ESA Summer School, Frascati, August 2004

Data Assimilation in Land Surface Modelling

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Programme

- Recap: Earth System, BETHY, Key Earth Observation Variables, (non-) Sequential Data Assimilation
- Assimilation of fAPAR Data

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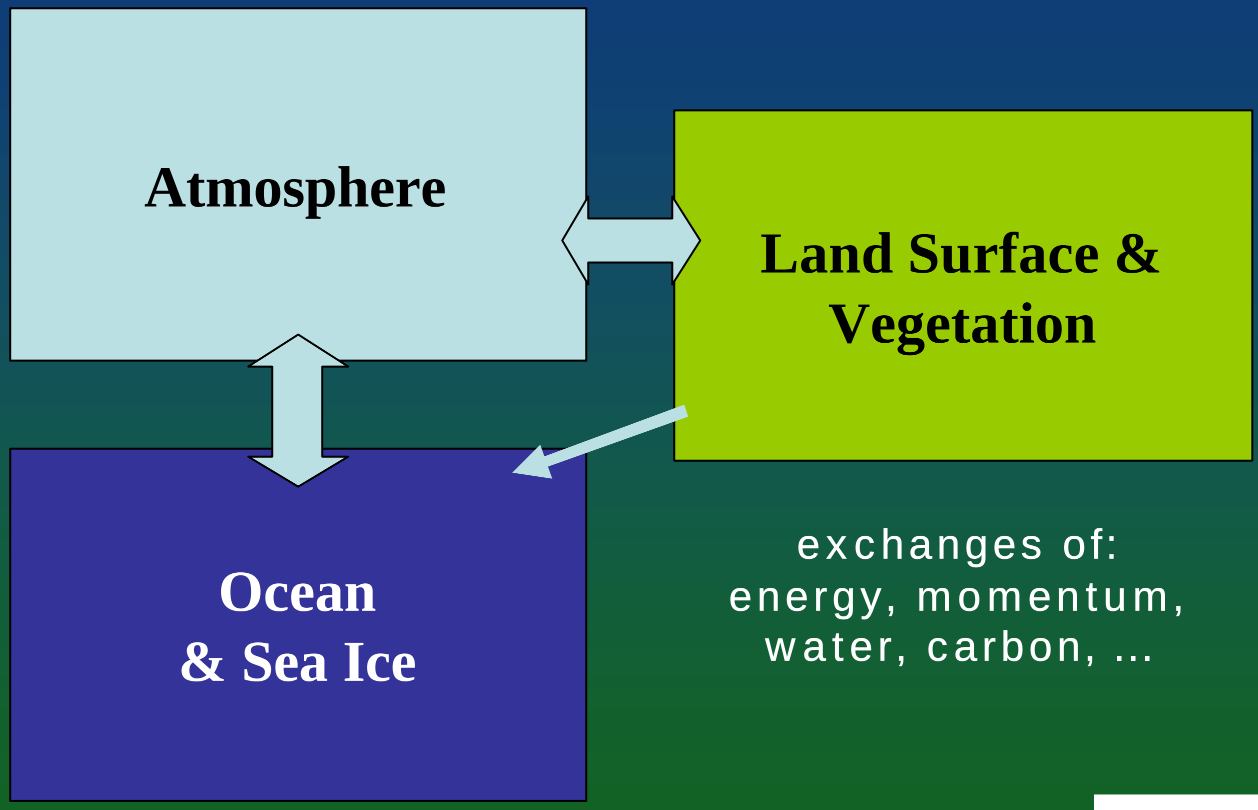
Earth System Feedbacks



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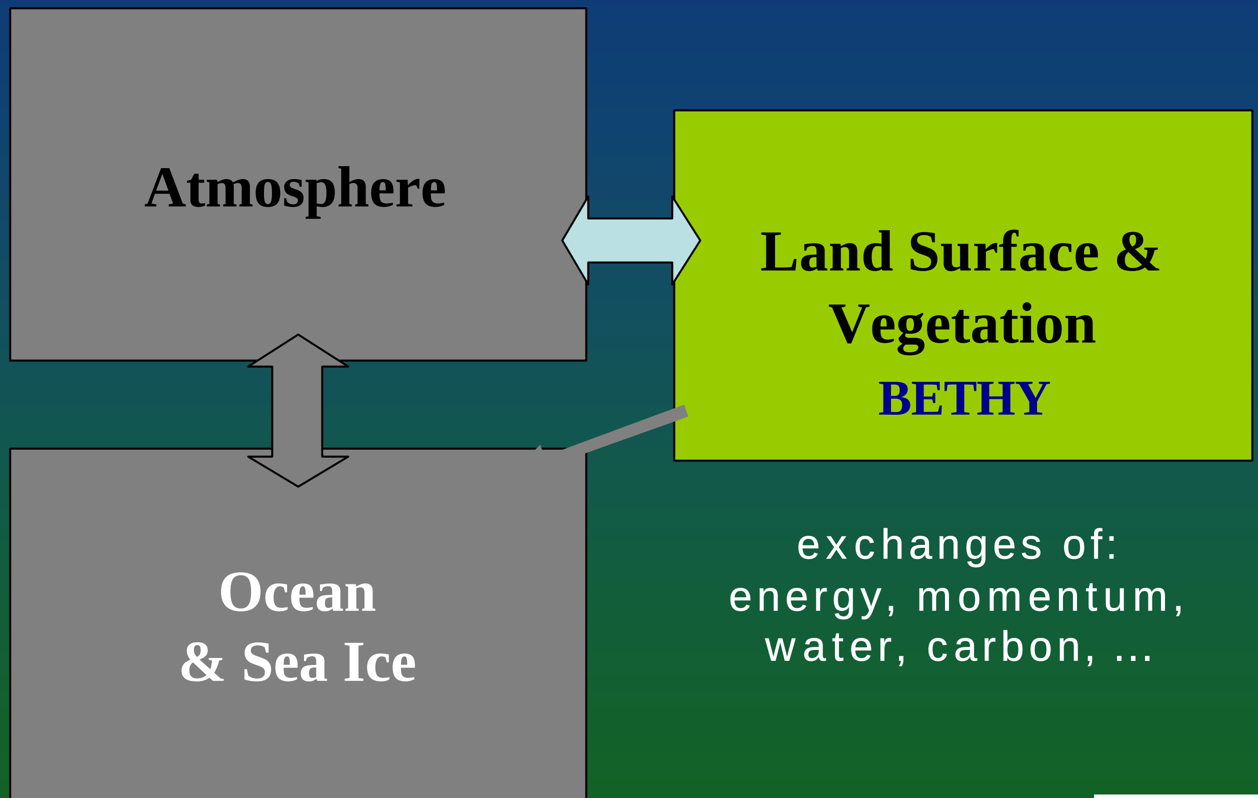
Earth System Feedbacks



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BETHY

(Biosphere Energy-Transfer-Hydrology Scheme)

- **gross primary productivity (GPP):**
  C3 photosynthesis – *Farquhar et al. (1980)*
  C4 photosynthesis – *Collatz et al. (1992)*
  stomata – *Knorr (1997)*
- **autotrophic respiration (R_{aut}):**
  maintenance respiration = $f(N_{leaf}, T)$ – *Farquhar, Ryan (1991)*
  growth respiration ~ NPP – *Ryan (1991)*
- **heterotrophic respiration (R_{het}):**
  fast/slow pool resp. = $w^k Q_{10}^{T/10} C_{fast/slow} / \tau_{fast/slow}$
- **leaf area index (LAI):**
  budbreak/shedding/leaf growth= f(T, NPP)
- **fraction of vegetation-absorbed PAR (fAPAR):**
  two-flux canopy + soil light absorption scheme
- ***spatial resolution*:**
  0.5°x0.5°, up to 6 plant functional types/grid cell
- ***time resolution*:**
  1 hour

definition:
net primary productivity
NPP=GPP–$\mathbf{R_{aut}}$

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BETHY

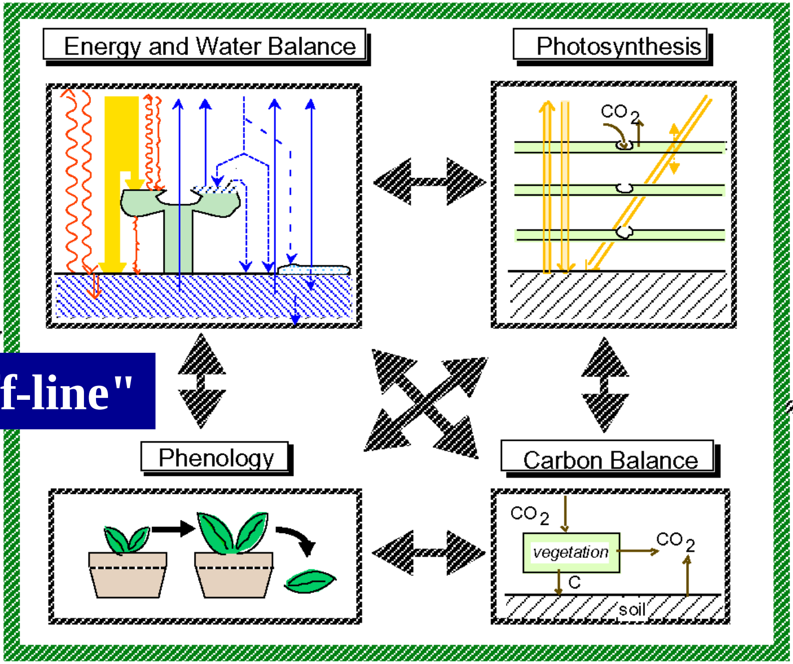
(Biosphere Energy-Transfer-Hydrology Scheme)

