Regional carbon sink estimates by the NTFVAR inverse model with surface and satellite observations.

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IWGGMS-21, 9-12 June, Takamatsu, Kagawa, Japan

Overview

- NIES-TM-FLEXPART - variational (NTFVAR) inverse model
  - Light-weight alternative to applying a full high-resolution model inversion like IFS
- OCO2 v10 MIP as comprehensive validation platform
  - Comparing CO_2 fluxes, mean sinks, data fit at sites
  - Data selection
- Flux results with GOSAT L2 v03.05 vs v02.97 data:
  - Getting moderate tropical region fluxes
- Future directions:
  - Higher spatial resolution, extension to dense satellite data

Why use NIES-TM-FLEXPART-var (NTFVAR)? - On the benefit of coupled global Eulerian-Lagrangian model

- Similar regional systems:

LUMIA and Carboscope-Reg – regional Lagrangian transport coupled one way to global model 3D fields as boundary: demonstrated good performance for flux CO_2 retrievals in Europe

In NTFVAR Lagrangian component is global and coupled to a global Eulerian model – online, has adjoint

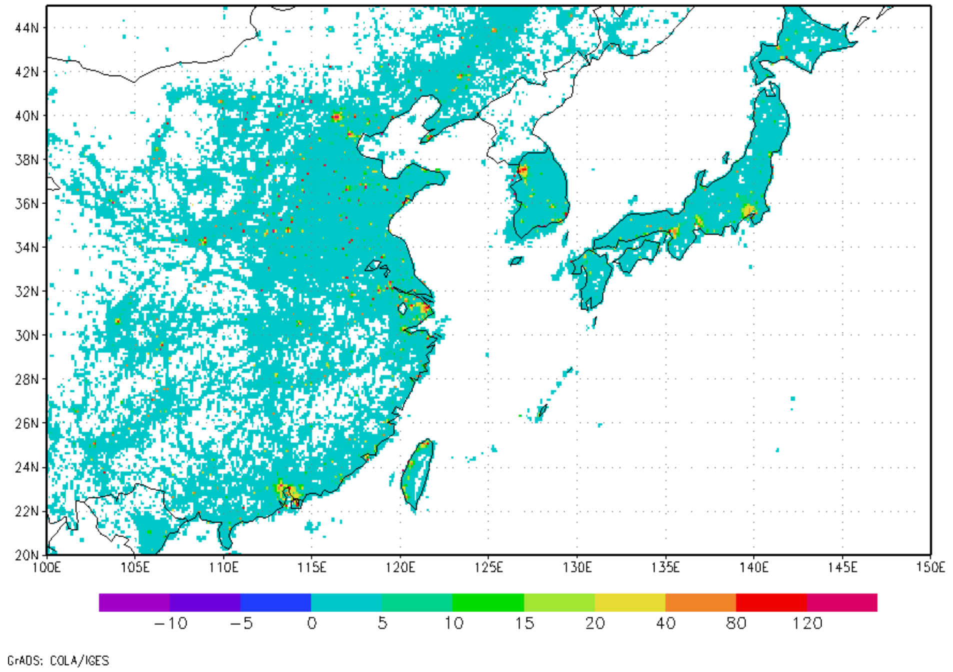
- can solve for fluxes at 0.1 deg globally
- can compare with regional and global models (GMB, GCB, MIP v10, European CH_4, Asian CH_4 inversions)

-NIES-TM (v20,21)
- resolution 2.5/3.75 degree;
  - v20 van Leer 2nd order reduced grid near poles;
  - v21 slopes (1st order moments), regular grid
- mass conserving meteorology,
- mass fluxes on hybrid sigma pressure vertical coordinates (42 levels),
-winds interpolated from hourly 132 lev ERA-5 winds on 0.625º
-model (eta-dot) vertical velocity provided by ERA5 reanalysis

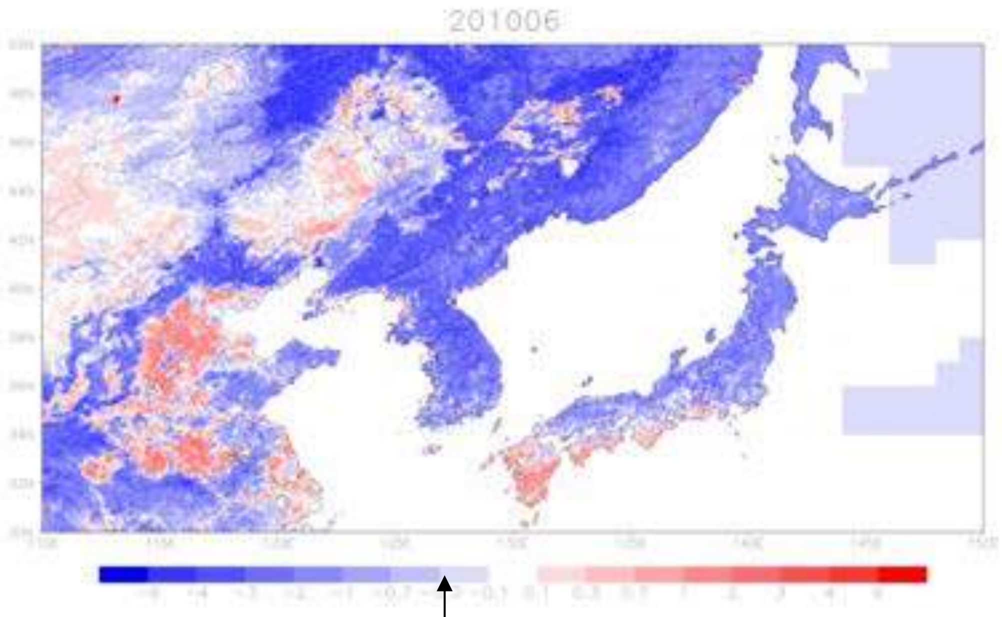
-Flexpart (with diurnal fluxes)
- -JRA-55 meteorology (1.25 deg, 40 model levels, 6 hourly)
- -surface flux footprints on 0.1x0.1 deg, daily and hourly time step
- -time window 3 days (for coupling to NIES-TM at 0 GMT)
- -for coupling to NIES-TM, 3D concentration on hybrid-sigma grid
- -tested use ERA5 wind at original resolution (0.25 deg)

-Inversion: Maksyutov et al ACP 2021 with revisions
- -data-driven prior fluxes for land 0.1 deg and ocean
- -storage of transport matrixes on disk, rather than RAM
- -separate resolutions for flux corrections (0.1 degrees) and flux scaling factors (0.2 degrees) – can run inversions at 0.05 and 0.025 deg

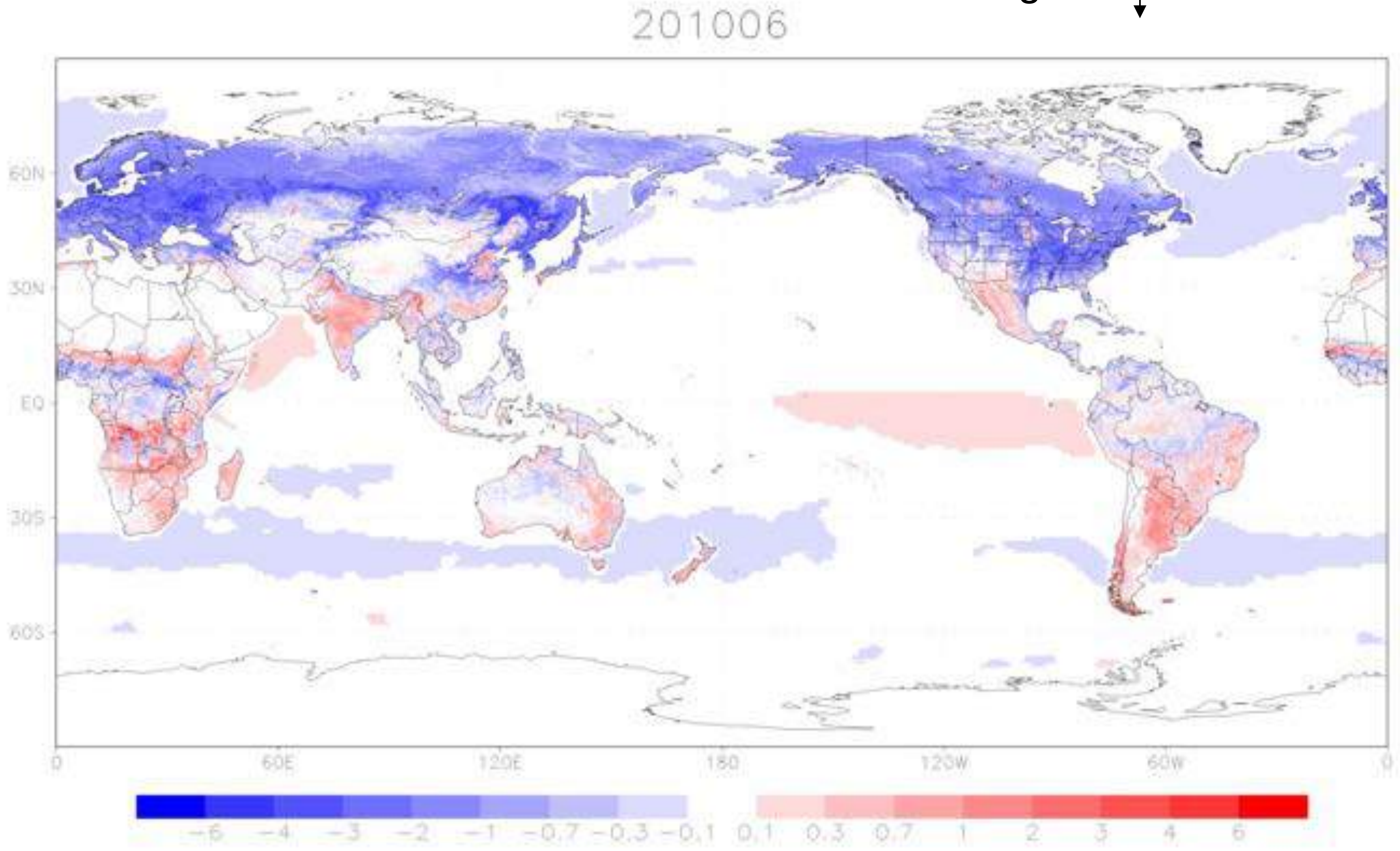
Prior fluxes: categories (wide range of amplitudes from 0.1 g/m2/day (ocean) to 100 g/m2/day (fossil and fires), and resolutions from 10 km to 100 km



