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**CO₂
Human
Emissions**

WP1

Reconciling top-down and bottom-up estimates

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This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 776186.





WP1

T1.1 Improve the processing chain for data assimilation





Filtering techniques to select high-quality data

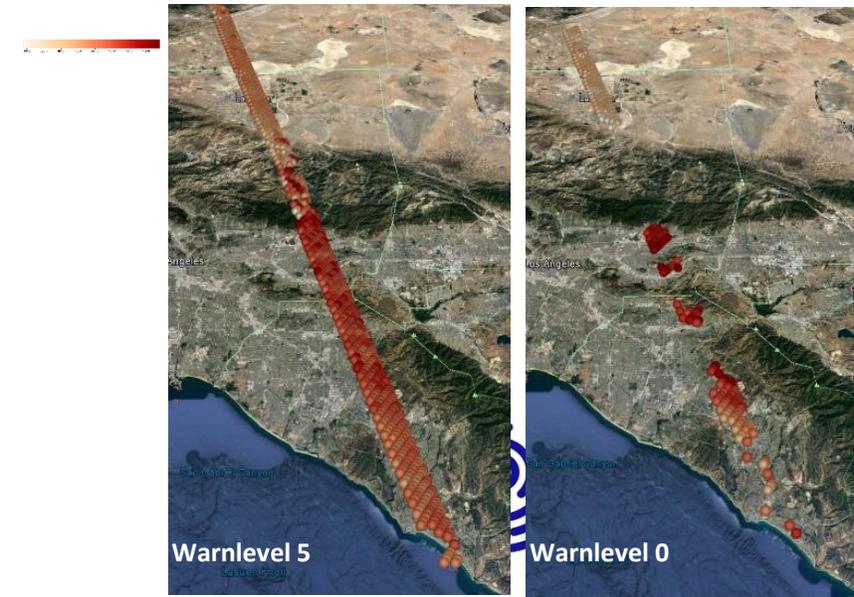
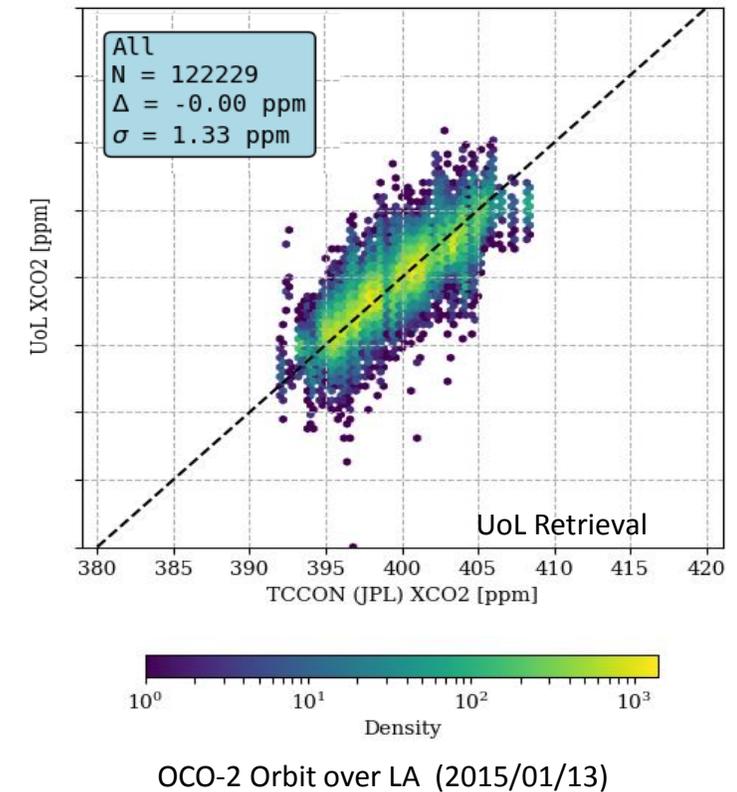
- Application of filtering and bias-correction methods are crucial for to obtain useful CO₂ datasets from satellites for flux inversions
- OCO L2 v8 includes sophisticated methods for bias correction and filtering based on global statistics

Goal is to apply anomalies detection methods from data science/ machine learning (Support vector machine, kth nearest neighbour)

- Establish criteria for anomaly filtering to remove outliers
- Identify locations of recurrent anomalies as an indicator of localized emission sources

Outcome

- 1 Year dataset of OCO2 L2 data based on NASA L2 but with modified filtering
- Software for anomaly detection





University of Bremen, OCO-2 XCO₂ retrieval: Status

Michael Buchwitz & Maximilian Reuter

Institute of Environmental Physics (IUP), Institute of Remote Sensing (IFE)

XCO₂ from NASA's OCO-2 mission using a new fast and accurate retrieval algorithm

- Algorithm development activity started already before proposal submission using UB's own financial resources with the hope that activity will be co-funded in the future
- This is now the case thanks to CHE (and VERIFY)
- Significant achievements in 2017: 2 peer-reviewed publications:

Retrieval algorithm (FOCAL):



remote sensing



Reuter et al., 2017a

Article

A Fast Atmospheric Trace Gas Retrieval for Hyperspectral Instruments Approximating Multiple Scattering—Part 1: Radiative Transfer and a Potential OCO-2 XCO₂ Retrieval Setup

Maximilian Reuter ^{*}, Michael Buchwitz, Oliver Schneising, Stefan Noël, Vladimir Rozanov, Heinrich Bovensmann and John P. Burrows

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First application to real OCO-2 data:



remote sensing



Reuter et al., 2017b

Article

A Fast Atmospheric Trace Gas Retrieval for Hyperspectral Instruments Approximating Multiple Scattering—Part 2: Application to XCO₂ Retrievals from OCO-2

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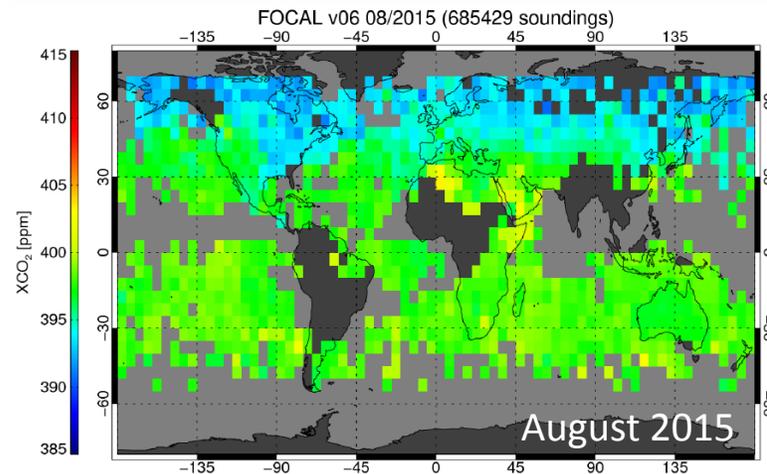
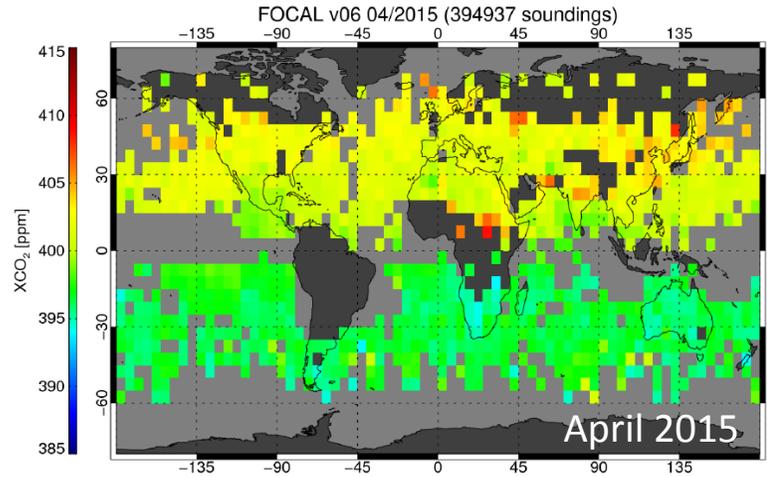




