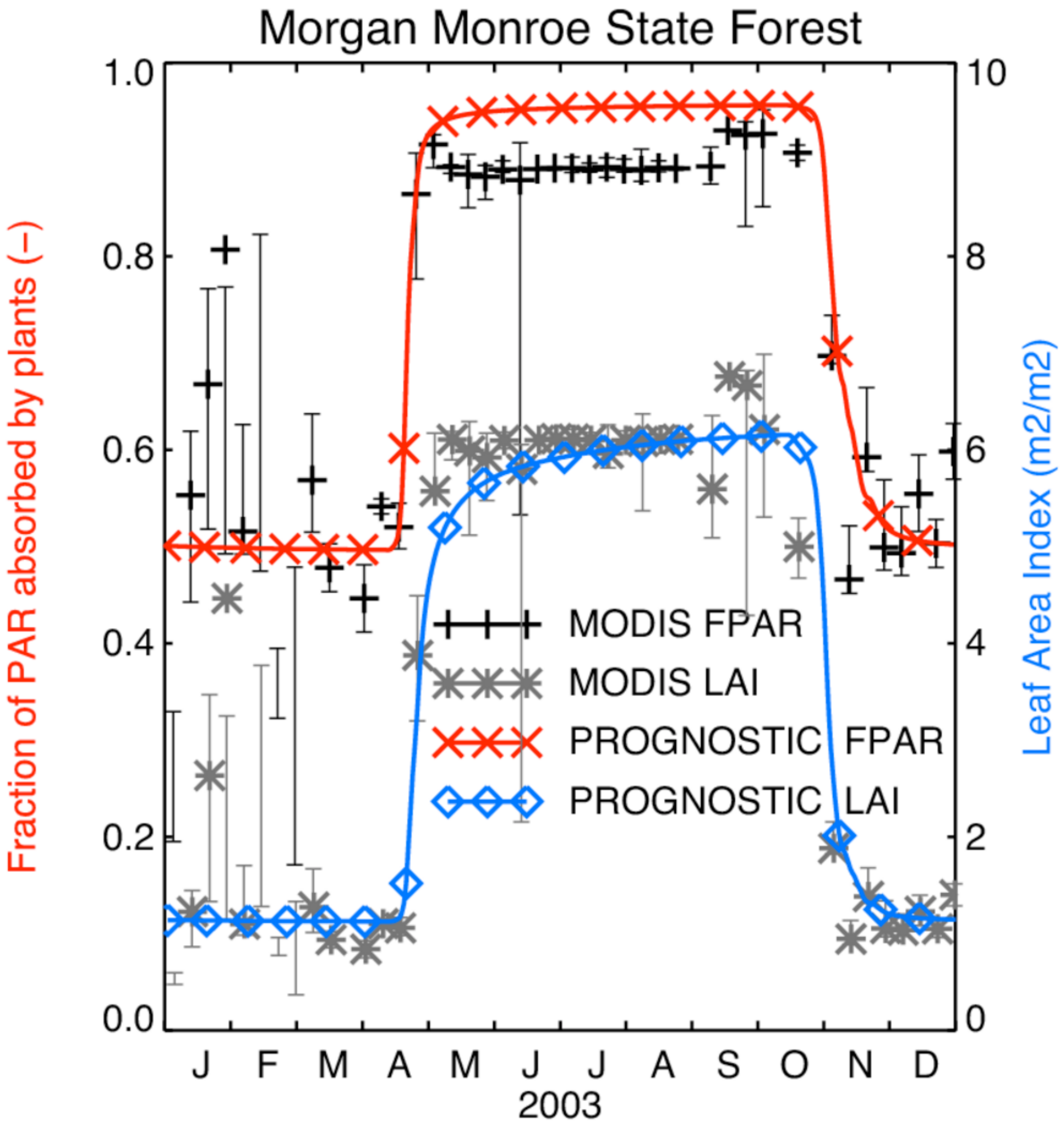
Observations:

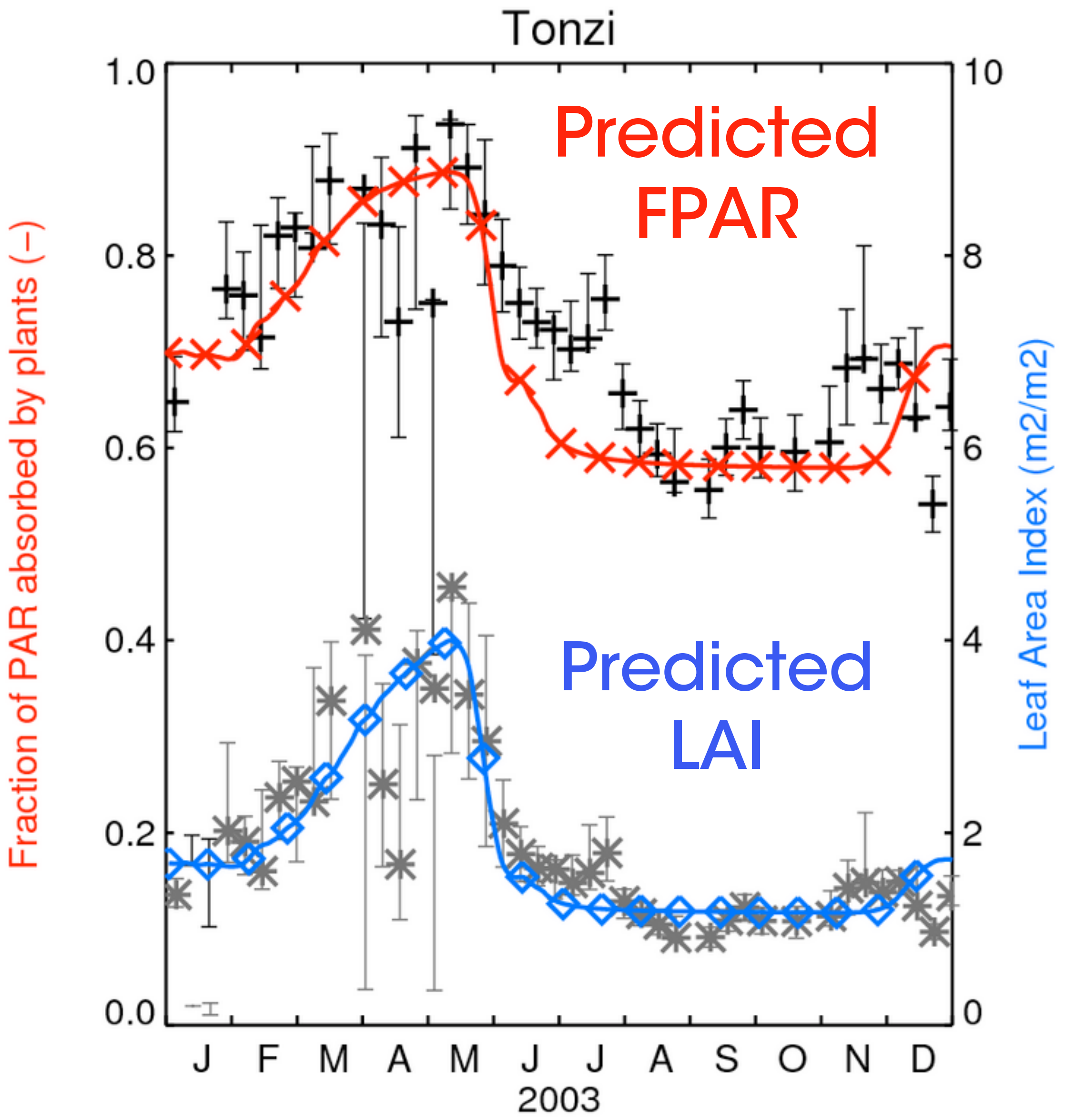
$$\mathbf{D} = (d_1, d_2, ..., d_N) \in \Re^{m \times N}$$

Analysis: (Model | Observations)

$$\mathbf{A}^a = \mathbf{A}^f + \mathbf{K}(\mathbf{D} - \mathbf{H}\mathbf{A}^f)$$

Model constrained by observations





Temperate deciduous PFT's:

- spring: light+temperature; autumn: light

Drought deciduous PFT's:

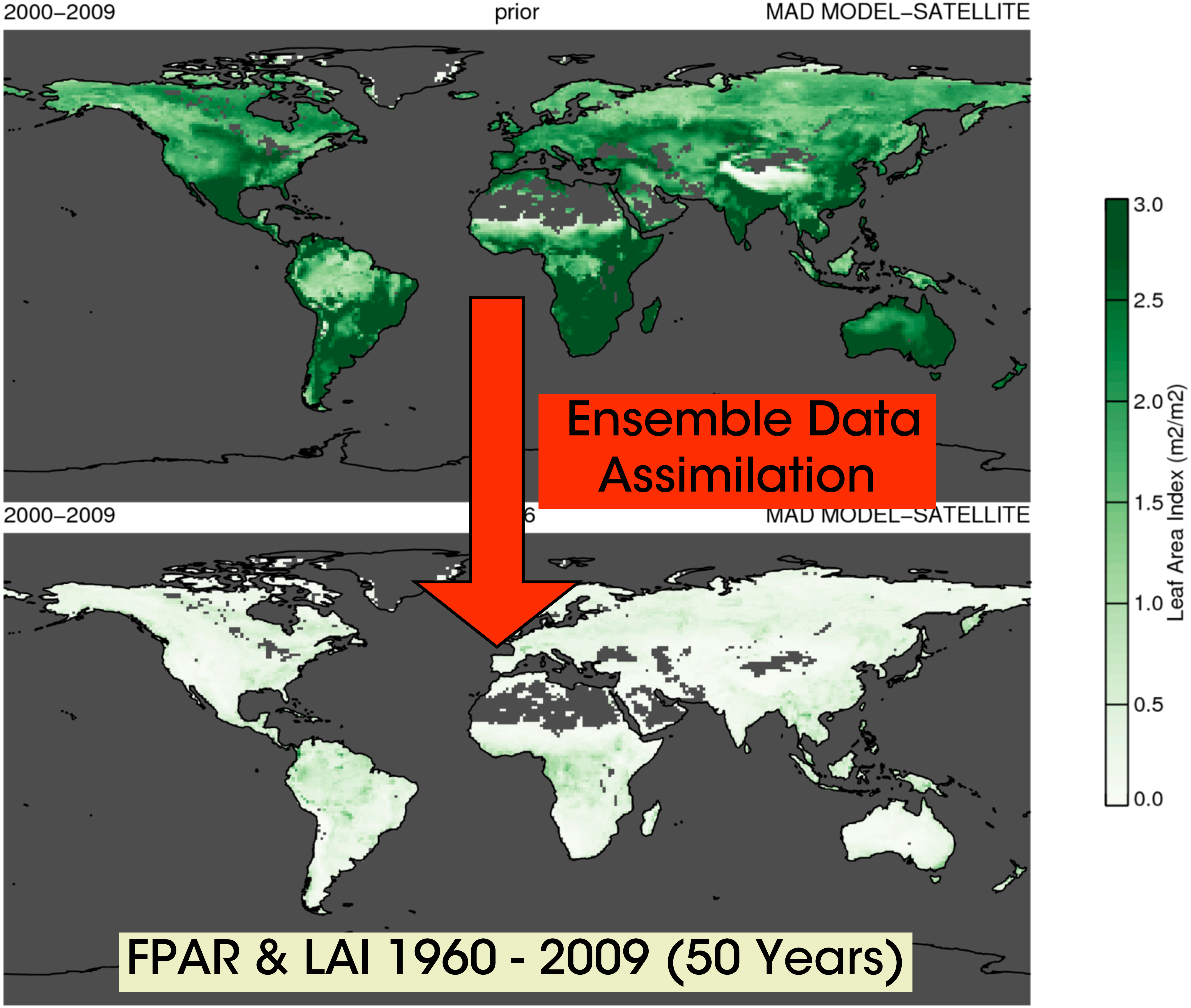
- vpd: good surrogate for soil moisture limitation

However: Parameters only valid for respective site

A Global Reanalysis of Phenology

Prior
Prediction Error

Posterior
Prediction Error



Ensemble Data Assimilation

FPAR & LAI 1960 - 2009 (50 Years)