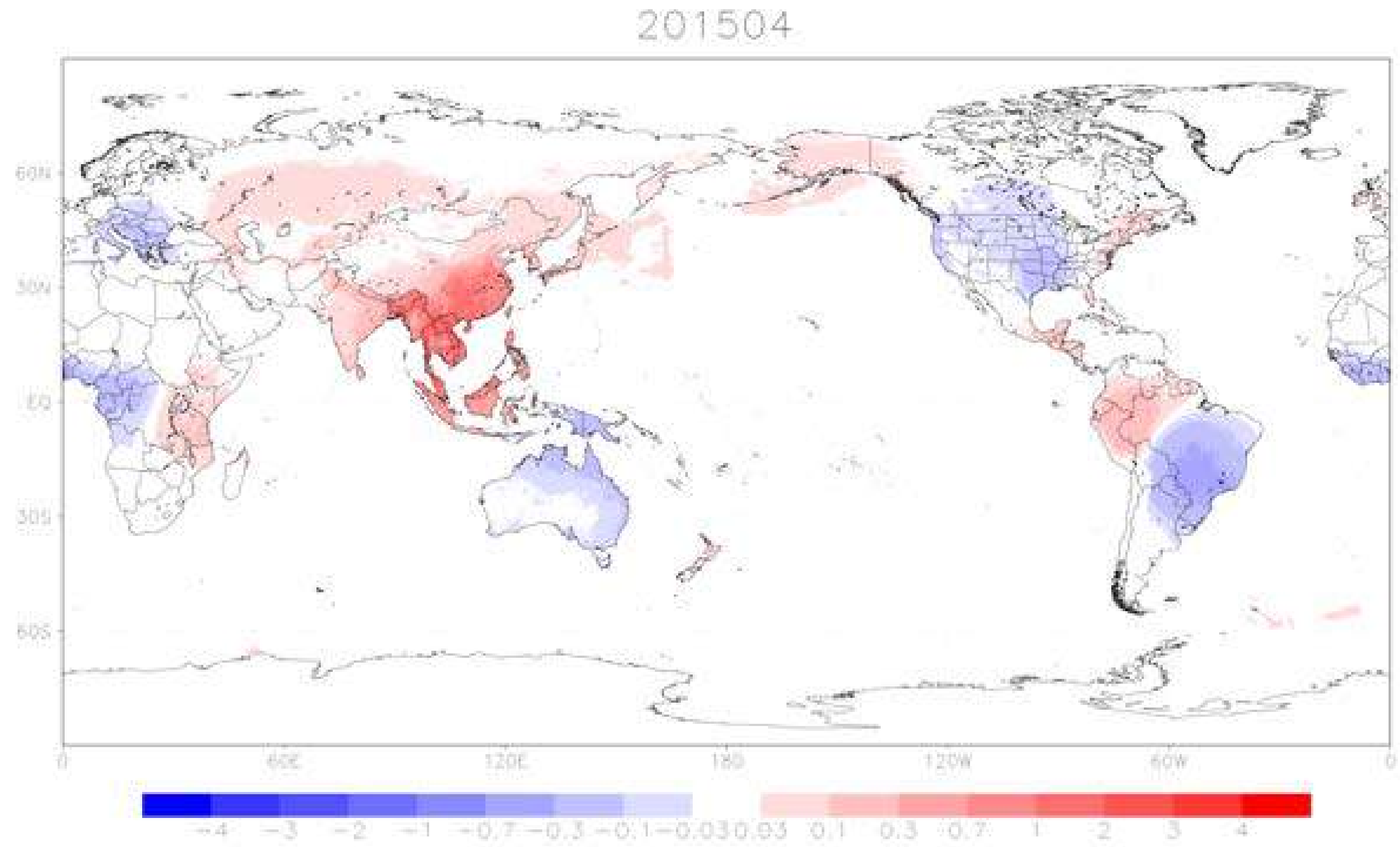
Fossil emissions ODIAC 2019 – MIP

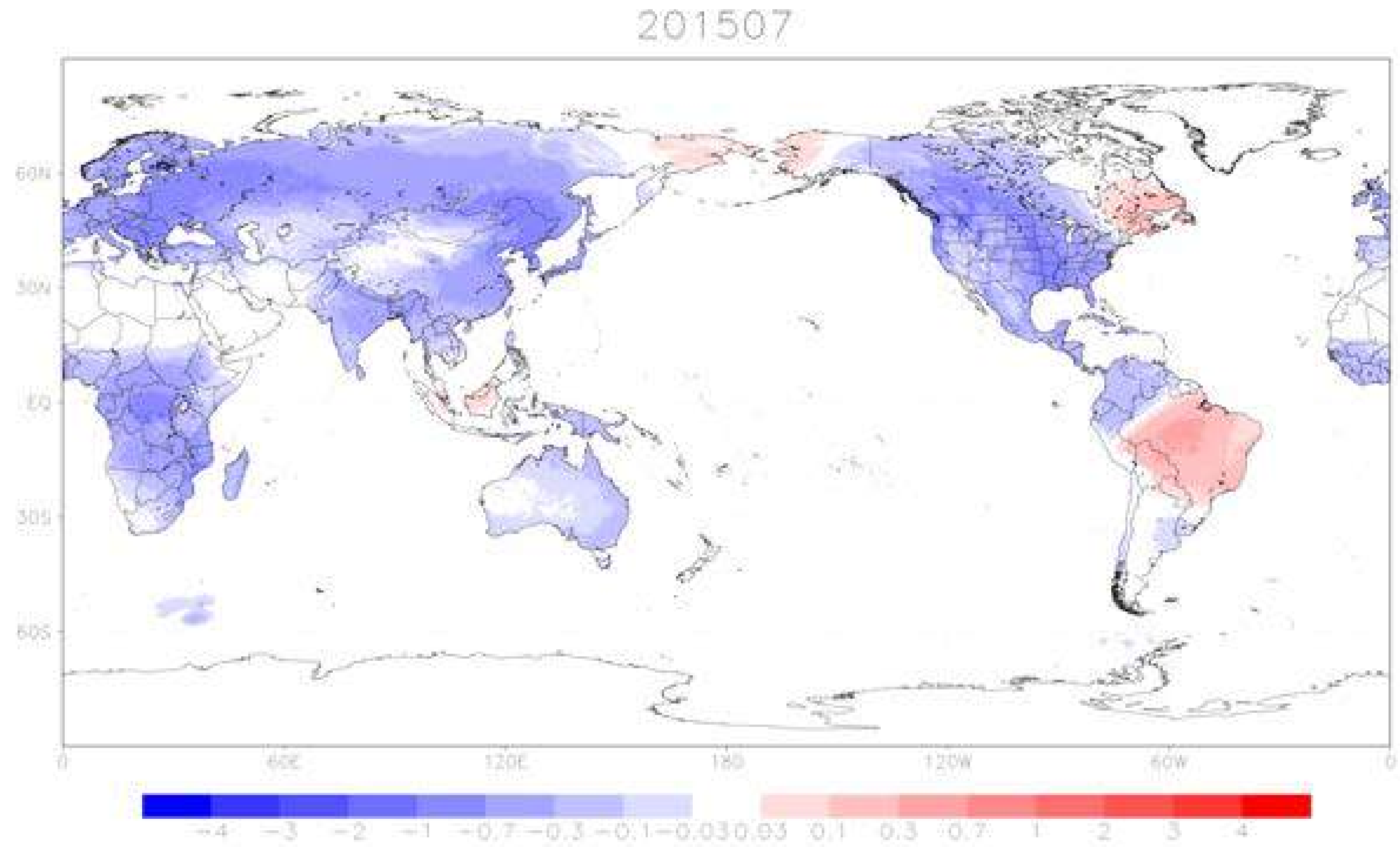


Terrestrial biosphere, flux upscaling with ML Zeng et al, Sci. Data 2020,
Ocean CO_2 surface exchange, with ML algorithm, Zeng et al et al 2014, 2022
Biomass burning: GFAS

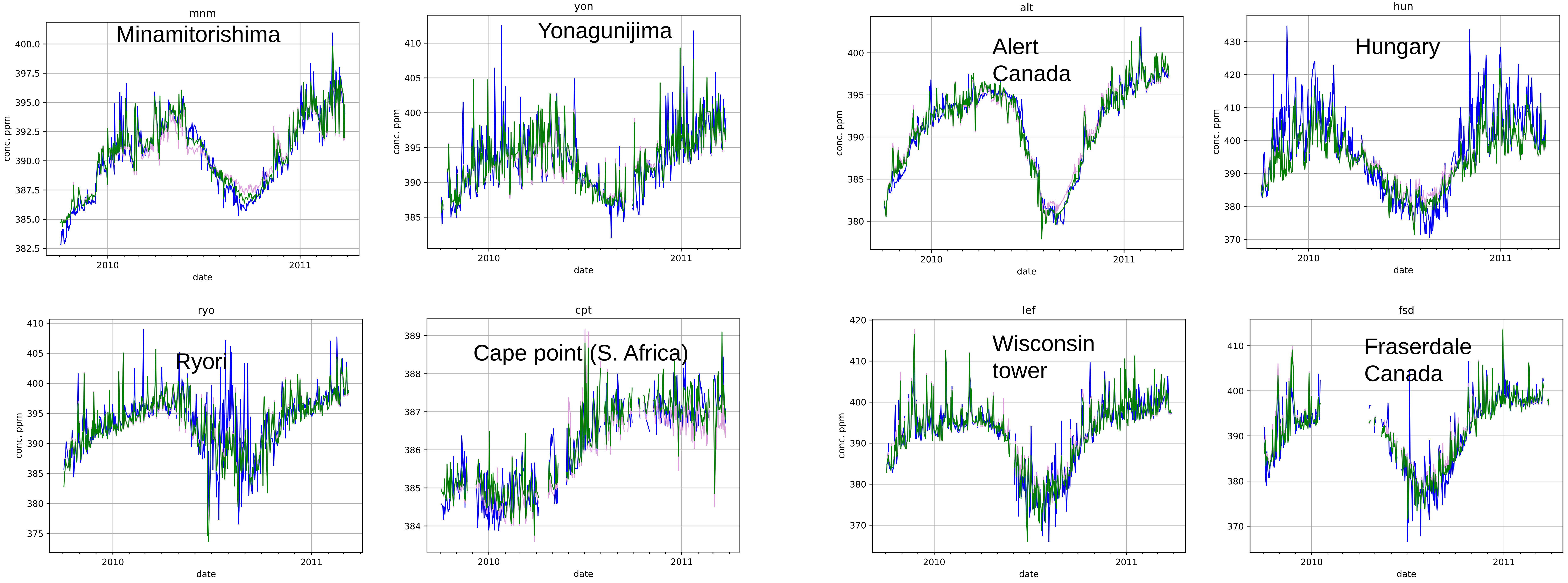


Posterior flux corrections (gC/m²/day) for 2015/04 and 2015/07





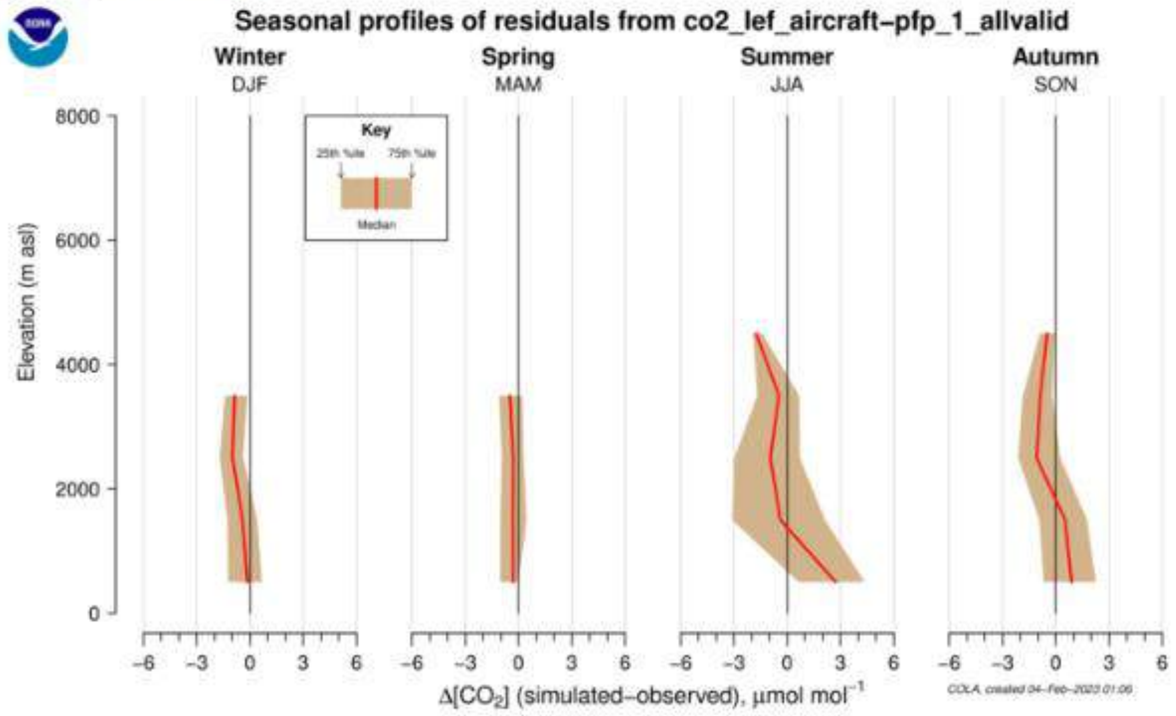
Simulated CO_2 concentrations (GOSAT+surface inversion)