Input data

monthly:
- temperature
  Cramer & Leemans
- precipitation
  Cramer & Leemans
- solar radiation
  ISCCP

fixed:
- soil type
- atmosph. CO2
- vegetation type
  (unless potential)

"off-line"



Output data

monthly:
- gross primary productivity
- net primary productivity
- soil respiration
- transpiration
- evaporation
- rainwater runoff
- soil water content
- leaf area index (LAI)

fixed:
- fractional vegetation cover
- vegetation type
  (if potential)

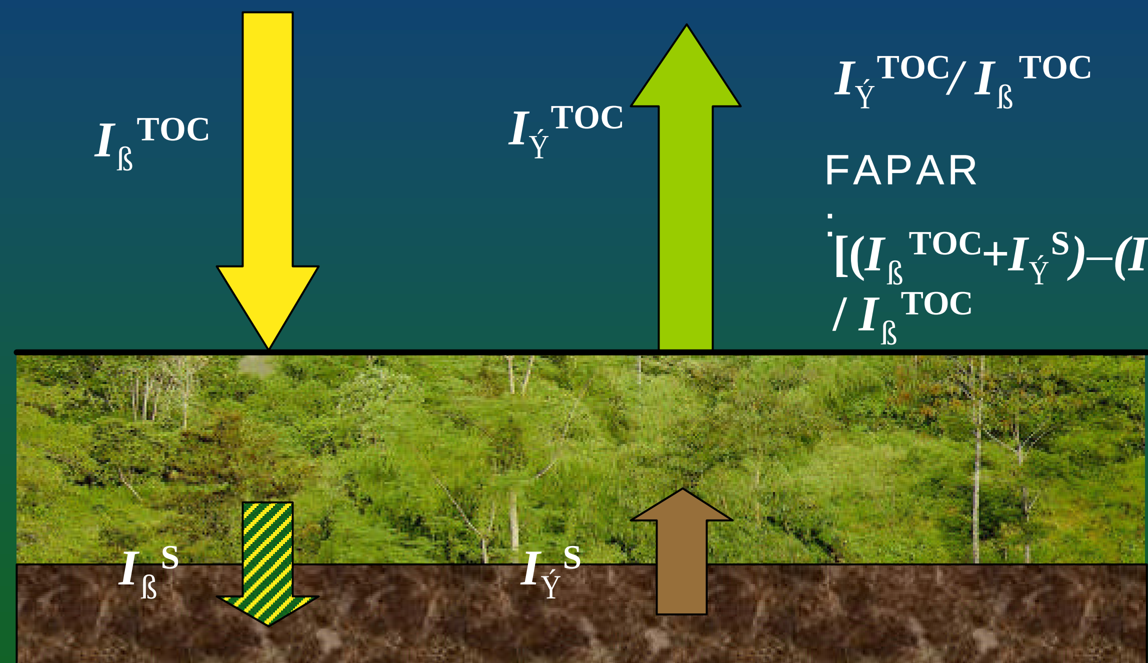
Key Remotely Sensed Variables

albedo:

$I_{Ý}^{TOC} / I_{ß}^{TOC}$

FAPAR:

$[(I_{ß}^{TOC} + I_{Ý}^{S}) - (I_{Ý}^{TOC} + I_{ß}^{S})] / I_{ß}^{TOC}$



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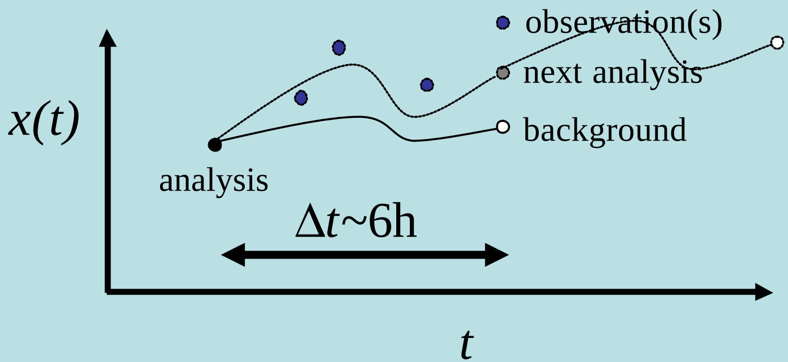
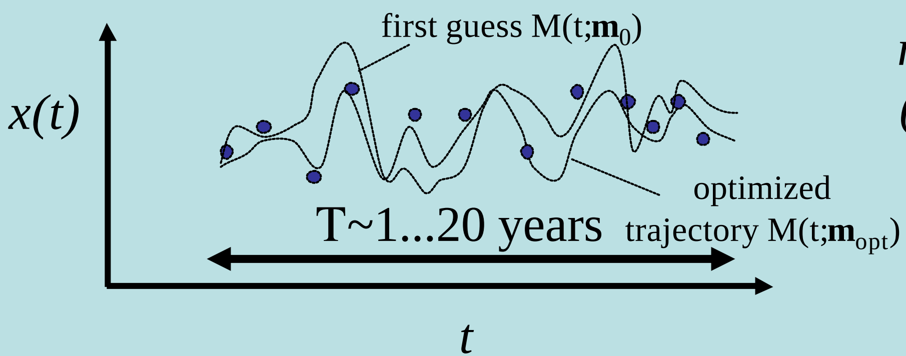
(Non-) Sequential DA



sequential DA
(e.g. NWP)

subsequently correct the state vector **x** by small amounts



non-sequential DA
(e.g. carbon cycle, hydrology)

correct model parameter vector **m**

Programme

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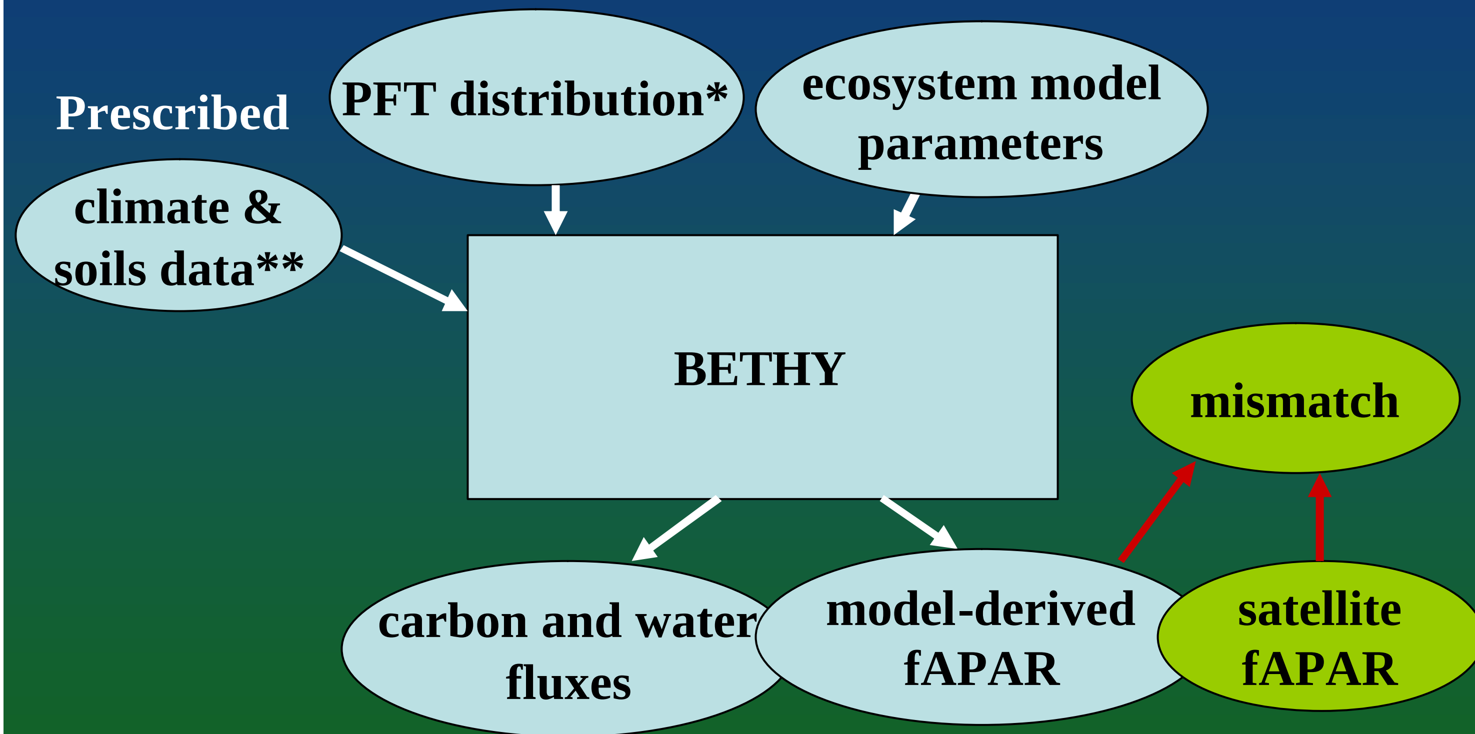
- Assimilation of fAPAR Data

