A new terrestrial community carbon assimilation system (TCCAS) for combining satellite and in-situ observations into a consistent view of the terrestrial carbon cycle

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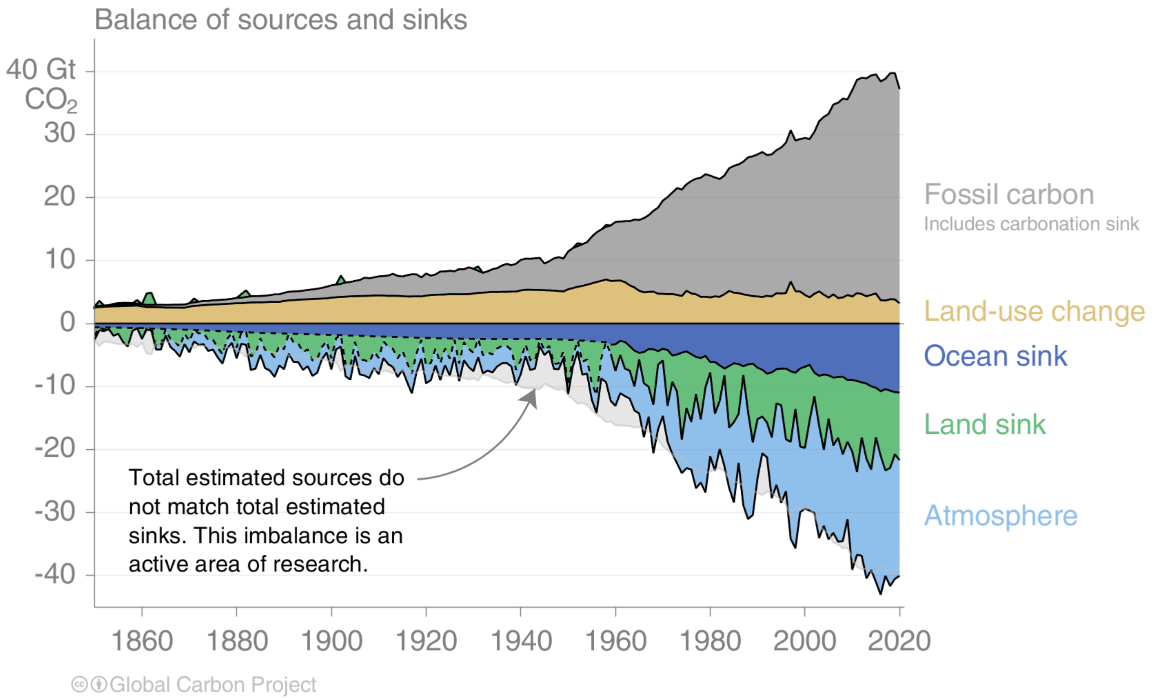
Matthias Drusch, and Dirk Schüttemeyer

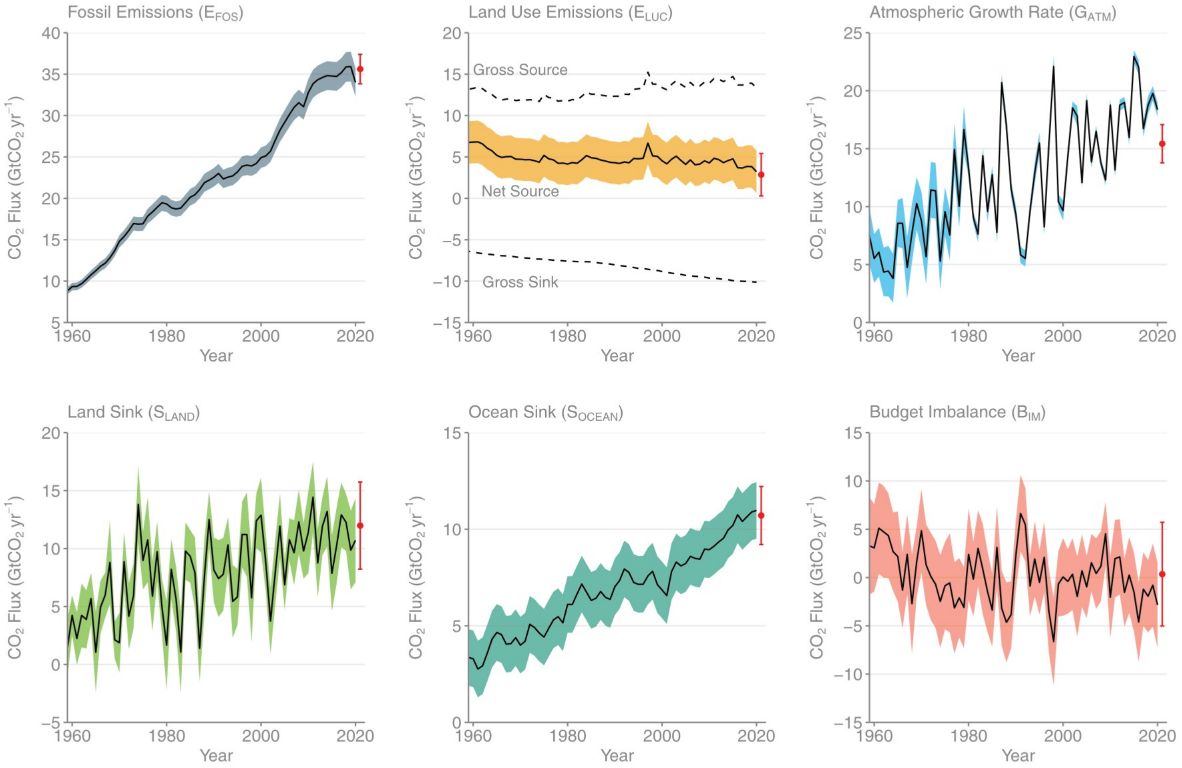
7th training course
New Advances in Land Carbon Cycle Modeling
Cornell and online, 7 June 2024

Background: Atmospheric CO_2 growth rate is offset by ocean and land sinks

CO_2 emissions from human activities and partitioning between ocean, land, and atmosphere (Global Carbon Project 2021)



Components of the global carbon budget



(Global Carbon Project 2021)

Objective

Investigate the **terrestrial biosphere's net ecosystem exchange** – photosynthetic CO_2 uptake minus respiratory CO_2 release – **response to climatic drivers** by means of combining a process-based model with a **wide range of observations (in-situ and remotely sensed) on local and regional scale** around two (three) sites (Sodankyla, Majadas, Reusel).

For this we:

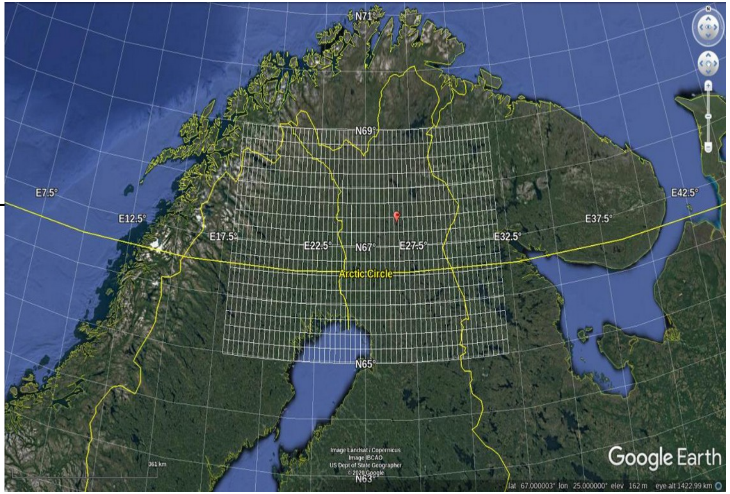
- Generated a **community land surface model for its application in a data assimilation framework**
- Acquired and analysed **EO and campaign data sets**

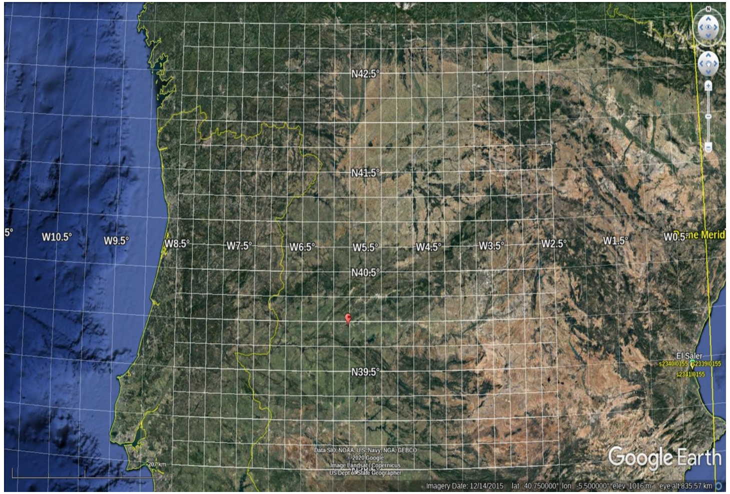
Motivation: Space Agencies point of view

*'… a number of **satellite missions from ESA and other Space Agencies are being developed**, **each of them addressing one or more geophysical parameters related to the carbon and water cycles**. In a few years from now, the **FLEX and BIOMASS missions** will provide new data related to photosynthetic efficiency and gross primary productivity and above ground biomass, respectively. These measurements will **complement information** that is already available **from low frequency passive microwave measurements** (soil moisture, vegetation optical depth), **active microwave measurements** (vegetation water content and roughness), and **optical measurements** …. While there is an **obvious complementarity** in the different data provided by each one of such missions, **so far there are no specific plans to combine the data together**. This is primarily because these measurements a) exhibit different sensitivities to the various geophysical parameters, b) address geophysical parameters characterised by different spatial and temporal variabilities, and c)*