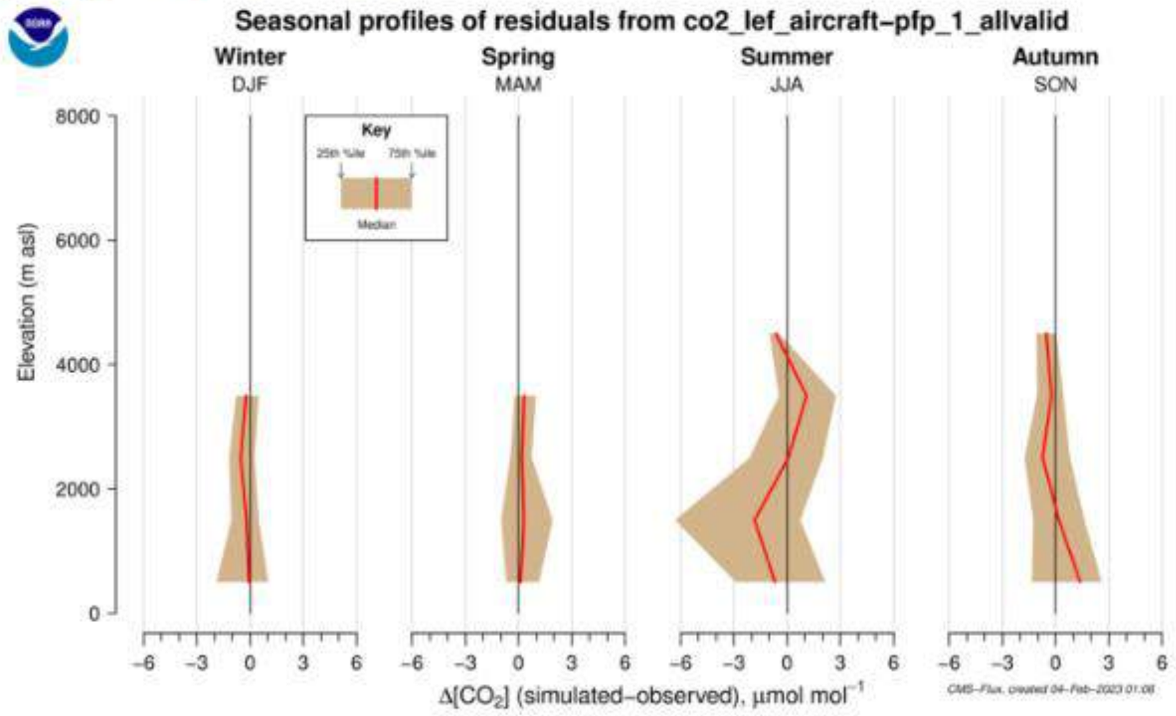
observations (blue), forward/prior (plum), inversion (green)