fAPAR Assimilation



*** derived from:** land cover info by Wilson and Henderson-Sellers; **PFT:** plant functional type

**** from:** CRU climate data archive, University of East Anglia; FAO soil type

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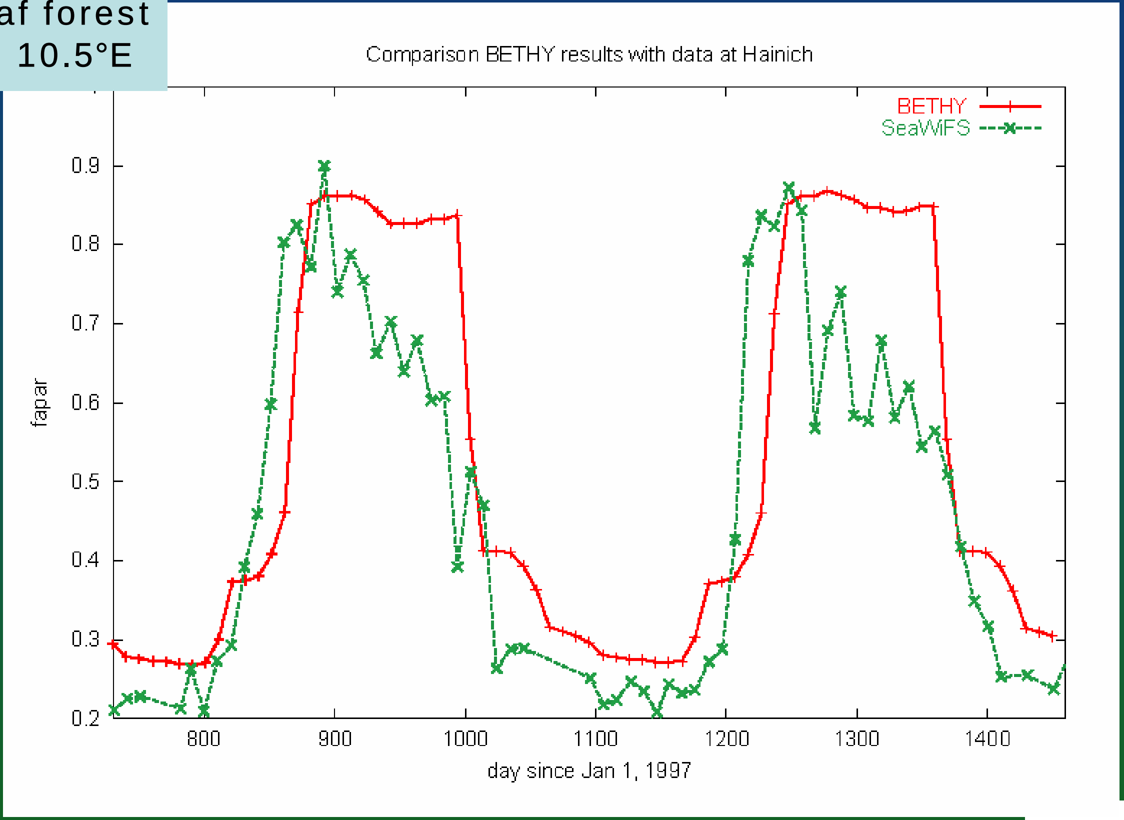
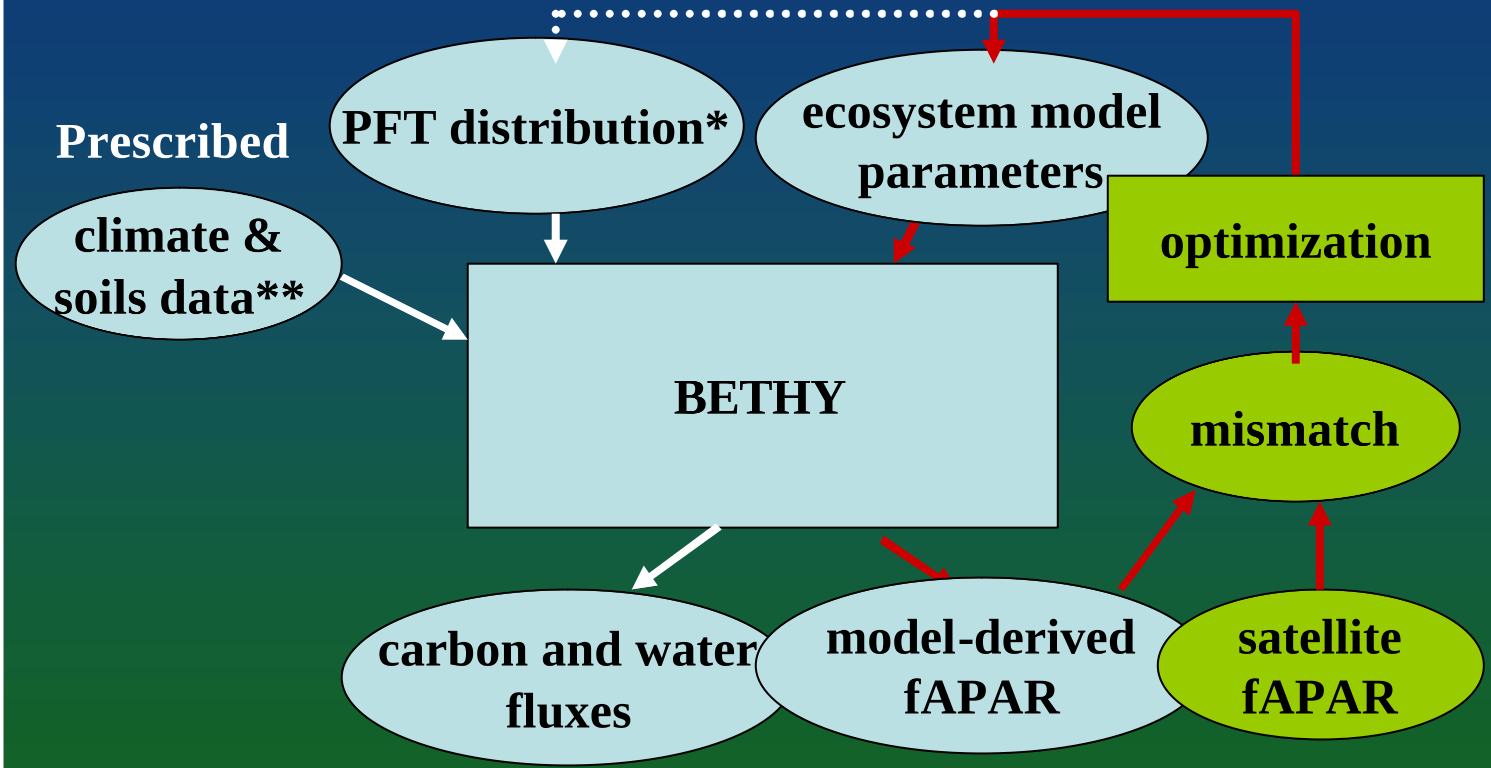
BETHY vs. SeaWiFS fAPAR

broadleaf forest
51.1°N, 10.5°E



fAPAR Assimilation



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The Cost Function

Measure of the mismatch (cost function):

$$J(\vec{m}) = \frac{1}{2}[\vec{m} - \vec{m}_0]\mathbf{C}^{\mathbf{-1}}_{m0}[\vec{m} - \vec{m}_0]^T + \frac{1}{2}[\vec{y}(\vec{m}) - \vec{y}_0]\mathbf{C}^{\mathbf{-1}}_{y}[\vec{y}(\vec{m}) - \vec{y}_0]^T$$

model diagnostics

measurements

assumed model parameters

a priori parameter values

a priori error covariance matrix of parameter s

error covariance matrix of measurements

aim: minimize $\mathbf{J}(\overline{m})$

[for each grid point separately]

The Parameters

parameter vector $\overline{m}=\{m_1,m_2,m_3\}$:			represents:	vector of prior parameter values m_0:
m_1	ΔT_ϕ	shift of leaf onset/shedding temperature	temperature limitation	$\Delta T_{\phi,0}=0$
m_2	w_{max}	maximum soil water holding capacity	water limitation	$w_{max,0}$ (derived from FAO soil map)
m_3	f_c	fraction of grid cell covered with vegetation	residual, unmodelled limitations (nitrogen, land use)	$f_{c,0}$ (function of P/PET and Temp. of warmest month)

Prior Parameter 1

phenology model:

$$\Lambda = \min\{\Lambda_T, \Lambda_W, \Lambda_G\}$$

temperature-limited LAI (Λ_T)

water-limited LAI (Λ_W)

growth-limited LAI (Λ_G)

temperature-limited phenology model:

$$\Lambda_T(T) = \begin{cases} 0 & \text{if } T < T_f \\ \hat{\Lambda}\left[1 - \left(\frac{\hat{T}_f - T}{\hat{T}_f - T_f}\right)^2\right] & \text{if } T_f < T < \hat{T}_f \\ \hat{\Lambda} & \text{if } T > T_f \end{cases}$$

T**: 0.5 m soil temperature (summergreen trees/shrubs, grass);**
or **mean of warmest month (boreal evergreen)**

Prior Parameter 1

prior parameters:

$T_f = 5°C$

$T_f = 12°C$ for crops

$\hat{T}_f = 15°C$

temperature-limited phenology model:

$$\Lambda_T(T) = \begin{cases} 0 & \text{if } T < T_f \\ \hat{\Lambda}\left[1 - \left(\dfrac{\hat{T}_f - T}{\hat{T}_f - T_f}\right)^2\right] & \text{if } T_f < T < \hat{T}_f \\ \hat{\Lambda} & \text{if } T > T_f \end{cases}$$

T: **0.5 m soil temperature (summergreen trees/shrubs, grass);**
or **mean warmest month (boreal evergreen)**

Prior Parameter 1

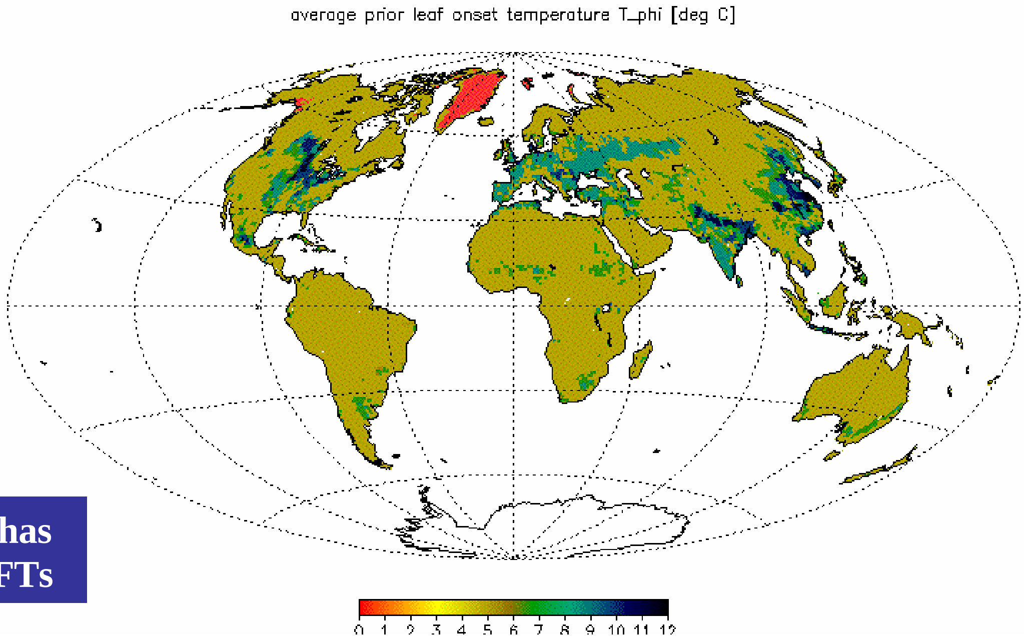
prior parameters:

T_f=5°C

T_f=12°C for crops

$\hat{T}_f$=15°C

note: each 0.5°x0.5° has mixture of up to 6 PFTs



map reflects presence of crops; red: unvegetated

Prior Parameter 2

phenology model:

$$\Lambda = \min\{\Lambda_T, \Lambda_W, \Lambda_G\}$$

temperature-limited LAI

growth-limited LAI

water-limited LAI

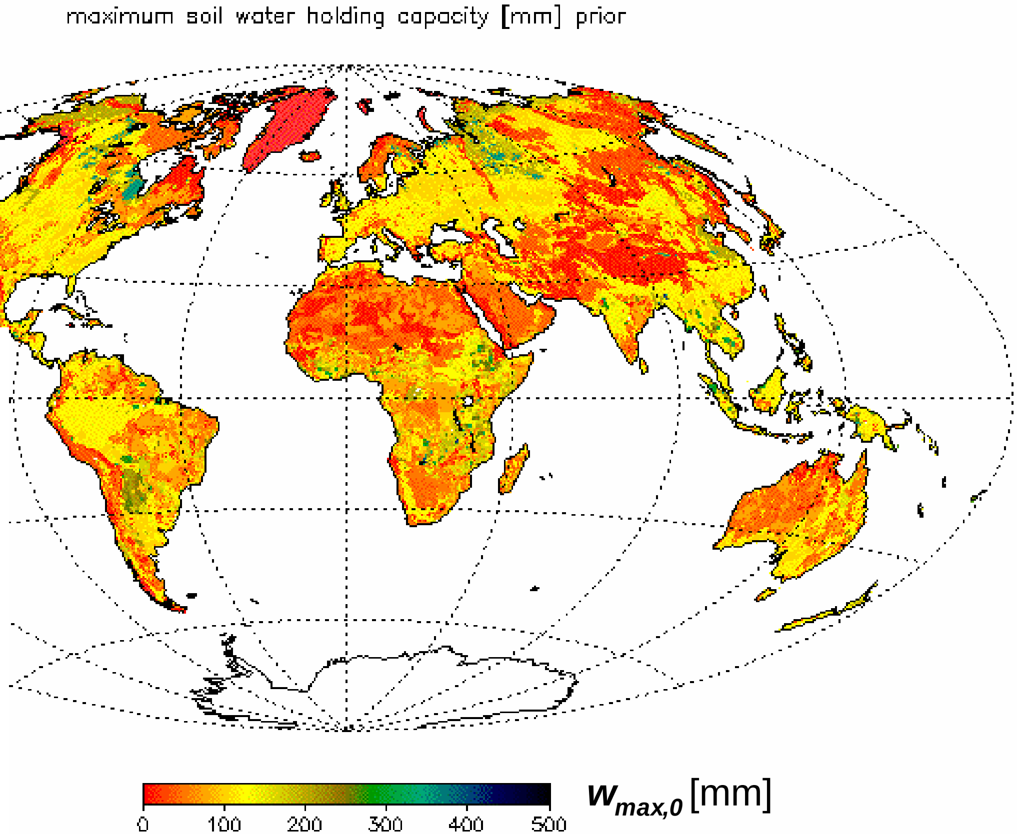
water-limited phenology model:

Λ_W: LAI value, that maximises NPP, if $>\Lambda_W(t-1)$
else, LAI value, where NPP=0

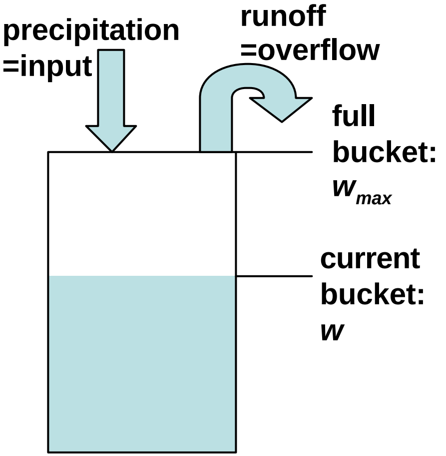
if soil moisture is limiting, stomata close, CO_2 uptake declines while respiration (~LAI) stays high => NPP drops

under water stress, too high LAI can lead to decline in, or even negative NPP

Prior Parameter 2



bucket model:



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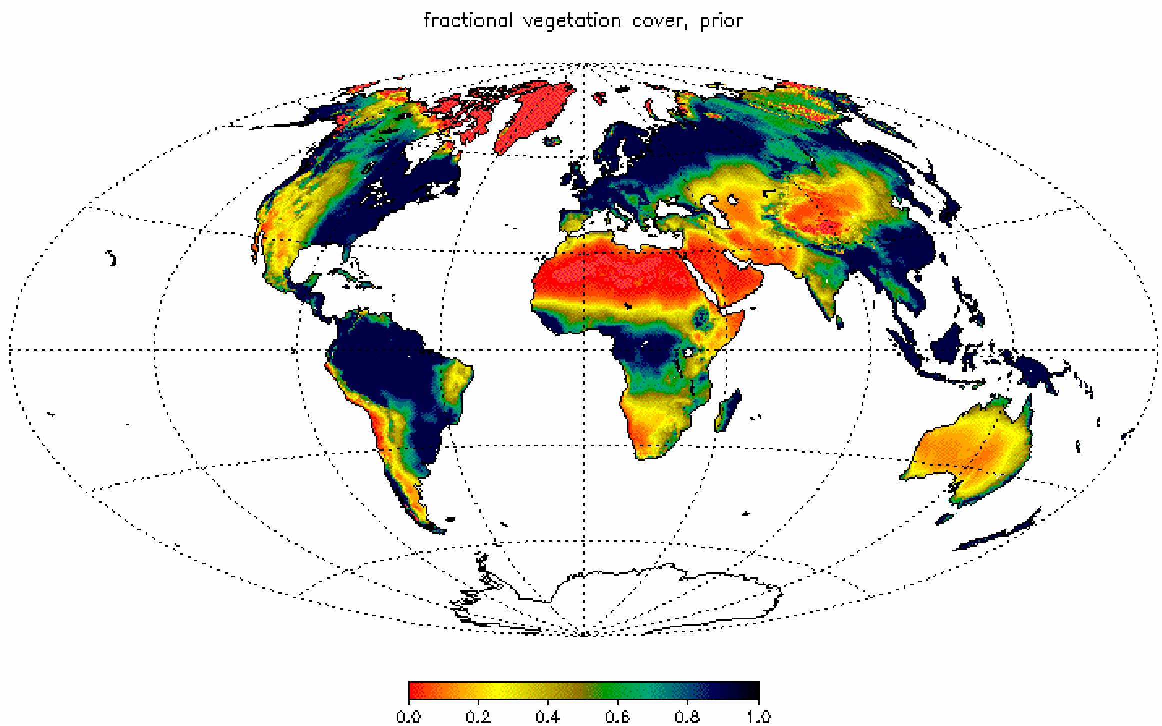
Prior Parameter 3



$$f_{c,0} = \mathrm{P}_{\mathrm{annual}} / \mathrm{PET}_{\mathrm{annual}} * \Lambda_W(T_{\mathrm{warmest\ month}}) / \hat{\Lambda}$$