A posterior Global-scale parameter set

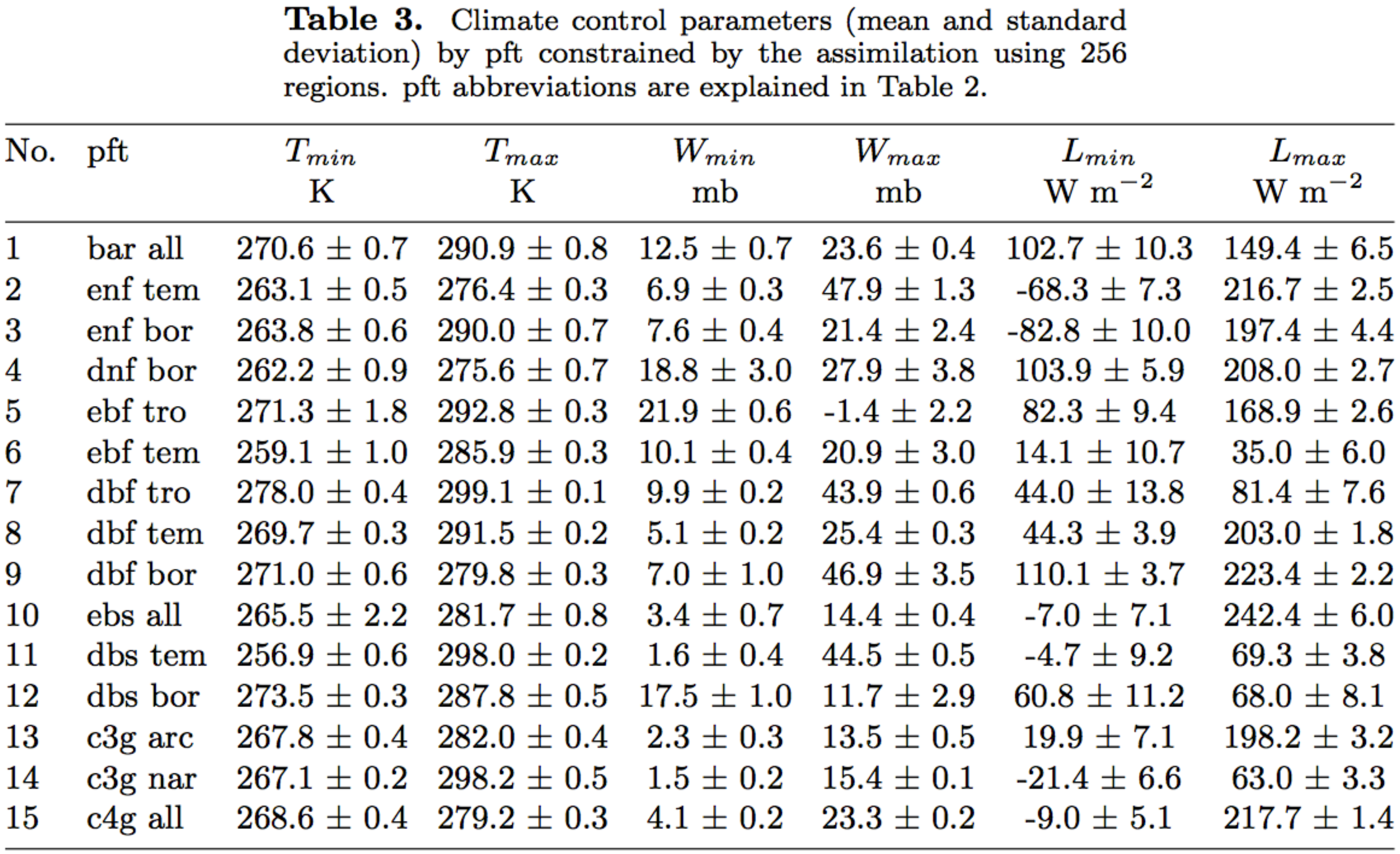


Table 3. Climate control parameters (mean and standard deviation) by pft constrained by the assimilation using 256 regions. pft abbreviations are explained in Table 2.