Model fit to aircraft profile observations over LEF (Wisconsin) in OCO-2 v10 MIP

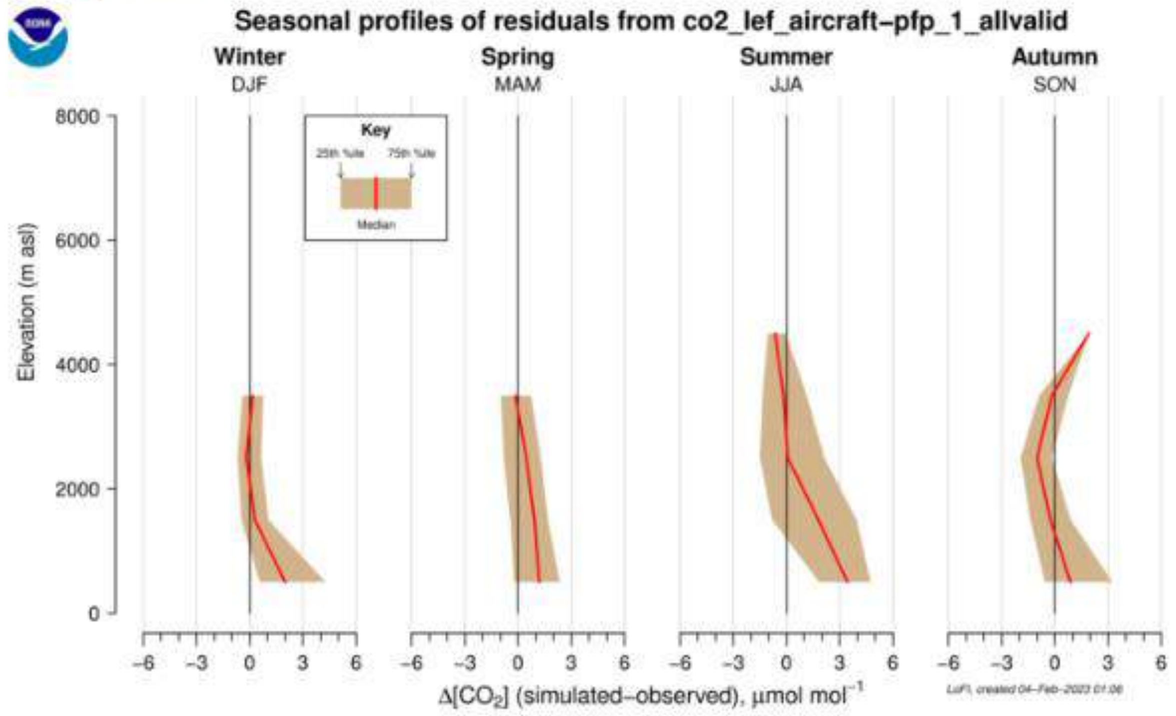
(1a) COLA



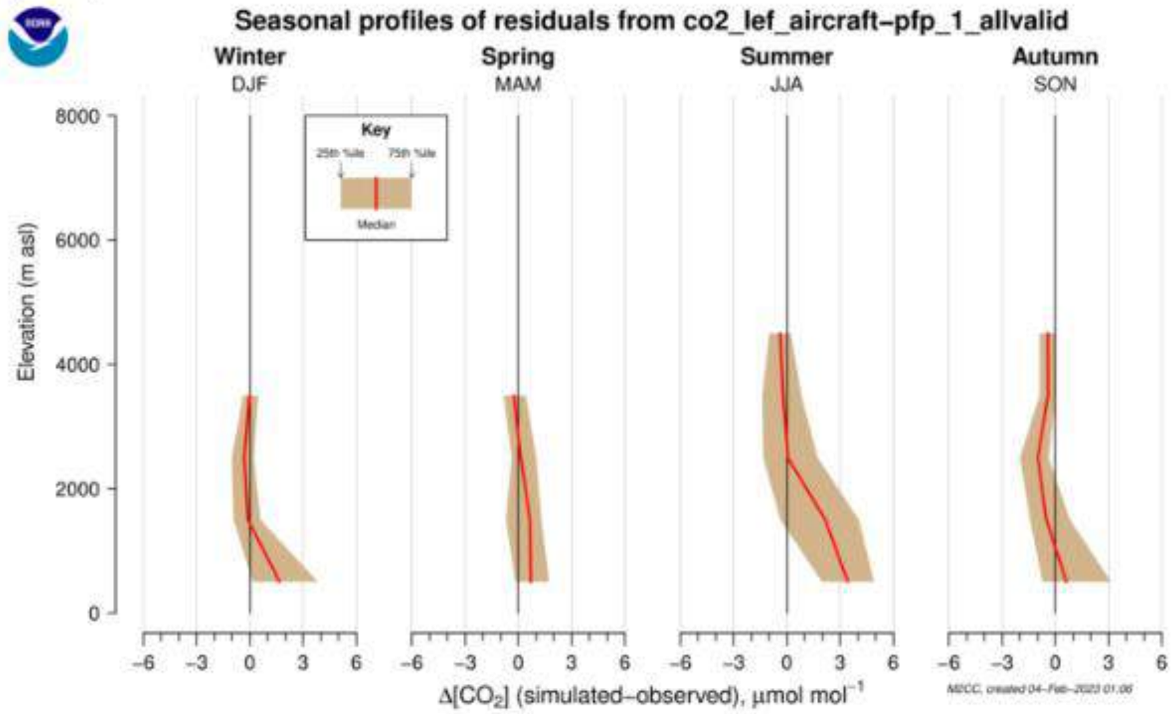
(1a) CMS-Flux



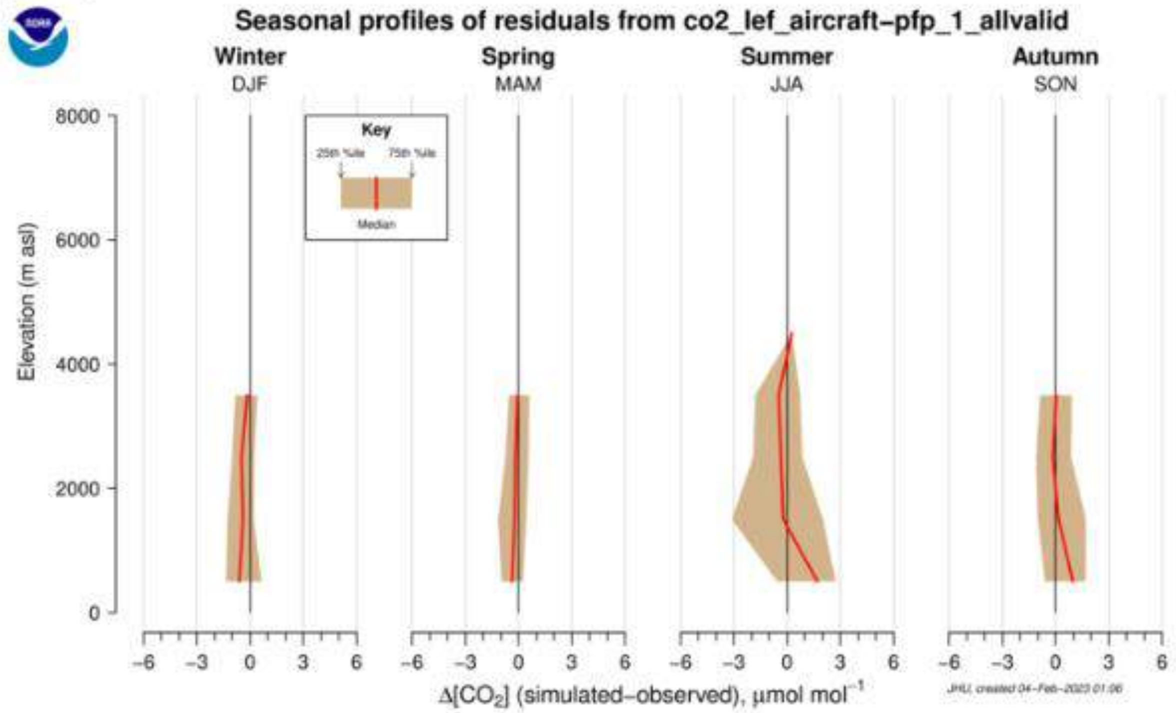
(1a) LoFI



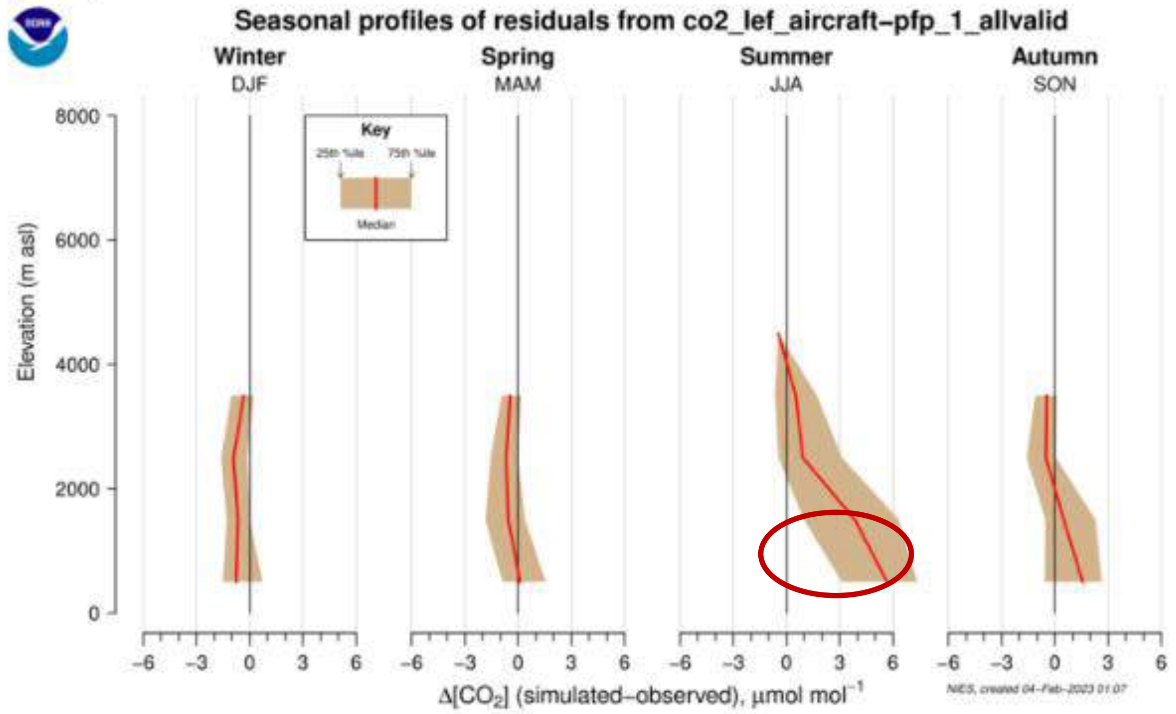
(1a) M2CC



(1a) JHU



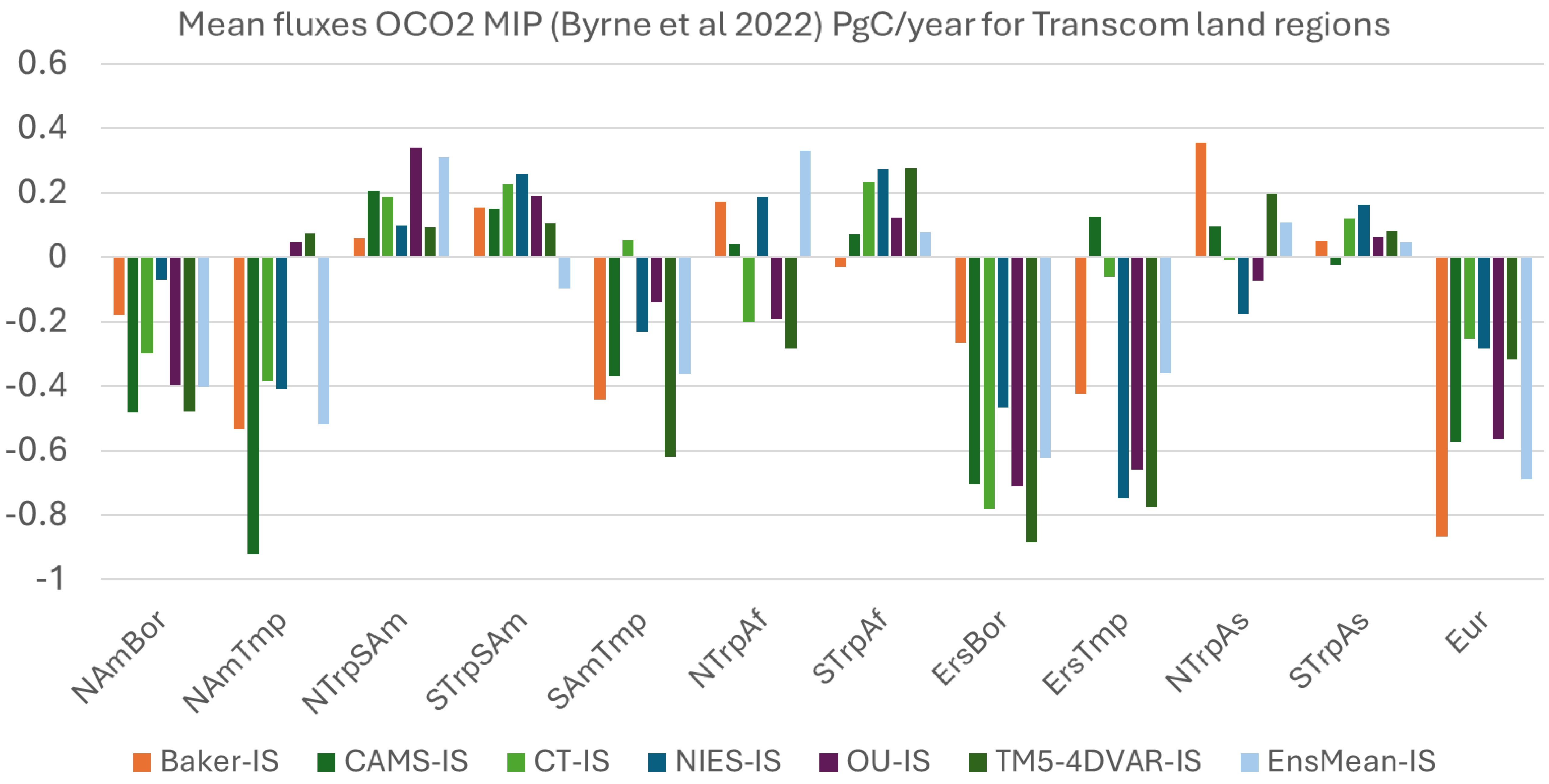
(1a) NIES



https://gml.noaa.gov/ccgg/OCO2_v10mip

Weak seasonal cycle at surface at LEF – fixed by giving larger data uncertainty – looser constrain on data

Mean land fluxes for Transcom-3 regions – balance of sources and sinks



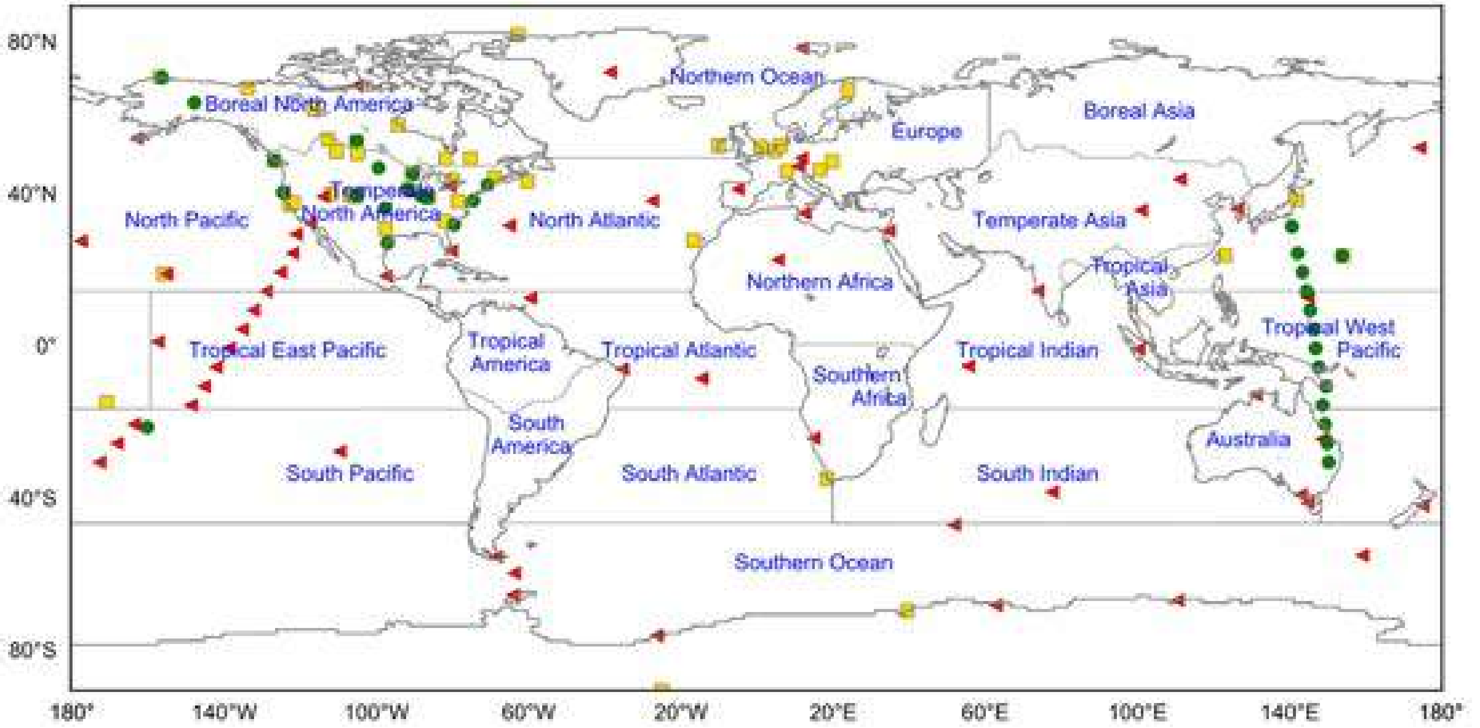


Fig. Mean regional land fluxes for Transcom regions by MIP models and NIES NTFVAR v21, NIES model show less sink in boreal regions, and temperate S. America, likely due to strong ocean prior. NIES Landschutzer 2020 ocean fluxes are scaled to produce global 3 PgC/y sink in 2010s. (IS–in situ case). MIP paper - Byrne et al ESSD 2023 Time period 2015-2020

Notes: Tropical emissions in NIES model<.3 Pg/yr/region
Some models give no sink in temperate N America

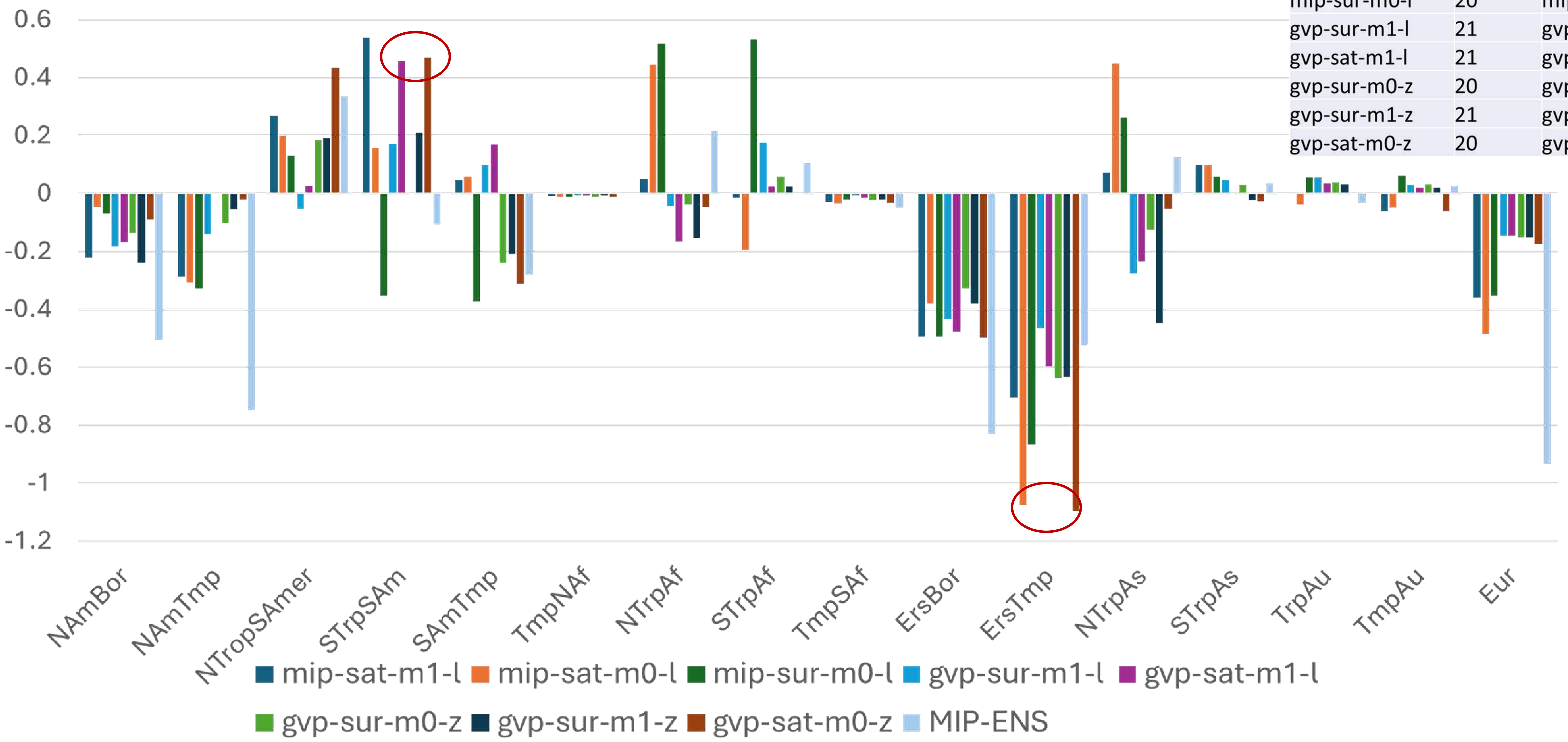
Inversion tests with GOSAT L2 v03.05 and a MIP-like Obspack selection