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Prior Parameter Errors

error covariance matrix of parameters C_{m0}:

$$\mathbf{C}_{m0} = \begin{pmatrix} 1\mathrm{K}^2 & 0 & 0 \\ 0 & (2w_{\max,0})^2 & 0 \\ 0 & 0 & 0.25^2 \end{pmatrix}$$

$\sigma_{m,1}{}^2$ (1K²), $\sigma_{m,2}{}^2$ ($(2w_{\max,0})^2$), $\sigma_{m,3}{}^2$ (0.25^2)

⇒ off-diagonal elements assumed 0 here

= no prior correlation between errors of different parameters

The Assimilated Data

model diagnostics vector $\overline{y}=\{y_1,y_2,...,y_{12}\}$:

y_i modelled fAPAR of month *i*

satellite-derived diagnostics vector $\overline{y_0}=\{y_{0,1},y_{0,2},...,y_{0,12}\}$:

$y_{0,i}$ SeaWiFS derived fAPAR of month *i*

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Prior Errors of Measurements

error covariance matrix of measurements C_y:

$$\mathbf{C}_{y\,i,j} \underset{i=j}{=} \begin{cases} 0.05^2 & \text{if valid measurement} \\ \infty & \text{if data gap} \end{cases}$$

$$= s_{y,i}^{\;2}$$

$\Rightarrow$ off-diagonal elements again 0
= no prior correlation between errors of different months

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Simple Case of Cost Function

Measure of the mismatch (cost function):

$$J(m_1, m_2, m_3) = \frac{1}{2}\sum_{i=1}^{3}\frac{\left(m_i - m_{i,0}\right)^2}{s_{m,i}^{2}} + \frac{1}{2}\sum_{i=1}^{12}\frac{\left(y_i(m_1, m_2, m_3) - y_{i,0}\right)^2}{s_{y,i}^{2}}$$

assumed model parameters

a priori parameter values

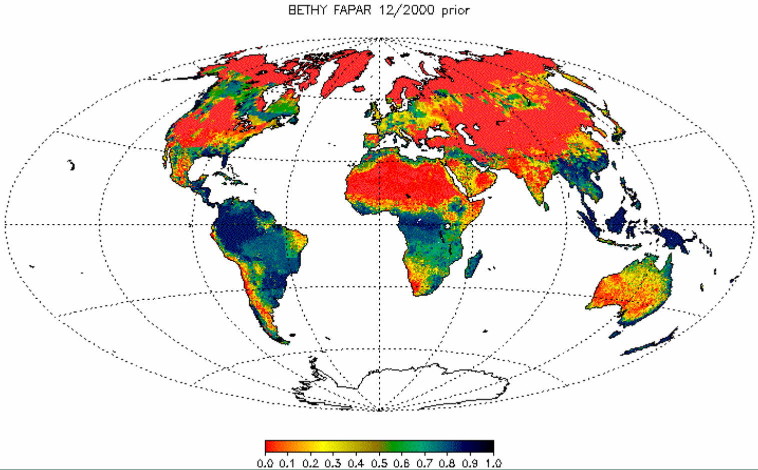
model diagnostics

measurements

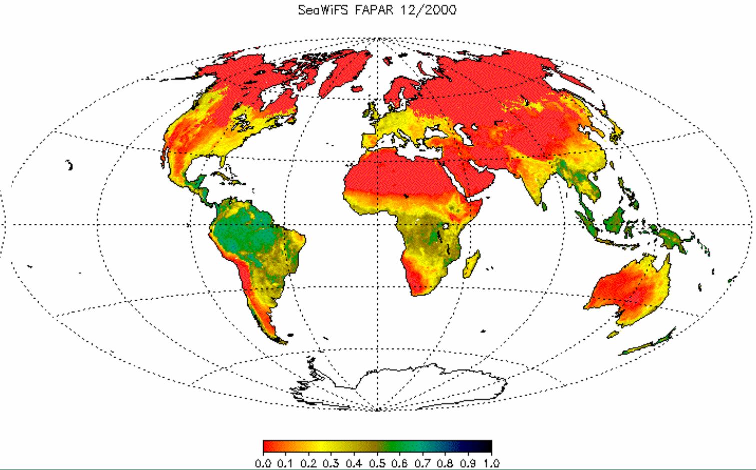
a priori error of parameters

error of measurements

fAPAR Assimilation



$y_{0,i}(\overline{x})$



$y_i(\overline{x})$

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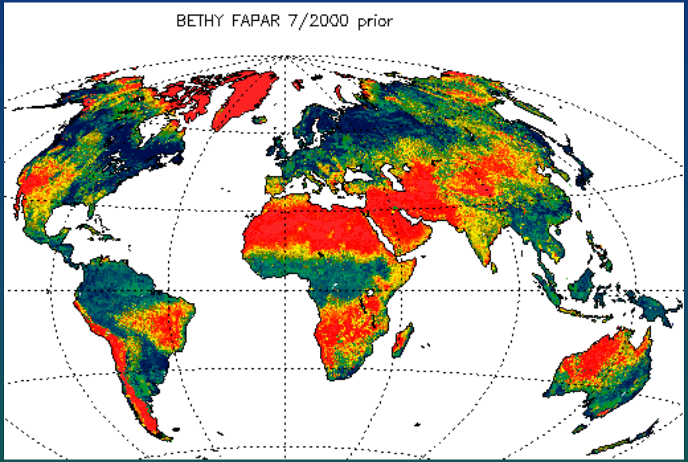
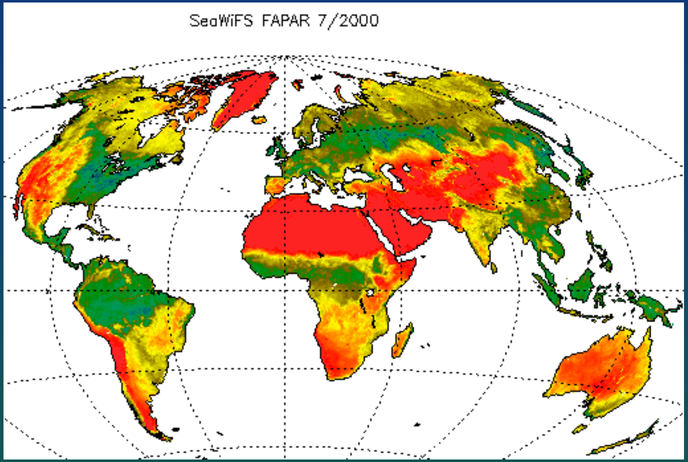
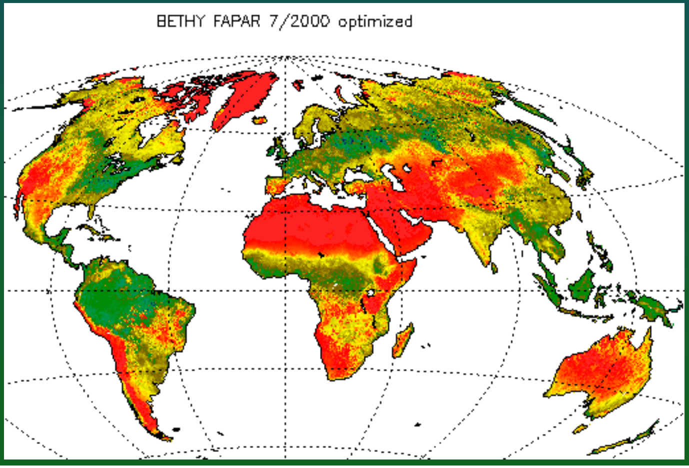
fAPAR Assimilation