Modelling at local and regional scales

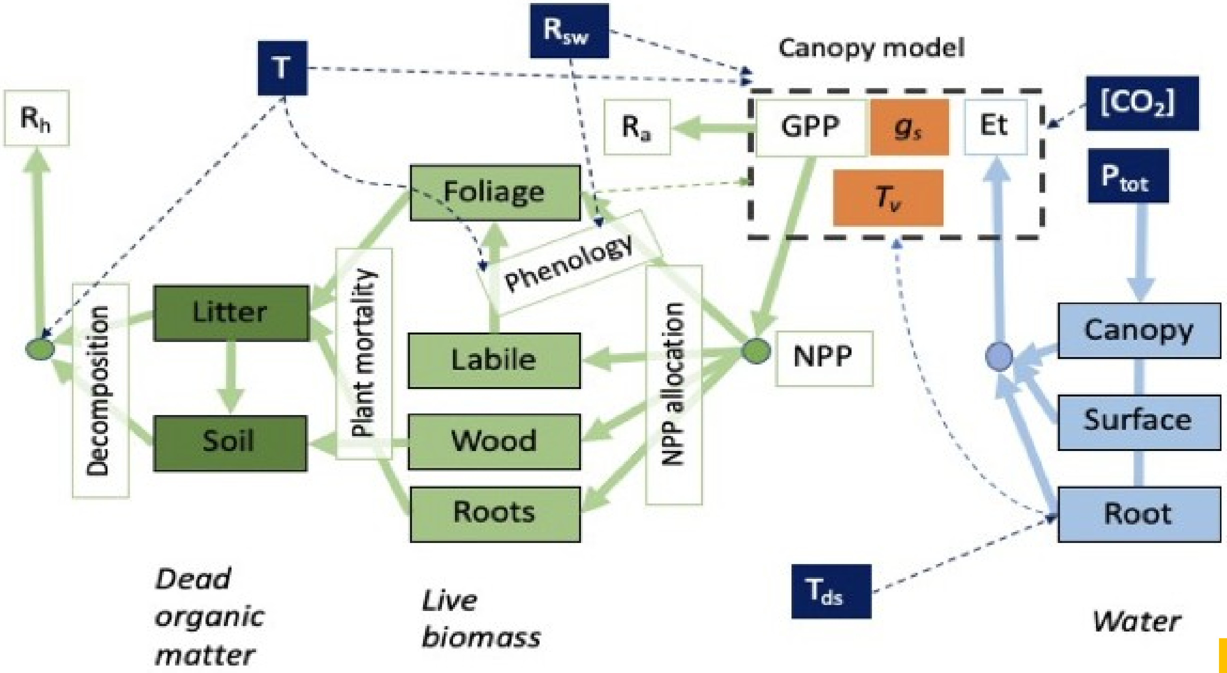
- Demonstration of synergistic use of observations at local and regional scale
- Regional scale: 500 km x 500 km area around the sites at 0.25 deg resolution (Sodankyla & Majadas)
- Broad range of activities:
  - EO data
  - Field activities
  - Model and observation operators
  - Data assimilation





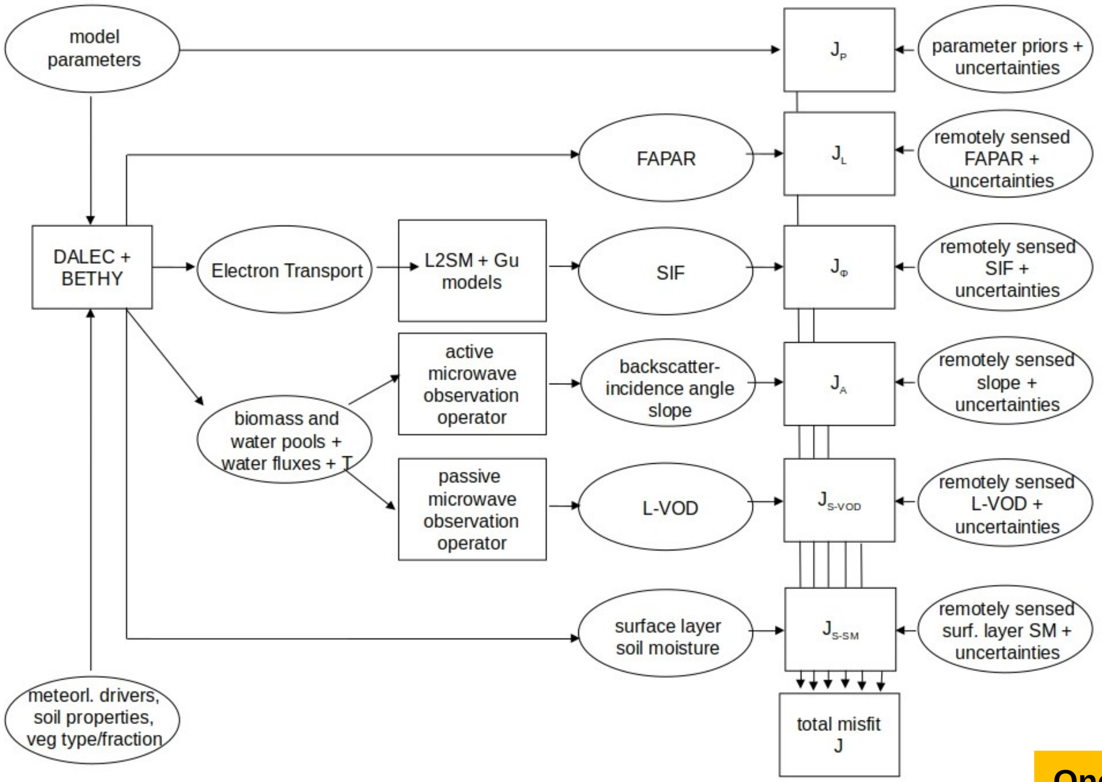
Community land surface model: D&B model

Based on a coupling of DALEC and BETHY



New Implementation

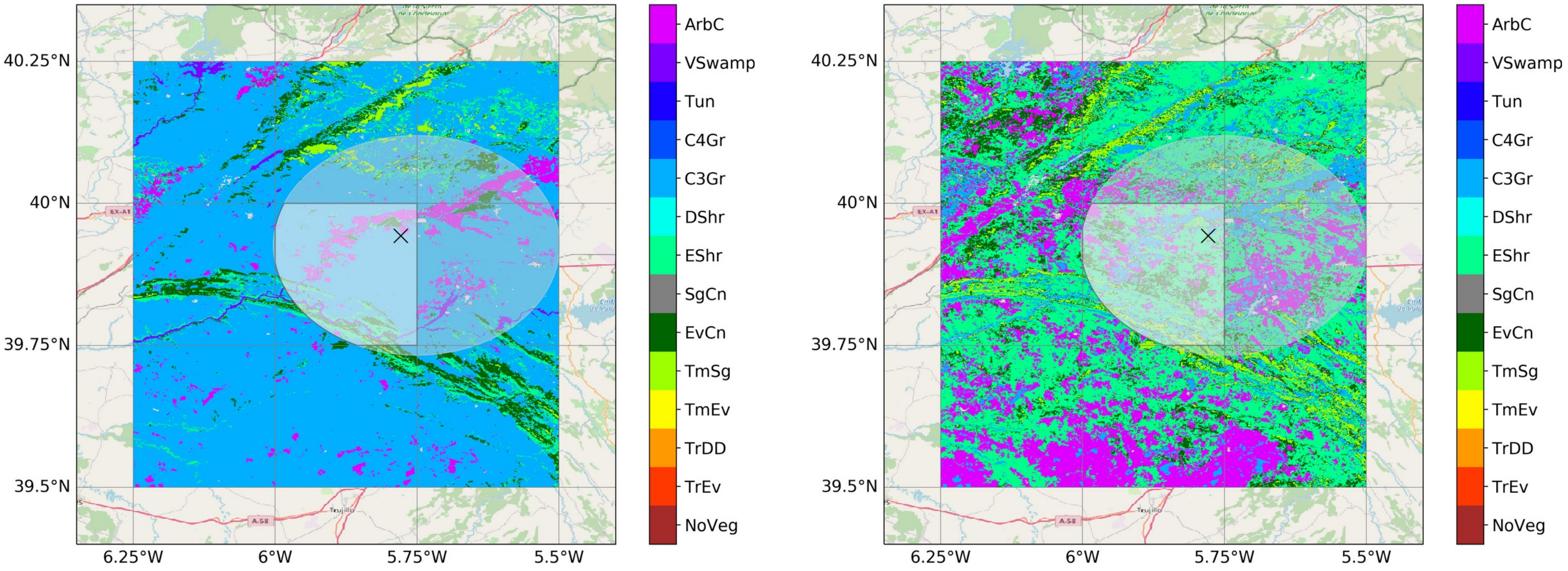
Observation operators and data assimilation (on the swath)



One long assimilation window

Simulation on the satellite footprint

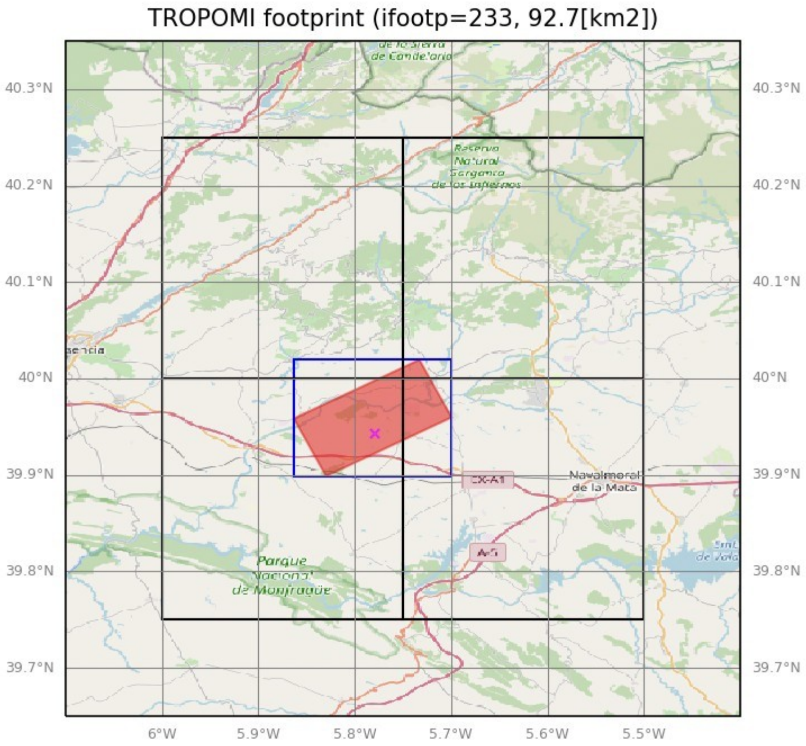
Example SMOS: PFT map provides spatial detail

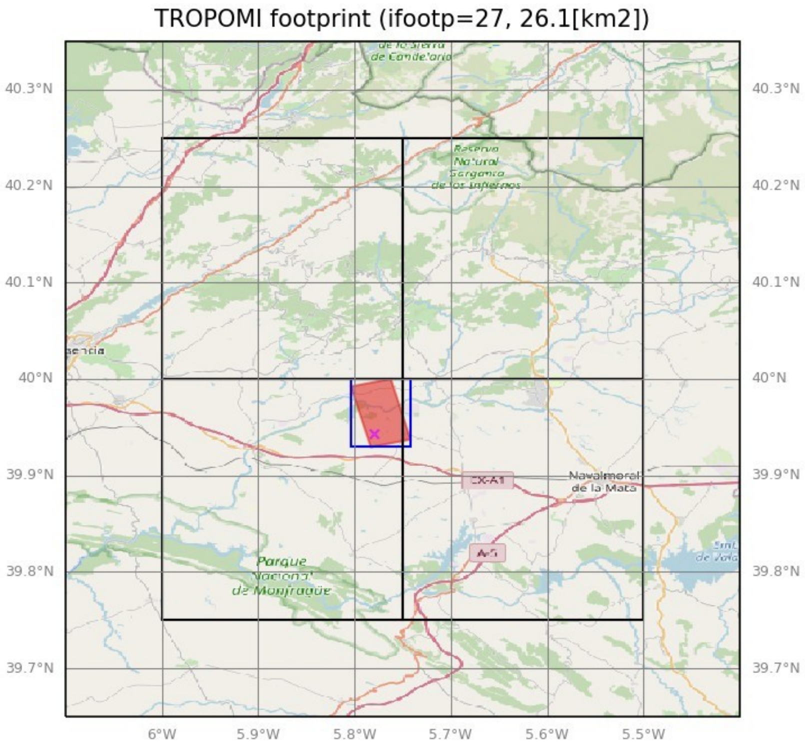


SMOS footprint (ellipse) along with the primary (left) and secondary (right) PFT over the grid defined by the meteorological driving data, with the location of the Majadas site indicated by a cross.