- 2 variants of Obspack dataset a) MIP v10 version used in Byrne et al 2022, and same uncertainties as NIES submission; b) extended set based on GVP 202309 version, using same temporal sampling as MIP dataset, but including all available stations in Europe and Asia. satellite data: GOSAT v03.05
- 2 ocean flux datasets (L) scaled Landschützer (Z) Zeng et al 2014
- 2 versions of transport. completed 6 years 2015-2020 inversions with 2 versions of NIES TM v20 (van Leer II) and v21 (slopes), and 2 sets of inversions for period of 2009-2022, with 8 combinations of prior ocean, model version and observation selection

case	NIES-TM version	Obspack mip/gvp	GOSAT	Ocean prior
mip-sat-m1-l	21	mip	yes	Landschutzer
mip-sat-m0-l	20	mip	yes	""
mip-sur-m0-l	20	mip	-	""
gvp-sur-m1-l	21	gvp	-	""
gvp-sat-m1-l	21	gvp	yes	""
gvp-sur-m0-z	20	gvp	-	Zeng 2014
gvp-sur-m1-z	21	gvp	-	""
gvp-sat-m0-z	20	gvp	yes	""

Mean land fluxes for Transcom-3 regions – balance of sources and sinks

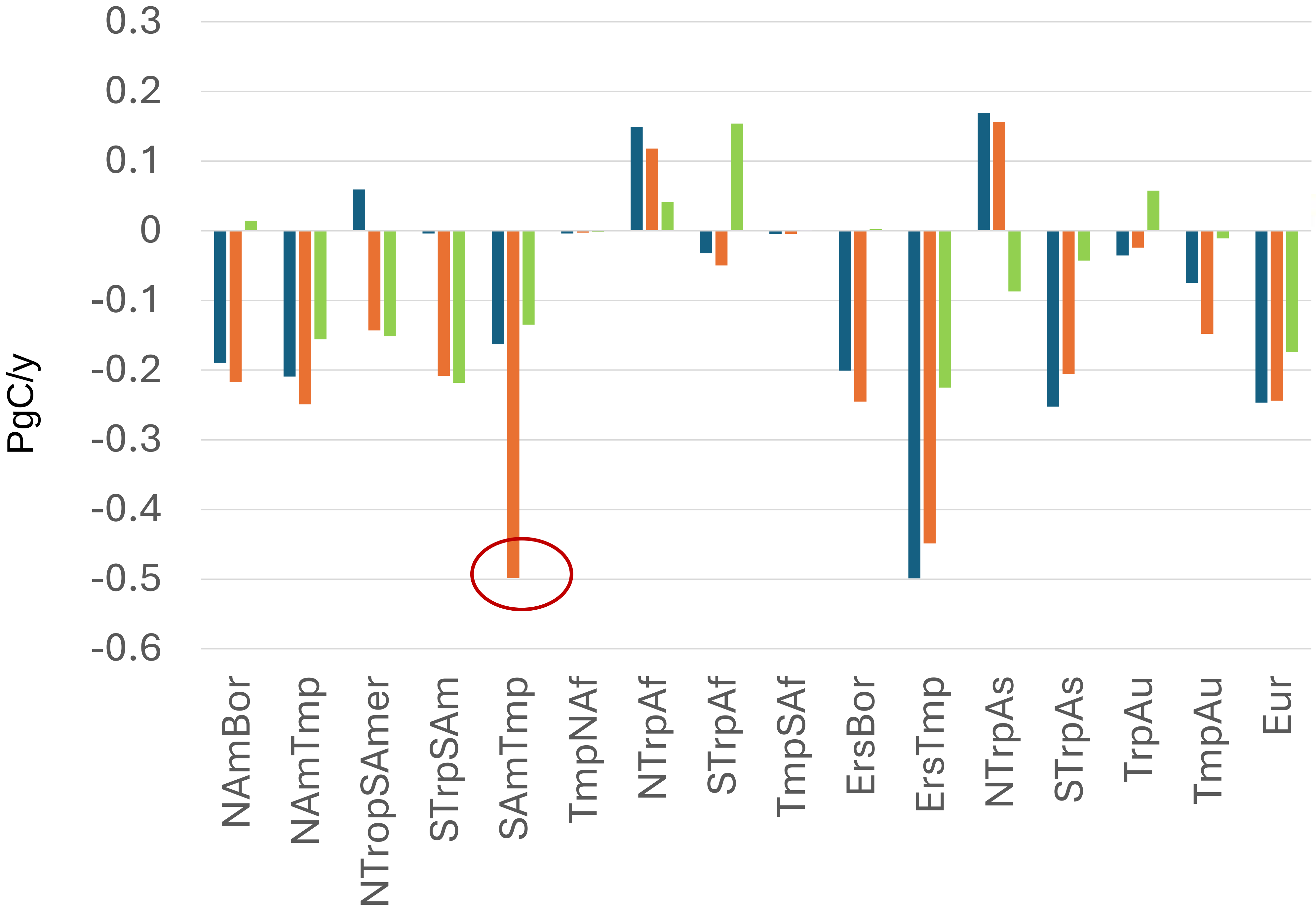
case	NIES-TM version	Obspack mip/gvp	GOSAT	Ocean prior
mip-sat-m1-l	21	mip	yes	Landschutzer
mip-sat-m0-l	20	mip	yes	""
mip-sur-m0-l	20	mip	-	""
gvp-sur-m1-l	21	gvp	-	""
gvp-sat-m1-l	21	gvp	yes	""
gvp-sur-m0-z	20	gvp	-	Zeng 2014
gvp-sur-m1-z	21	gvp	-	""
gvp-sat-m0-z	20	gvp	yes	""



Notes: sat (GOSAT v03.05) – problems with large emissions in some tropical regions.
MIP obspack data selection – stronger Europe, N America sink, GVP – sink in N Trop Asia, S America temperate Units PgC/y, 2015-2020

Regional land fluxes 2010-2023 in PgC/year with 2 ocean priors and GOSAT L2 v02.97:

note: separate data uncertainty scaling for background and continental sites (where rmse > 3ppm);



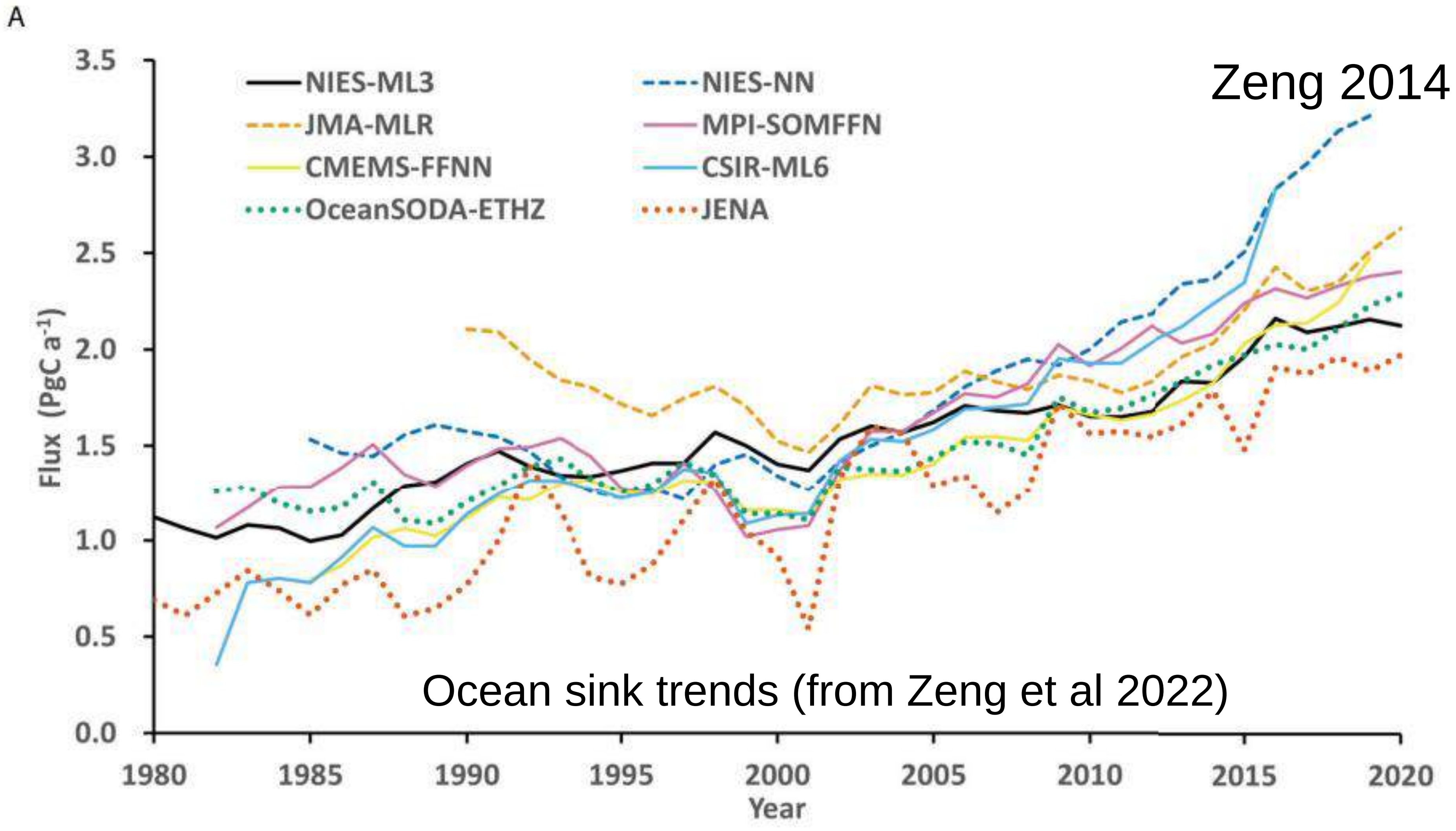
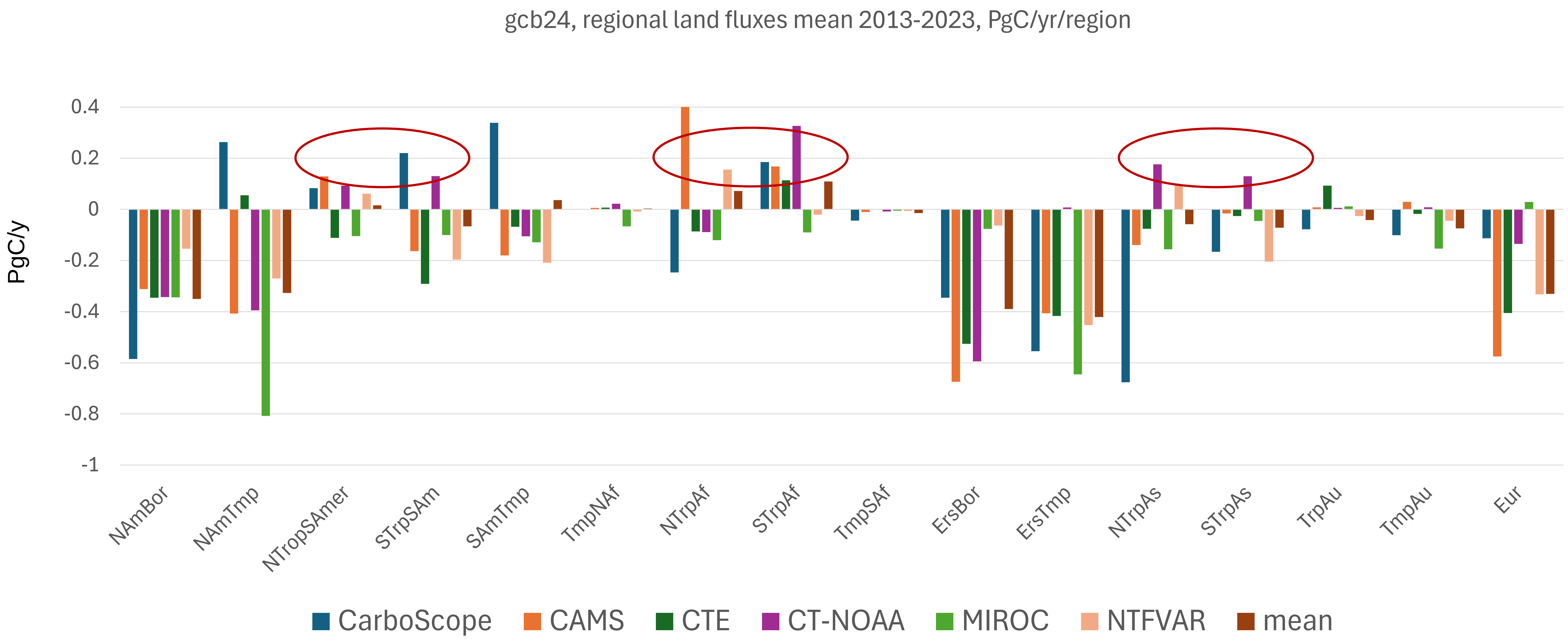