- model, prior
- SeaWiFS
- model, optimized



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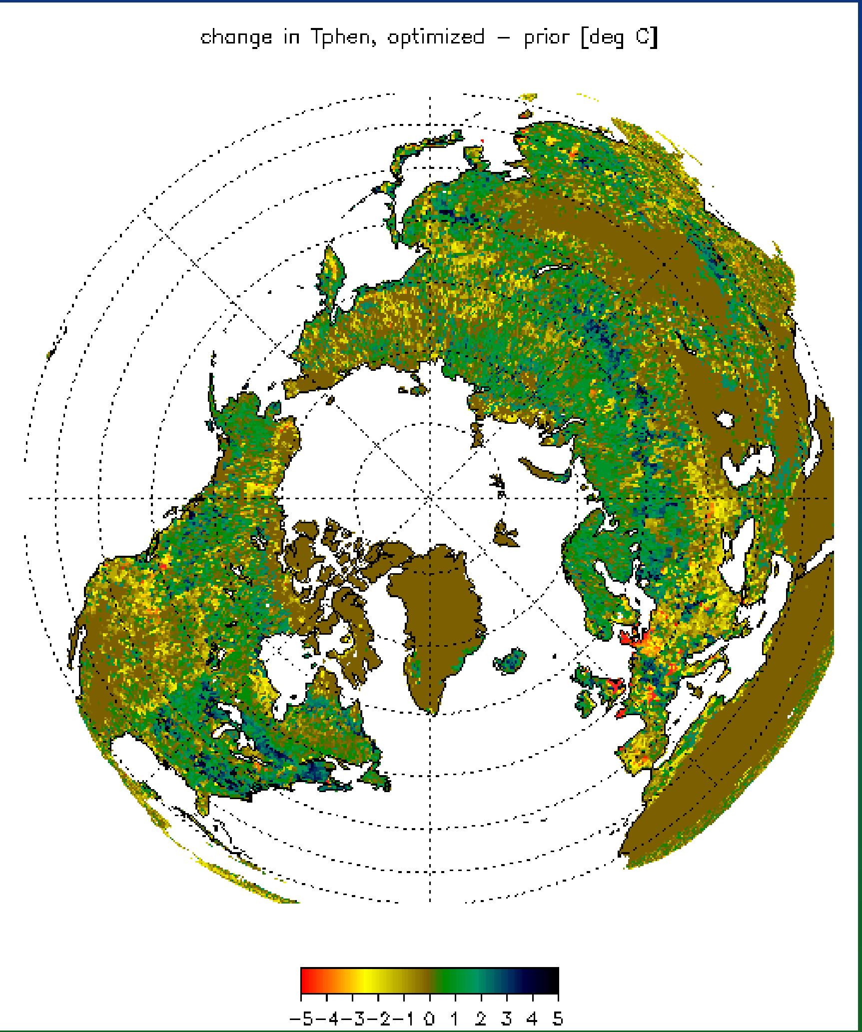

Parameter 1

shift of temperature trigger of leaf onset / shedding

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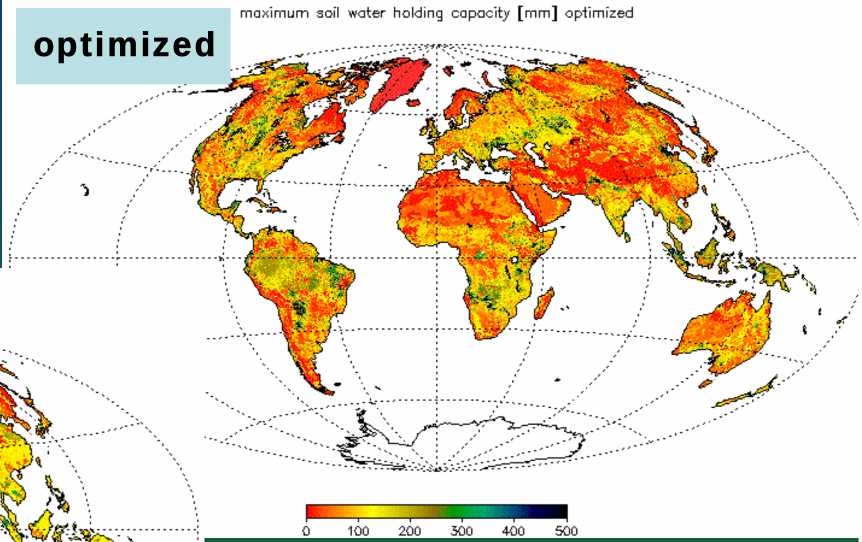
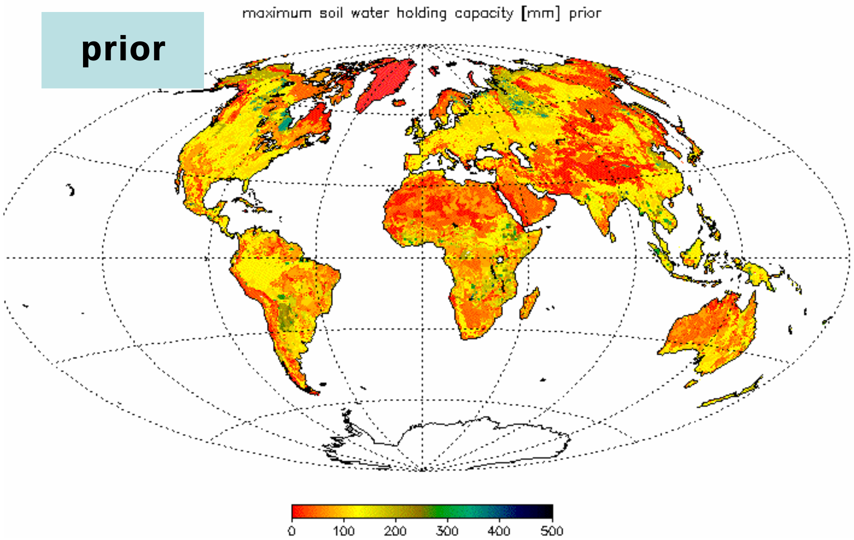
Parameter 2

soil water-holding capacity

optimized



prior



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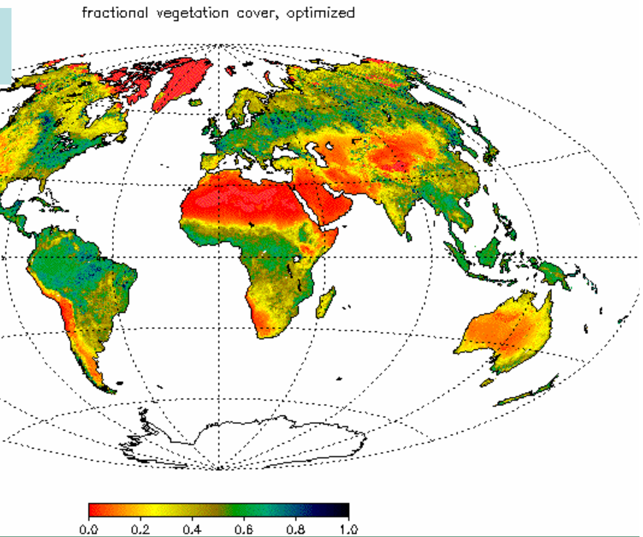
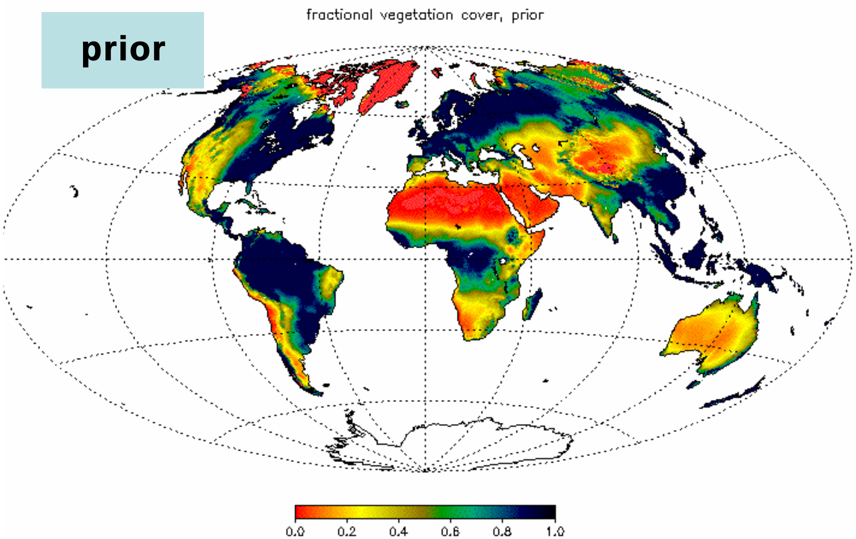
Parameter 3

fraction vegetation cover

optimized



prior



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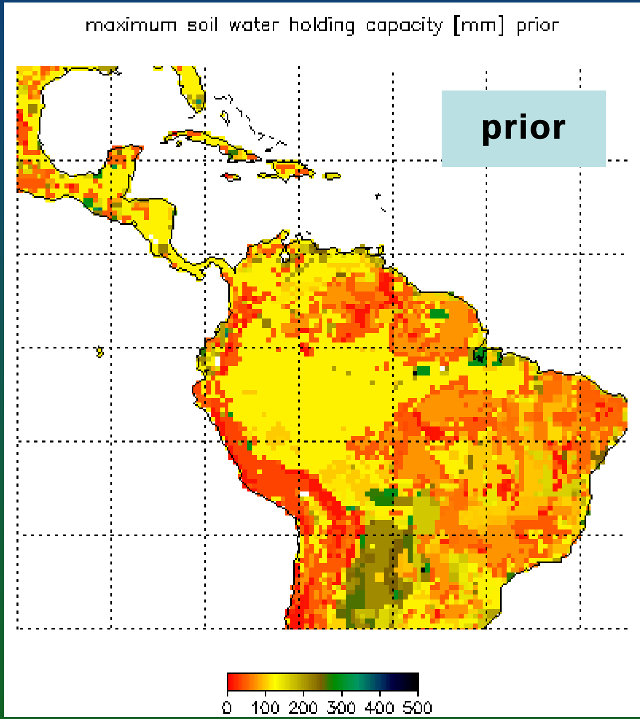
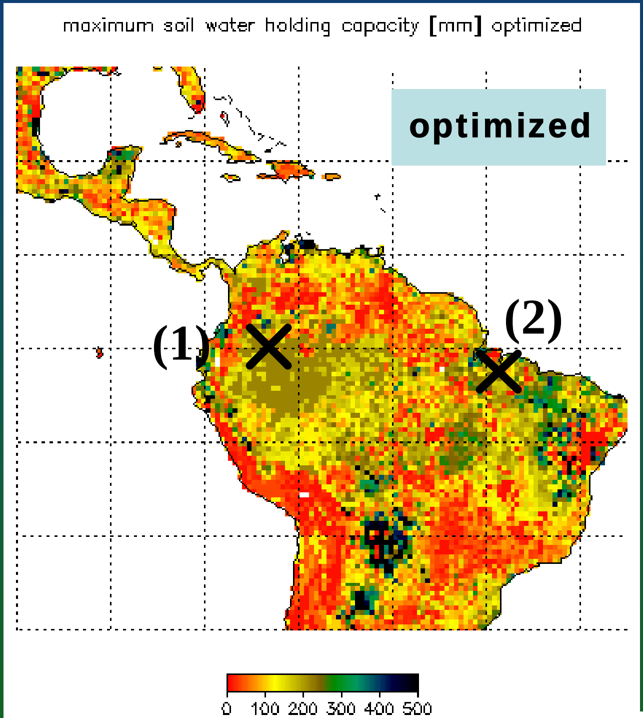
Parameter 2 (regional)