University of Bremen, OCO-2 XCO₂ retrieval: Status

Michael Buchwitz & Maximilian Reuter

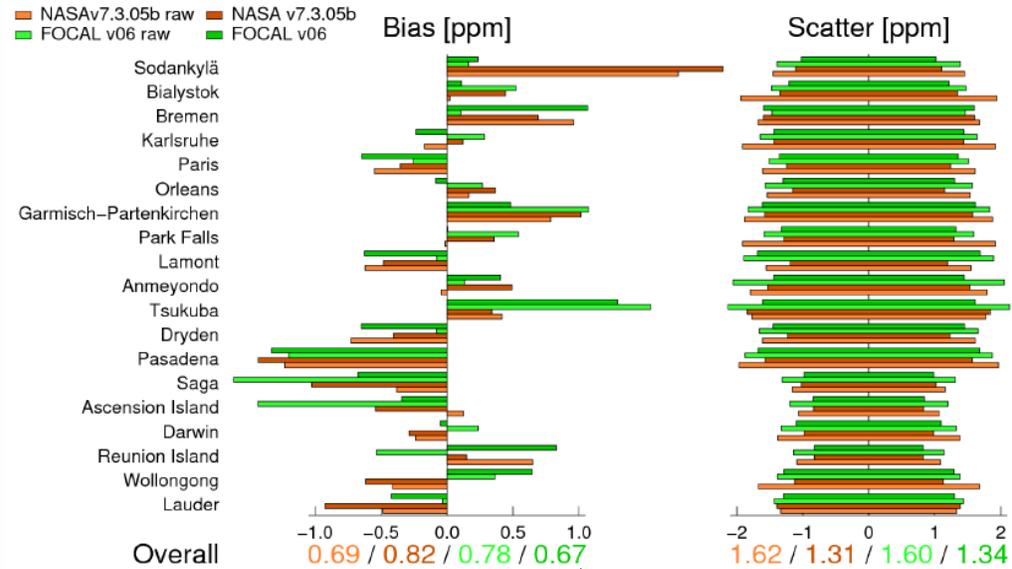
From: Reuter et al., 2017b



First OCO-2/FOCAL XCO₂
Gaps due to clouds, too large SZA, ...

Validation via comparison with TCCON:

- FOCAL without and with bias correction
- NASA v7 without and with bias correction



FOCAL-TCCON with bias correction:

bias (std.dev.) 0.67 ppm,
single footprint scatter: 1.34 ppm
(similar as NASA v7)



WP1

T1.2 Develop novel data fusion techniques for joint surface and space-based carbon cycle data



LSCCE innovation run

Frédéric Chevallier

XCO₂ + solar-induced-fluorescence (SIF) retrievals

- XCO₂ informs about a net budget (Resp + Fire + GPP). SIF Informs about one of its components (GPP).
- *In principle*, simultaneously assimilating XCO₂ and SIF together should improve the estimation of the net budget (Resp + Fire + GPP).
- *In practice*, the quality of the result will be driven by our capability to correctly assign prior error statistics on (Resp.+Fire) and GPP, which is even more complex than assigning prior error statistics on the net budget (Resp + Fire + GPP).
 - Resp. linked to C stocks (large scale respiration prior error structures? To be studied).
 - GPP linked to phenology and biomass amount (small-scale prior error structures? To be studied).
- The observation operator between GPP and SIF is also not trivial. We will use a physical approach (“Fluor” version of ORCHIDEE with a leaf-level fluorescence model scaled up to the canopy level) to estimate GPP maps from SIF in a pre-processing step. Then we will assimilate XCO₂ with the corresponding improved prior net flux.

WU base run

Wouter Peters and Maarten Krol



CTDAS inversion system

- Modular inversion system written in Python.
- Ensemble Kalman Smoother, serial assimilation of observations in 5 week windows.
- Flux optimization at $1^\circ \times 1^\circ$ weekly resolution, with ecosystem types separated.
- Includes the global TM5 transport model, driven by ERA-I meteorology (written in Fortran, also parallelized).
- Prior error statistics include spatial (200 km / 1000 km) correlation e-folding lengths.
- Posterior error statistics computed from covariance estimate of inversion method.
 - Created in 2007 and further developed since (Peters et al., 2007, 2010; van der Laan-Luijkx et al., 2017).
 - Has been the CarbonTracker Europe atmospheric inversion system for CO_2 since 2010, assimilating surface air-sample measurements.
 - Used to assimilate $\delta^{13}\text{C}$ in CO_2 in GEOCARBON project, and airborne Amazon isotope measurements in the ERC project “ASICA” .
 - Currently participates in the EUROCOM inversions, Global Carbon Project, and H2020-VERIFY

WU innovation runs

Wouter Peters and Maarten Krol

(1) Online meteorology for TM5 with ECMWF's Integrated Forecast System (IFS)

- Transport model TM5 can be run *offline* with ERA-I reanalysis, or *online* with (Open)IFS meteorological model + nudging
 - *online* allows higher spatial resolution, later IFS model versions, and use of ensembles of meteorology
 - first steps towards merging NWP and CO₂ assimilation codes.
 - Ongoing tests within EC-Earth: running IFS to drive TM5 online is fast, and affordable

(2a) Parameter optimization in surface flux model

- Following work of C. Rödenbeck, optimize parameters in a simple surface flux model
 - biosphere: diurnal cycle, seasonal cycle amplitude, T-NEE (γ), CO₂-NEE (β), drought-NEE
 - fossil fuels: Kaia identity parameters
 - Use ensembles of (Open)IFS for long integration

WU innovation runs

Wouter Peters and Maarten Krol

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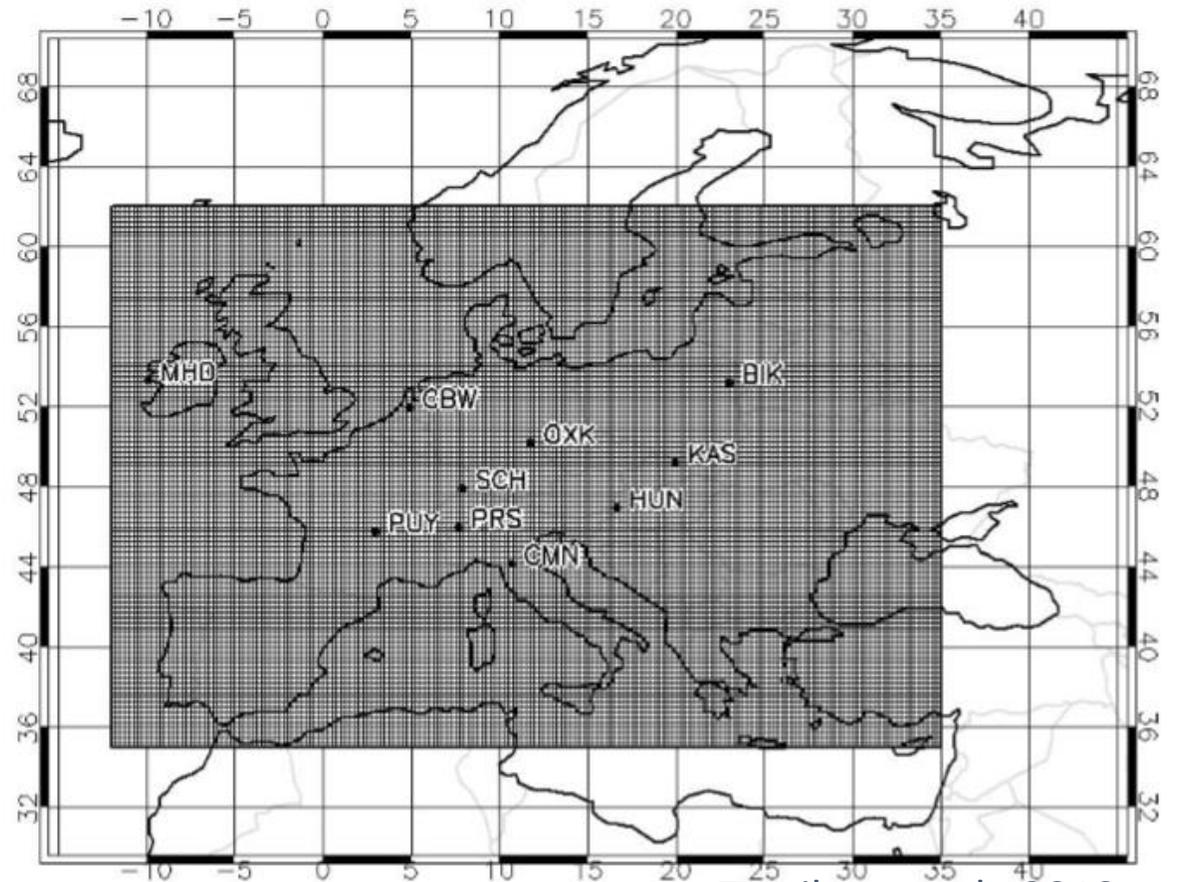
(2b) Short window data assimilation (also in WP5)