Figure: regional fluxes: blue Zeng 2014 ocean, orange with Zeng 2022, light green – prior
Improved balance tropical emissions <0.2 Pg/yr/region
weak ocean sink (Zeng 2022) demands land sink in tropical, temperate S America

Zeng 2022 revision of 2010-2020 sink downwards may contradict ocean sink estimates with O2/N2 observations by Tohjima et al 2019 (~3 PgC/y), - should we apply Watson et al 2020 correction (~0.5 Pg)?

Regional land fluxes 2013-2023 for selected GCB 2024 model outputs

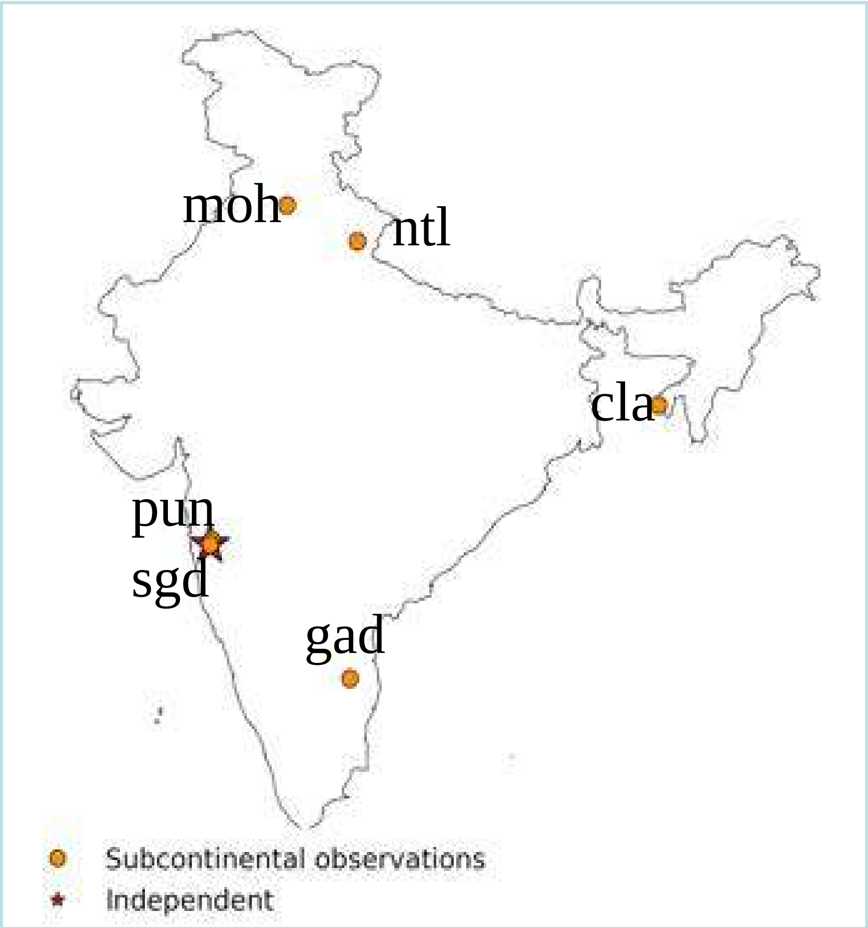
… most models have mean tropical emissions below .2 PgC/yr/region



As in previous slide NTFVAR submission uses GOSAT v02.97 and Zeng 2014 ocean

Good test for inversion fluxes – comparing with observations over India

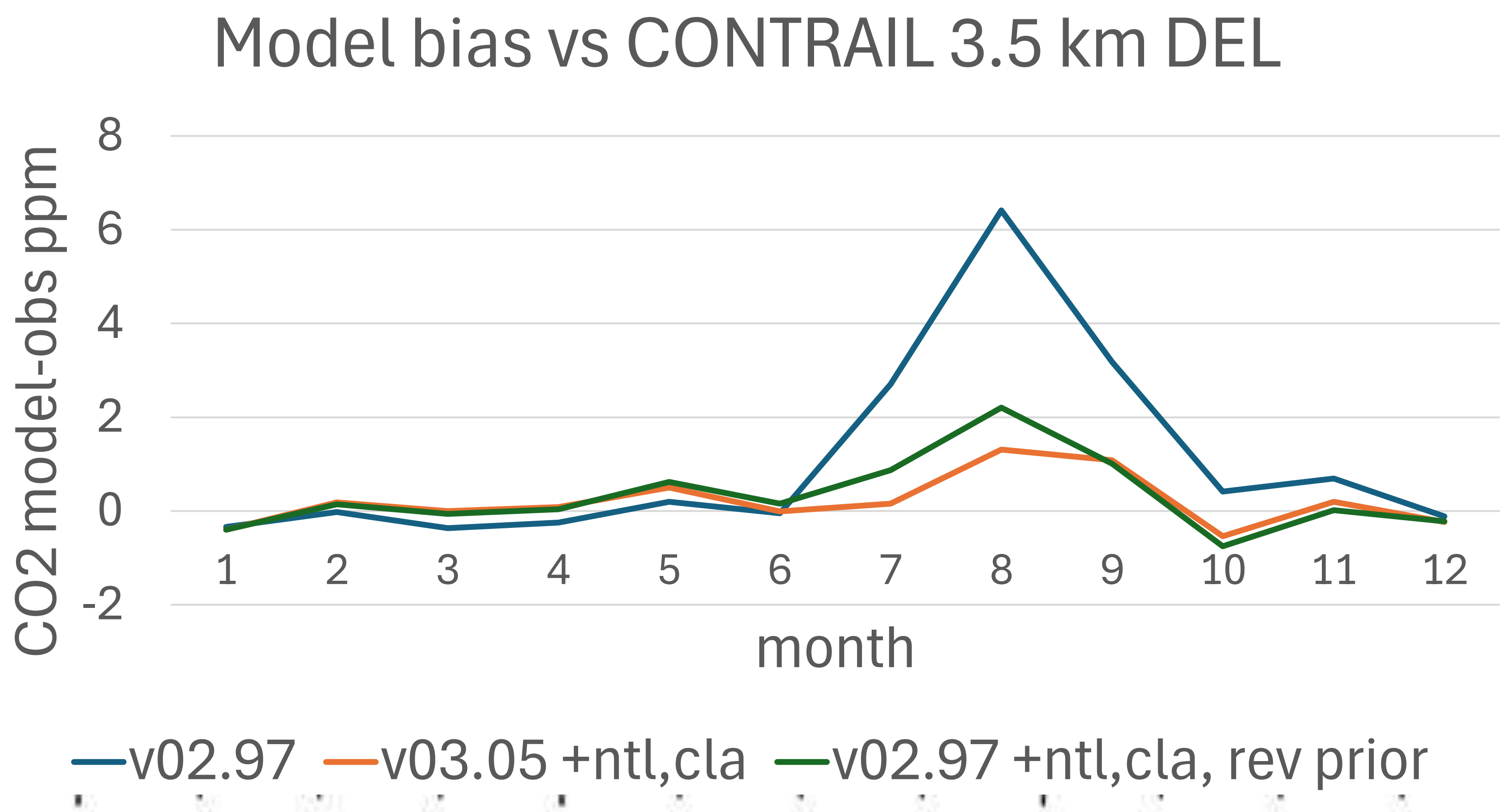
Nayagam et al. Indian Land Carbon Sink Estimated from Surface and GOSAT Observations, Remote Sensing 2025

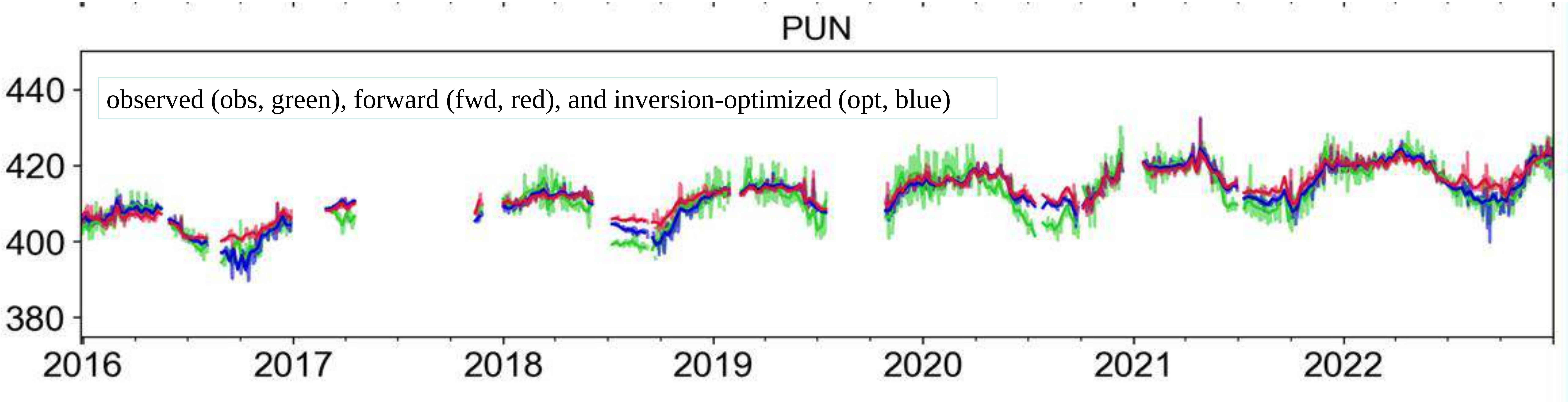


Site Code	Station	Sampling
CLA	Comilla	Flask
GAD	Gadanki	in-situ
MOH	Mohali	in-situ
NTL	Nainital	Flask
PUN	Pune	in-situ
SNG	Sinhagad	in-situ

Table 1. Sites from Indian subcontinent

Adding observations over India produces stronger seasonal cycle that matches better with CONTRAIL profiles over Delhi 2010-2014





High spatial resolution biospheric CO2 flux optimization at 0.025x0.025° - can we replicate success of ODIAC, VPRM?

