Using SMOS observations in a carbon cycle data assimilation system

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ECMWF/ESA WS on low frequency passive microwave measurements
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stse
support to science element

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Global Carbon Budget (GCP 2016)

9.3±0.4 PgC/yr 91%

+

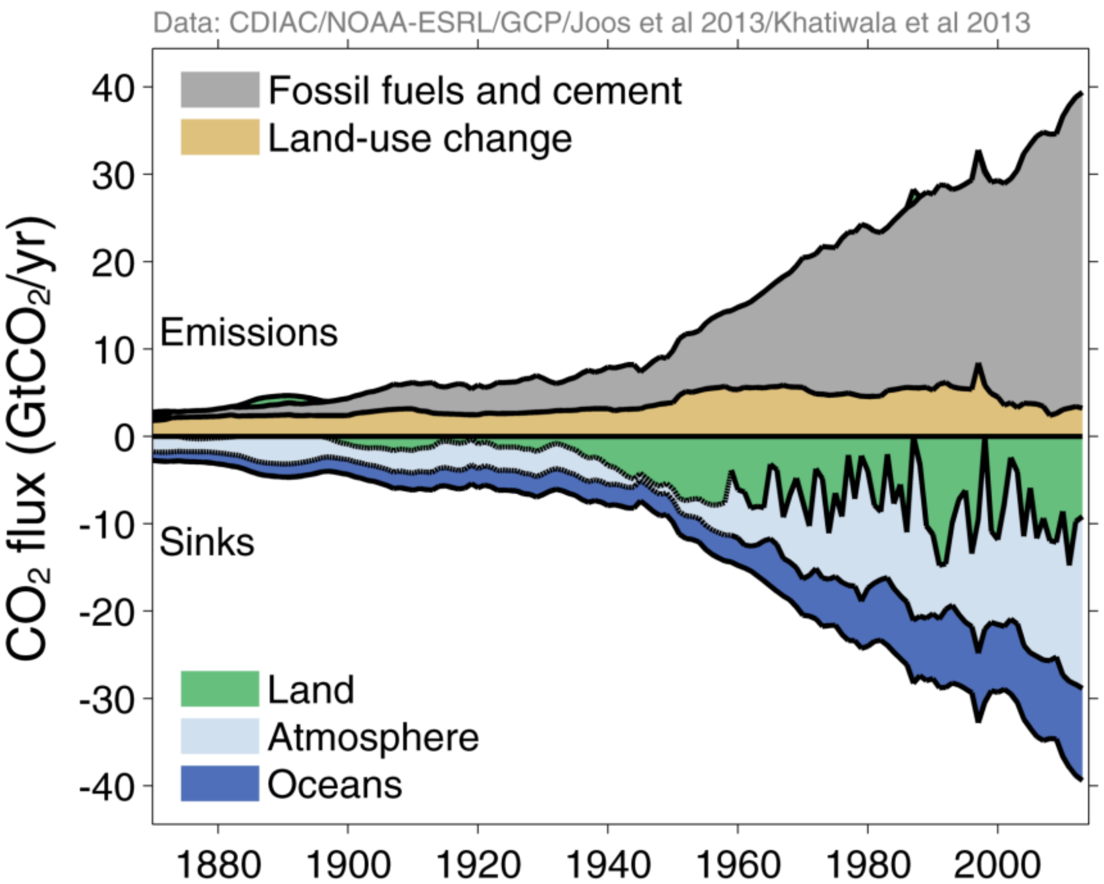
1.0±0.5 PgC/yr 9%

4.5±0.1 PgC/yr
Atmosphere
44%

3.2±0.8 PgC/yr
Land
31%

2.6±0.5 PgC/yr
Oceans
25%

Global budget of the CO_2 fluxes



Need for monitoring the land ecosystem sinks and sources at high spatial and temporal resolution to understand and forecast their evolution

Methods for the estimation of CO_2 fluxes

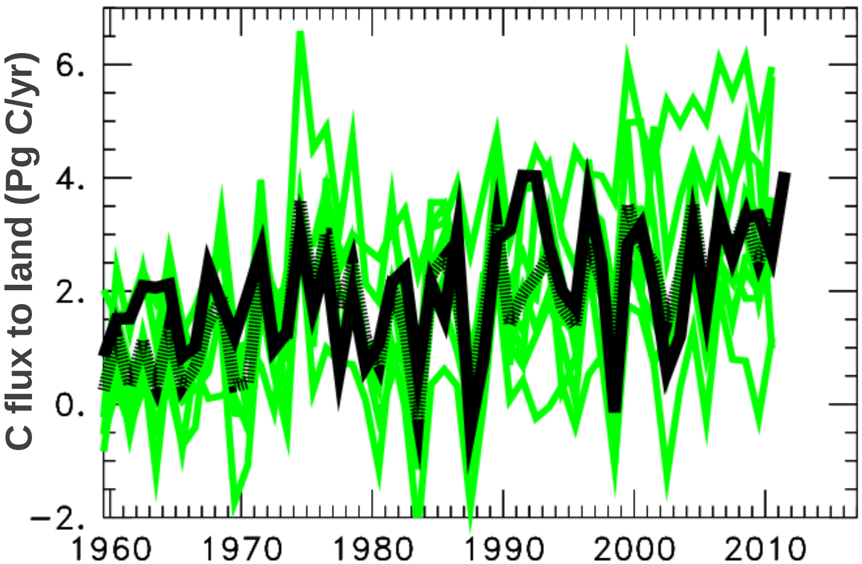
Most common methods to estimate the net CO_2 ecosystem exchange (NEE):

- Process models or diagnostic models based on local flux measurements, satellite measurements of vegetation indices and biomass data
- atmospheric inversion systems assimilating atmospheric concentration data

Carbon Cycle Data Assimilation Systems (CCDAS): optimization of parameters in process models using ideally all types of data

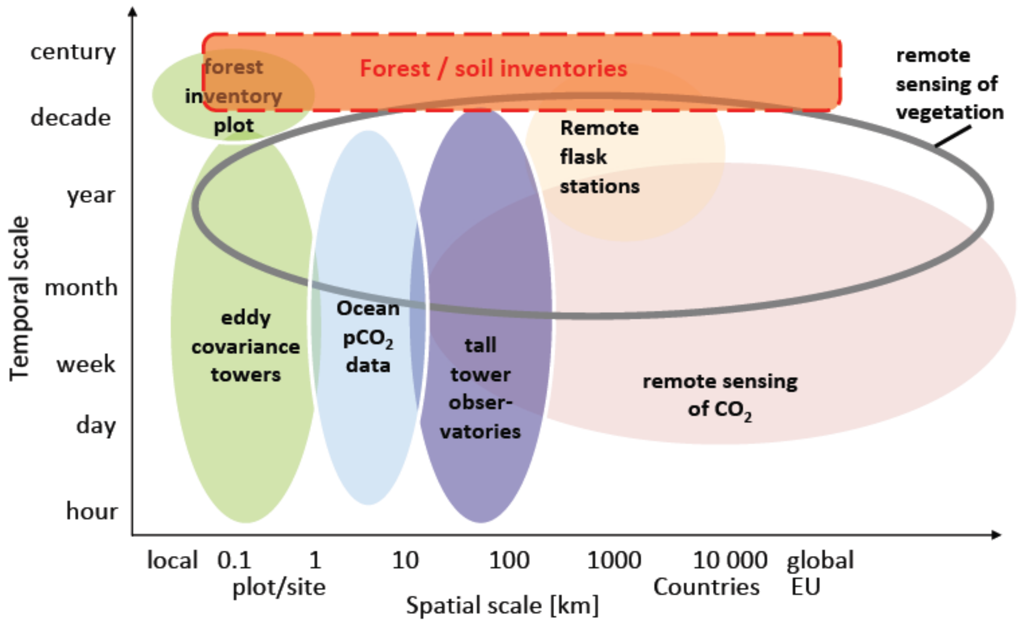
The case for data assimilation

Large uncertainty from land to predict C-balance (GCP)



Le Quéré et al. 2013

Available Observations



⇒ Carbon Cycle Data Assimilation System

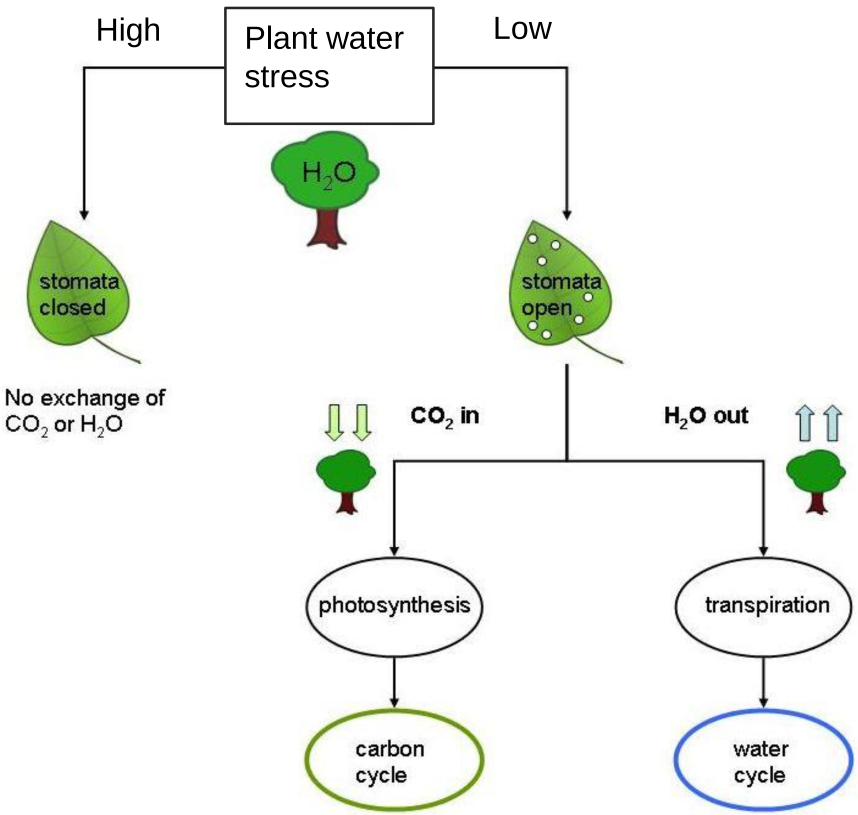
= ecophysiological constraints from forward modelling

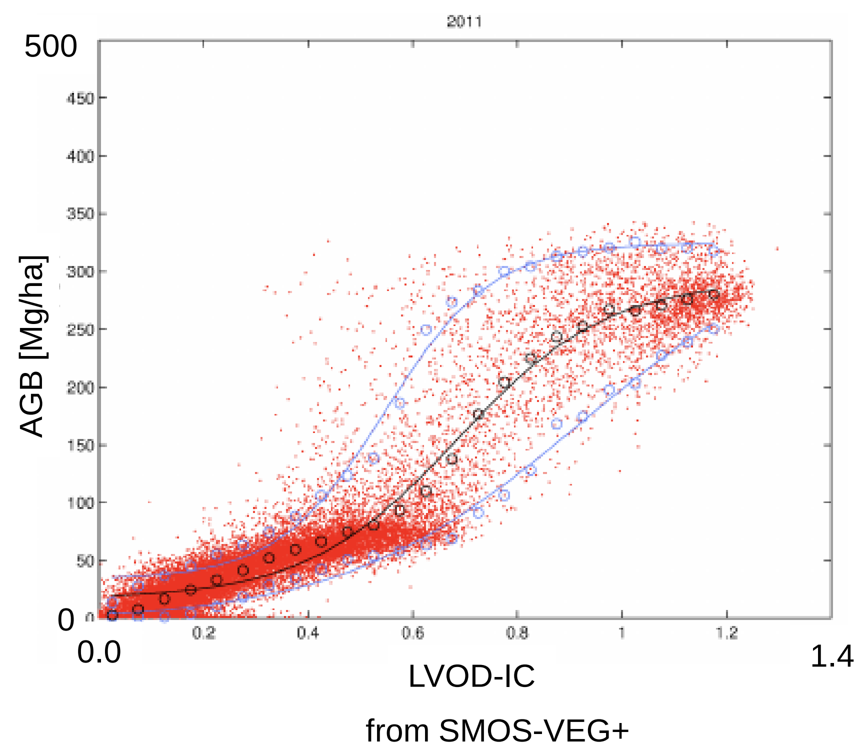
+ observational constraints from inverse modelling

Low frequency passive microwave measurements (i.e. SMOS)

How are SMOS measurements linked to the carbon cycle?

