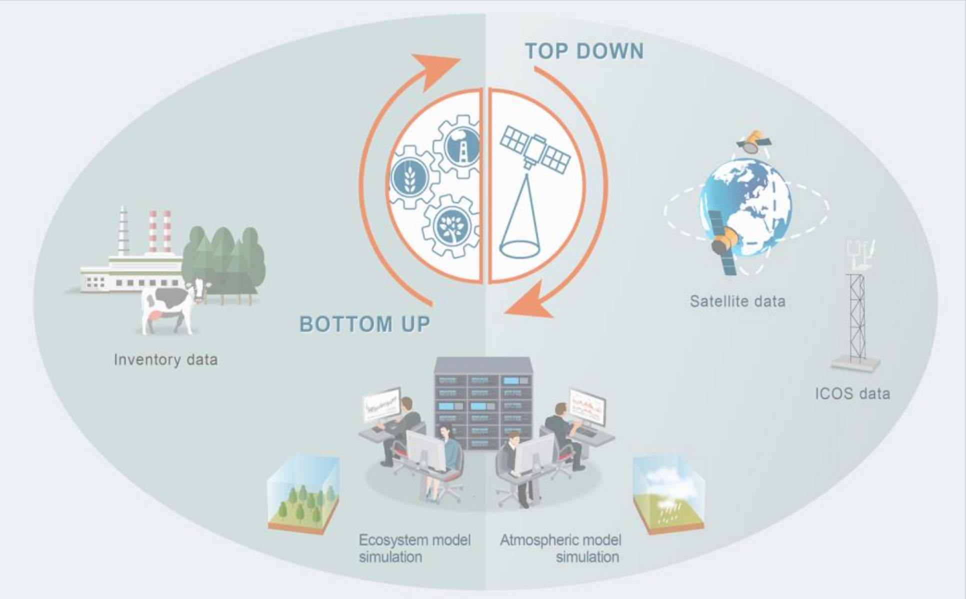
VERIFY General Assembly

WP2 Verification methods for CO2_ff emissions

Hugo Denier van der Gon, Samuel Hammer, Claudius Rosendahl, Gregoire Broquet, Paul Palmer(all on behalf of WP2 team)

May 9th -11th , 2022

WP leader	**TNO / UEDIN**
Participants	TNO, CEA, JRC, KIT, UHEI, UEDIN, ULUND, WU



This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 776810

Contents

- **Main achievements from last year**
  - Emission time series 2005-2020 including the Covid-19 impact
  - T2.4 Exploring the potential of new data, upcoming instruments, and new methods to improve the pre-operational ffCO2 estimation system
  - Claudius Rosendahl et al, *Verifying proxy/ffCO2 emission ratios: a highway measurement campaign (T2.2)*
  - Audrey Fortems-Cheiney et al. , *Inferring ffCO2 emissions using satellite observations of NO2 and CO (T2.3)*
- **Key scientific results over the project duration**

- What did we learn? Next steps?
- (discussion slide / legacy in next projects!)

CO_2 AND INVENTORY COMPILERS

- Anthropogenic fossil fuel CO_2 is the best known and “easiest” pollutant
- The CO_2_ff uncertainty in the EU at national level is small, order ~3-6%
- But total CO_2 uncertainties are much higher (biomass/biofuel (bf), AFOLU sector, land use source / sinks)
- In the end…..What matters is concentration in the atmosphere……

SO…WHY WORK ON INDEPENDENT VERIFICATION OF CO_2?

- **Current inventories may not be sufficient to monitor the effectiveness of climate policy**
  - Currently in some countries outside of Europe
  - In the future maybe even in Europe?
- Bottom-up (national) inventories with detailed source sector information are & will remain crucial to inform, negotiate and design action.
- Measurement-based verification will increase transparency, help building trust between parties and can confirm trends or mitigation
- Links what we see in the atmosphere with what we report on paper!