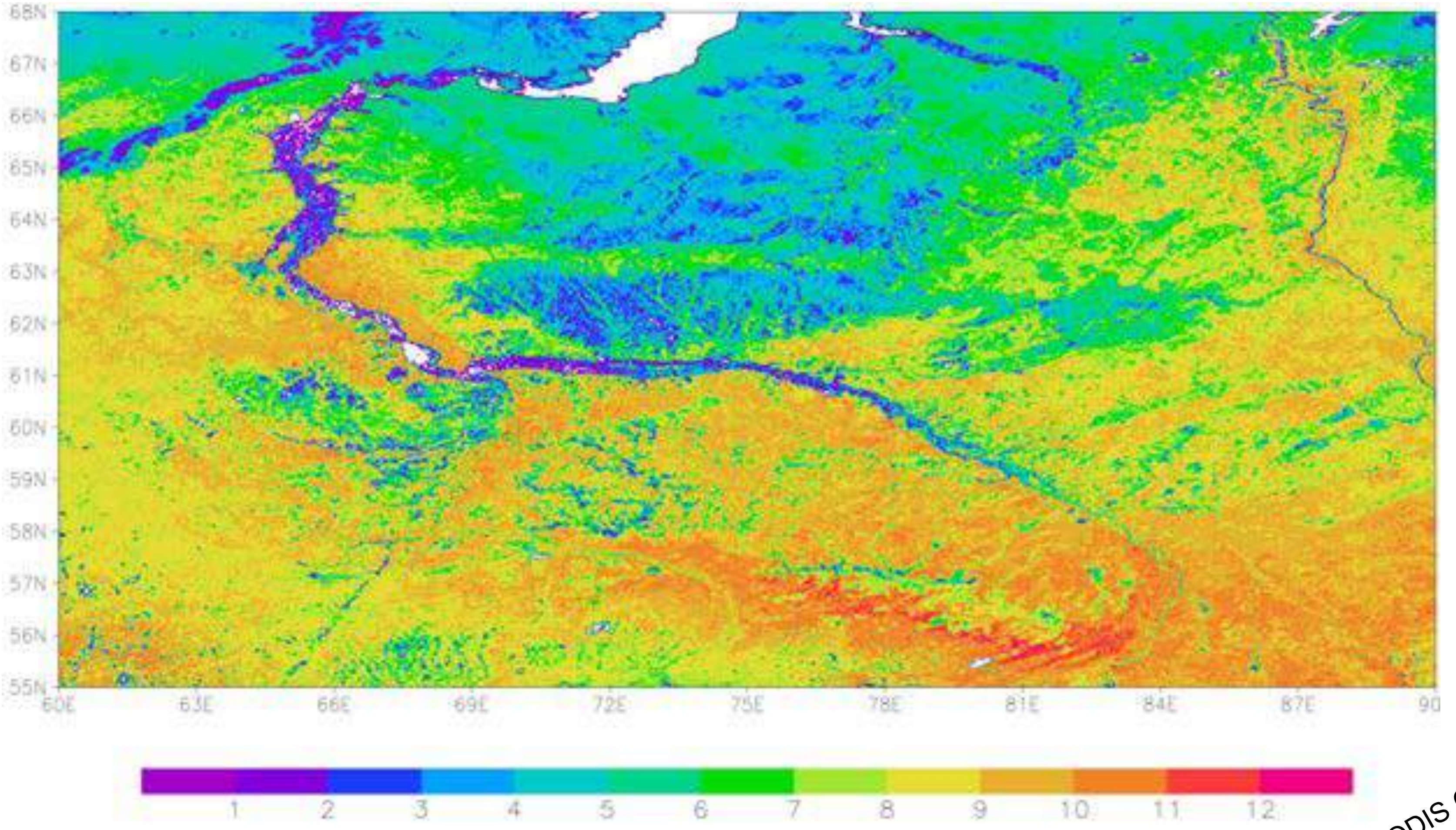
Nayagam et al. ERL 2024 used modified NTFVAR to include optimization of natural and fossil fluxes at high resolution 0.025, while using annual MODIS GPP to downscale 0.1 GPP, RE, NEE fluxes by Zeng et al 2020a.

Here we use 8-day 500 m MODIS GPP to make 10-day GPP at 0.025° resolution

Coupled with high resolution FLEXPART model v.8.0 (Stohl et al., 2005) (0.025° x 0.025°)

Optimize biospheric fluxes at 0.025° resolution

Uses native high-resolution fluxes and uncertainty files (0.025° x 0.025°)



new GPP top – (West Siberia) right (Japan)
Below - Nayagam et al. ERL 2024 priors

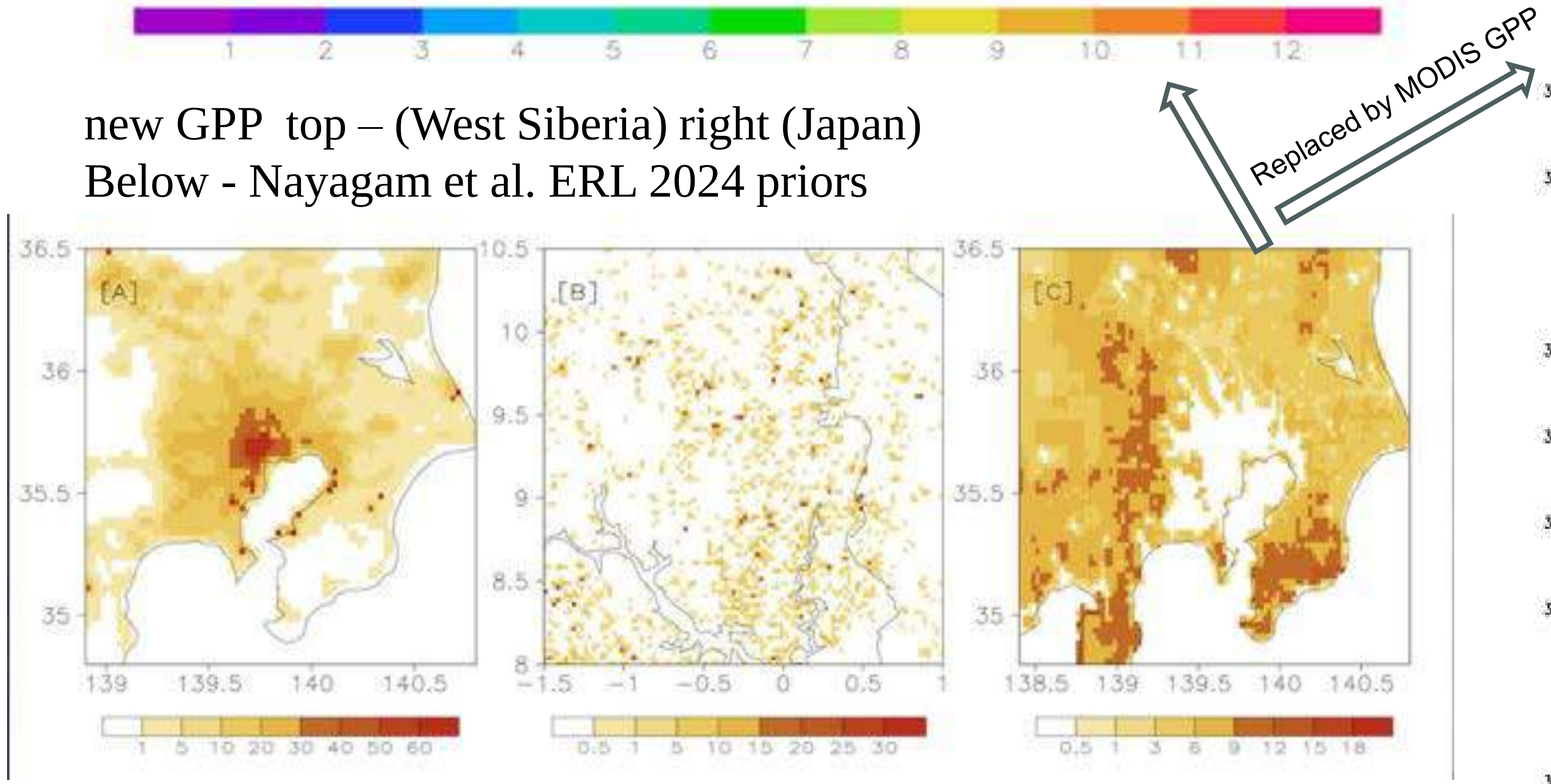
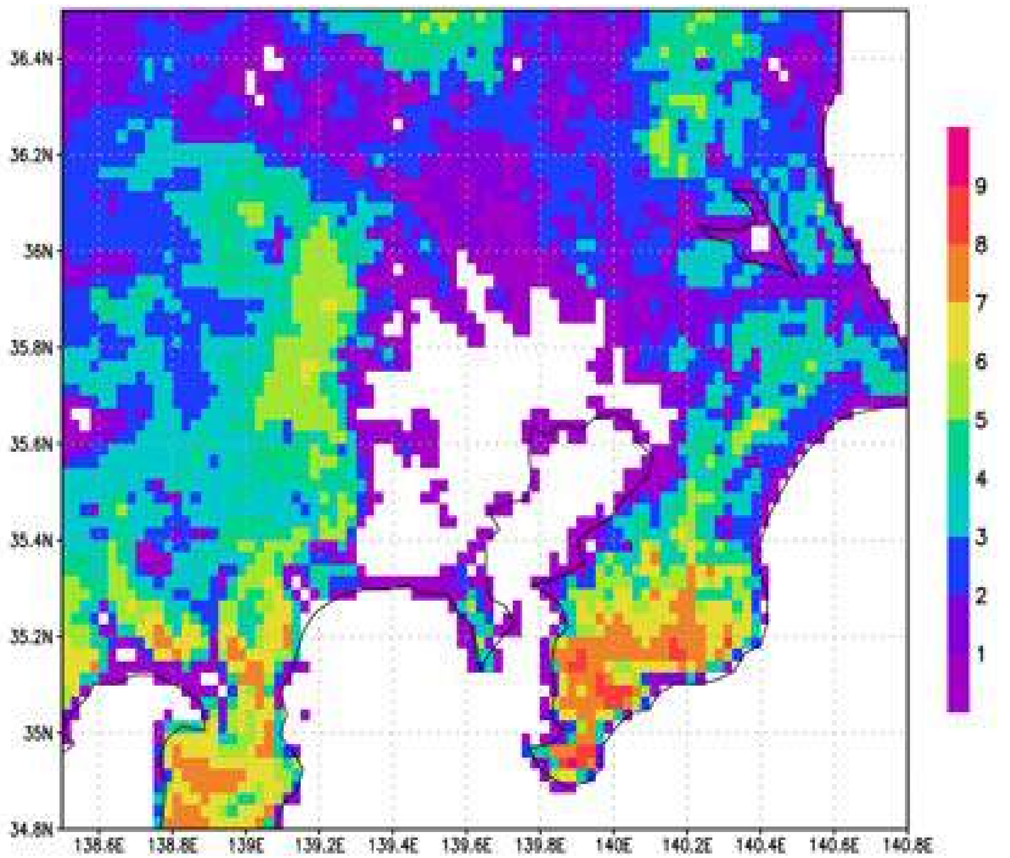


Figure 1. Top: MODIS GPP in Jul for West Siberia. Bottom: the prior fields of (A) fossil fuel emissions from ODIAC, (B) biomass burning emissions of Jan 2018 from GFAS, and (C) GPP of April 2018 from Zeng et al (2020b), as in Nayagam et al 2024. GPP downscaled from original dataset to model resolution of 0.025° × 0.025° . (A), (C) Tokyo region and (B) Africa, Ghana. Units gC m^{-2} d^{-1}.