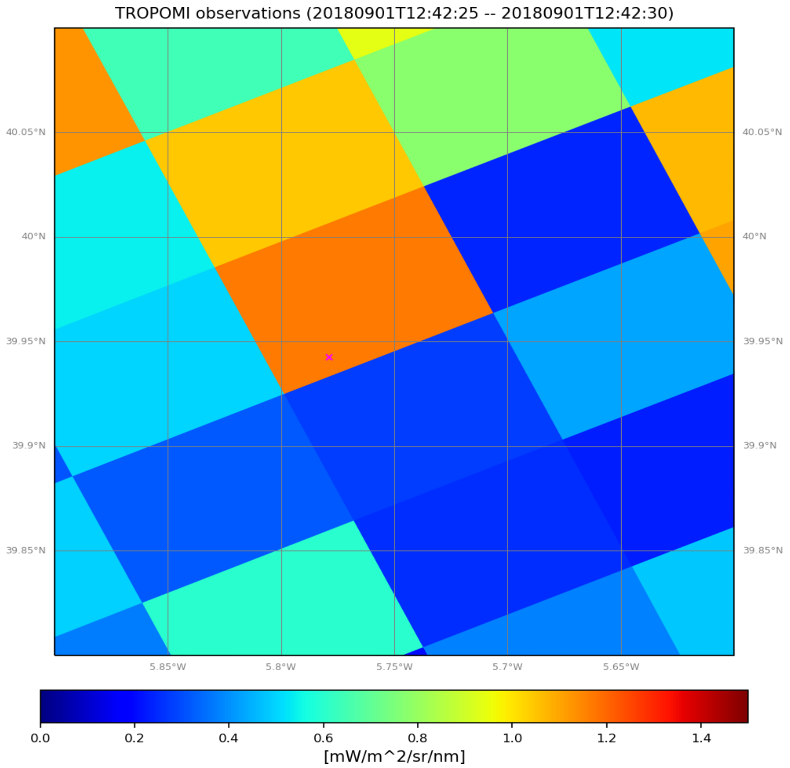
Simulation on the satellite footprint

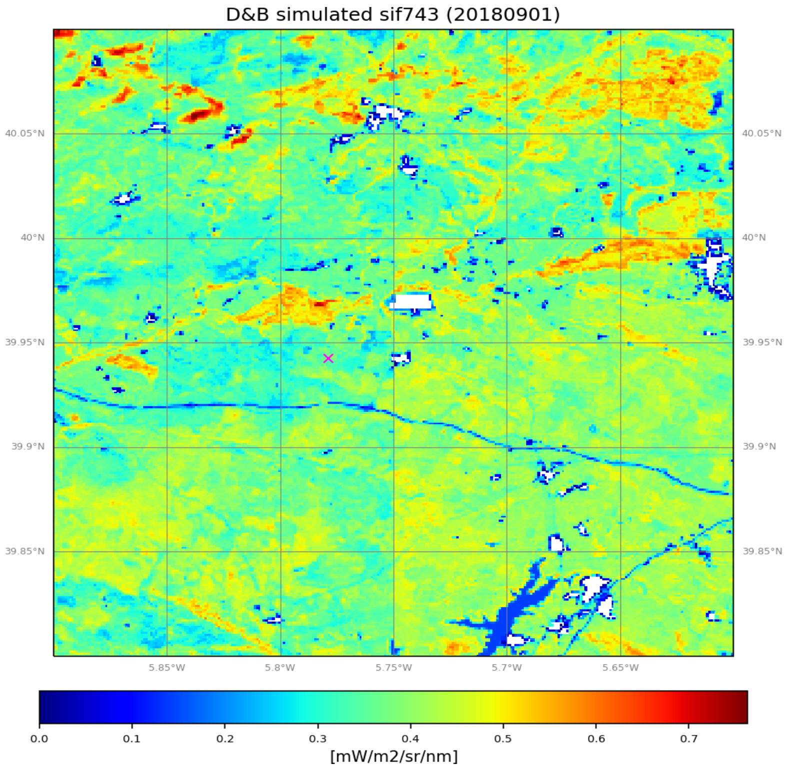
Example TROPOMI: Two different images





Spatial Detail
Examples: TROPOMI (left) and simulated (right) SIF





Control Space (unknowns): Model parameters & initial condition (example for site in Spain)

#	varname	PFT	active	prior	sigma	min	max	nbound	process	description (don't use commas!)
1	vmax	3	1	0.000041	0.0000082	0.00001	0.00008	2	photosynthesis	maximum carboxylation rate at ref. Temperature [mol(CO2) / m^2 s]
2	vmax	9	1	0.000042	0.0000084	0.00001	0.00008	2	photosynthesis	maximum carboxylation rate at ref. Temperature [mol(CO2) / m^2 s]
3	root_depth_scale	-1	1	1.	0.2	0.	5.	1	soilwater	"root_depth_scale"
4	soil_theta_scale	-1	1	1.	0.2	0.	5.	1	soilwater	"soil_theta_scale"
5	DALEC P1	3	1	0.0003038811	0.00006077622	0.00001	0.01	2	cbalance+pheno	fractional turnover rate of litter to soil organic matter at 0oC
6	DALEC P2	3	1	0.4016085	0.0803217	0.2	0.8	2	cbalance+pheno	fraction of gross primary productivity allocated to autotrophic respiration
7	DALEC P3	3	1	0.04980515	0.00996103	0.01	0.5	2	cbalance+pheno	fraction of gpp-ra allocated to leaves
8	DALEC P4	3	1	0.3553572	0.07107144	0.1	0.8	2	cbalance+pheno	fraction of gpp-ra-alloc_fol-alloc_lab allocated to fine roots
9	DALEC P5	3	1	1.104317	0.2208634	1.001	8	2	cbalance+pheno	maximum leaf lifespan
10	DALEC P6	3	1	0.00006646695	0.00001329339	0.000009	0.001	2	cbalance+pheno	fractional daily turnover of the wood pool
11	DALEC P7	3	1	0.005876034	0.0011752068	0.001368925	0.02	2	cbalance+pheno	fractional daily turnover of the fine root pool
12	DALEC P8	3	1	0.006875432	0.0013750864	0.0001141	0.02	2	cbalance+pheno	fractional daily turnover of the litter pool to heterotrophic respiration
13	DALEC P9	3	1	0.00002478762	0.000004957524	1.37E-06	9.13E-05	2	cbalance+pheno	fractional daily turnover of the soil organic matter pool to heterotrophic respiration
14	DALEC P10	3	1	0.05102073	0.010204146	0.019	0.08	2	cbalance+pheno	coefficient for exponential temperature sensitivity for litter decomposition and litter and som turnover to heterotrophic respiration
15	DALEC P11	3	1	22.29913	4.459826	1.64	42	2	cbalance+pheno	Canopy photosynthetic efficiency parameter
16	DALEC P12	3	1	74.3057	14.86114	10	350	2	cbalance+pheno	Day of year for maximum labile turnover to foliage (i.e. bud burst)
17	DALEC P13	3	1	0.2200071	0.04400142	0.01	0.5	2	cbalance+pheno	fraction of gpp-ra-alloc_fol allocated to labile pool (which supports seasonal leaf growth)
18	DALEC P14	3	1	74.18161	14.836322	10	100	2	cbalance+pheno	Number of days over which labile turnover to leaves occurs
19	DALEC P15	3	1	157.3799	31.47598	10	350	2	cbalance+pheno	Day of year for maximum leaf turnover to litter (i.e. leaf senesence)
20	DALEC P16	3	1	54.62658	10.925316	20	150	2	cbalance+pheno	Number of days over which leaf turnover to litter occurs
21	DALEC P17	3	1	67.66937	13.533874	20	180	2	cbalance+pheno	Leaf carbon per unit leaf area
22	DALEC P1	9	1	0.002584829	0.0005169658	0.00001	0.01	2	cbalance+pheno	fractional turnover rate of litter to soil organic matter at 0oC
23	DALEC P2	9	1	0.5392843	0.10785686	0.2	0.8	2	cbalance+pheno	fraction of gross primary productivity allocated to autotrophic respiration
24	DALEC P3	9	1	0.3613487	0.07226974	0.01	0.5	2	cbalance+pheno	fraction of gpp-ra allocated to leaves
25	DALEC P4	9	1	0.7058508	0.14117016	0.1	0.8	2	cbalance+pheno	fraction of gpp-ra-alloc_fol-alloc_lab allocated to fine roots
26	DALEC P5	9	1	1.008241	0.2016482	1.001	8	2	cbalance+pheno	maximum leaf lifespan
27	DALEC P6	9	1	0.0007320861	0.00014641722	0.000009	0.001	2	cbalance+pheno	fractional daily turnover of the wood pool
28	DALEC P7	9	1	0.008705515	0.001741103	0.001368925	0.02	2	cbalance+pheno	fractional daily turnover of the fine root pool
29	DALEC P8	9	1	0.0005506519	0.00011013038	0.0001141	0.02	2	cbalance+pheno	fractional daily turnover of the litter pool to heterotrophic respiration
30	DALEC P9	9	1	0.00003957299	0.000007914598	1.37E-06	9.13E-05	2	cbalance+pheno	fractional daily turnover of the soil organic matter pool to heterotrophic respiration
31	DALEC P10	9	1	0.03424815	0.00684963	0.019	0.08	2	cbalance+pheno	coefficient for exponential temperature sensitivity for litter decomposition and litter and som turnover to heterotrophic respiration
32	DALEC P11	9	1	14.25688	2.851376	1.64	42	2	cbalance+pheno	Canopy photosynthetic efficiency parameter
33	DALEC P12	9	1	77.34133	15.468266	10	350	2	cbalance+pheno	Day of year for maximum labile turnover to foliage (i.e. bud burst)
34	DALEC P13	9	1	0.4192669	0.08385338	0.01	0.5	2	cbalance+pheno	fraction of gpp-ra-alloc_fol allocated to labile pool (which supports seasonal leaf growth)
35	DALEC P14	9	1	28.08799	5.617598	10	100	2	cbalance+pheno	Number of days over which labile turnover to leaves occurs
36	DALEC P15	9	1	121.9728	24.39456	10	350	2	cbalance+pheno	Day of year for maximum leaf turnover to litter (i.e. leaf senesence)
37	DALEC P16	9	1	65.04758	13.009516	20	150	2	cbalance+pheno	Number of days over which leaf turnover to litter occurs
38	DALEC P17	9	1	46.94364	9.388728	20	180	2	cbalance+pheno	Leaf carbon per unit leaf area
39	DALEC IC P18	3	1	34.5735	6.9147	1	2000	2	cbalance+pheno	Initial size of the labile pool
40	DALEC IC P19	3	1	36.33911	7.267822	1	2000	2	cbalance+pheno	Initial size of the foliage pool
41	DALEC IC P20	3	1	34.91805	6.98361	1	2000	2	cbalance+pheno	Initial size of the fine root pool
42	DALEC IC P21	3	1	6737.396	1347.4792	1	30000	2	cbalance+pheno	Initial size of the wood pool
43	DALEC IC P22	3	1	12.89959	2.579918	1	2000	2	cbalance+pheno	Initial size of the litter pool (NOTE: this is for foliage and fine root only)
44	DALEC IC P23	3	1	11818.84	2363.768	200	250000	2	cbalance+pheno	Initial size of the soil organic matter pool (NOTE: this is the soil plus wood litter)
45	DALEC IC P18	9	1	60.98822	12.197644	1	2000	2	cbalance+pheno	Initial size of the labile pool