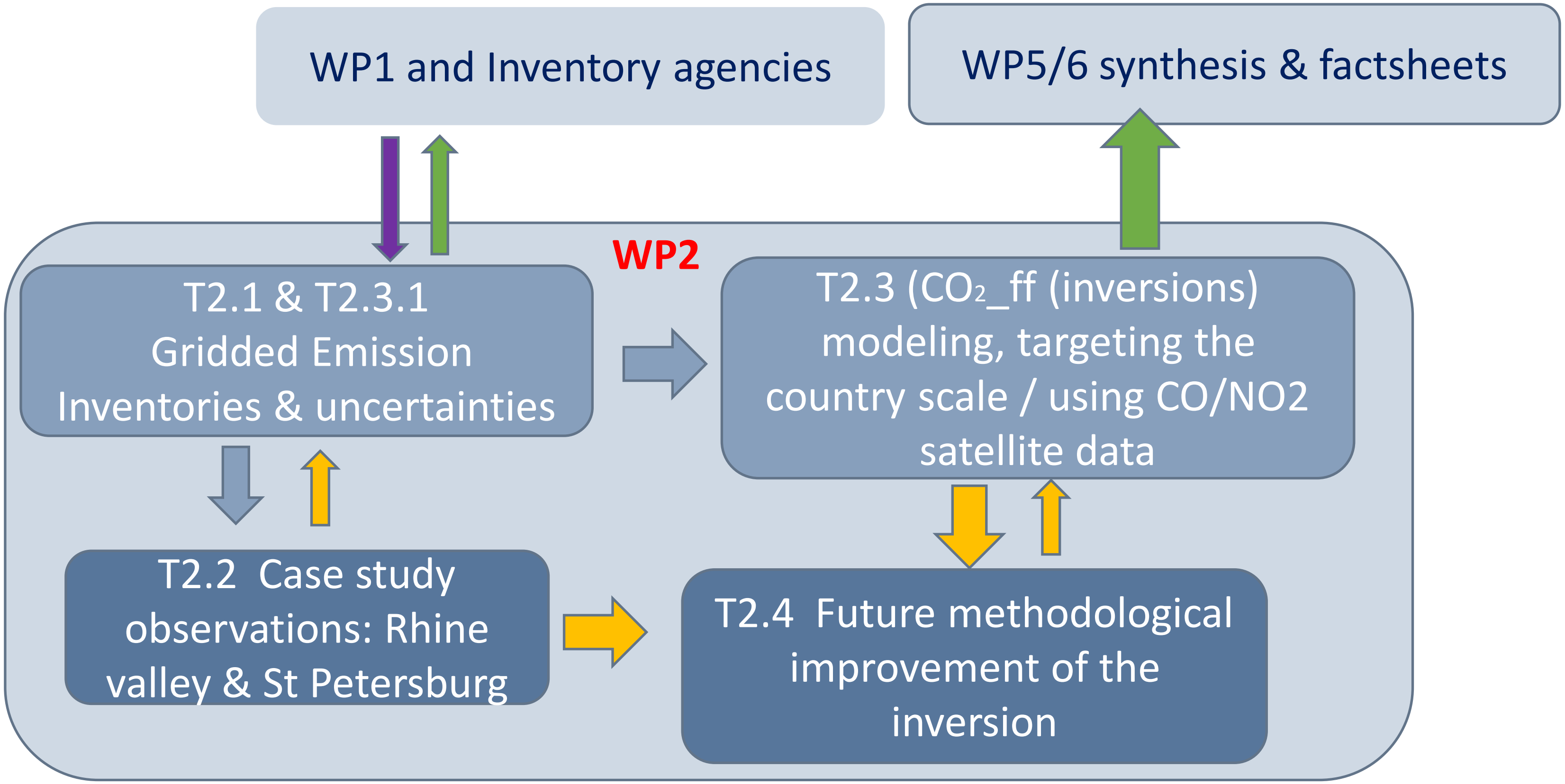
- **We need novel methods! - VERIFY contributes but not finished.**
- **To apply these methods we need observations, emission inventories & models**

OVERARCHING OBJECTIVES WP2

Develop the components of the observation based monitoring and verification system dedicated to fossil fuel CO_2 emissions, using in situ and remotely sensed atmospheric measurements of CO_2 and co-emitted tracers.