- Following work of Kalnay, Kang, Liu, use shorter assimilation windows (24 hours) with more complex background covariances
 - augmented state vector with CO₂ mixing ratios and CO₂ flux parameters, both optimized
- Correlation between T, q, u, v, Ps, CO₂_mix, CO₂_flux in background, propagated by IFS-TM5

MPG INVERSION APPROACH

Making use of the nested TM3-STILT 2-step inversion

- Nested domain at 0.25 degree resolution
- Already in use semi-operationally with *in situ* measurements (e.g. Kountouris et al., ACP, 2018)
- 1st step constrains the boundary conditions based on an inversion with the TM3
- Using VPRM for prior biosphere fluxes



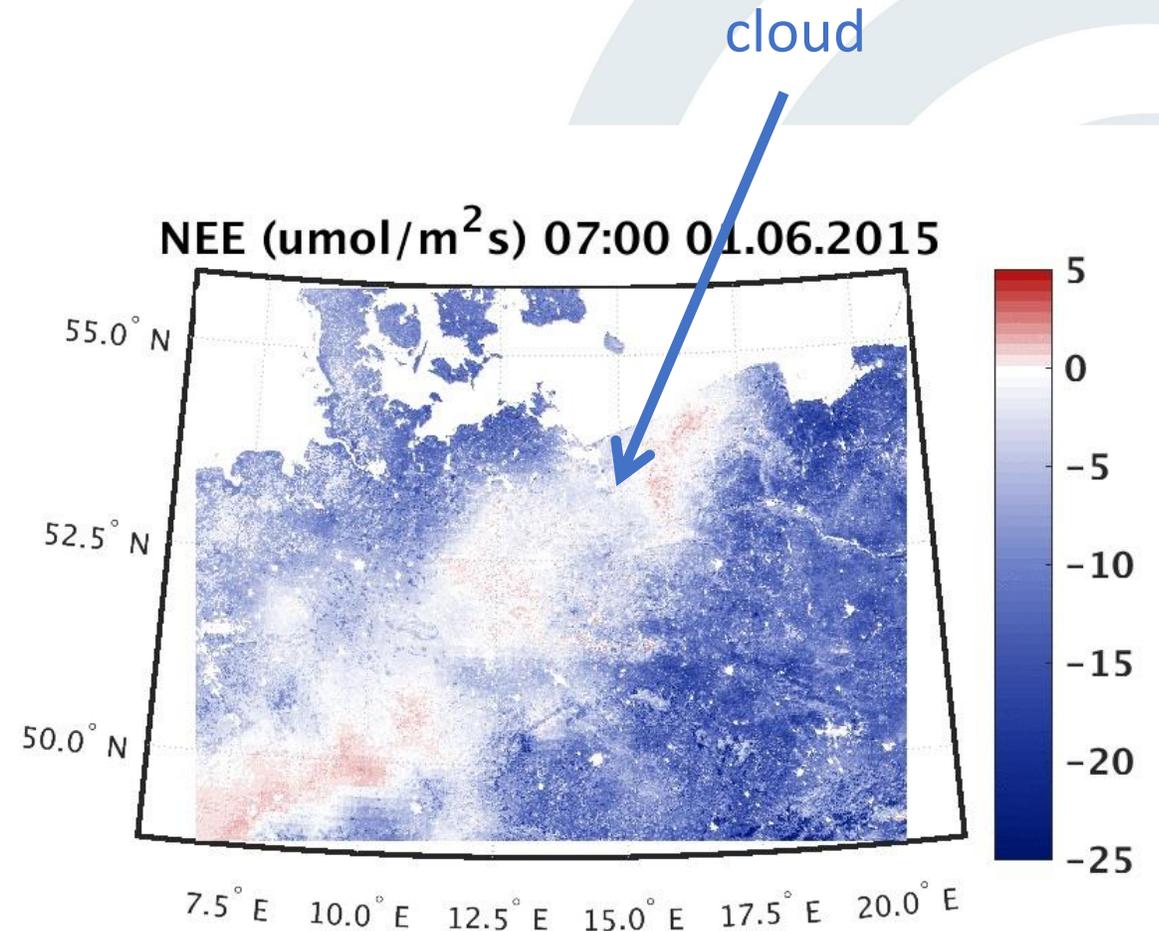
MPG INVERSION: INNOVATION

Using satellite measurements in both the outer domain and the inner domain

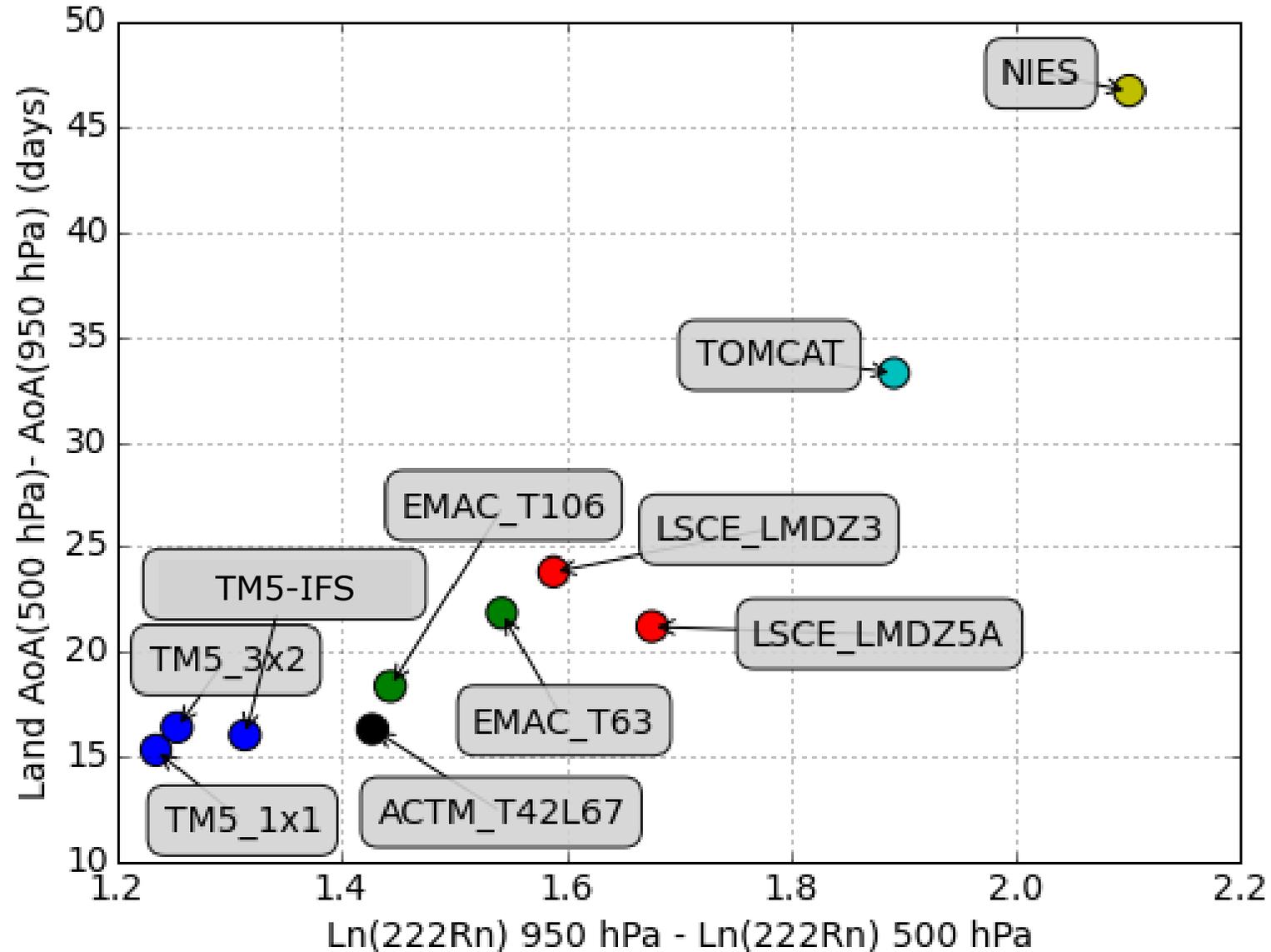
- Test combinations of data (sat. + *in situ*, *in situ* only, sat. only) in outer and inner domain to better develop consistent boundary conditions

Using geostationary cloud data as input to drive VPRM prior

- Previous studies have shown clear-sky bias might contribute to satellite/*in situ* disagreement
- Including high-res. Info in the prior might improve agreement



TM5, LMDz, and TM5-IFS





WP1

T1.3 Reconcile carbon source/sink estimates from different top-down approaches with each other, and with bottom-up constraints



Comparing top-down and bottom-up estimates

Penelope Pickers and Corinne Le Quéré

Have compared 2009-2015 means and IAV for total sink, land sink and ocean sink at the global scale.