Variational data assimilation

- Uses gradient of cost function in iterative search of the control space
- Gradient information efficiently provided by so- called adjoint code of J(x)

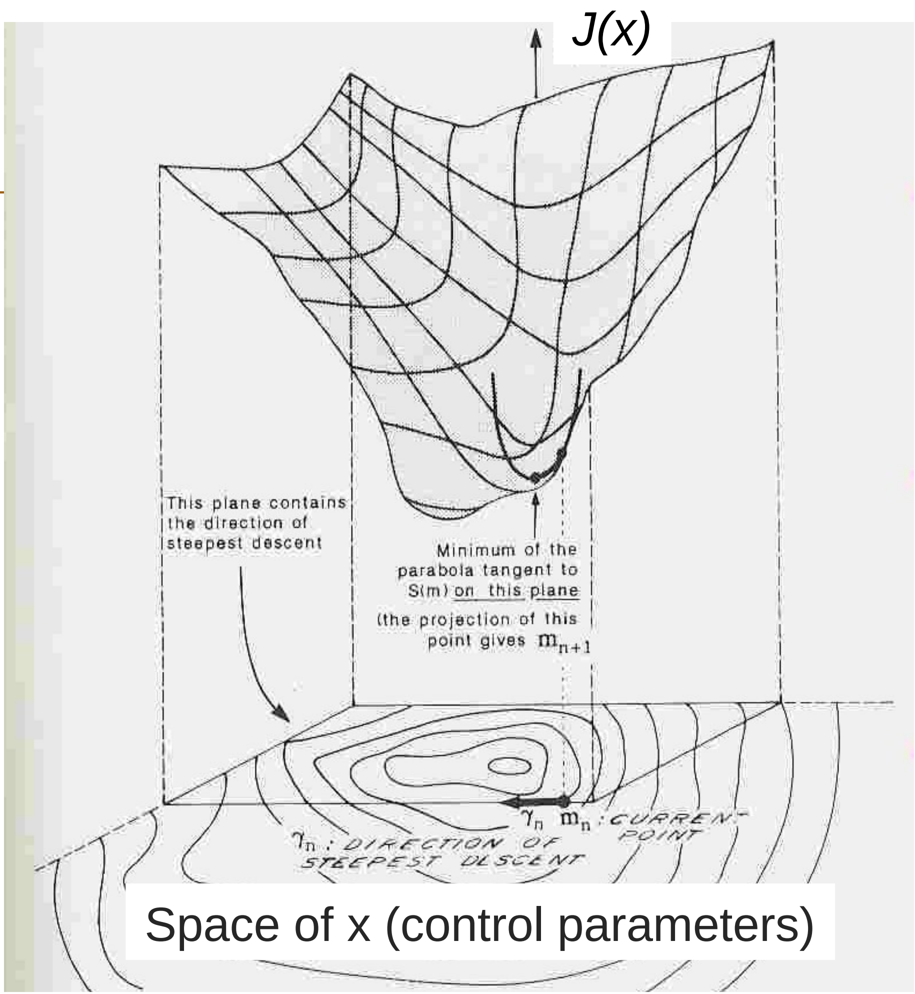


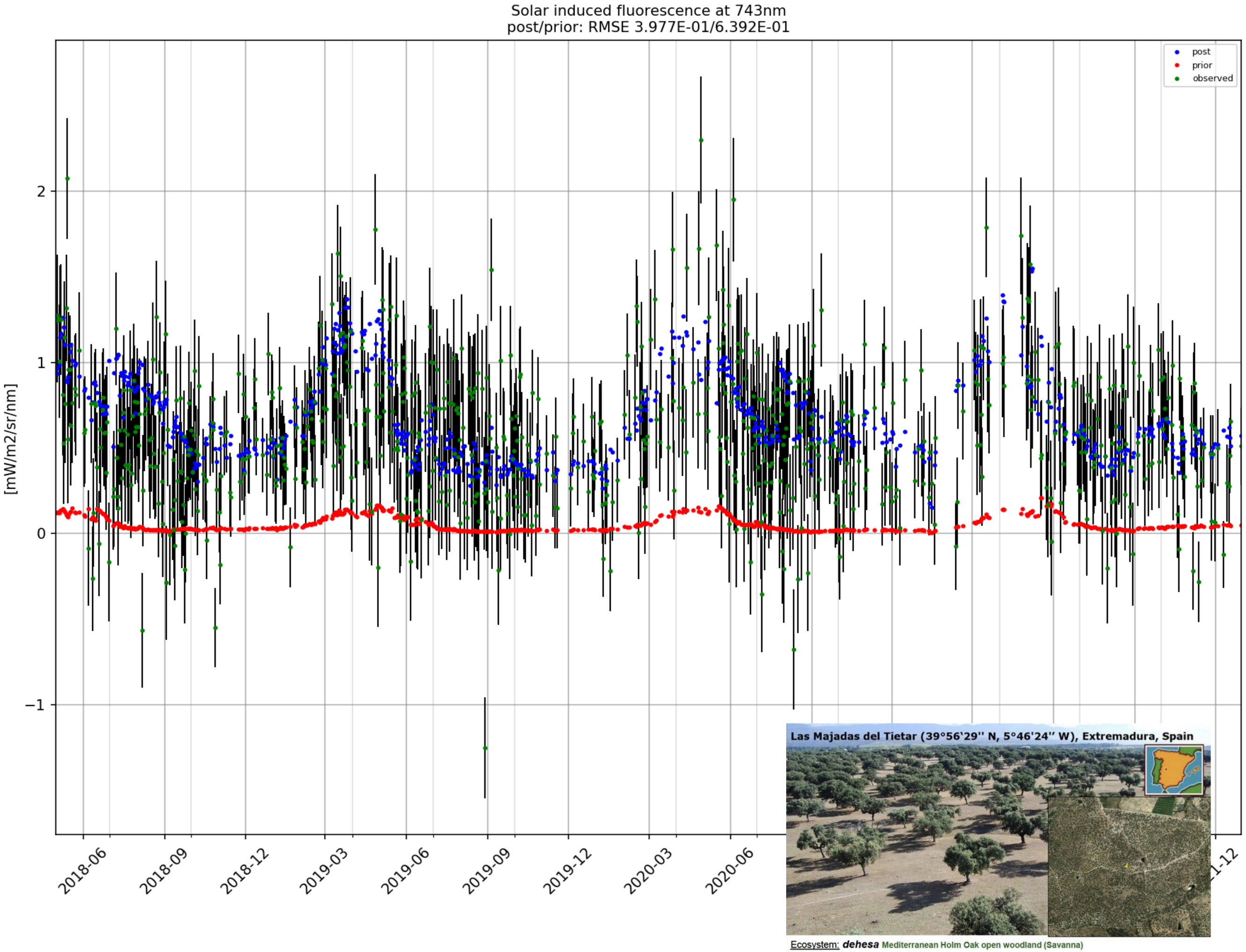
Figure: Tarantola (1987)

Assimilation results

TROPOMI SIF

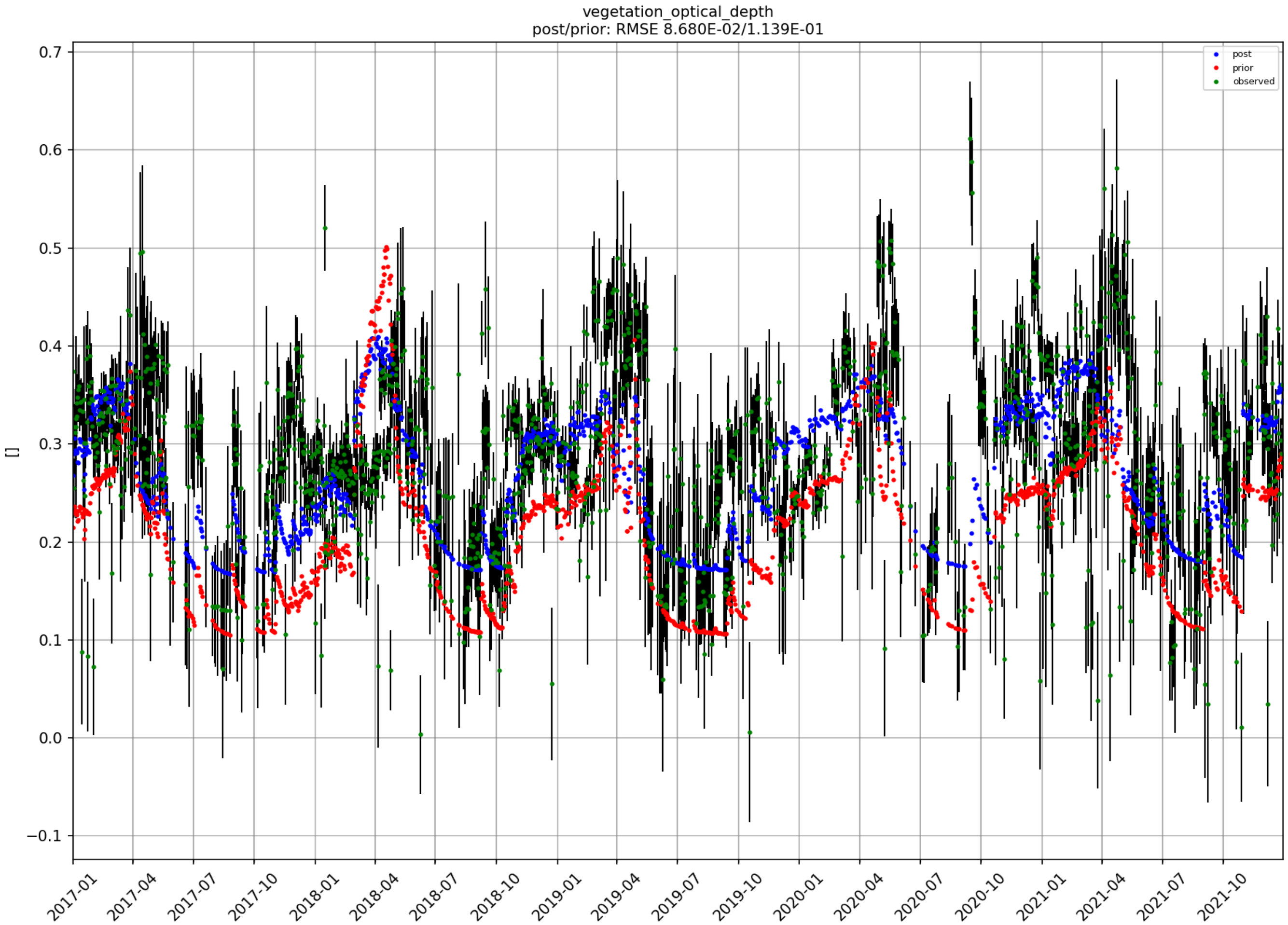
Site-scale assimilation at Majadas, Spain:

- Simulation : 2015 – 2021
- Assimilation window : 2017-2021
- Data Streams : SIF, LVOD, surface layer SM, FAPAR



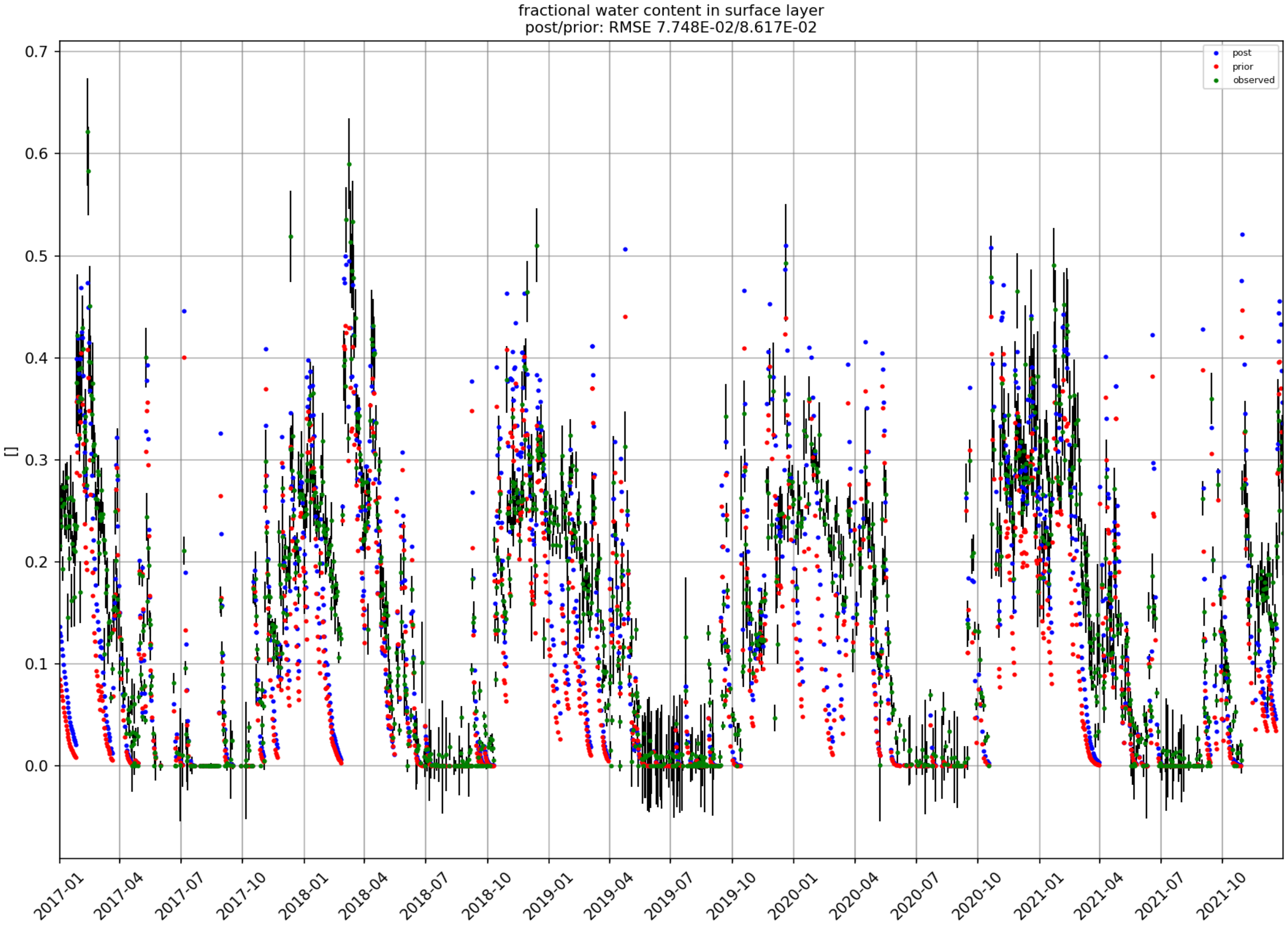
Assimilation results

SMOS VOD



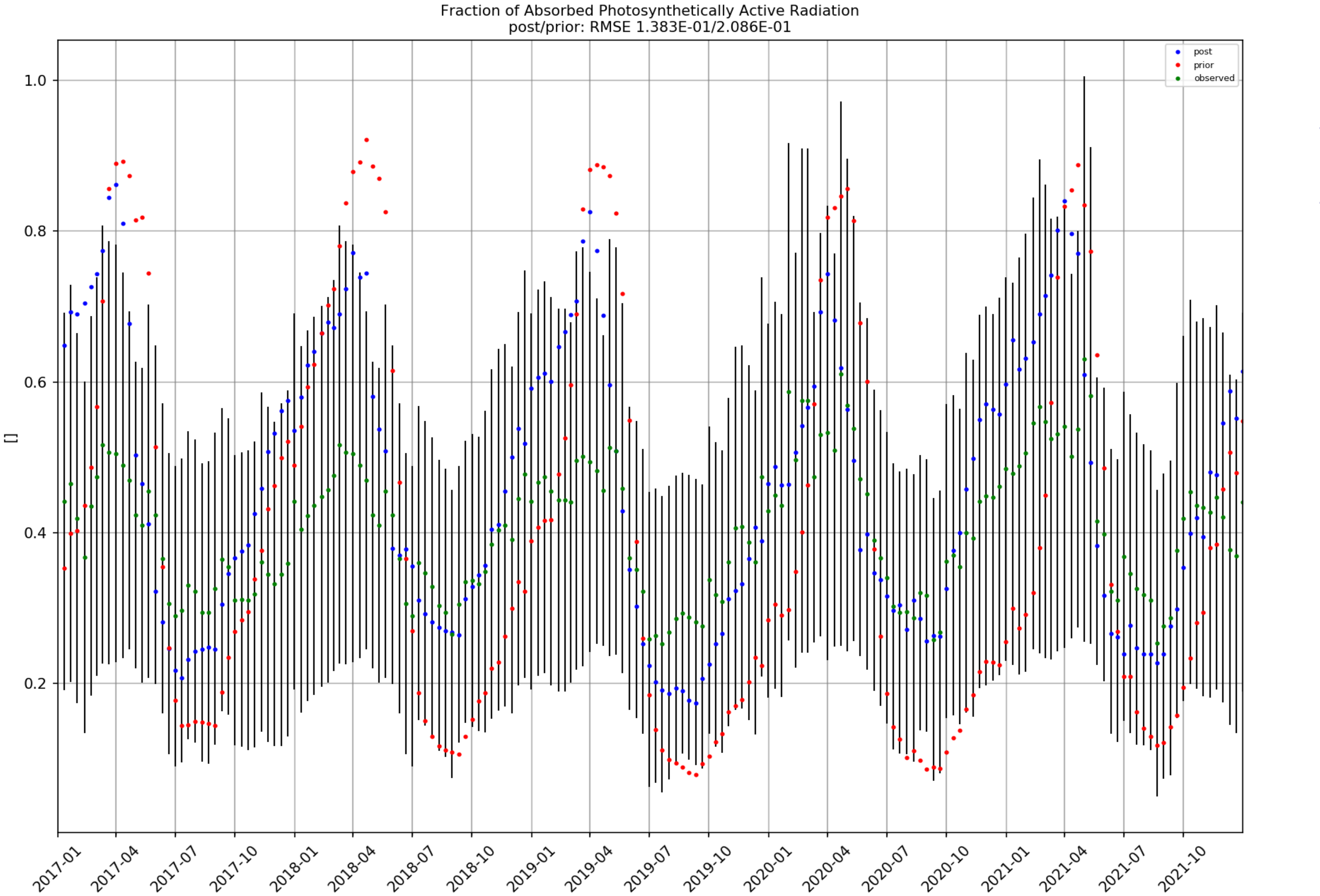
Assimilation results

SMOS surface layer soil moisture



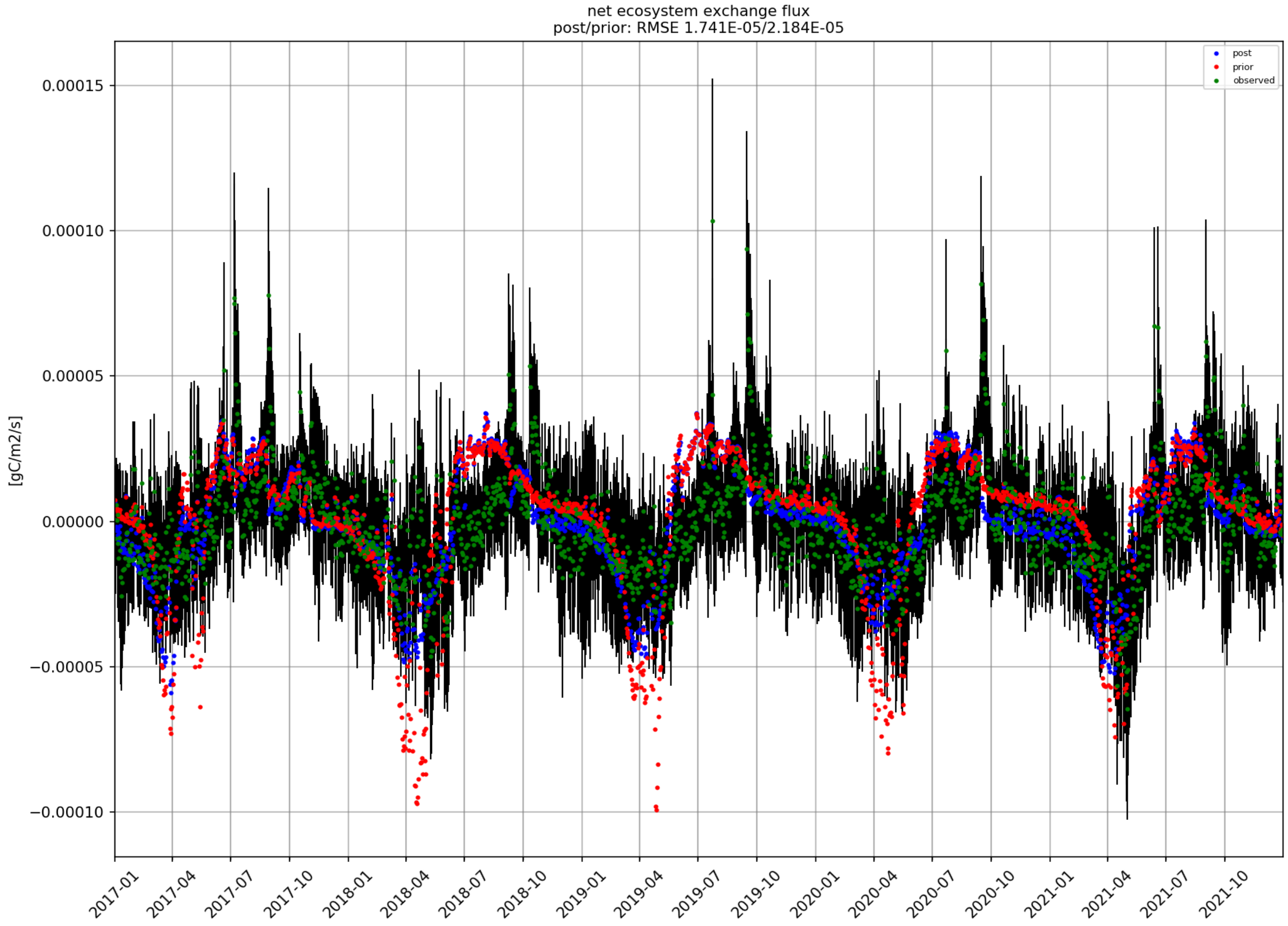
Validation