soil water-holding capacity





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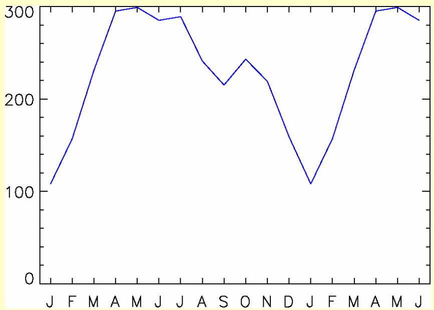
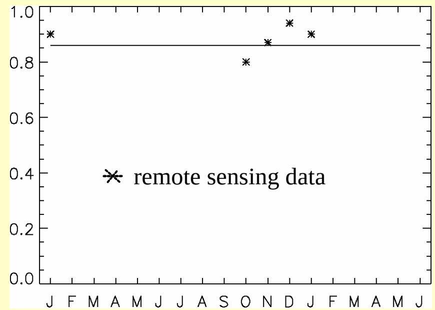
Local Simulations

La Tagua
0°N 74°W 300 m

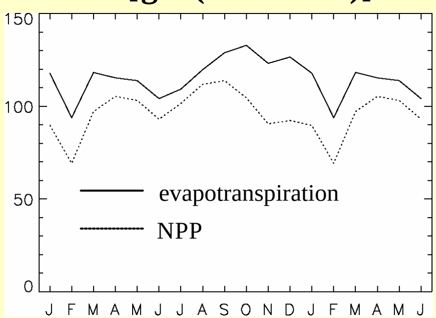
precipitation [mm/month]



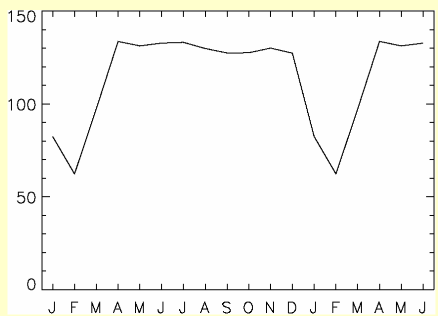
fAPAR



evapotranspiration [mm/month]
NPP [gC/(m^2 month)]



soil moisture [mm]



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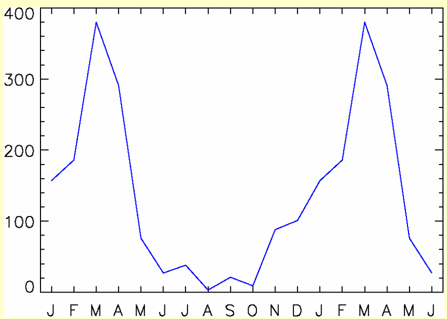
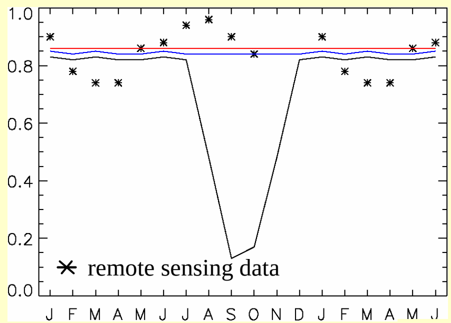
Local Simulations

Paragominas
3°S 48°W 63 m

precipitation [mm/month]

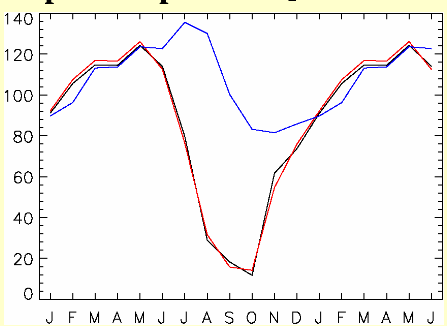


fAPAR

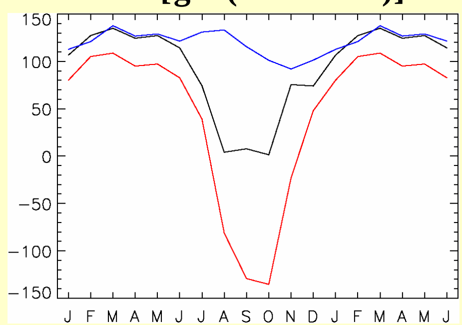


no remote sens. data
fAPAR prescribed
fAPAR assimilated

evapotranspiration [mm/month]



NPP [gC/(m² month)]



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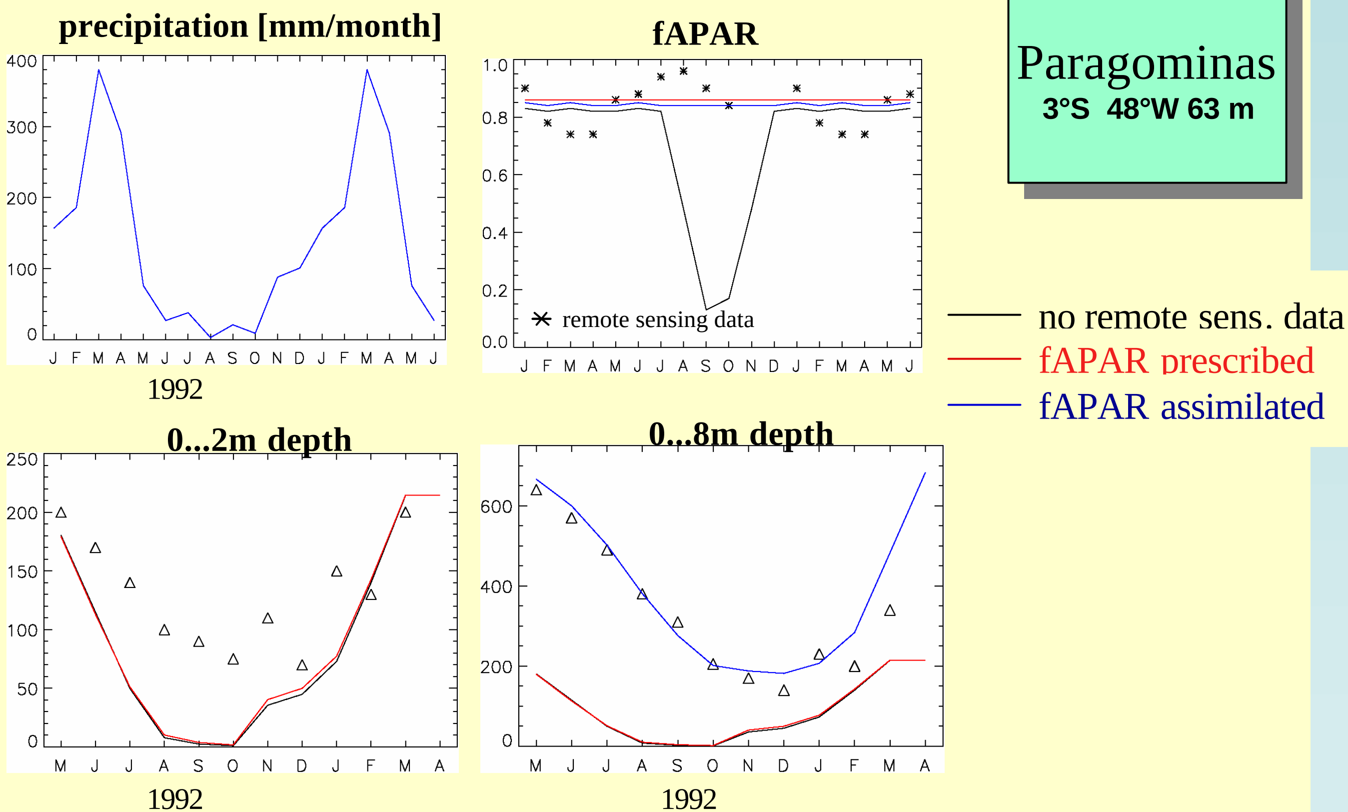
Measured Soil Moisture