- Construct a **Fossil Fuel Data Assimilation System (FFDAS)** to estimate ffCO_2 emissions at a sub-national resolution (25-50 km)
- **Dedicated field campaigns** for evaluation of the dynamical emission model and the inverse modeling strategy
- Explore the theoretical **potential of new and future satellite data products**

VERIFY WP2 VERIFICATION METHODS FOR CO2_FF EMISSIONS INFORMATION FLOW CHART



T2.1 – Bottom-up emission estimates for anthropogenic CO2 and co-emitted tracers (TNO, JRC, WU; M01 M48)

Specific objective: Deliver high-resolution emission data of ffCO2, bfCO2 & co-emitted tracers (CO, NOx, NMVOC) for Europe, 2005-present

Achievements

- Fast-track global CO_2 emissions from JRC / EDGAR
- Supply 1x1 km inventories for Rhine valley case study domain with most recent point source emissions (see results T2.2)
- System/method in place to deliver yr-1 and yr-2 for European domain (cyclic improvement)
- Timely (cyclic) delivery of European regional (~6x6 km) inventory 2005-2020 for VERIFY synthesis.
- **Focus today on a few important issues: biofuel/mass; point sources; Covid impact for time series**

T2.1 CONTINUOUS UPDATES OF EDGAR FAST TRACK CO_2 EMISSIONS (JRC)

	Globe 2020 vs 1990 (fossil CO_2)	EU27 2020 vs 1990 (fossil CO_2)	EU27 2018 vs 1990 (GHG)
Power industry	↗ + 72 %	↘ - 43 %	↘ - 24 %
Other industrial combustion	↗ + 58 %	↘ - 46 %	↘ - 39 %
Buildings	→ + 1 %	↘ - 32 %	↘ - 26 %
Transport	↗ + 59 %	↗ + 8 %	↗ + 23 %
Other sectors	↗ + 97 %	↘ - 23 %	↘ - 24 %
All sectors	↗ + 58 %	↘ - 31 %	↘ - 21 %

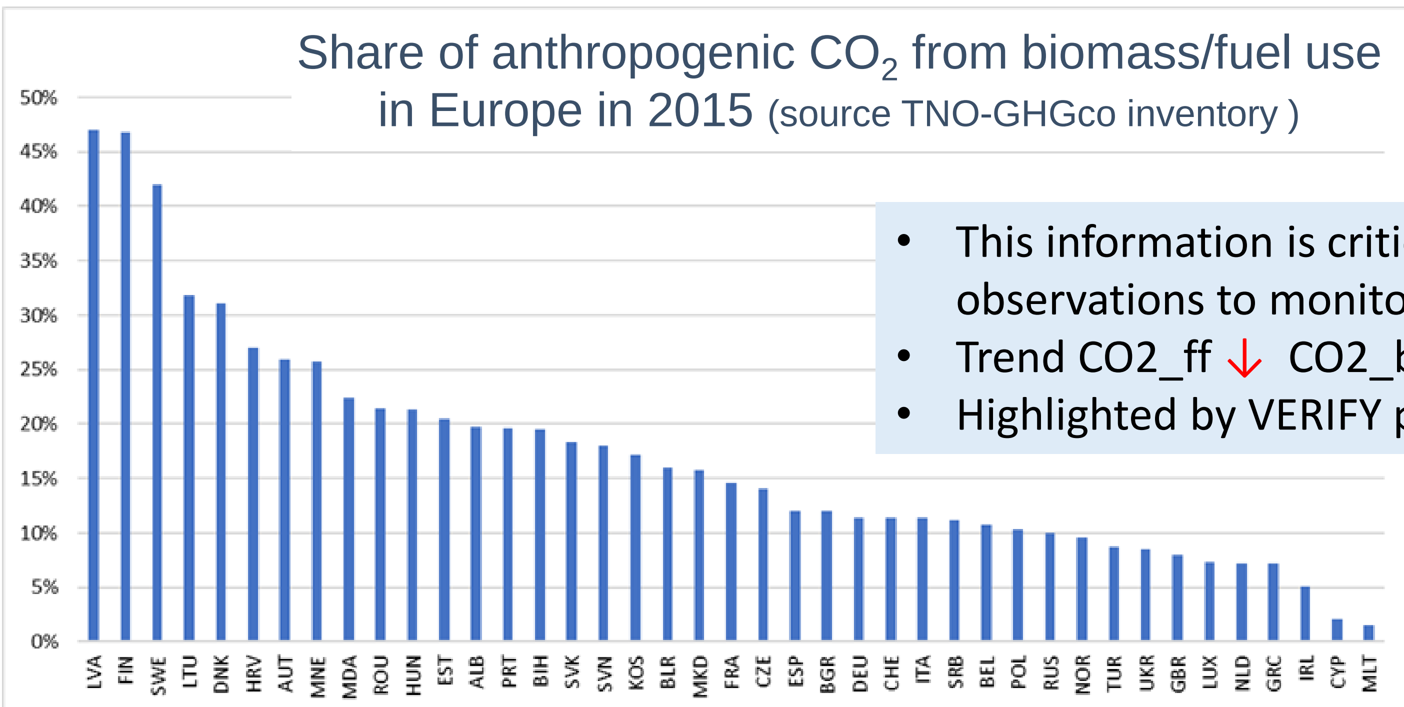
Crippa, M., et al.,GHG emissions of all world countries - 2021 Report, EUR 30831 EN, Publications Office of the European Union, Luxembourg, 2021, ISBN 978-92-76-41547-3, doi:10.2760/173513, JRC126363