JRC-TIP FAPAR



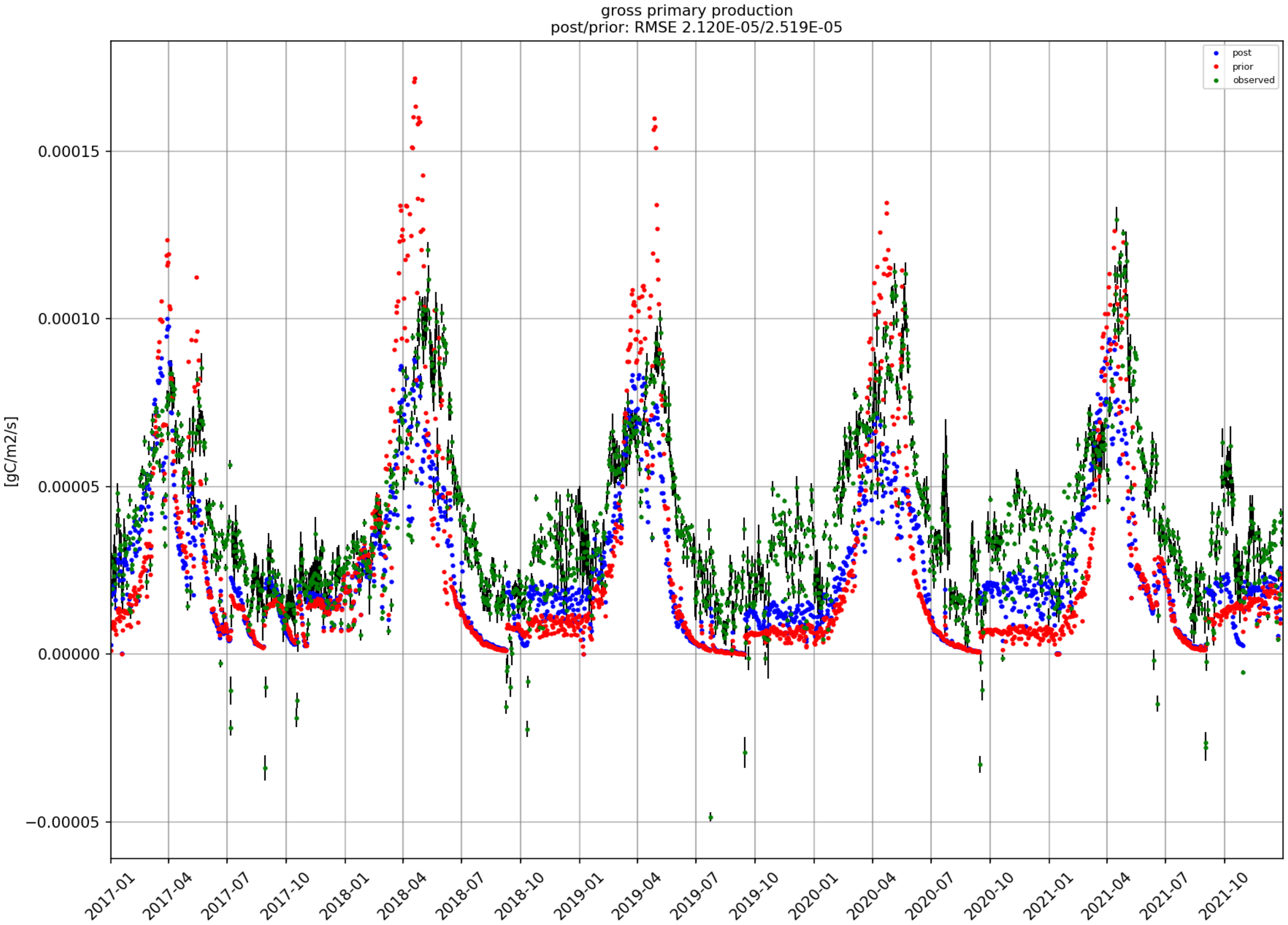
Validation

Fluxnet NEE

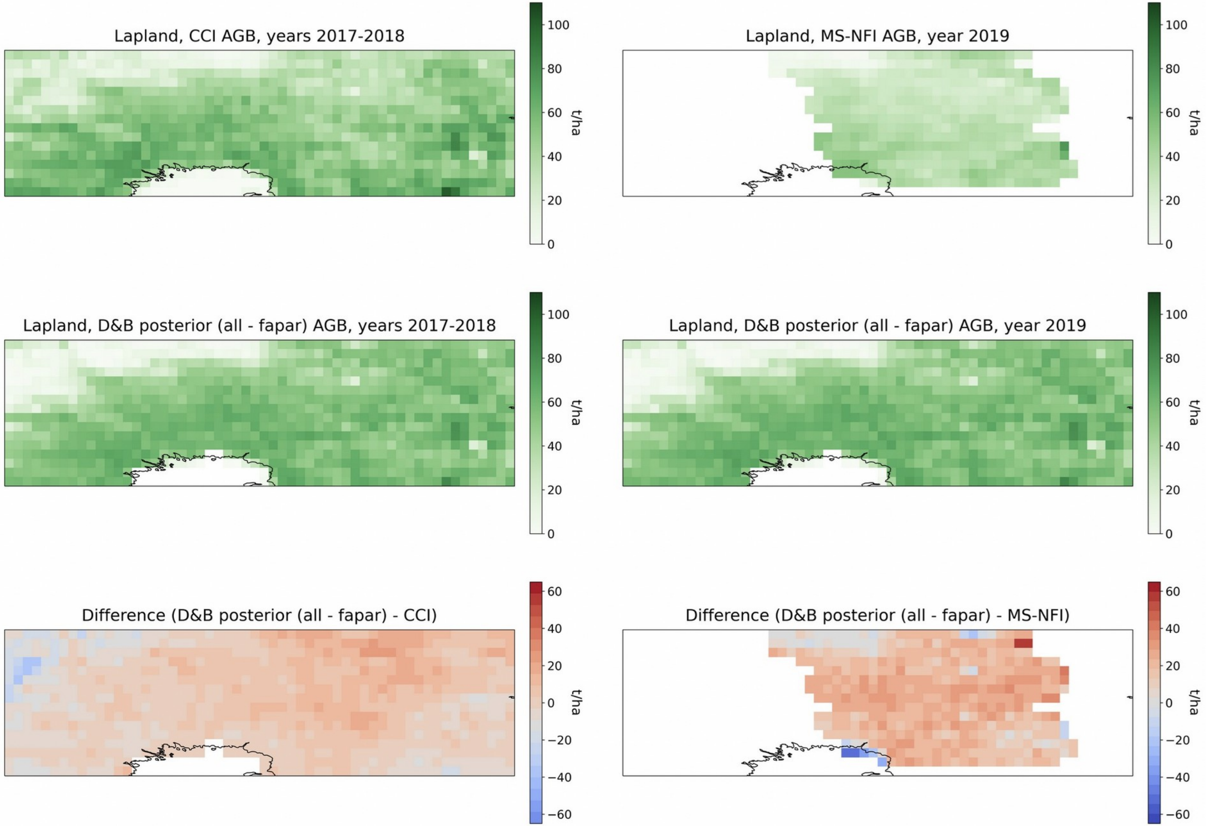


Validation

Fluxnet GPP



Example of posterior validation
2 AGB products over Lapland



Regional-scale assimilation

- Simulation: 2015 - 2021
- Assim. window : 2017-2021
- Data Streams : SIF, LVOD, surface layer