Paragominas
3°S 48°W 63 m



△ measurements: Nepstad D.C. & al. (1994) *Nature* **372,** 666-669

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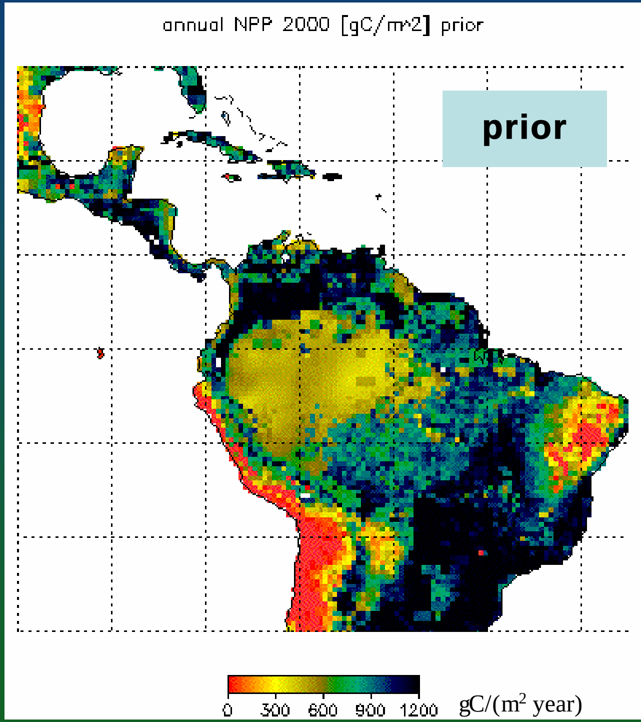
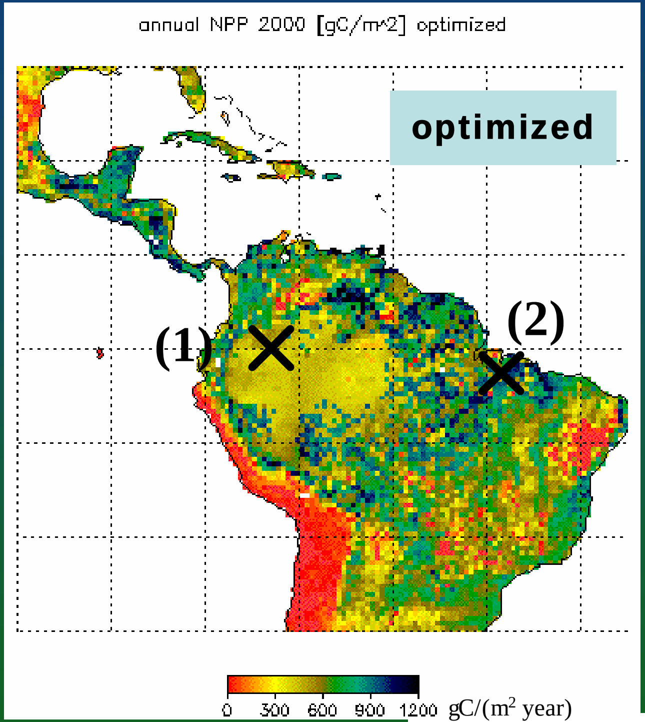
NPP (regional)





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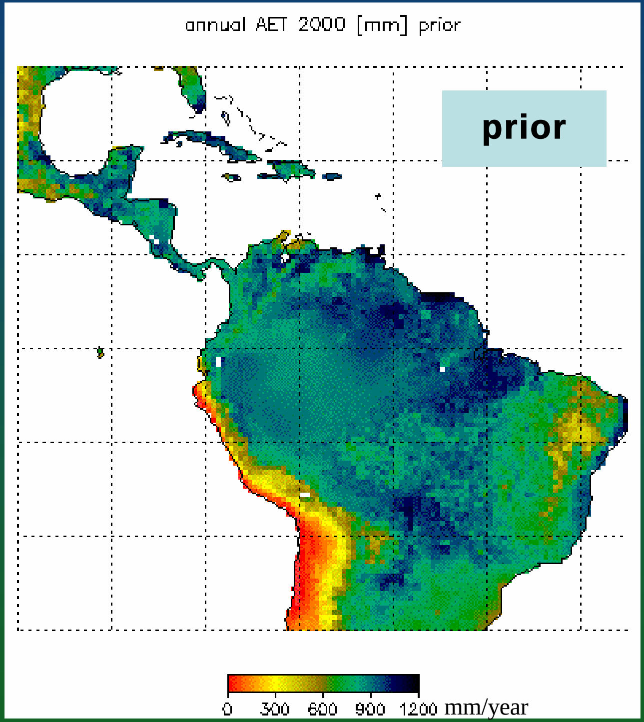
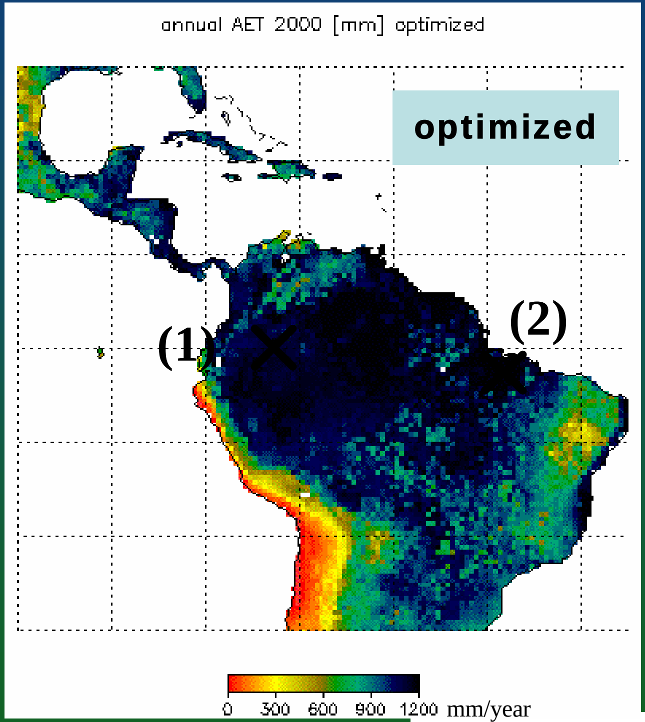
evapotranspiration (regional)





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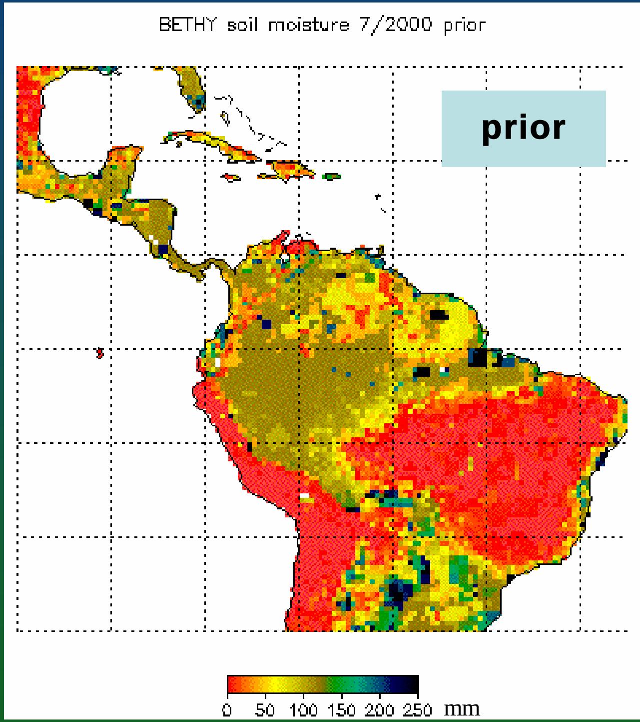
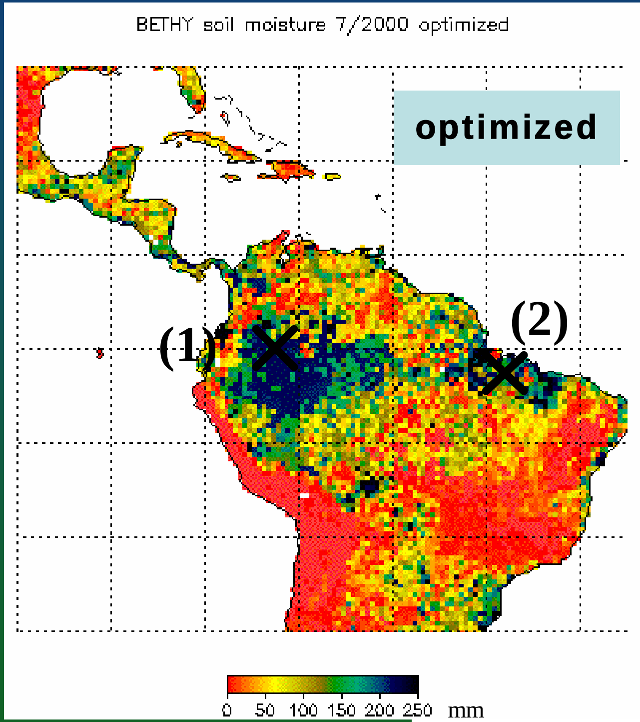
July soil moisture (regional, dry season)





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Next Lecture:

- Data assimilation in CO_2 science – including uncertainties

= more maths...

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