- SMOS surface SM: Water and carbon cycles tightly coupled
- SMOS VOD: A proxy for aboveground biomass





Study objectives

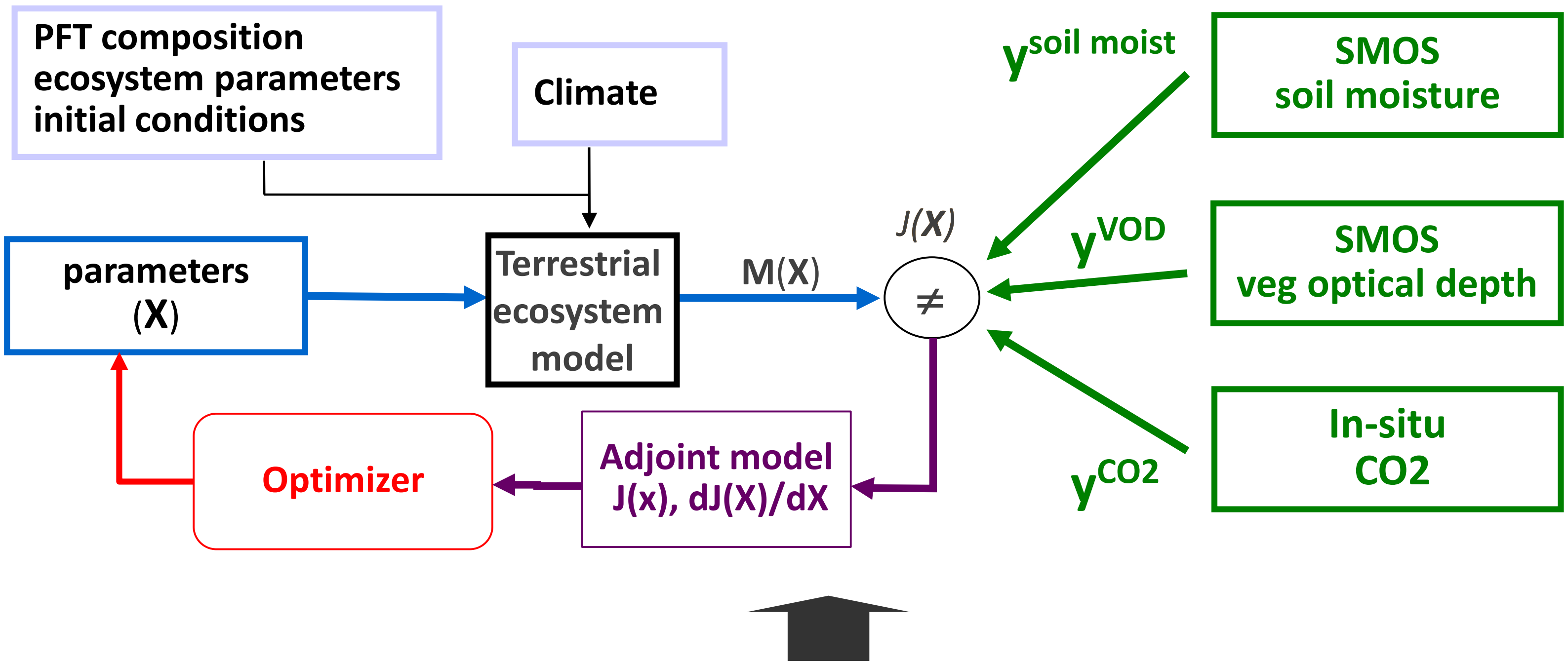
ESA SMOS-NEE project: Assimilation of SMOS L3 soil moisture together with atmospheric CO_2 concentration:

- quantify the added value of SMOS soil moisture observations on constraining terrestrial carbon fluxes
- assess the potential of a SMOS based Level 4 NEE product

ESA-STSE ’SMOS + Vegetation’ project:

- improve the SMOS VOD product
- derive further SMOS L4 vegetation products (e.g. biomass)
- quantify the constraint of a SMOS VOD product on carbon and water fluxes, when assimilated individually and in conjunction with SMOS soil moisture and flask samples of atmospheric CO_2

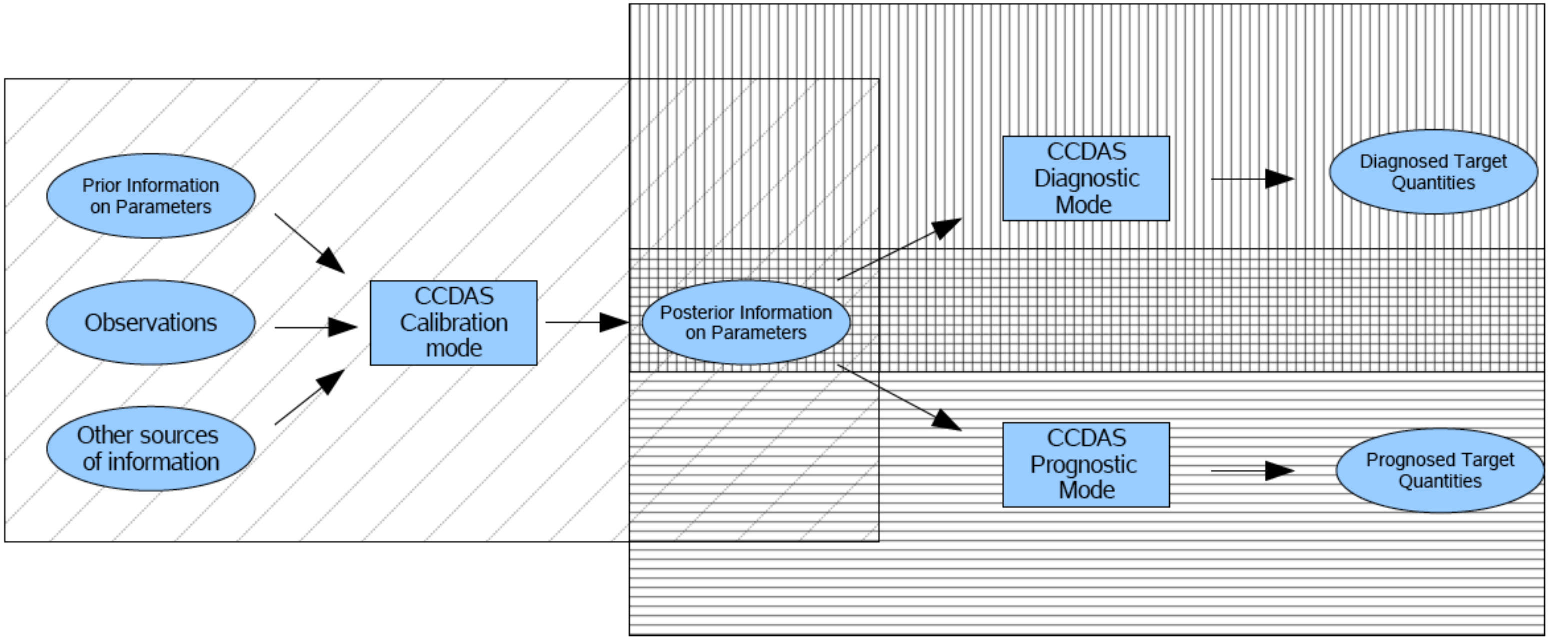
C-cycle data assimilation system



Cost function: $J(x) = \frac{1}{2}\left[\left(x - x_p\right)^t C_p^{-1}\left(x - x_p\right) + \sum \left(y - M(x)\right)^t C_y^{-1}\left(y - M(x)\right) \right]$

CCDAS methodology

- Based on process-based terrestrial ecosystem model (BETHY)
- Optimizing parameter values (~100) based on gradient method
- Hessian (2nd deriv.) to estimate posterior parameter uncertainty
- Error propagation by using linearised model

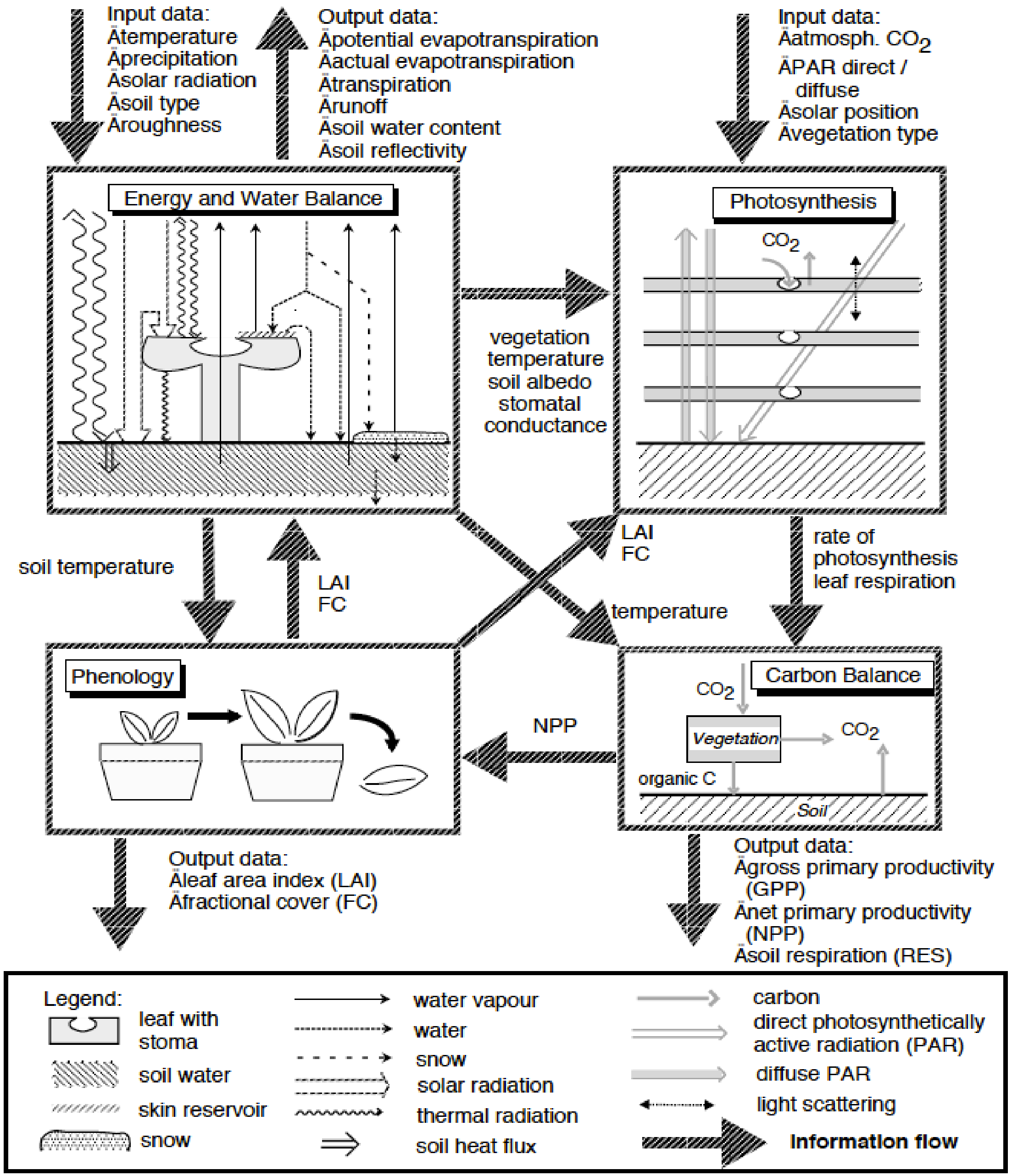


Scholze et al. (2007)

BETHY

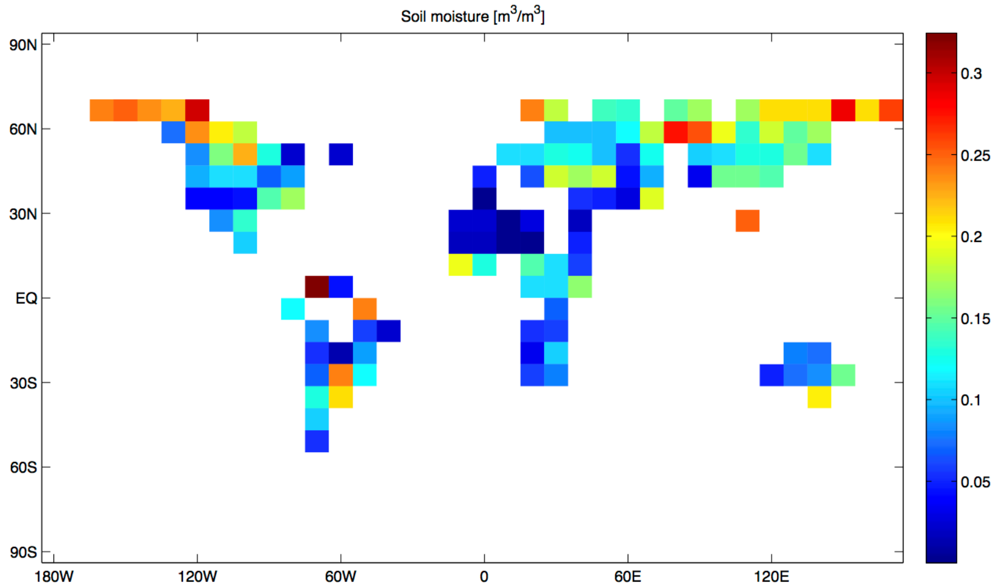
Biosphere Energy-Transfer Hydrology (BETHY) scheme (Knorr 2000) with a number of extensions:

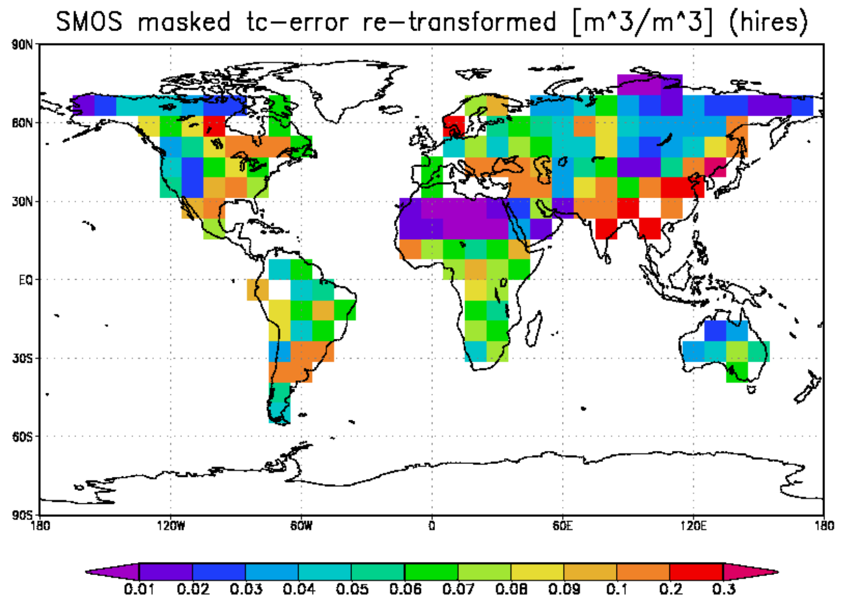
- Globally 0.5/0.25 degree
- Set up with meteorological driving fields for 2010-15
- 13 Plant functional types
- Estimating some 50-100 process parameters
- Derivative code generated with TAPENADE (Hascoet & Pascal, 2013)



Global SM assimilation

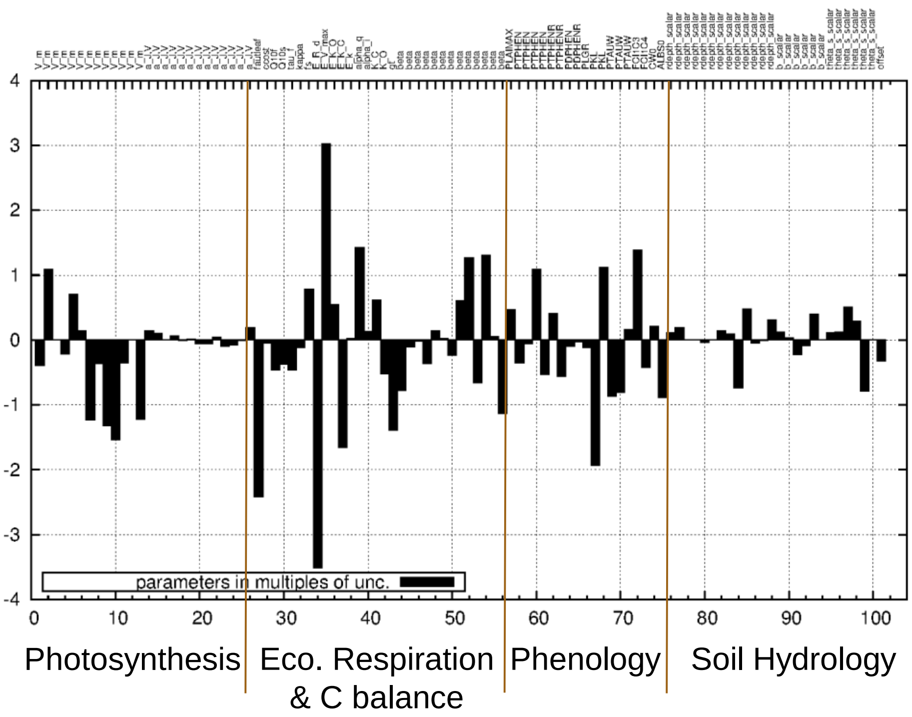
- Coarse resolution, 2 years (2010/11)
- Running 3-member ensembles from different starting points
- Baseline: in-situ atm. CO_2 (10 sites) concentrations only
- Baseline + SMOS daily soil moisture with variance/mean scaling



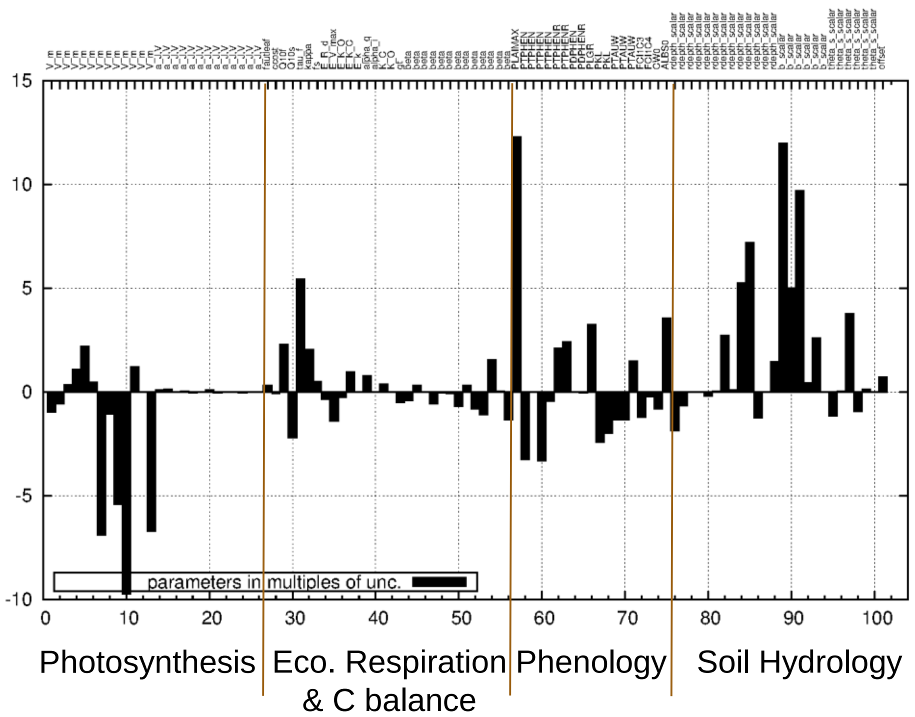


Results: process-parameters

CO_2 only

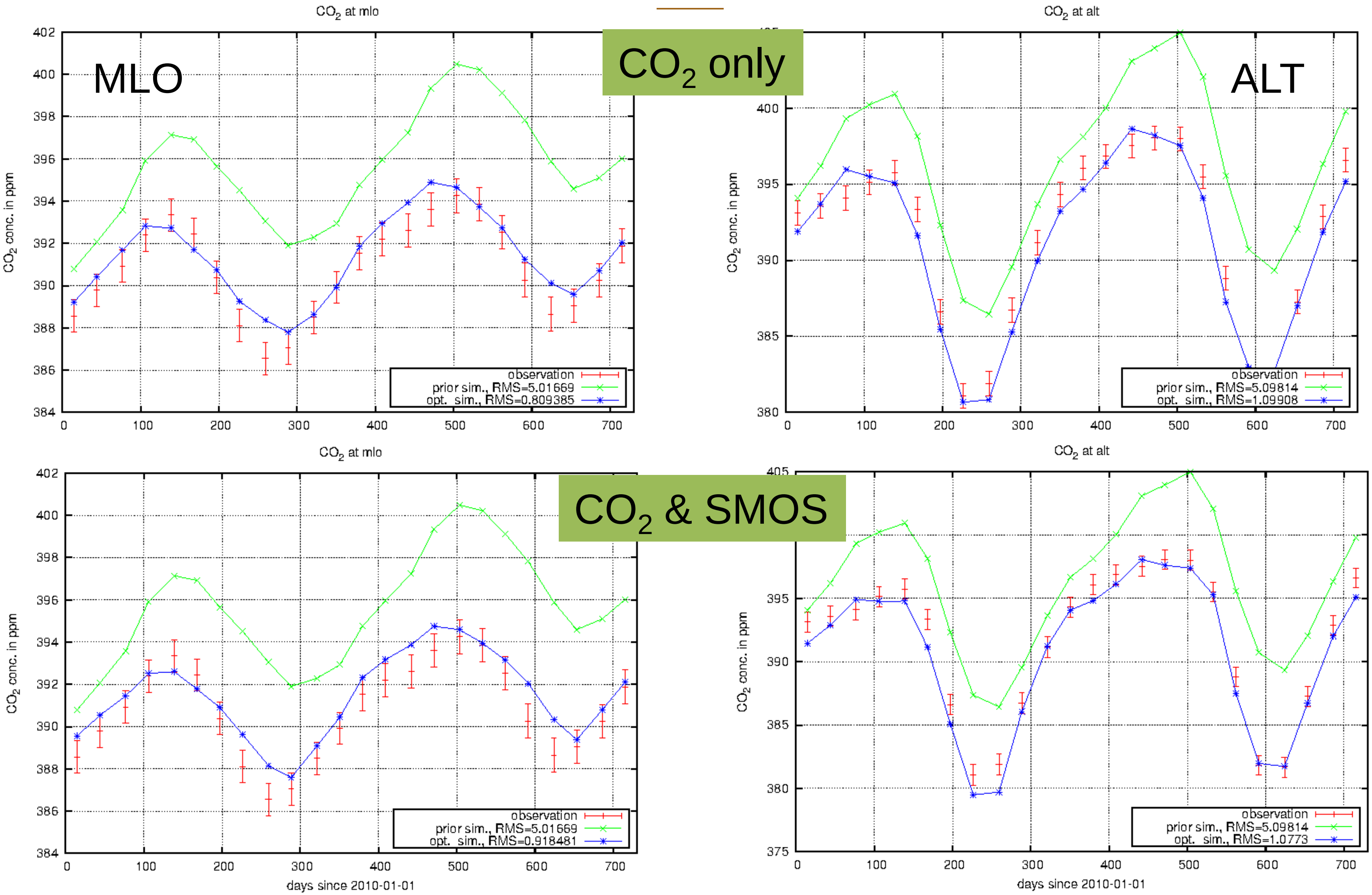


CO_2 & SMOS



Scholze et al. (2016)

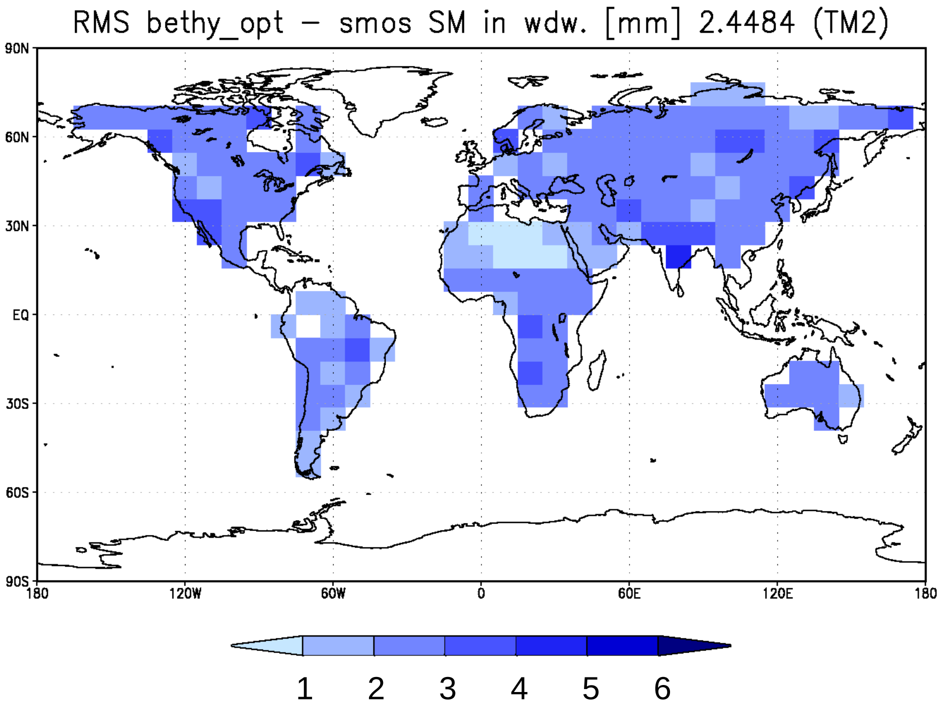
Results: atm CO_2 (also for validation)