Analysis of Information Content

A: posterior parameter uncertainty:

$$A = (M^T R^{-1} M + B^{-1})^{-1}$$

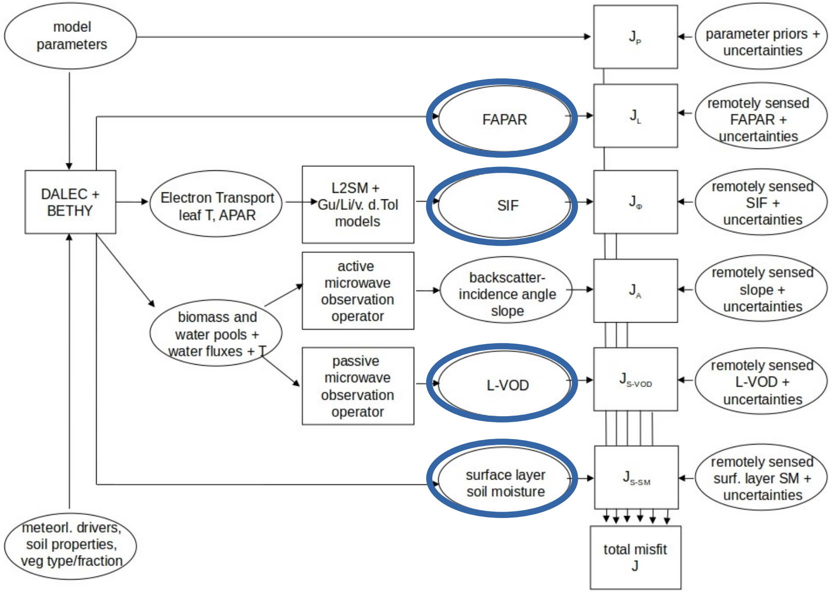
B: prior parameter uncertainty

R: data uncertainty

M: linearised model

Plots show unc. reduction:

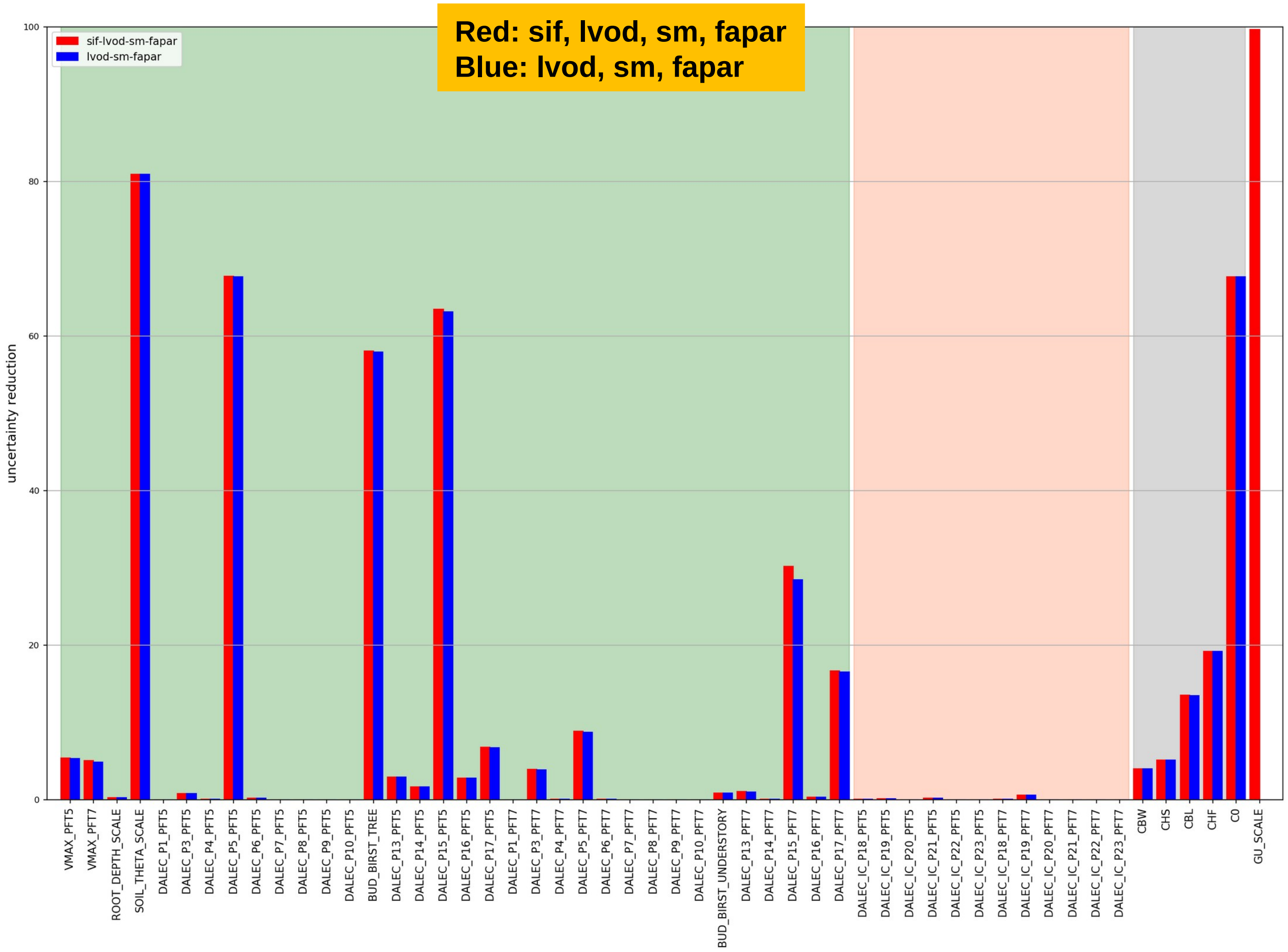
$$(\sigma_{prior} - \sigma_{posterior}) / \sigma_{prior}$$



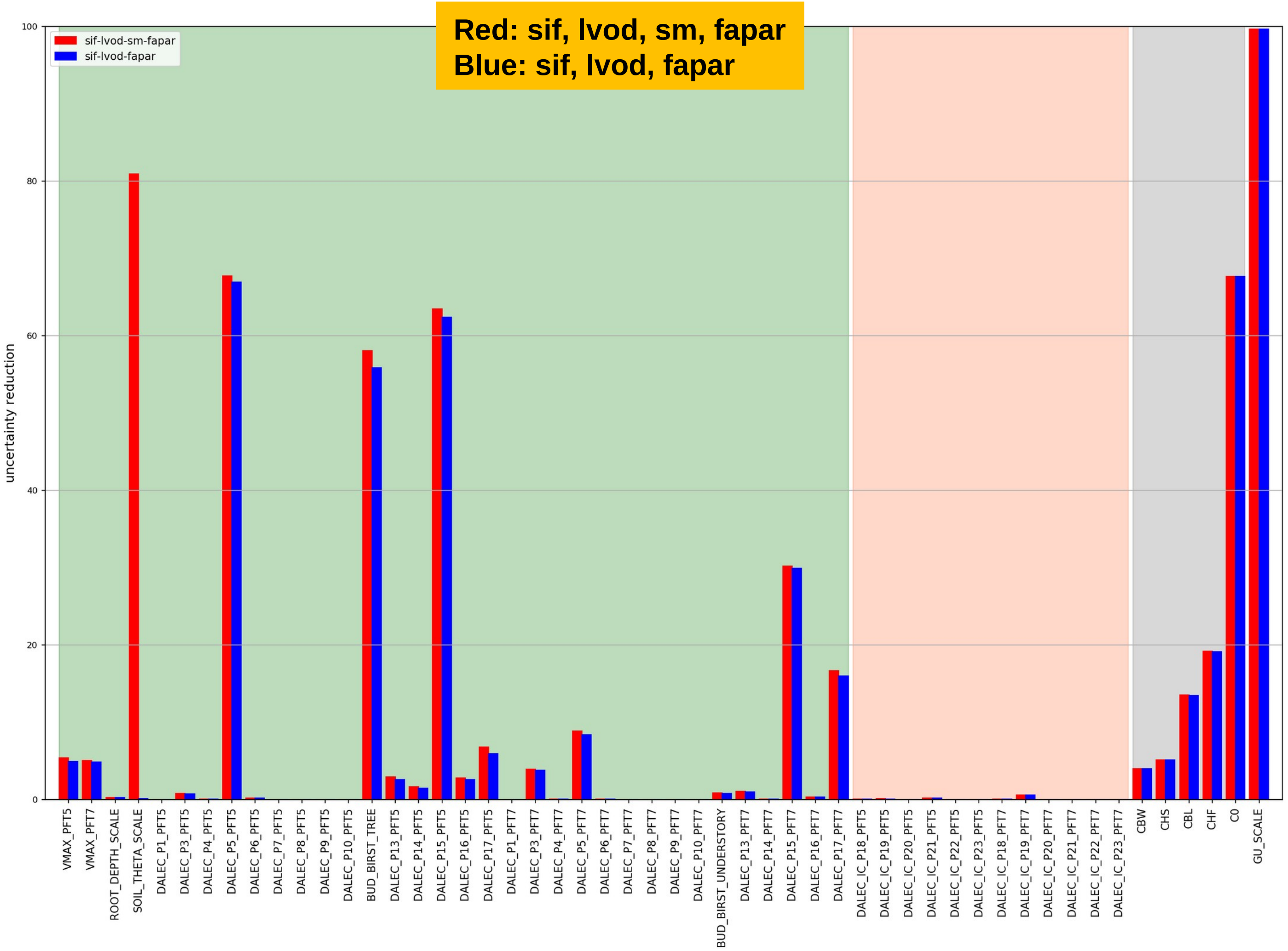
5 Experiments at Sodankylä (Everg. Conifer and understorey):

- First, joint assimilation of all 4 data streams
- Then, leaving one data stream out (in turn)