No.	pft	T_{min} K	T_{max} K	W_{min} mb	W_{max} mb	L_{min} W m^{-2}	L_{max} W m^{-2}
1	bar all	270.6 ± 0.7	290.9 ± 0.8	12.5 ± 0.7	23.6 ± 0.4	102.7 ± 10.3	149.4 ± 6.5
2	enf tem	263.1 ± 0.5	276.4 ± 0.3	6.9 ± 0.3	47.9 ± 1.3	-68.3 ± 7.3	216.7 ± 2.5
3	enf bor	263.8 ± 0.6	290.0 ± 0.7	7.6 ± 0.4	21.4 ± 2.4	-82.8 ± 10.0	197.4 ± 4.4
4	dnf bor	262.2 ± 0.9	275.6 ± 0.7	18.8 ± 3.0	27.9 ± 3.8	103.9 ± 5.9	208.0 ± 2.7
5	ebf tro	271.3 ± 1.8	292.8 ± 0.3	21.9 ± 0.6	-1.4 ± 2.2	82.3 ± 9.4	168.9 ± 2.6
6	ebf tem	259.1 ± 1.0	285.9 ± 0.3	10.1 ± 0.4	20.9 ± 3.0	14.1 ± 10.7	35.0 ± 6.0
7	dbf tro	278.0 ± 0.4	299.1 ± 0.1	9.9 ± 0.2	43.9 ± 0.6	44.0 ± 13.8	81.4 ± 7.6
8	dbf tem	269.7 ± 0.3	291.5 ± 0.2	5.1 ± 0.2	25.4 ± 0.3	44.3 ± 3.9	203.0 ± 1.8
9	dbf bor	271.0 ± 0.6	279.8 ± 0.3	7.0 ± 1.0	46.9 ± 3.5	110.1 ± 3.7	223.4 ± 2.2
10	ebs all	265.5 ± 2.2	281.7 ± 0.8	3.4 ± 0.7	14.4 ± 0.4	-7.0 ± 7.1	242.4 ± 6.0
11	dbs tem	256.9 ± 0.6	298.0 ± 0.2	1.6 ± 0.4	44.5 ± 0.5	-4.7 ± 9.2	69.3 ± 3.8
12	dbs bor	273.5 ± 0.3	287.8 ± 0.5	17.5 ± 1.0	11.7 ± 2.9	60.8 ± 11.2	68.0 ± 8.1
13	c3g arc	267.8 ± 0.4	282.0 ± 0.4	2.3 ± 0.3	13.5 ± 0.5	19.9 ± 7.1	198.2 ± 3.2
14	c3g nar	267.1 ± 0.2	298.2 ± 0.5	1.5 ± 0.2	15.4 ± 0.1	-21.4 ± 6.6	63.0 ± 3.3
15	c4g all	268.6 ± 0.4	279.2 ± 0.3	4.1 ± 0.2	23.3 ± 0.2	-9.0 ± 5.1	217.7 ± 1.4

Minimize PFT-dependent phenology parameter uncertainty

- less than 1% of global MODIS observations used (QA-screening)
- global LAI prediction error: 2.3 ➔ 0.3 m^2 m^{-2}
- result: model (1), FPAR+LAI data set (2), parameter set by pft (3)

Experiments to estimate physiological parameters with FLUXNET data

- V_{cmax}, root parameters, decomposition parameterizations etc.
- Richardson et al. (2010), Knorr et al. (2010), Pettijohn et al. (20xx)

Summary

We simulate decadal-centennial carbon-climate interactions, but with often unrealistic seasonal cycle of the terrestrial water and carbon fluxes

FLUXNET: the "reality check" for LSM development

- How are CLIMMANI & INTERFACE linked to FLUXNET?
- User requirements known from global modelers?

Many biophysical parameters estimated by satellite data

- How can CLIMMANI & INTERFACE help to re-define global biogeochemistry parameters in models?
- Are current parameters valid for Climate Change?

The Future of Carbon Cycle Modeling:
Data Assimilation. Not just for NWP, but for Climate!

➔ Please make use of: http://phenoanalysis.sourceforge.net & Model Farm

➔ Good reading: Rayner, P. J. (2010), The current state of carbon-cycle data assimilation, Current Opin. Environ. Sustain., 2(4), 289–296, doi:10.1016/j.cosust.2010.05.005.