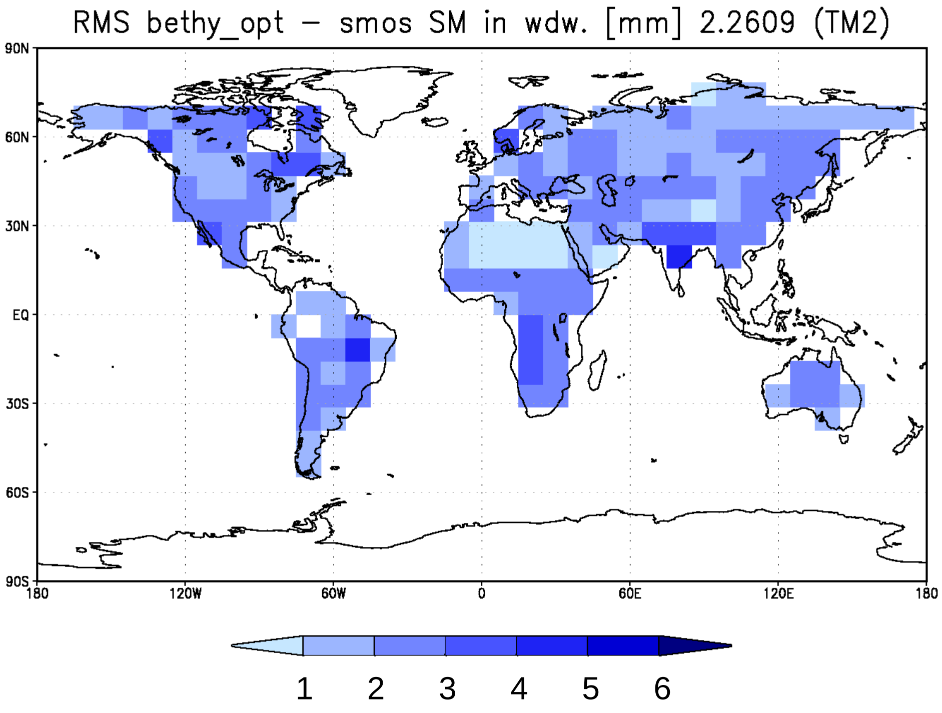


Results: soil moisture (RMS)

CO_2 only

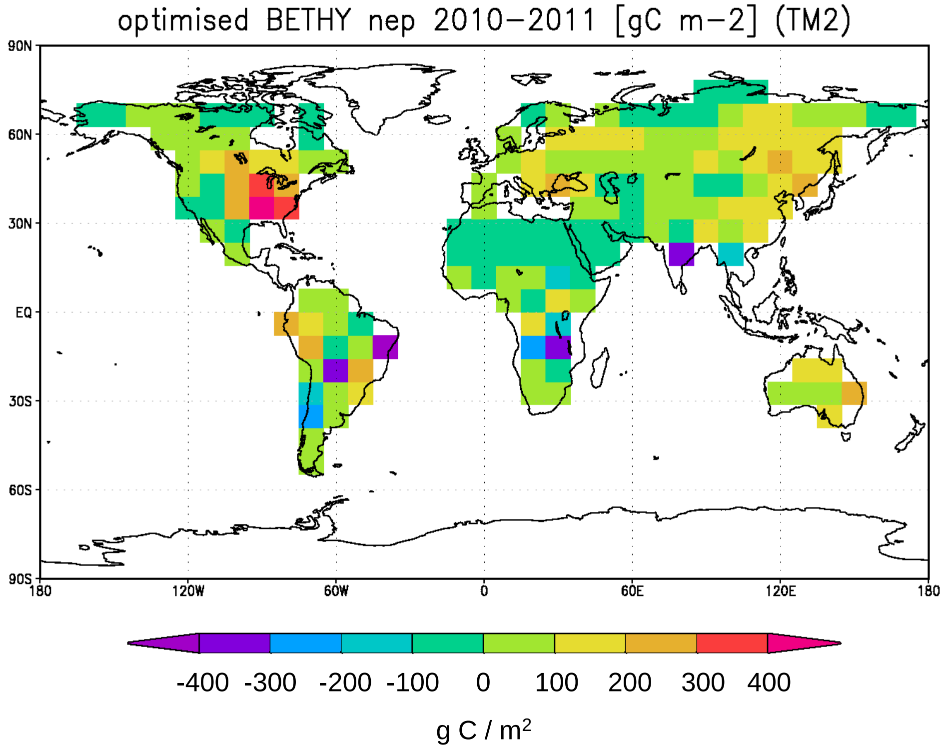
CO_2 & SMOS



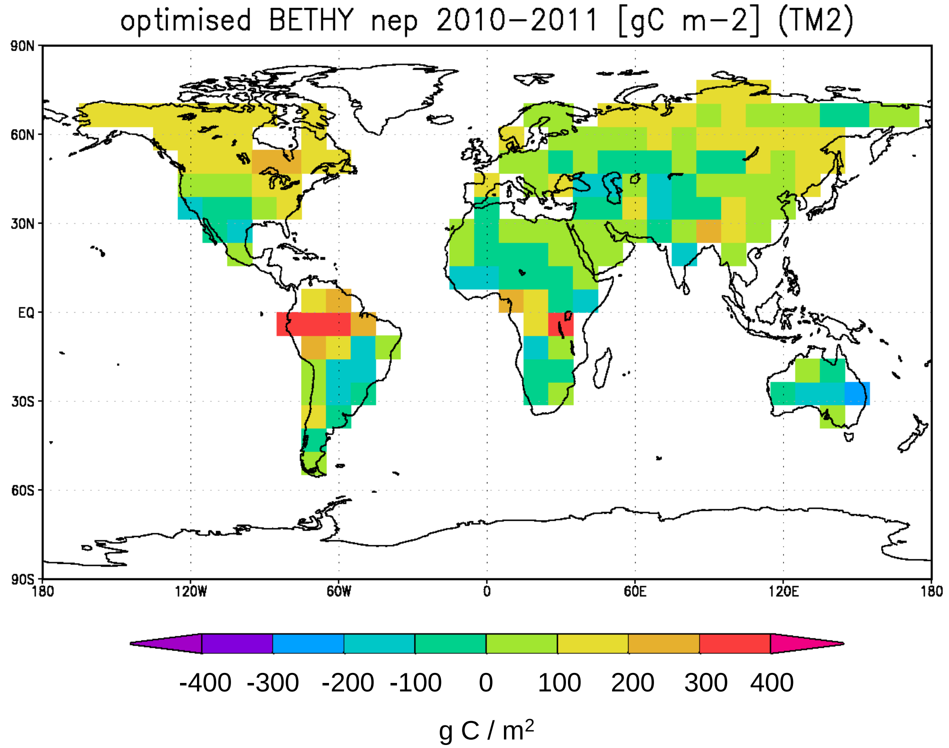


Results: CO_2 fluxes (NEP)

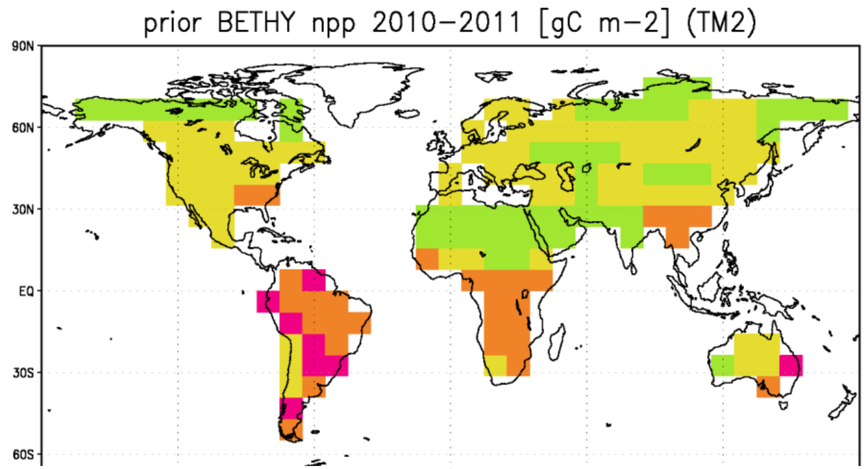
CO_2 only



CO_2 & SMOS

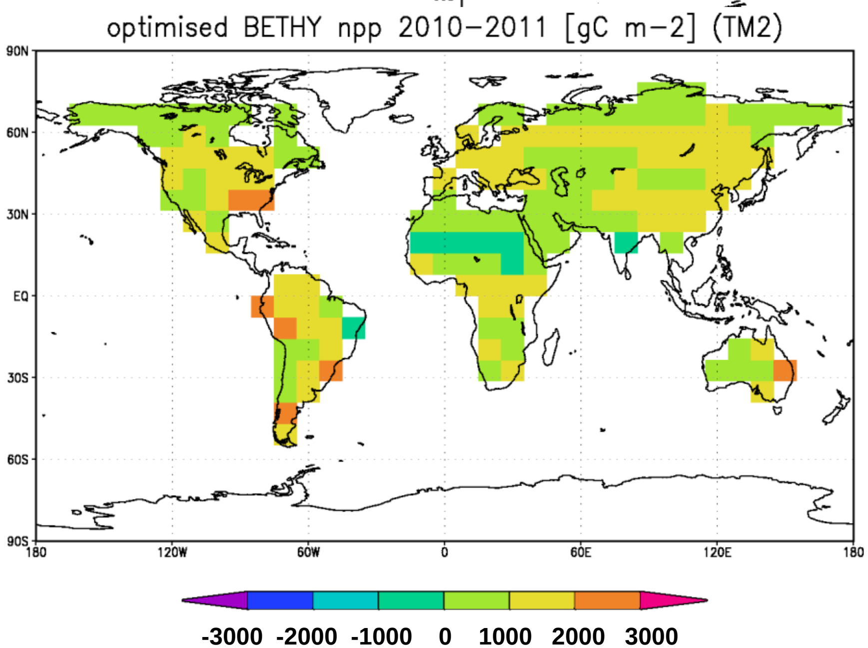


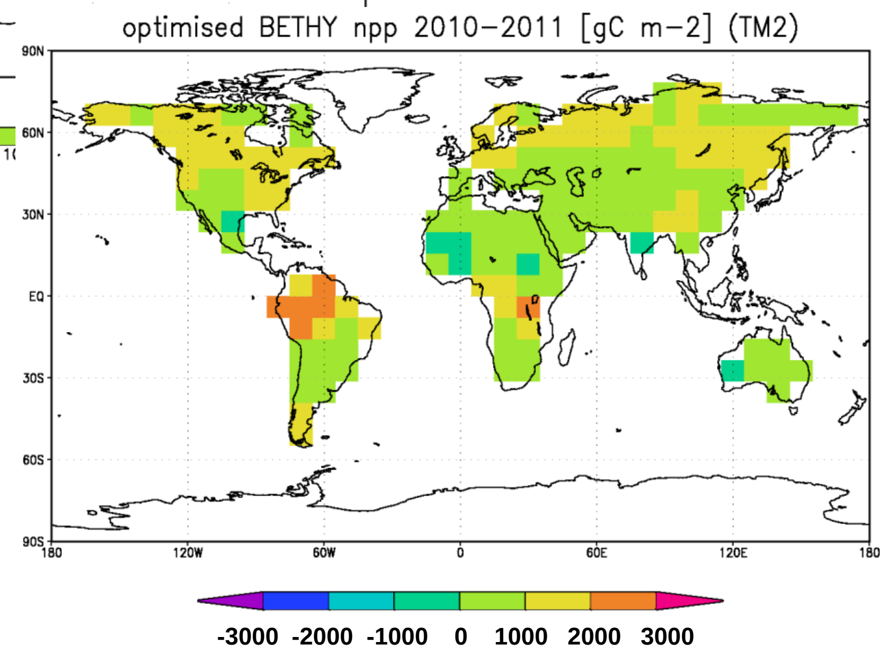
Results: CO_2 fluxes (NPP)