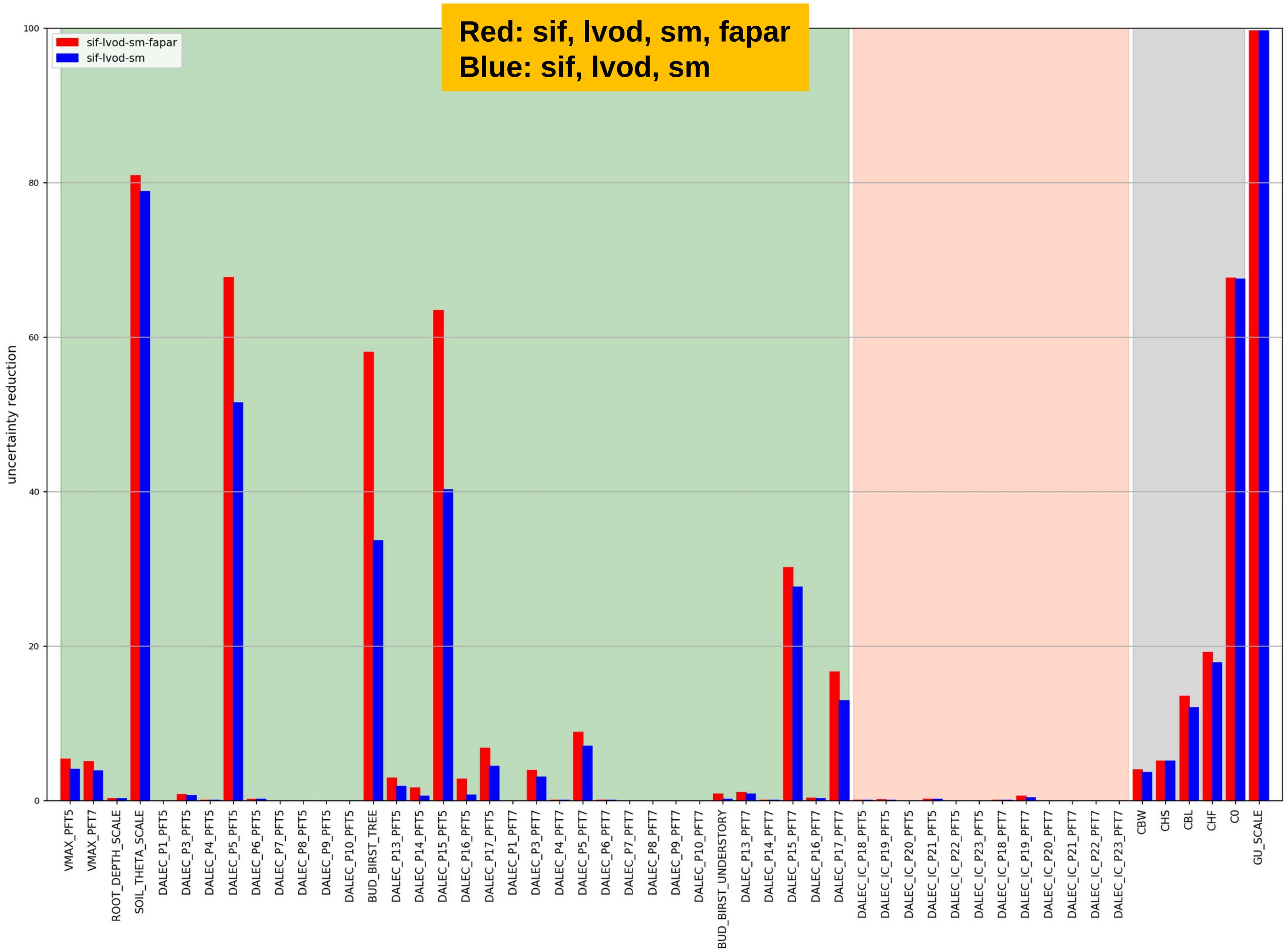
Uncertainty reduction



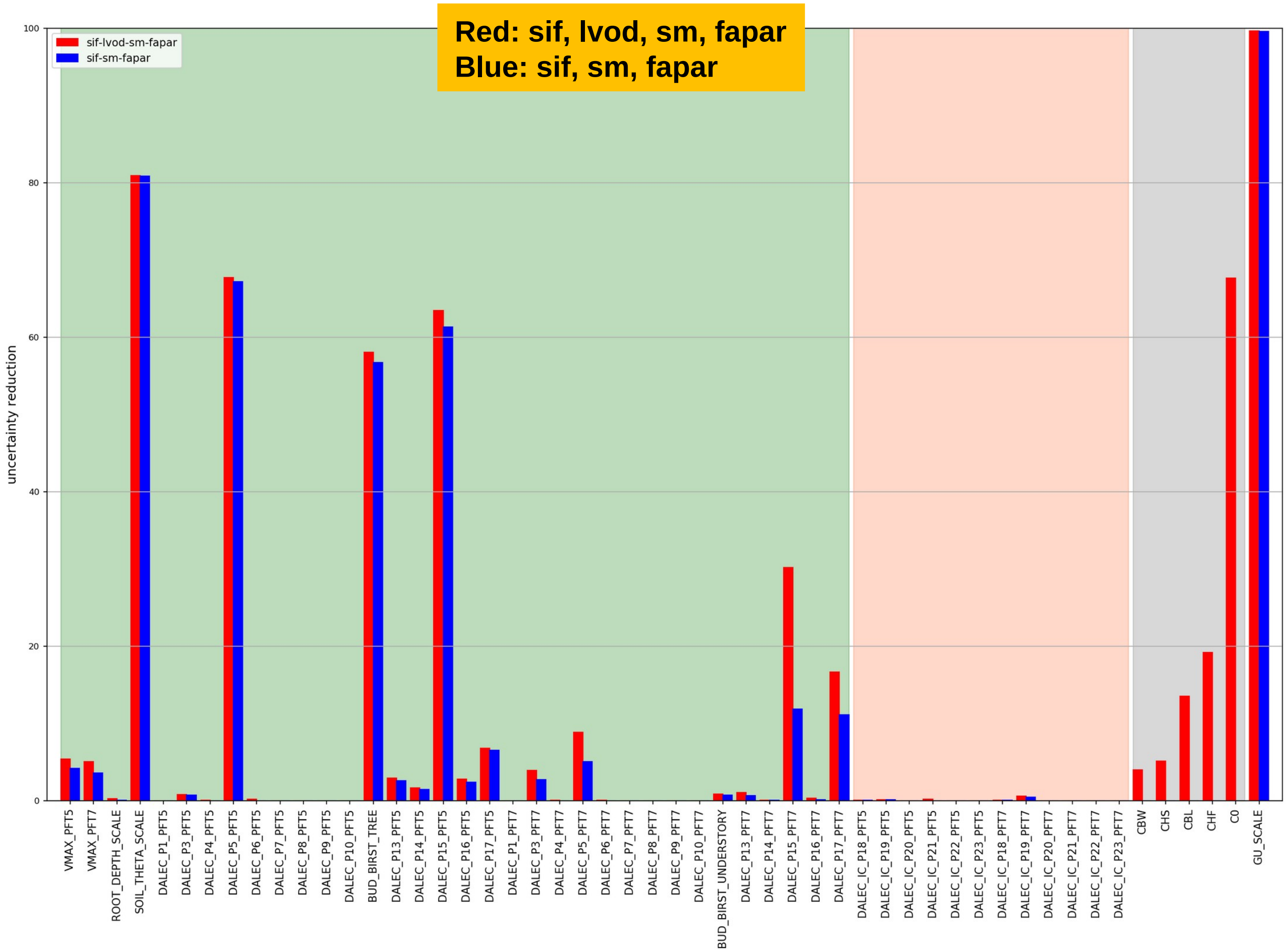
Uncertainty reduction



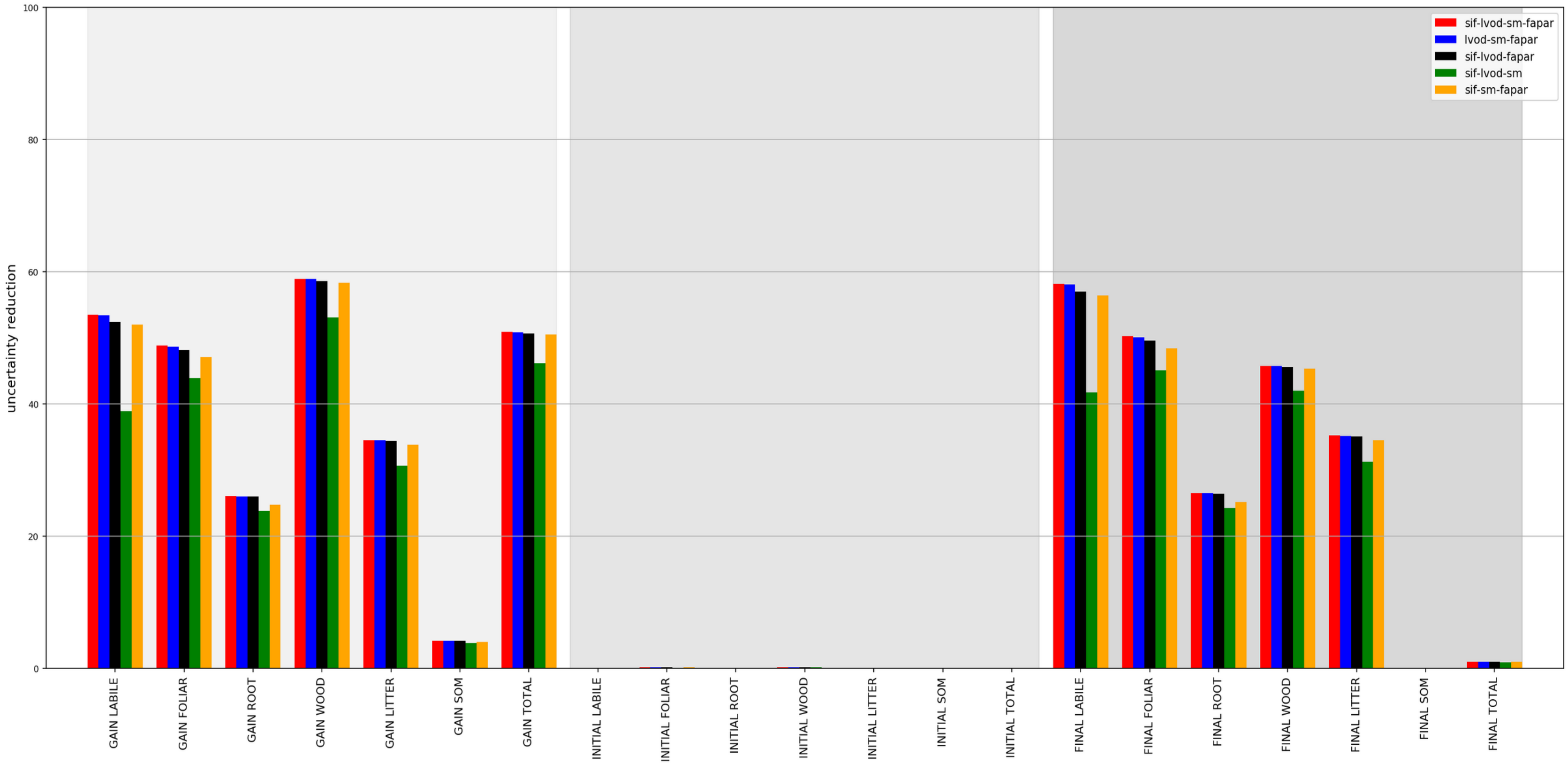
Uncertainty reduction



Uncertainty reduction



Uncertainty reduction: Fluxes (left), initial (middle) and final (right) Carbon Pools



Take home messages I

D&B model and Terrestrial Carbon Community Assimilation System (TCCAS):

- developed for simulation and assimilation of EO and field data
- to provide an integrated perspective on terrestrial carbon and water cycles
- flexible implementation of observation operators, to allow assimilation “on the swath”
- field data essential for model development and validation
- includes tangent and adjoint codes for efficient data assimilation (system needs to be applicable at high spatial resolution)
- modular set-up
- computational efficient code

Community system TCCAS

D&B model and Terrestrial Carbon Community Assimilation System (TCCAS):

- model development paper submitted to GMD
- open-source community system
    - Documentation
    - User support / training
- to be released to public domain as community tool soon

https://tccas-study.inversion-lab.com/

Planned training event (online and in person at ESRIN, Frascati, Italy) for TCCAS:

7/8 October 2024

If you are interested in participating, please contact me:

marko.scholze@nateko.lu.se

Thank you!