- Bottom-up:

- 1: using Global Carbon Budget (GCB) 2017 estimates (largely based on land and ocean models)
- 2: ocean sink: independent estimates from two pCO₂ data-based products.

- Top-down:

- 1: atmospheric inversions using the surface CO₂ measurement network:
 - CAMS
 - Jena CarboScope s76
 - Carbon Tracker
- 2: atmospheric inversions using satellite CO₂ measurements:
 - currently comparing estimates from three inverse models used with two satellite retrieval products

Satellite inversions

Products compared to-date:

Satellite retrieval algorithm	Provider of satellite data	Inverse model	Provider of inverse model	Coverage	Resolution (lat x lon)	File format
OCFP (from GOSAT)	University of Leicester	LMDZ	LSCE	Global, 2010-2015	1.9° x 3.8°	NetCDF, each year in separate file, gridded monthly data, units: kg C/m ² /month*
		TM3	MPI-BGC	Global, 2009-2015	3.8° x 5.0°	NetCDF, gridded monthly data, units: kg C/month
		TM5	SRON	Global, 2009-2015	2.0° x 3.0°	NetCDF, gridded monthly data, units: kg CO ₂ /second **
SRFP (from GOSAT)	SRON/KIT	LMDZ	LSCE	Global, 2010-2015	1.9° x 3.8°	NetCDF, each year in separate file, monthly data, units: kg C/m ² /month*
		TM3	MPI-BGC	Global, 2009-2015	3.8° x 5.0°	NetCDF, gridded monthly data, units: kg C/month
		TM5	SRON	Global, 2009-2015	2.0° x 3.0°	NetCDF, gridded monthly data, units: kg CO ₂ /second **

Satellite inversions

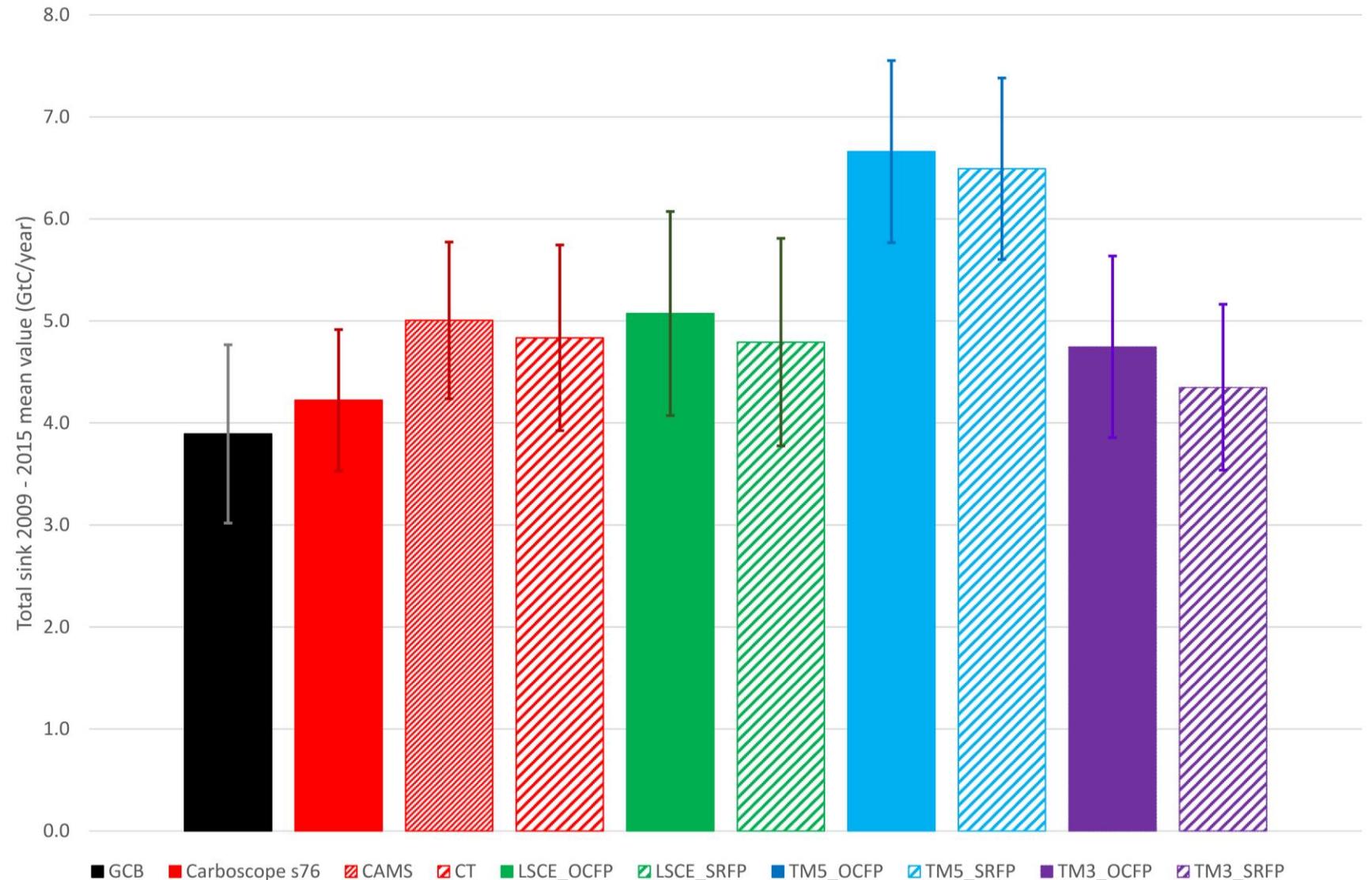
Other available products (not compared in this analysis):

Satellite retrieval algorithm	Provider of satellite data	Inverse model	Provider of inverse model	Coverage	Spatial resolution (lat x lon)
BESD (SCIAMACHY)	iUP-UB	LMDZ	LSCE	Land only, 2004 – 2010	1.9° x 3.8°
		TM3	MPI-BGC	Land only, 2003 – 2012	3.8° x 5.0°
		CCDAS	Inversion Lab	Land only, 2010	5.0° x 7.5°
EMMA (SCIAMACHY/GOSAT)	iUP-UB	TM3	MPI-BGC	Land only, 2009 – 2012	3.8° x 5.0°
		CCDAS	Inversion Lab	Land only, 2010	5.0° x 7.5°

- GOSAT RA2 inversion comparison has just started, so these may be available in ~1 year from now.

Total sink means (2009-2015)

- Top-down estimates higher than bottom-up
- TM5 satellite inversion is too high (not well-constrained over the oceans).
- SRFP based inversions give lower estimates than OCFP based inversions.
- Surface based and satellite based inversion estimates overlap (except for TM5), but there is still a lot of variability between models/products.