CO_2 only

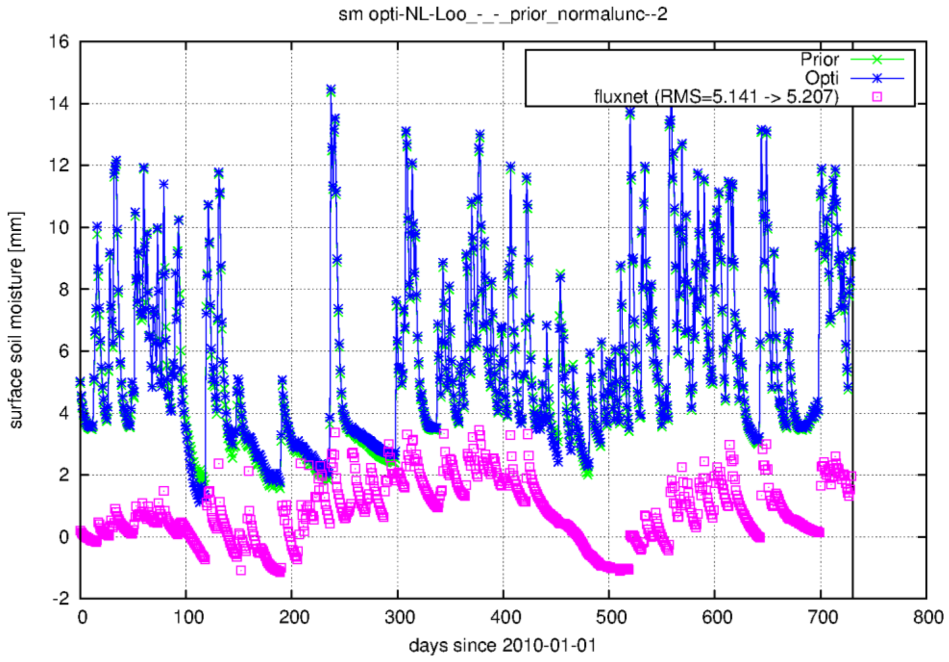
CO_2 & SMOS



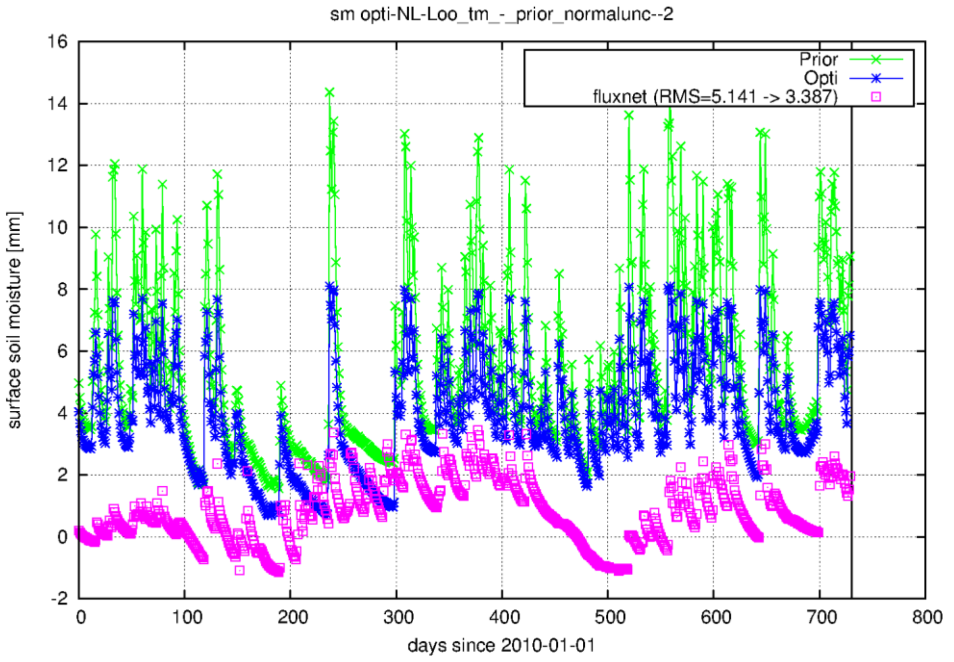


Validation: soil moisture at site level

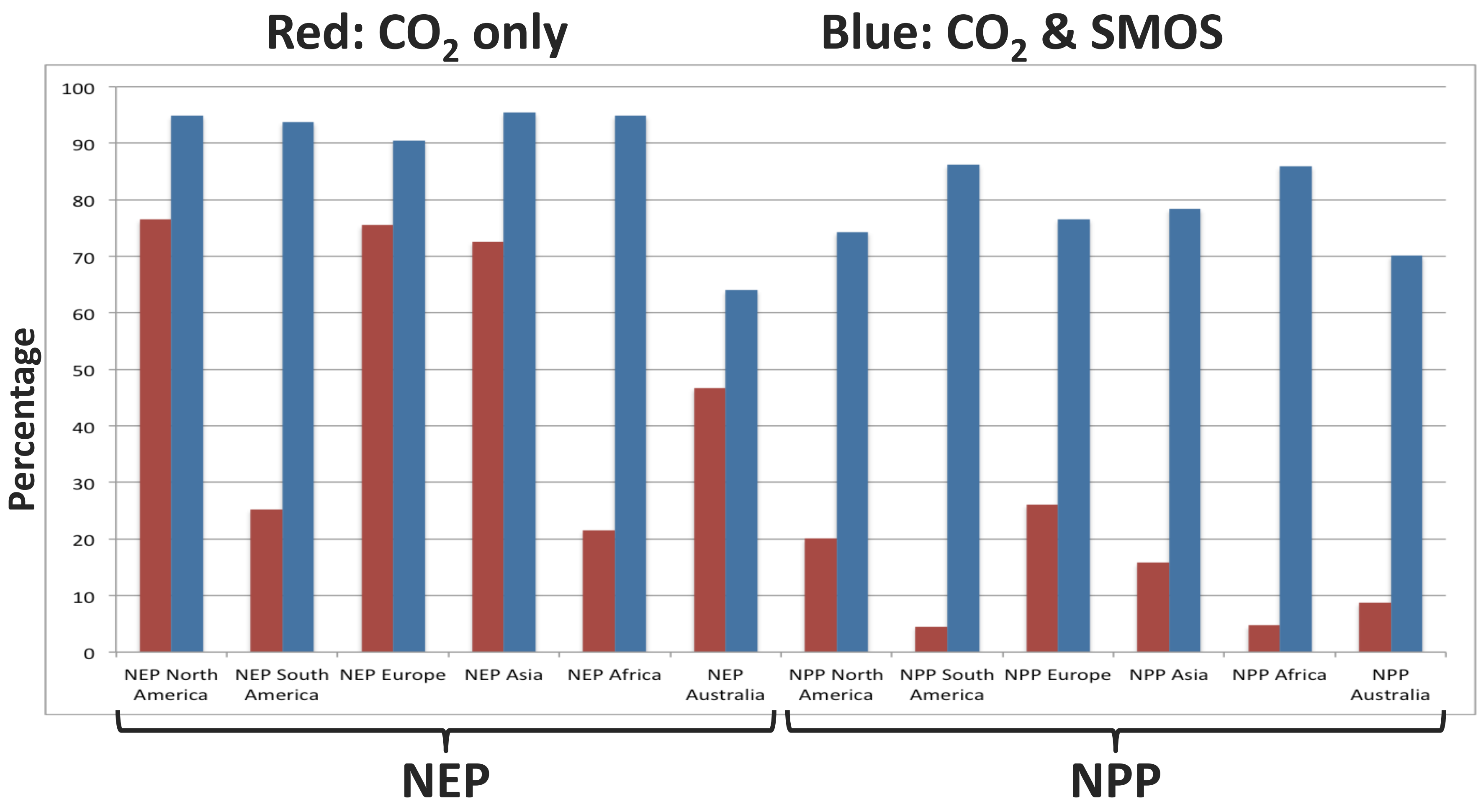
CO$_2$ only



CO$_2$ & SMOS

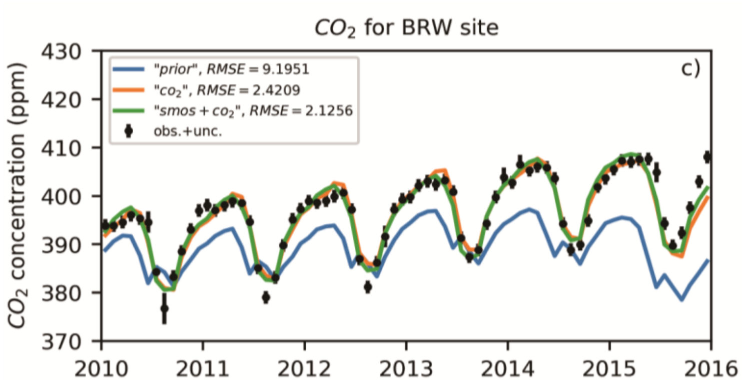


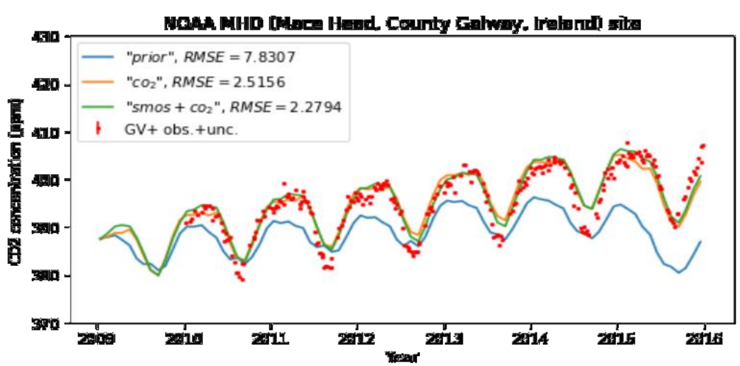
Relative flux (NEP & NPP) uncertainty reduction for 6 regions

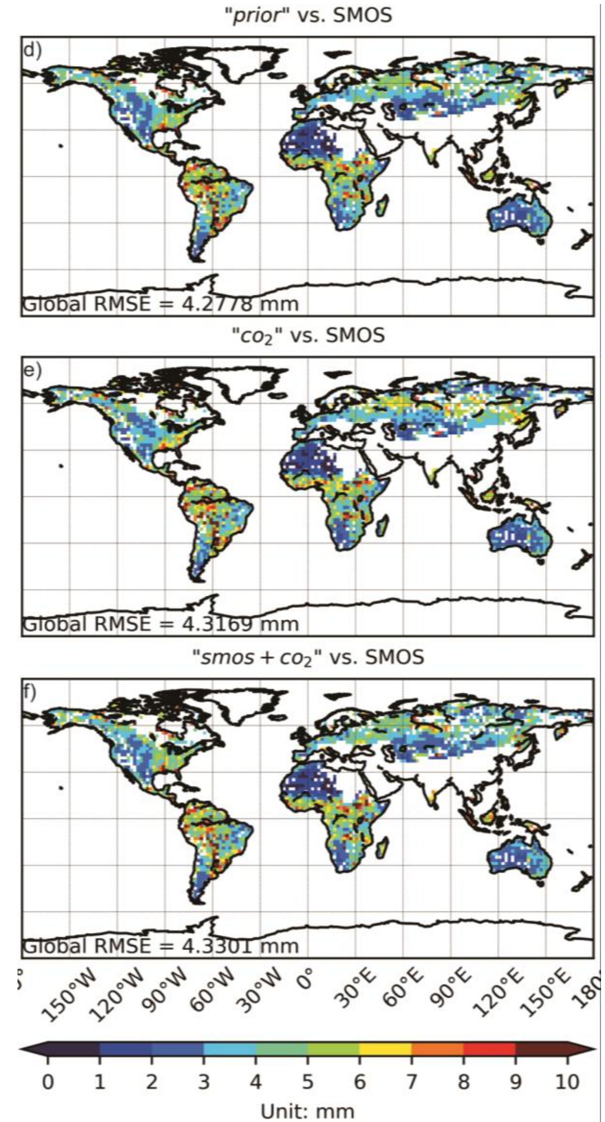


Refined global SM assimilation

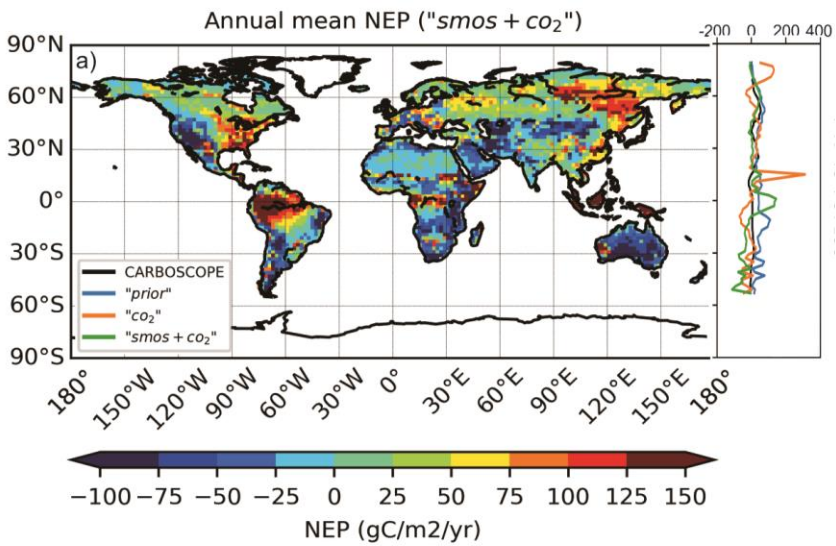
- Higher resolution (2 x 2 deg)
- Covering 2010-2015
- 2 Experiments: CO2 and SMOS+CO2