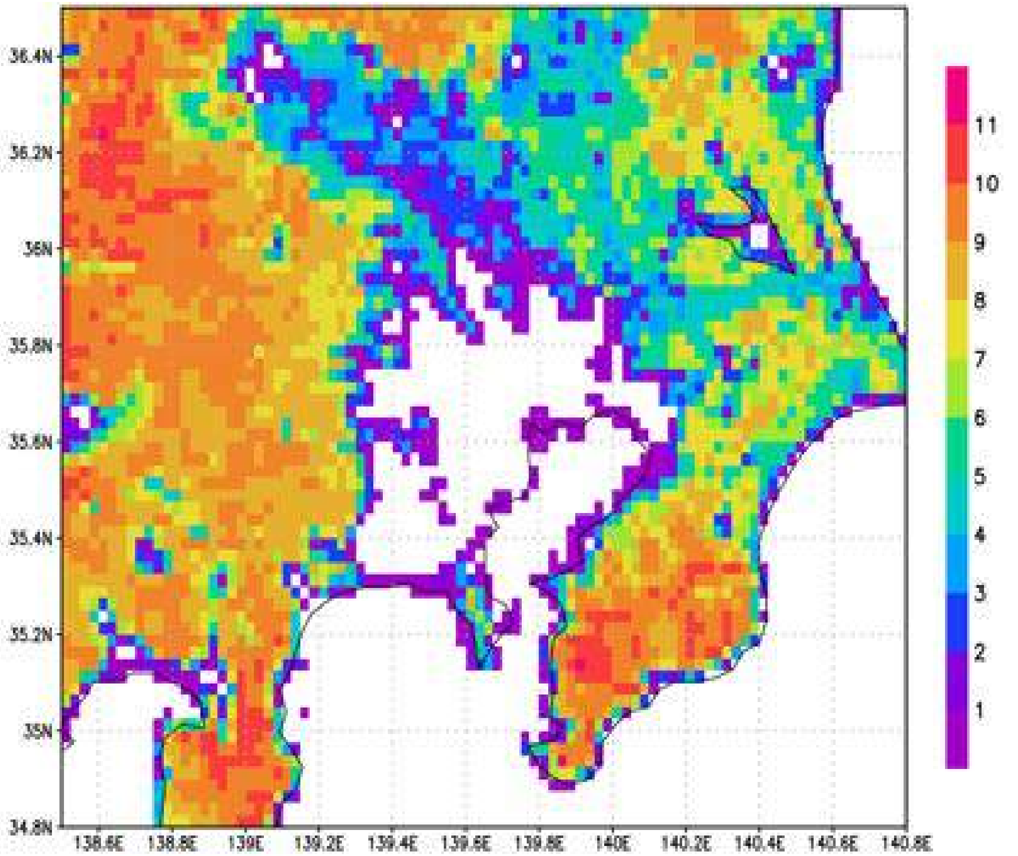
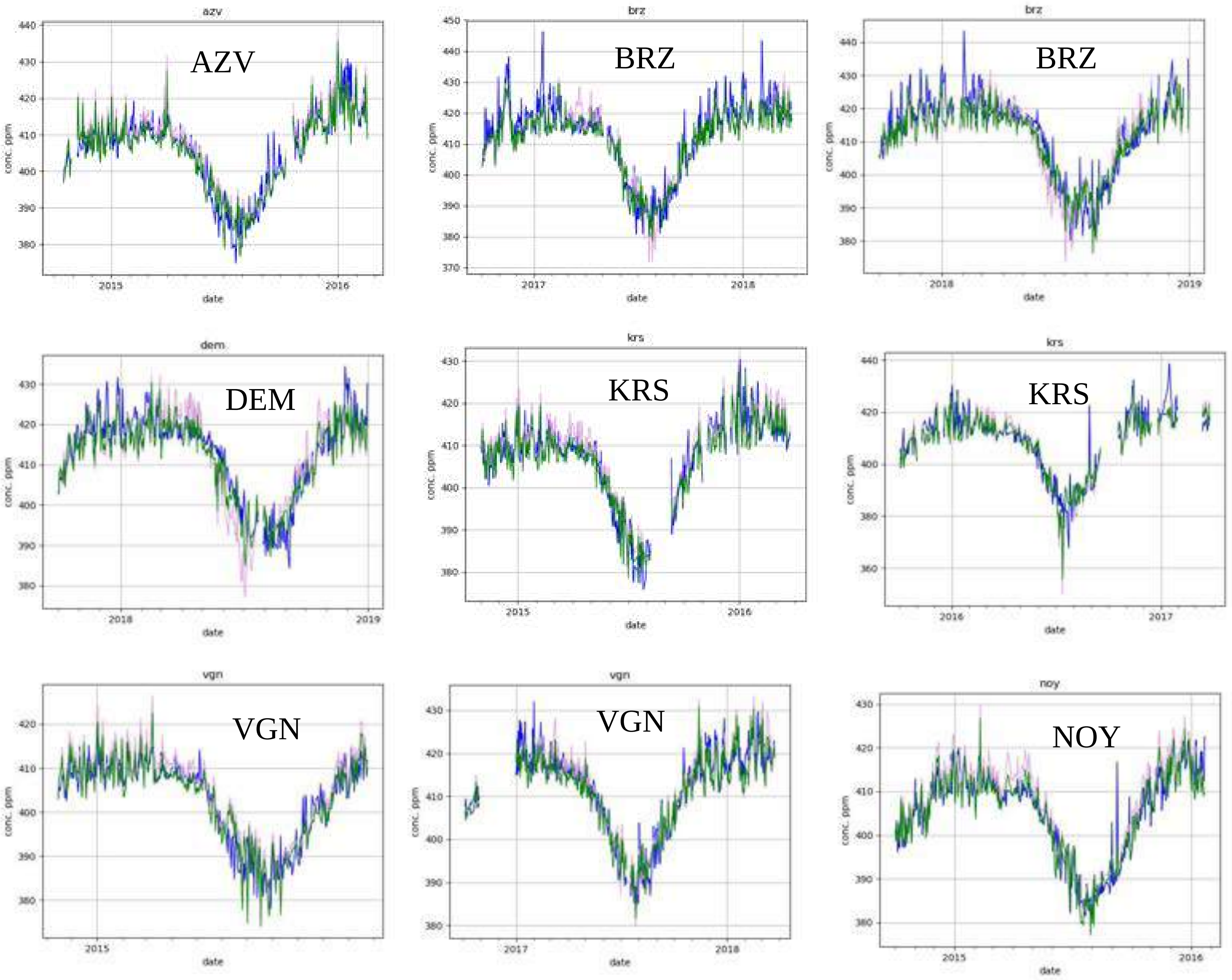
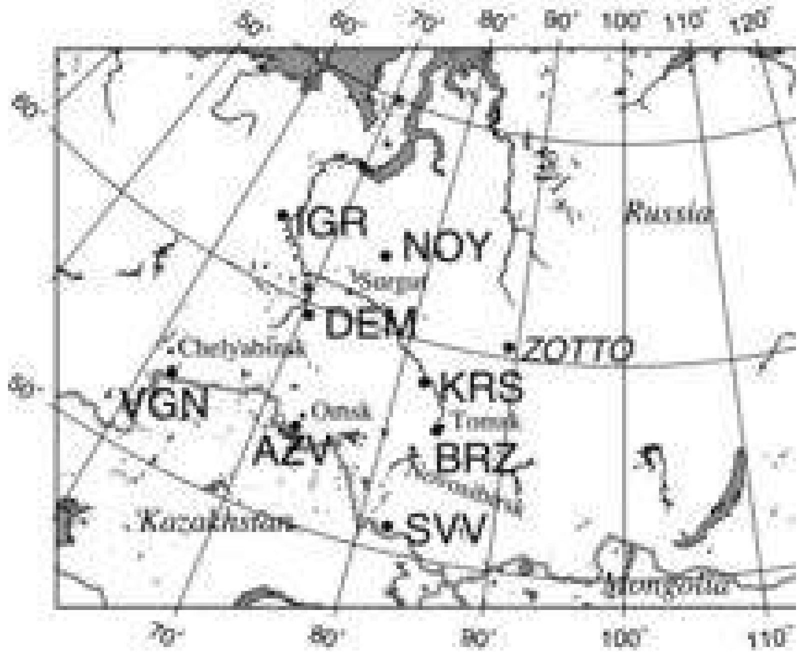


Figure 2. MODIS GPP climatology remapped to 0.025° and 10-daily timestep: top Apr 5 bottom Jun 5, around Tokyo

Confirming good posterior fit with 0.025x0.025° model - at individual sites: West Siberia, LEF, SYO





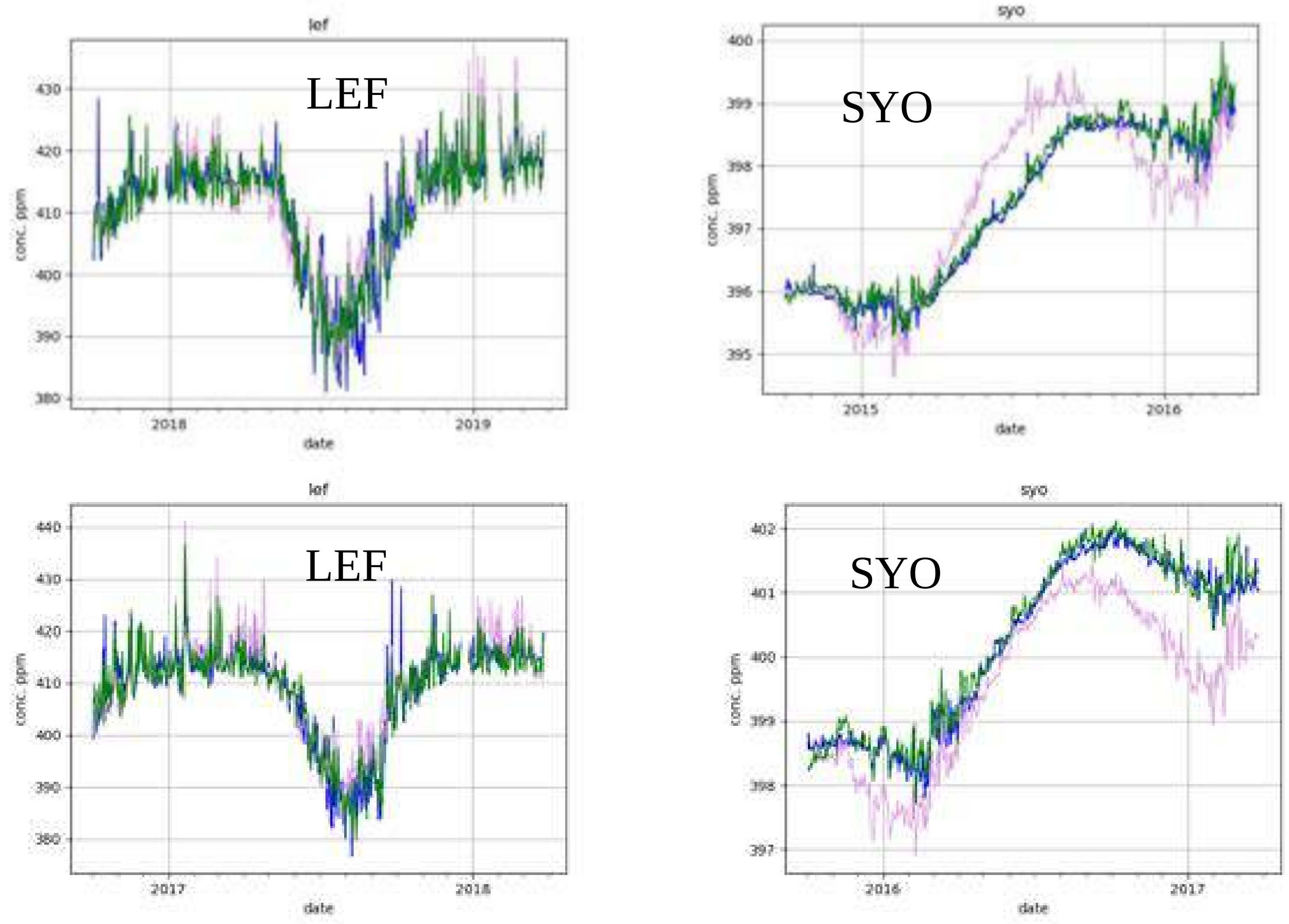


Figure 1. Model and observations simulated at sites AZV, KRS, DEM, BRZ, NOY, VGN and LEF (Wisconsin, USA), SYO (Antarctica); blue – observed, plum – forward, green - inversion

Summary

1. NIES-TM with ERA5 - improved transport
2. Revised NTFVAR inverse model - compact memory, can operate under 100 GB RAM and up to very high resolution (0.025 deg joint fossil-biogenic-ocean inversion)
3. CO_2 inversion - regional sinks comparable to OCO2 v10 MIP
4. Refinements to data and flux uncertainties: observation fit improved after MIP v10
5. Adding GOSAT L2 v03.05 data to surface set leads to larger tropical emissions
6. Using GOSAT L2 v02.97 reduced the problem of large tropical emissions

Reflections

1. Even with high resolution transport, CO_2 inversion has to be continuously improved and rely on various know-how to produce reasonable results
2. Future directions - large volume (100-200 obs/sec) satellite data inversion need to use data aggregation/size reduction, Lagrangian transport simulation with ML
3. High resolution (0.025°) global inversion is possible/attractive direction.