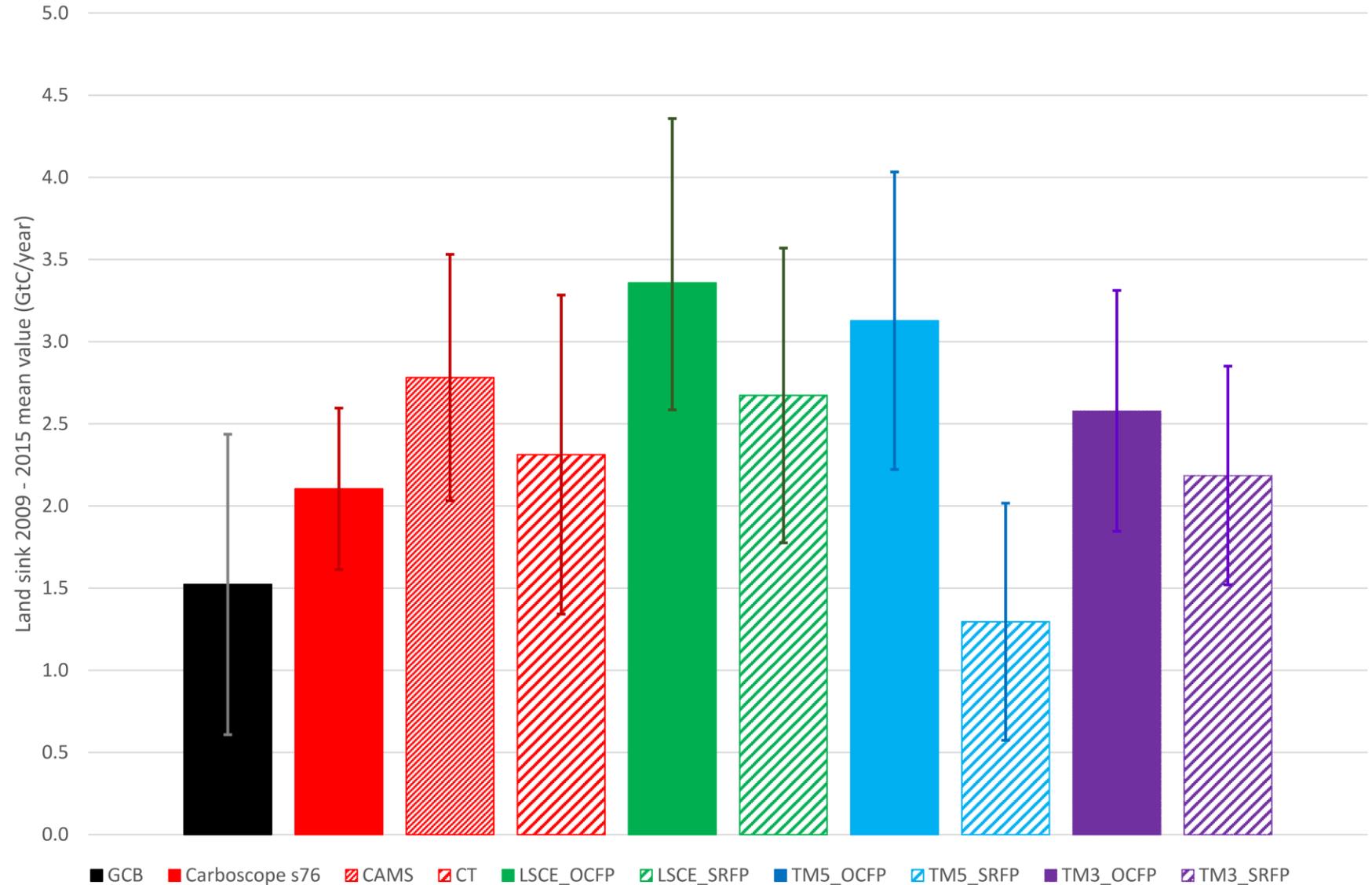


CO₂ HUMAN EMISSIONS

Error bars represent the $\pm 1\sigma$ of the 2009-2015 mean values.

Land sink means (2009-2015)

- TM5_SRFP seems to be somewhat of an outlier wrt other top-down estimates, but is more in-line with GCB bottom-up mean.
- Again, SRFP based inversions give lower estimates than OCFP based inversions.