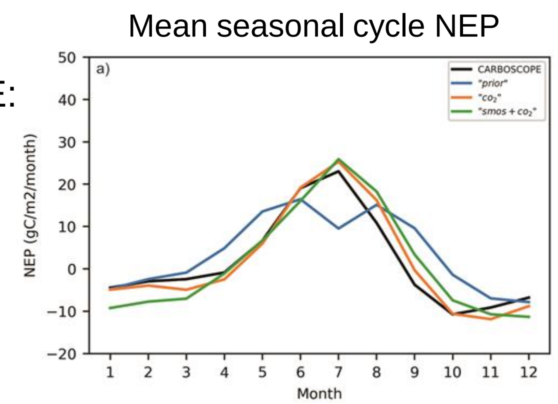




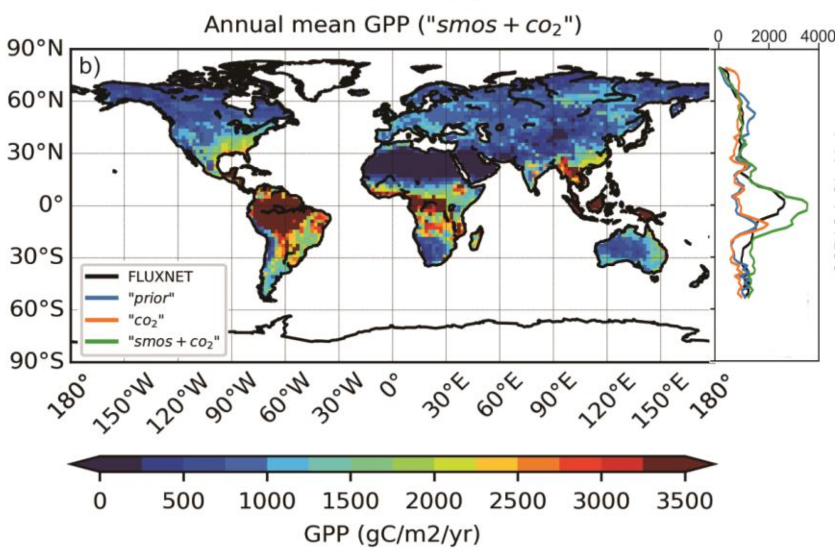


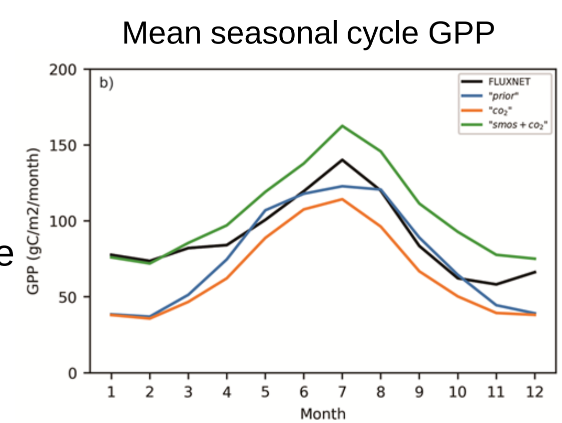
Comparison of carbon fluxes against independent data





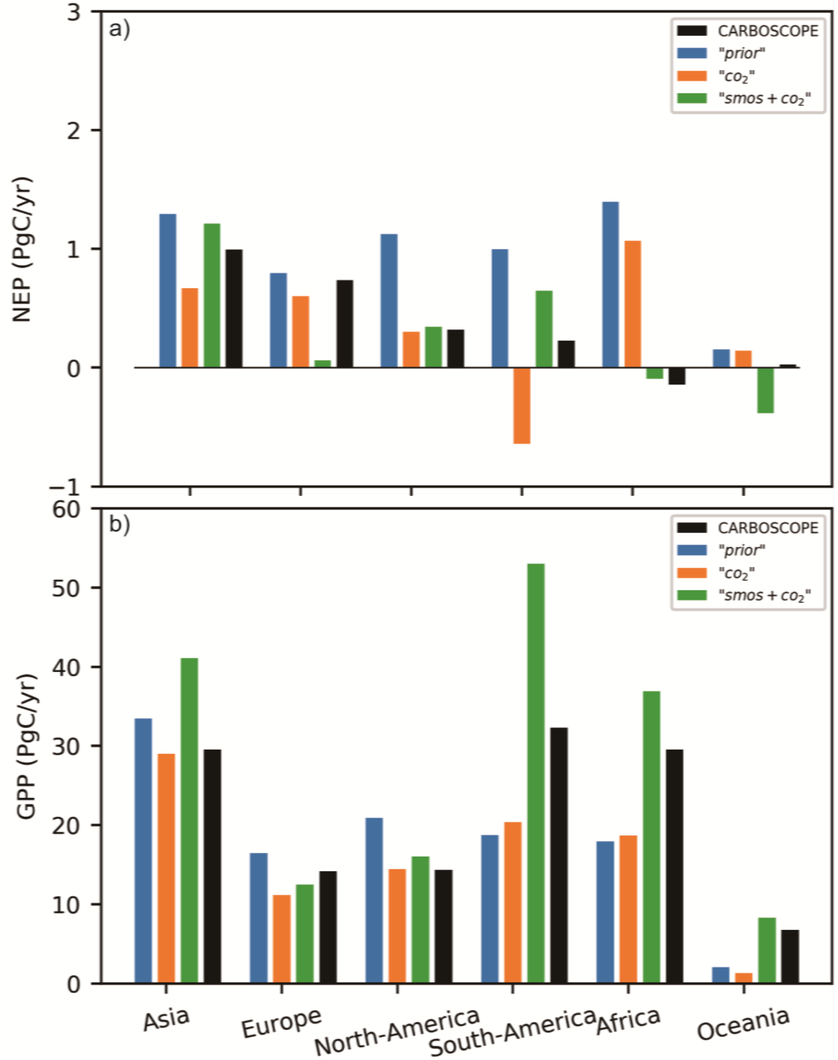
CARBOSCOPE: Net flux from atmospheric inversion





FLUXNET: Photosynthesis from upscaled eddy covariance measurements

Regional carbon budgets

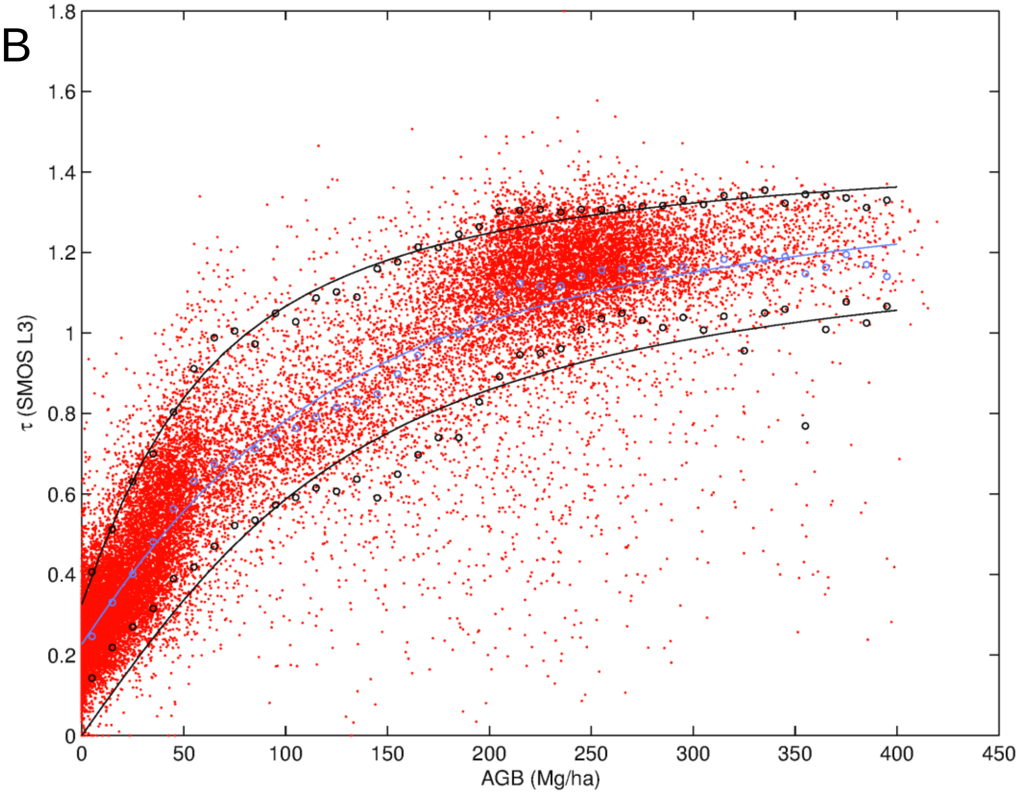


Towards VOD assimilation SMOS+VEG
L-VOD observation operator

L-VOD from SMOS fitted against AGB from Saatchi et al., 2017:

f(AGB) = a * atan(b * AGB)
a = 0.81759
b = 0.0087253

- 1.4 GHz
- right direction (i.e. AGB->VOD)
- through 0/0
- only two parameters to calibrate



on next slide we explain:

VOD=f(NPP * τ_{eff}(PFT)) + D_0(PFT) * LAI

L-VOD observation operator

More generalized approach, allowing for seasonal changes in VOD driven by leaf area. (Influence of vegetation water included in leaf area, wet leaves – dry branches...):

$$AGB = NPP * \tau_{eff}(PFT)$$
$$VOD = f(AGB) + D_0(PFT) * LAI$$

with total VOD for PFT mixture: $\exp(-VOD_{tot}) = \Sigma_i f_i \exp(-VOD_i)$

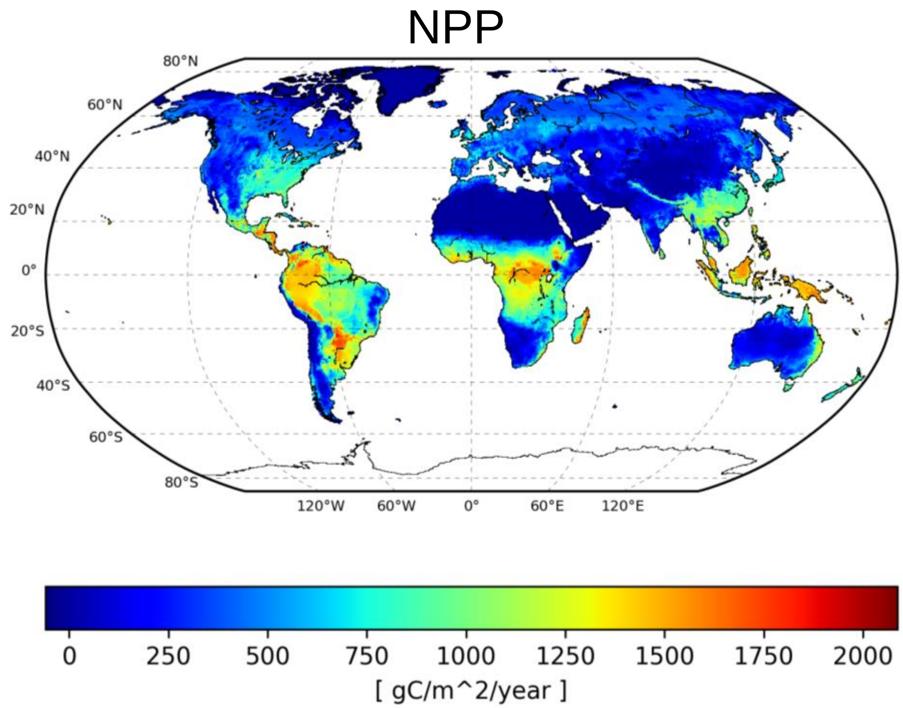
τ_{eff}: effective biomass turnover time