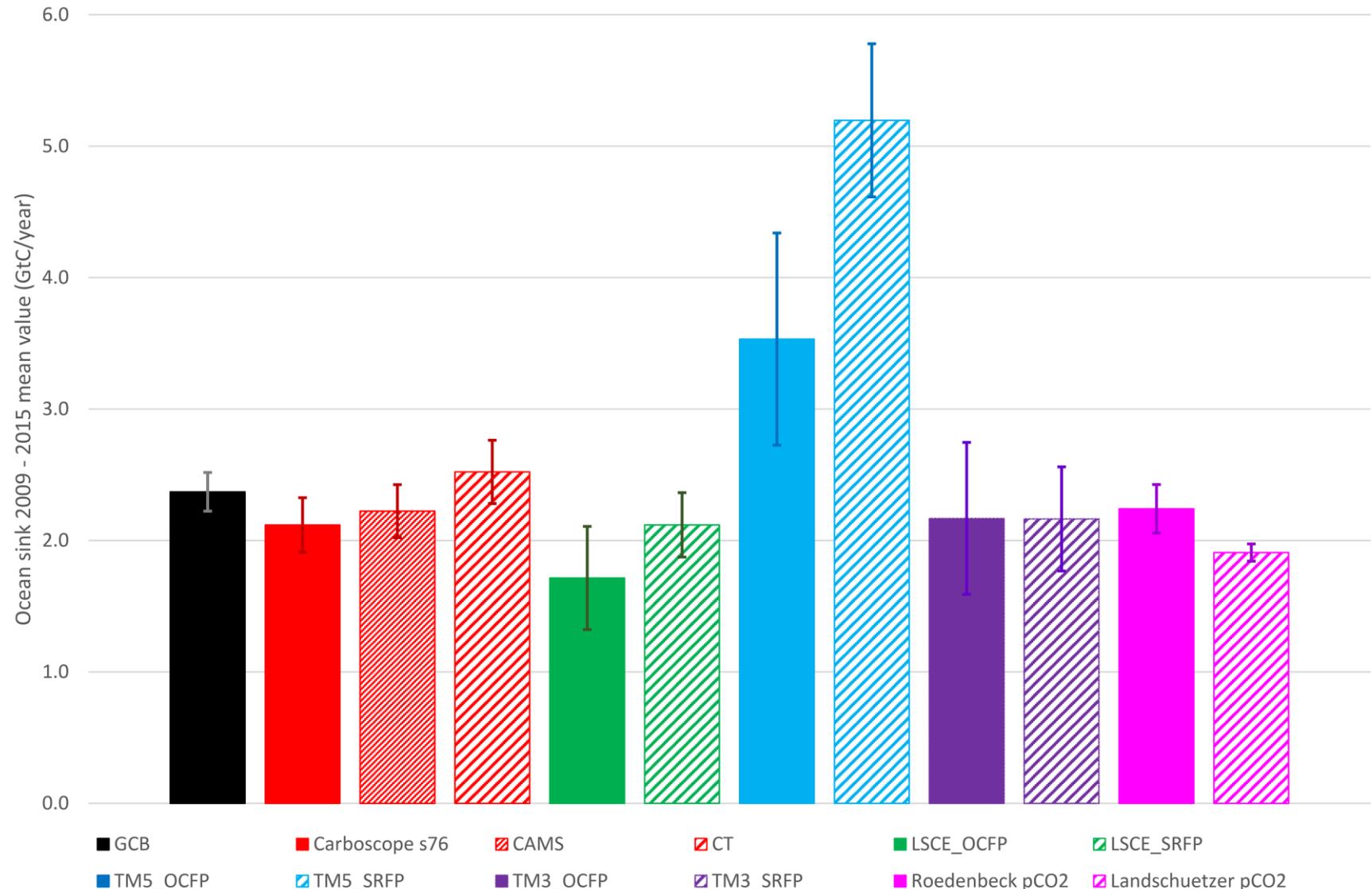


CO₂ HUMAN EMISSIONS

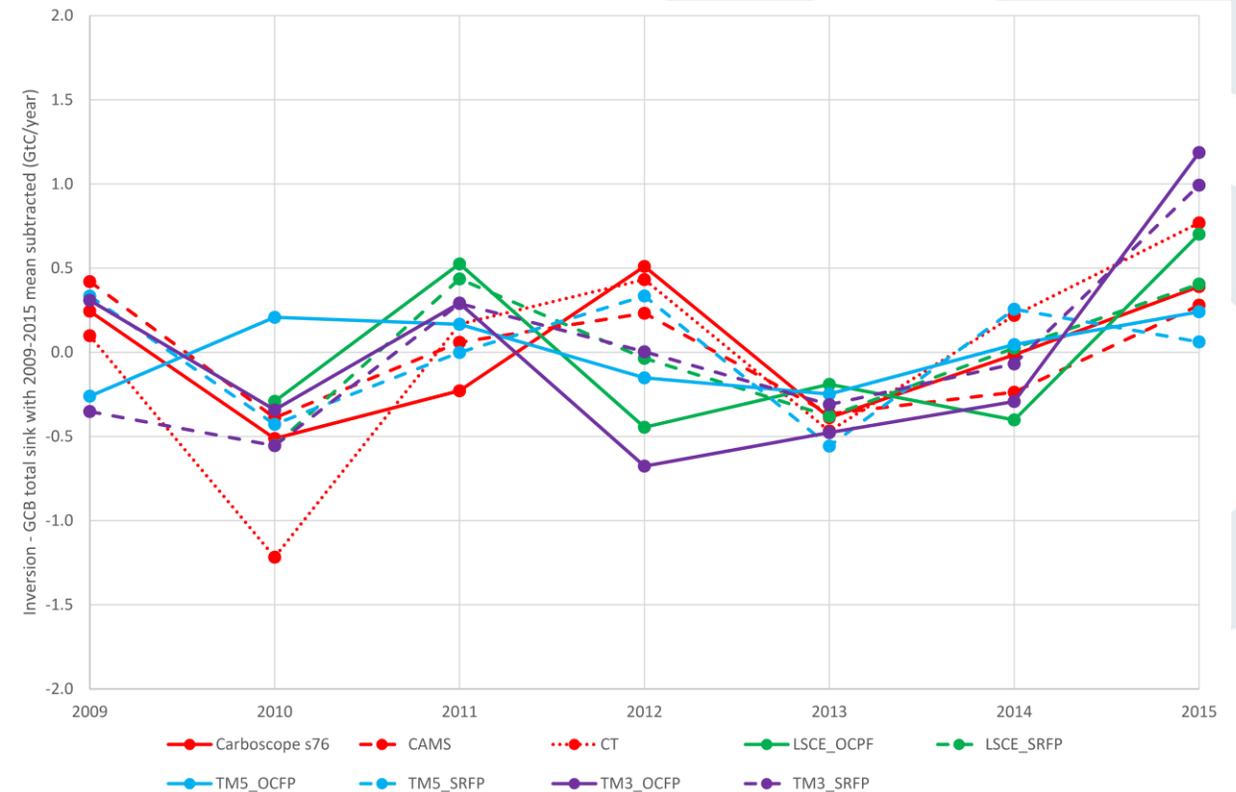
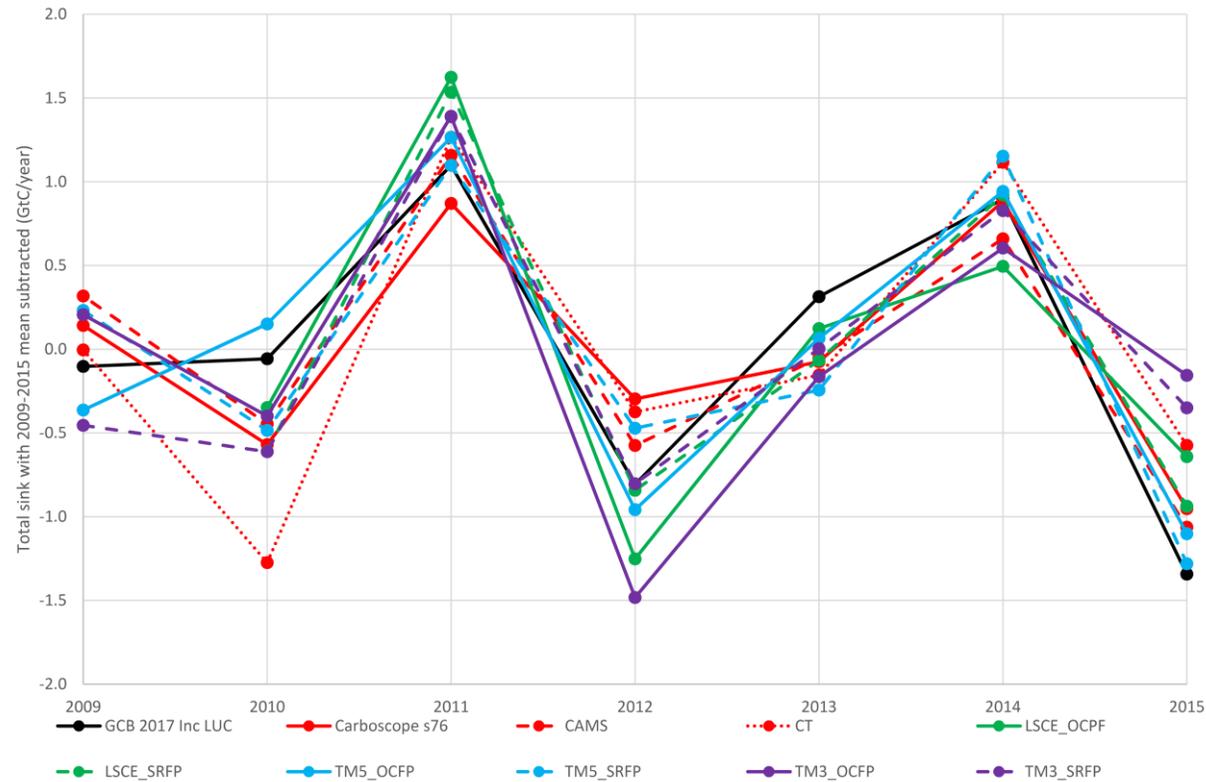
Error bars represent the $\pm 1\sigma$ of the 2009-2015 mean values.

Ocean sink means (2009-2015)

- TM5 estimates are again very large (poorly constrained over the oceans).
- Distinction between SRFP and OCFP based satellite estimates is not as clear.
- There is general overlap between bottom-up (GCB and pCO₂) and top-down estimates (excluding TM5) but not always within the error bars and still a lot of variability between products.

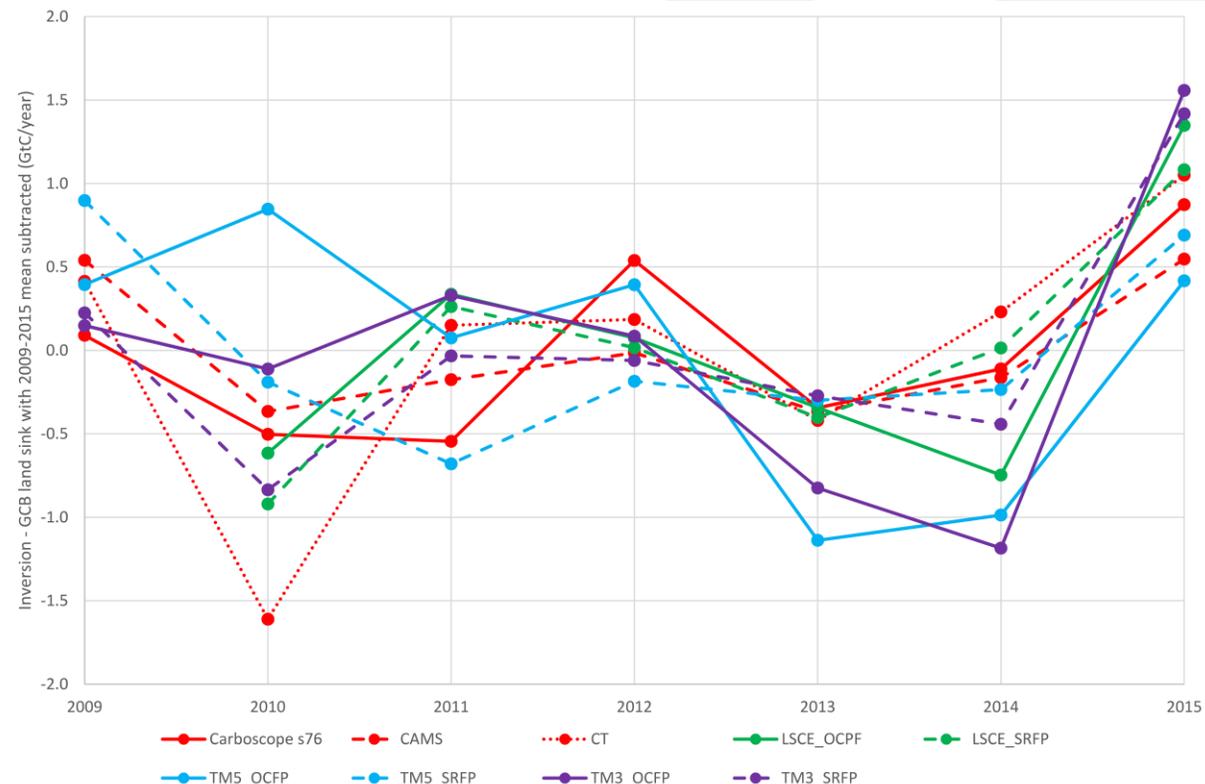
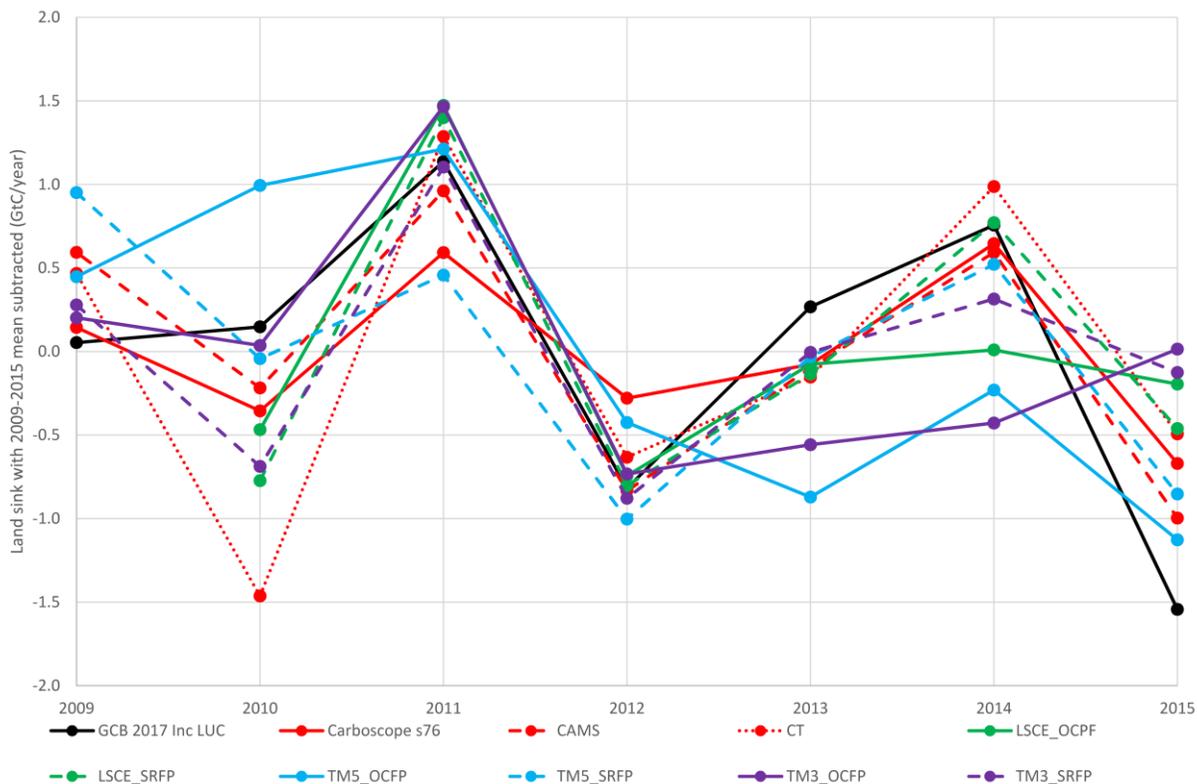


Total sink IAV (2009-2015 mean subtracted)



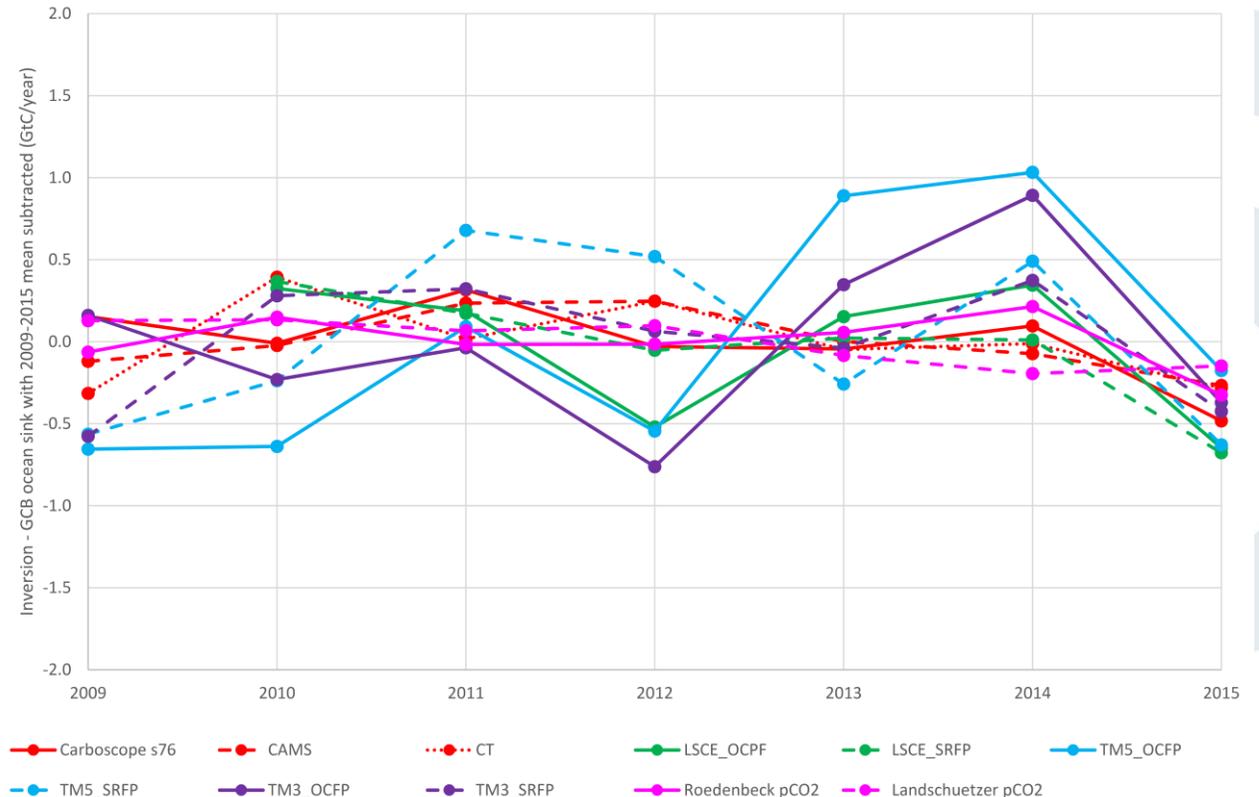
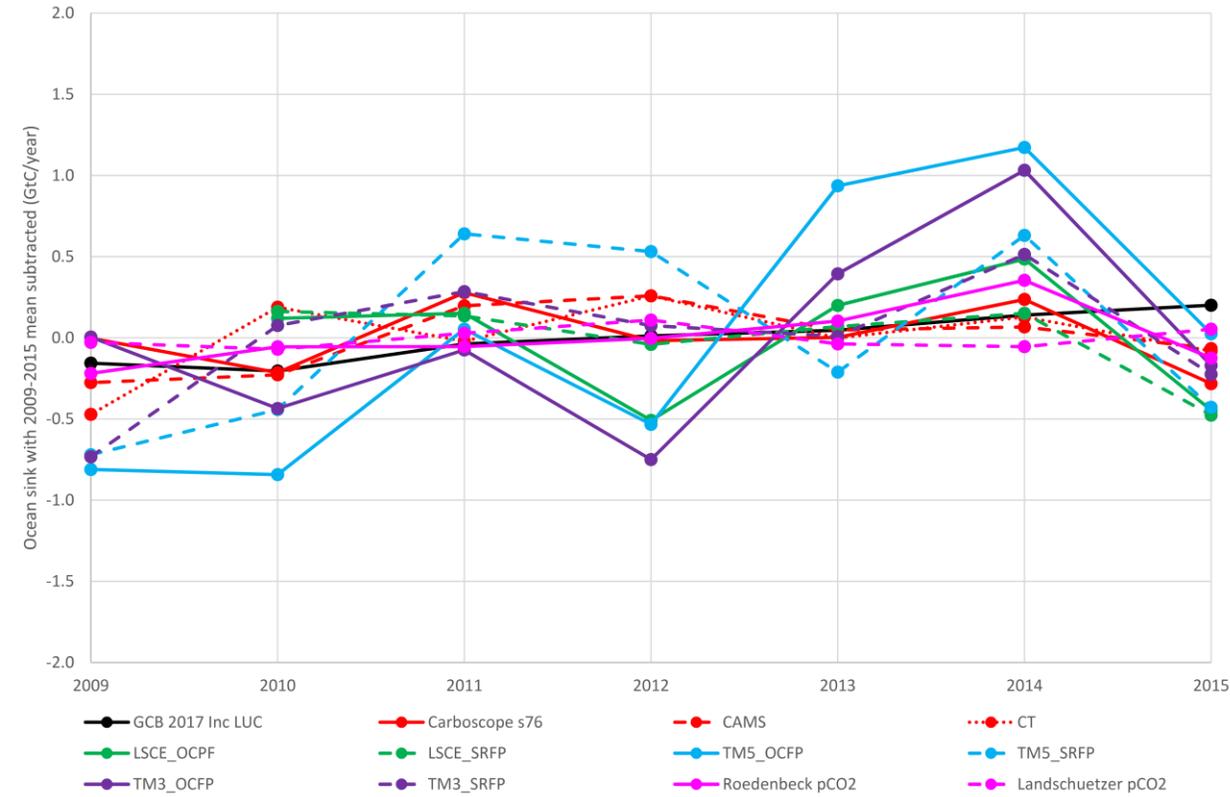
- Pattern of IAV generally agrees between different top-down and bottom-up estimates, but there are large differences (e.g. >1 GtC/year) for some years and between some products.
- OCFP satellite based inversions display larger IAV between 2011-2013 than SRFP based satellite estimates.
- Some clear disparities emerge between satellite-based and surface-based inversions when looking at IAV as difference from GCB (right plot). E.g. in 2012, the satellite inversions are \leq GCB (except for TM5_SRFP) but the surface inversions are $>$ GCB.