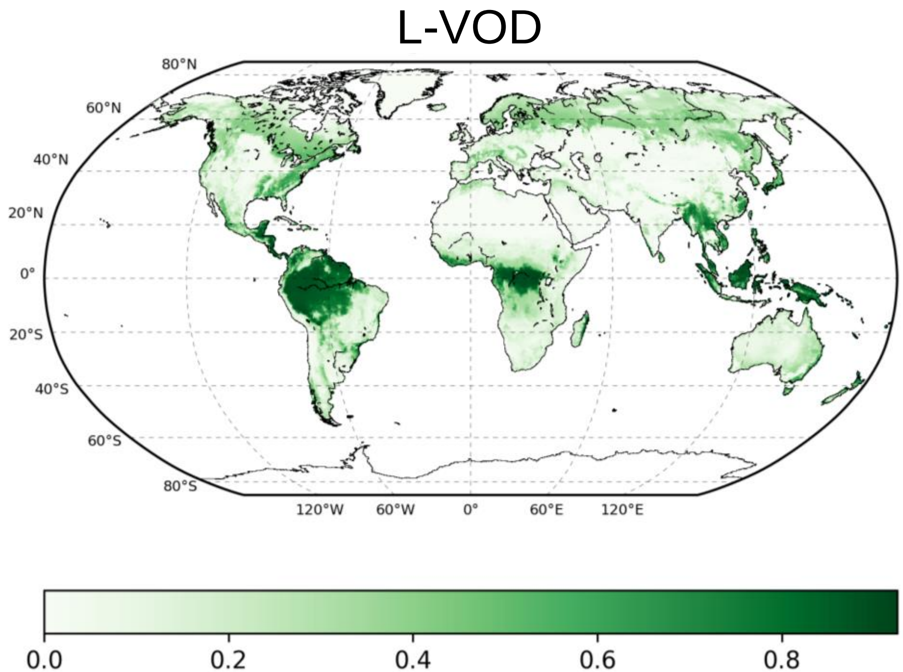
- PFT-dependent; grasses: small; trees/shrubs: large
- Accounts for NPP fraction going to AGB and differences in turnover time above/below ground
- Prior values/uncertainties could be obtained by comparing BETHY NPP with ABG data set

D_0: vegetation-optical depth at LAI=1

- A priori value 0, uncertainty ~0.5 (value for random leaf-angle distribution with diffraction/scattering)

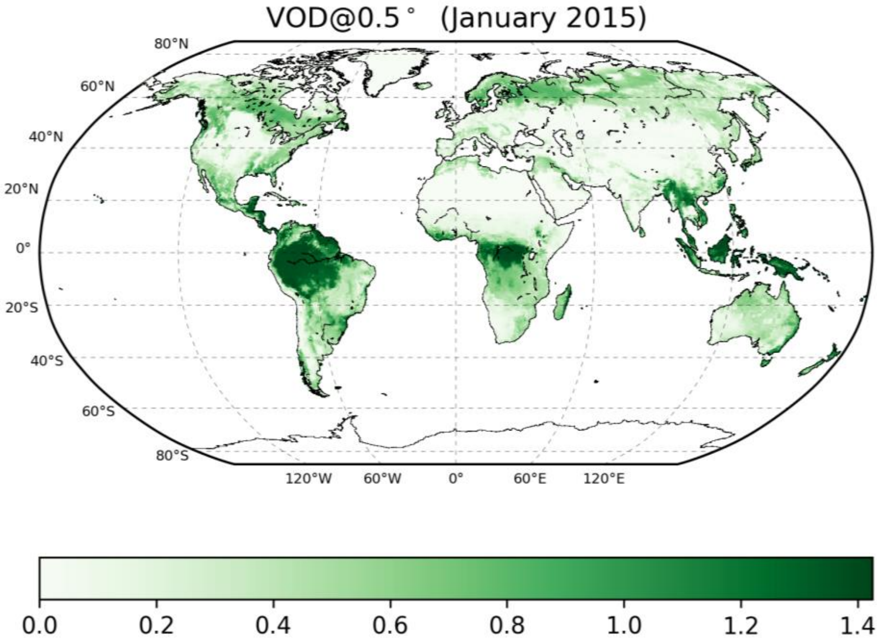
NPP and L-VOD simulation

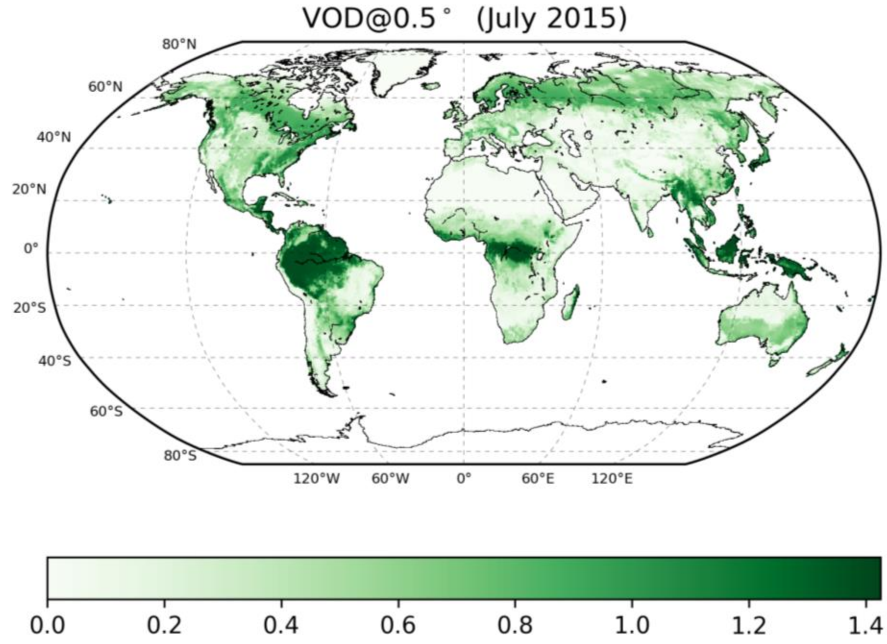




VOD=f (AGB) + D_0(PFT) * LAI,
D_0 = 0

L-VOD simulations





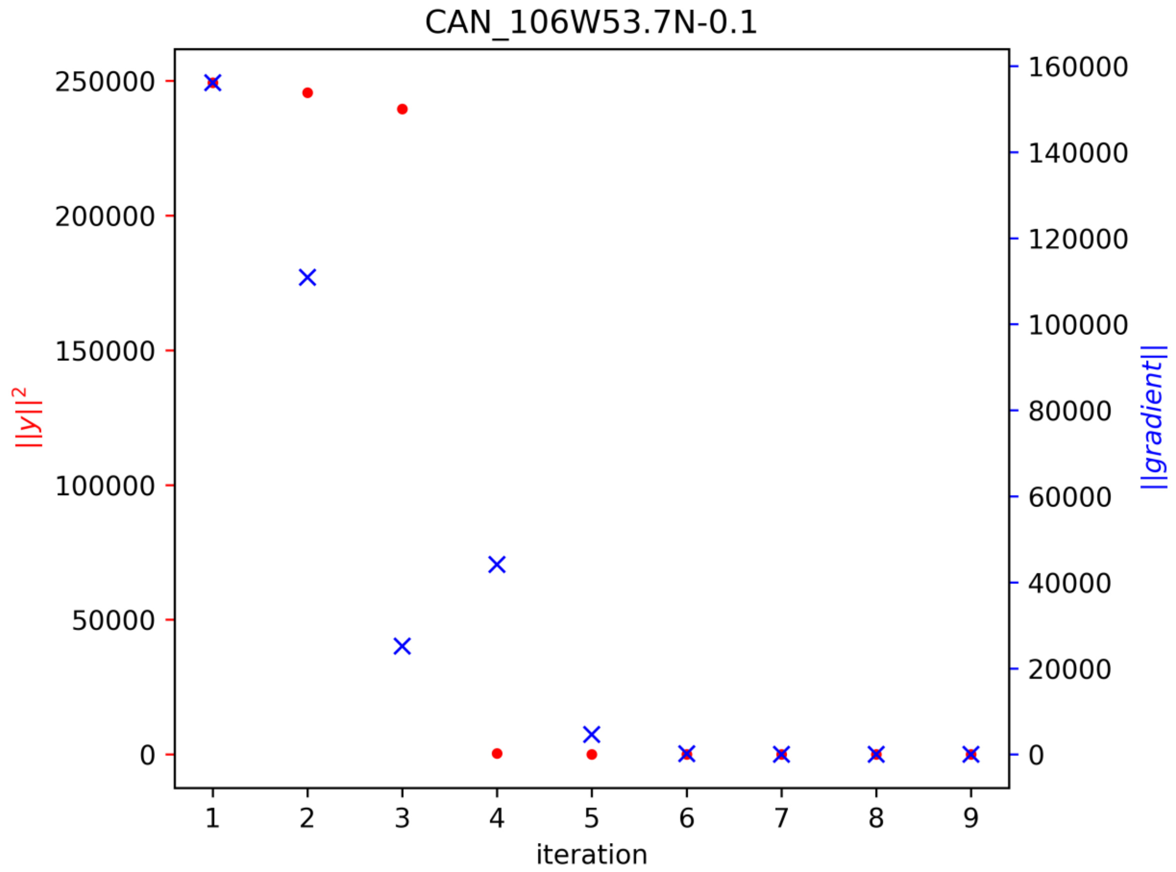
$VOD = f\,(AGB) + D_0(PFT) * LAI,$

$D_0 = 0.1$

VOD assimilation: Identical Twin

- 10 sites
- fast convergence
- for seven sites:
  - all parameters exactly recovered
  - pseudo-observations exactly matched
  - Final cost function gradient 0
- for three sites:
  - max parameter difference to truth below 5%
  - pseudo-observations almost exactly matched
  - gradient reduction by a factor of 50/1000/1.e6
  - needs further investigation

Identical twin experiment at site level

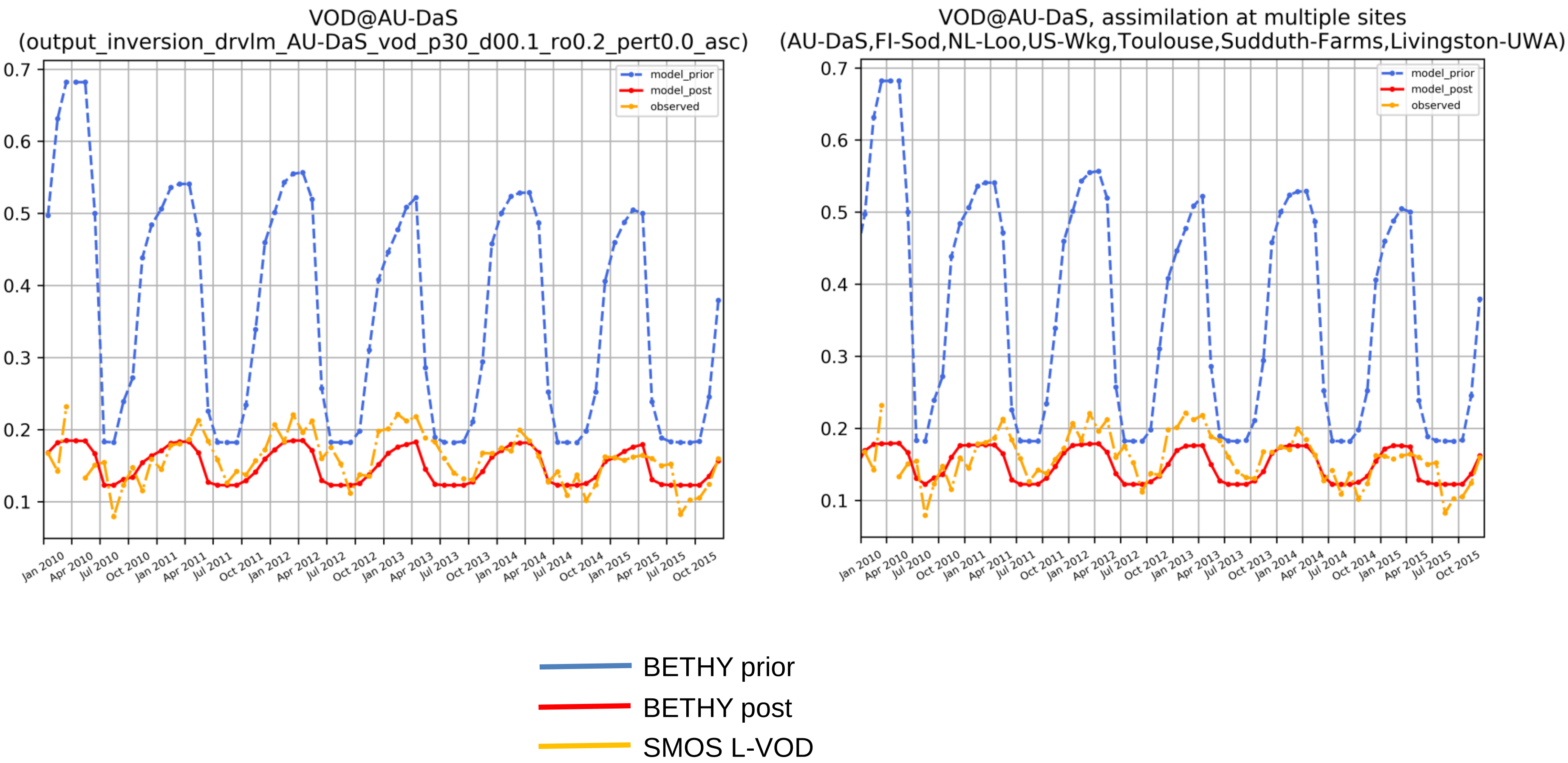


- pseudo observations of monthy VOD and SM from prior parameters for 2010-2015
- parameters are recovered after 10% perturbation