Land sink IAV (2009-2015 mean subtracted)



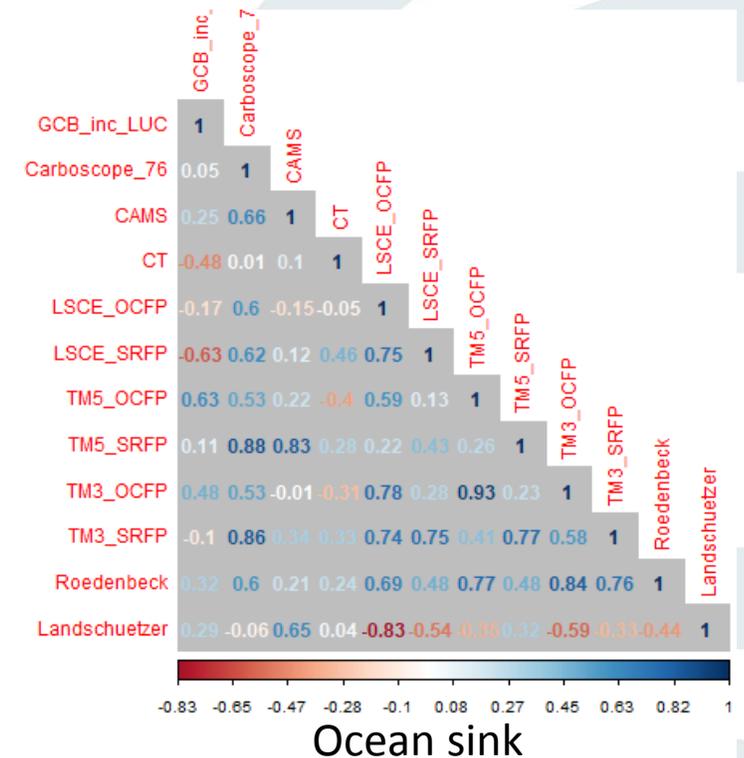
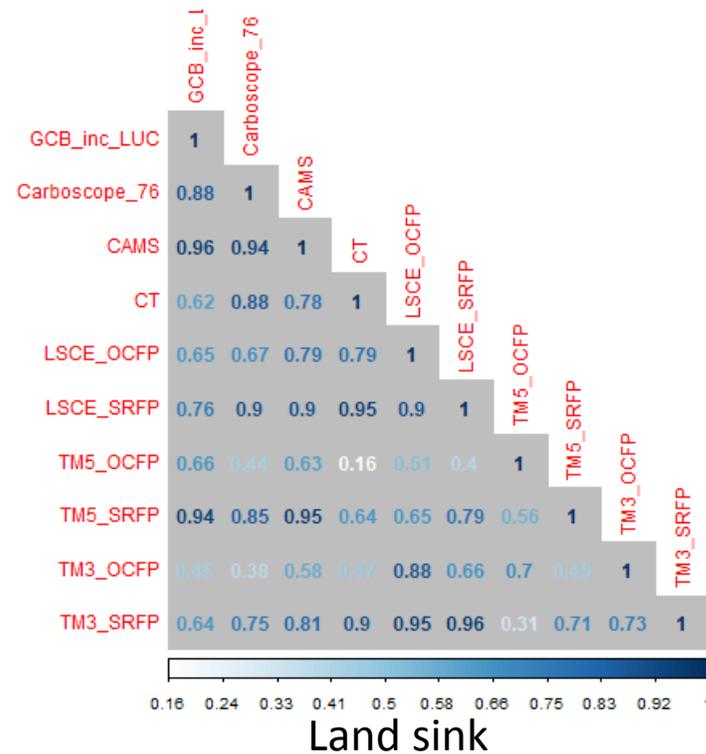
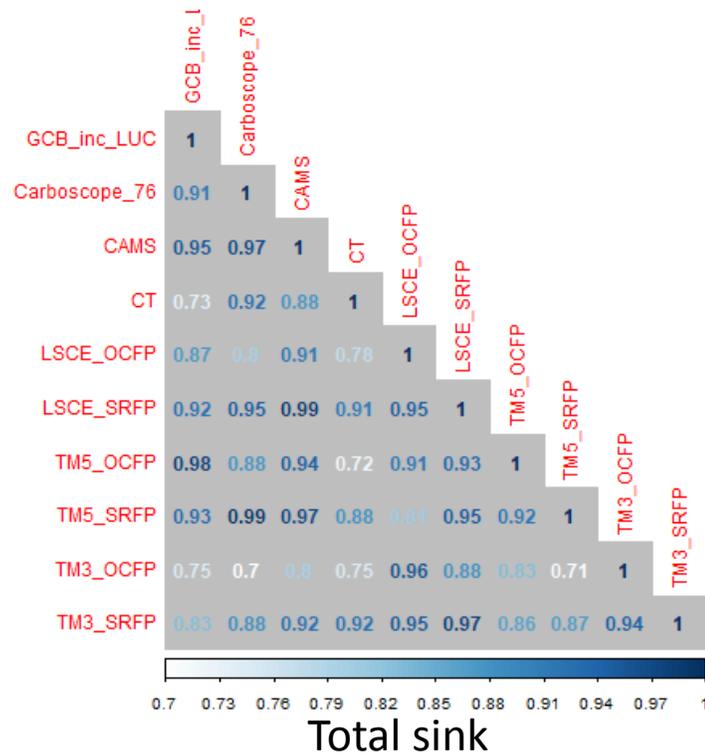
- Significant differences between SRFP and OCFP IAV between 2009-2010 and 2013-2015 for land sink (and this time SRFP IAV is generally larger than OCFP IAV).
- Spread of IAV around GCB (right plot) is larger for the land sink than for the total sink, mostly from satellite-based products (but not always the case, e.g. Carbon Tracker has a large difference in 2010).

Ocean sink IAV (2009-2015 mean subtracted)



- OCFP IAV generally larger than SRFP IAV throughout 2009-2015 period for ocean sink. This larger ocean sink OCFP IAV seems to drive the larger OCFP IAV in the total sink (as SRFP has the larger IAV for land sink).
- Satellite products generally have larger differences from GCB than other estimates (right plot). But GCB IAV is very small and likely underestimated (due to some processes not well represented in ocean models).
- Outliers in the ocean sink tend to be largely compensated by outliers of opposite magnitude in the land sink and vice versa (e.g. TM5_OCFP and TM3_OCFP 2013-2014 ocean sink estimates are relatively high, while the land sink estimates are relatively low for these same products in the same years).

Correlation coefficients for IAV



- Total sink correlation coefficients are all positive and fairly robust (0.7 – 0.99).
- There is large variability in the land sink correlation coefficients (0.16 to 0.96), but all are still positive.
- Ocean sink correlation coefficients vary the most (-0.83 to 0.93) and several are negative (Landschützer pCO₂ product in particular is negatively correlated with many of the other estimates, including the Rödenbeck pCO₂ estimate).
- The choice of satellite retrieval product generally has more bearing on the satellite inversion result than the choice of inverse model (with some exceptions, such as TM5 over the oceans).

Next steps...

To investigate...

- Differences in means and variability on monthly timescales (to look for sub-annual patterns of variability, e.g. El Nino).
- Zonal and regional differences in the annual/monthly means and variability.
- Seasonal differences on various scales/regions (looking at residuals from mean climatologies).

... so that we can say more about why and where these differences occur and how we may be able to move forwards with respect to resolving them.

Next steps WP1...

Protocol to get satellite data, including inversion output (building from ECV)

- Produce standard output
- transcom-like protocol
- define the output, metadata, naming conventions

Determine working practice

- work in sub-groups to deliver first inversions quickly
- agree on timing



CO₂
Human
Emissions