VOD assimilation

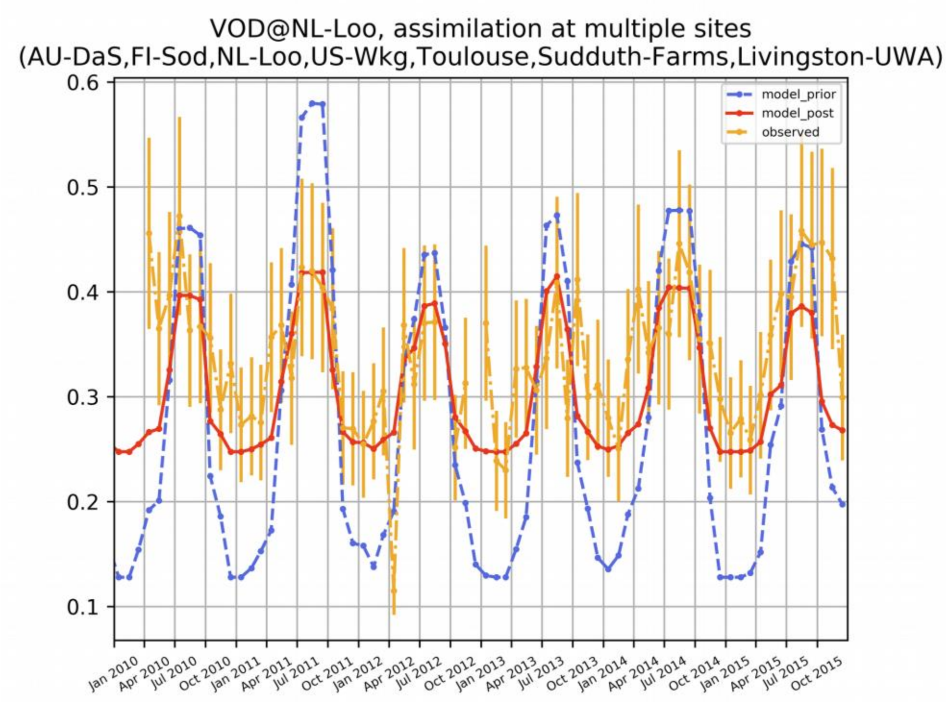
- Preliminary SMOS IC VOD product
- monthly median, 20% uncertainty
- first individually for each site
- then for all sites
- then for all but “problematic” sites

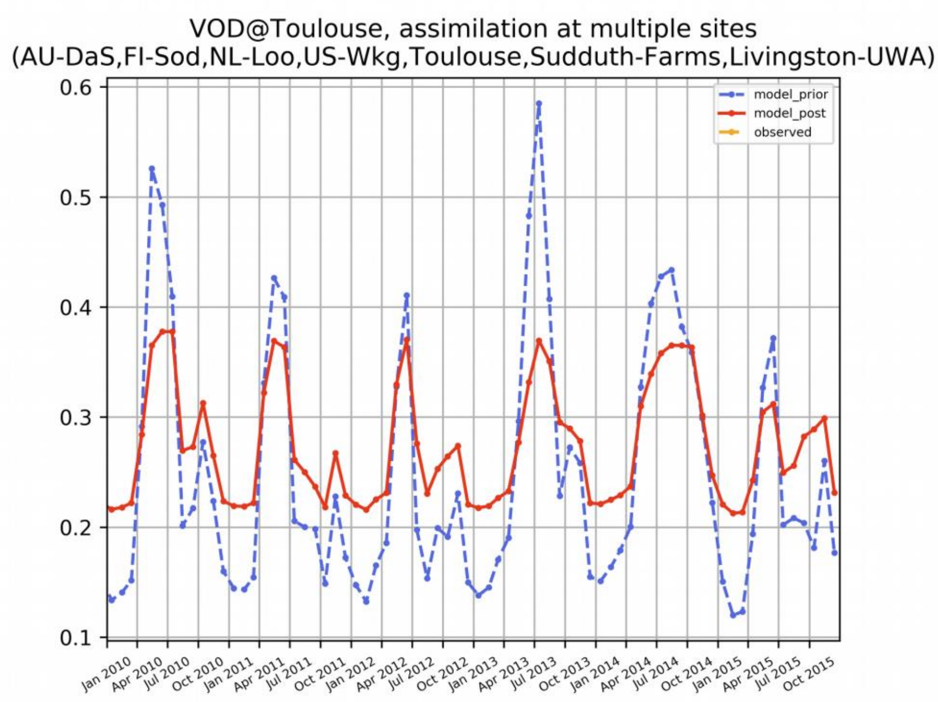
VOD assimilation single- vs multi-site



Data reference: Fernandez-Moran R., et al. "SMOS-IC: An Alternative SMOS Soil Moisture and Vegetation Optical Depth Product", Remote Sensing, 9, 457; doi:10.3390/rs9050457, 2017.

VOD assimilation multi-site

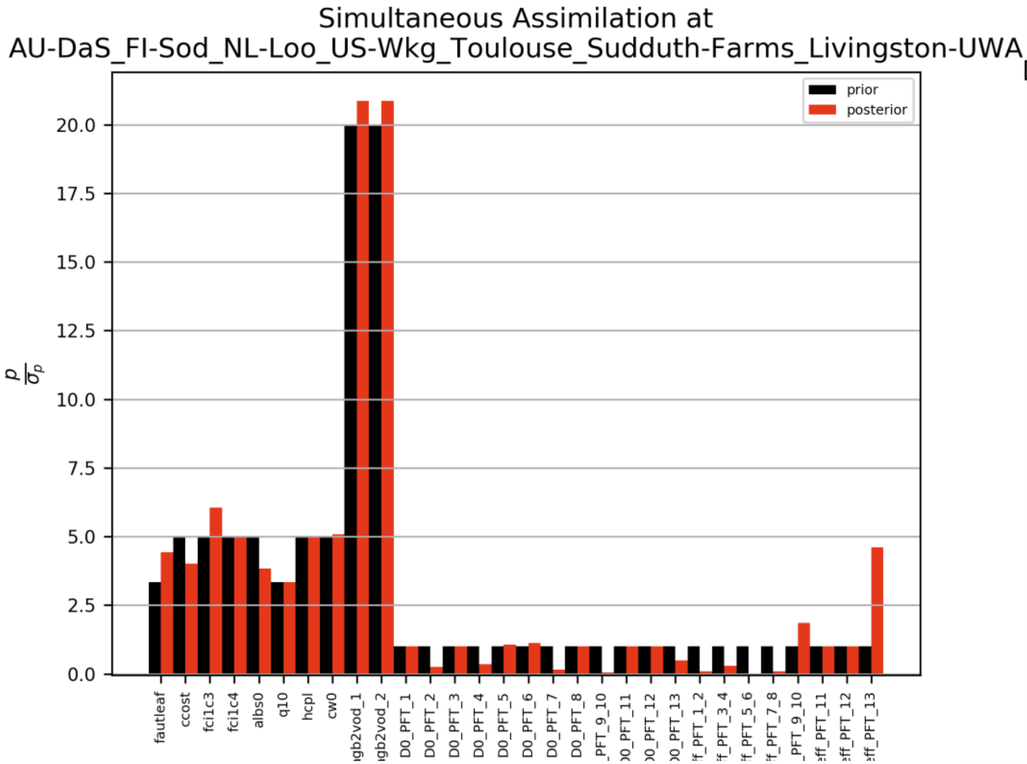


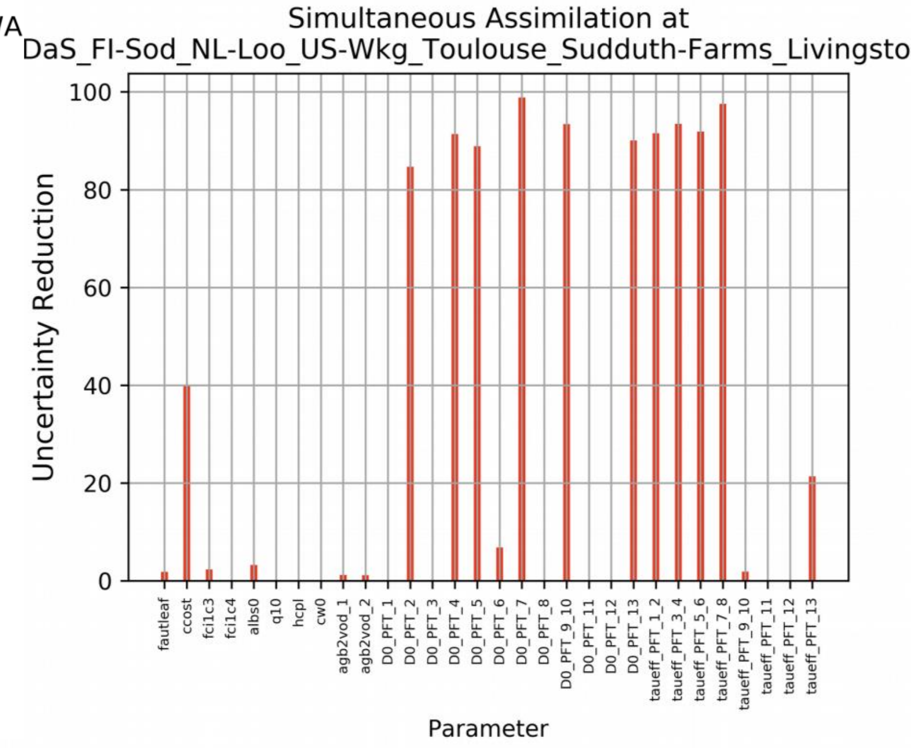


BETHY prior
BETHY post
SMOS L-VOD

Data reference: Fernandez-Moran R., et al. "SMOS-IC: An Alternative SMOS Soil Moisture and Vegetation Optical Depth Product", Remote Sensing, 9, 457; doi:10.3390/rs9050457, 2017.

VOD assimilation multi-site





Conclusions

- Global experiments simultaneously assimilating SMOS soil moisture and atmospheric CO_2 (also at high resolution)
- Significant added value (unc. reduction) when assimilating both SM and CO_2 as compared to CO_2 only
- Developed observation operator for L-VOD based on AGB, parameters in VOD = f(AGB, LAI) are part of the optimisation
- First successful identical twin experiments at site level
- First successful L-VOD assimilation experiments at site level
- Work in progress:
  - assimilate SMOS L-VOD data at global level
  - combined assimilation SMOS L-VOD, SM and atm CO_2 concentration
  - Evaluation against independent data (e.g. carbon fluxes such as NEE and NPP, atmospheric CO_2)
- CCDAS combines process understanding with a range of observations, provides an integrated view on global carbon cycle and delivers elaborated products based on SMOS data as well as further data (e.g. FAPAR, SIF,…)