EU CO_2 emissions are important; The rest of the world is a lot more important

Focussing on “only” our own emission problem will not solve climate change

CO_2 INVENTORIES: COMPLEXITY INCREASES WITH TIME

1. In Europe already 12-15% of the anthropogenic CO2 emission is from biofuel/biomass combustion; large variation between countries (see figure)
2. Biomass as a fuel is increasing – how short cycle is this?
   https://www.scientificamerican.com/article/congress-says-biomass-is-carbon-neutral-but-scientists-disagree/



- This information is critical when using observations to monitor CO2_ff
- Trend CO2_ff ↓ CO2_bf ↑
- Highlighted by VERIFY project

Inventory data on biomass and biofuels is more uncertain than fossil fuels!

*Land Use, Land Use Change, Forestry

A MORE COMPLETE INVENTORY OF PUBLIC POWER AND HEAT PLANT POINT SOURCE EMISSIONS IN THE EU

STIJN Dellaert, Hugo Denier van der Gon, Antoon Visschedijk, Jeroen Kuenen, Ingrid Super (TNO)

(Presented at ICOS science conference 2020)

More than 50% of CO2ff emissions in EU from point sources

(but also true for CO2 from biomass!)

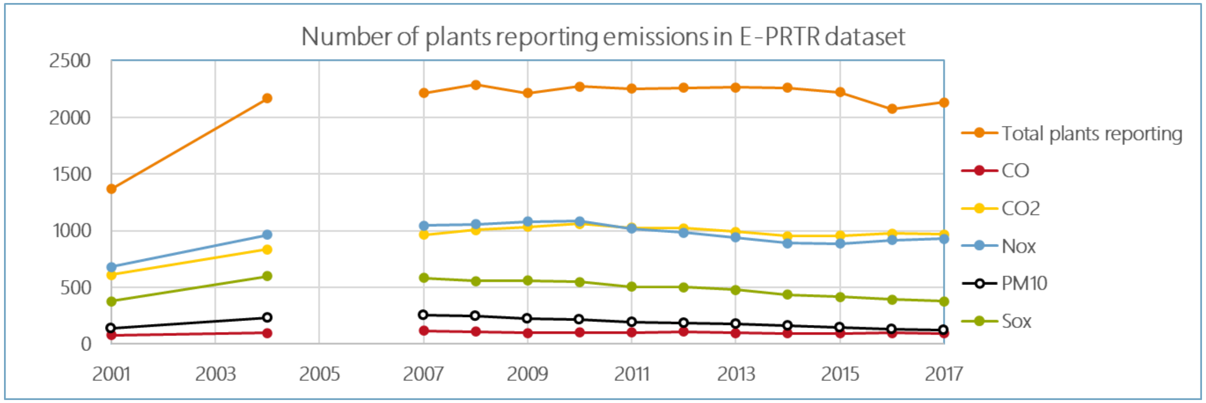
- European Pollutant Release and Transfer Register (E-PRTR) → AP & GHG
- Large Combustion Plants (LCP) → NOx, SOx & PM

CURRENT PROBLEMS

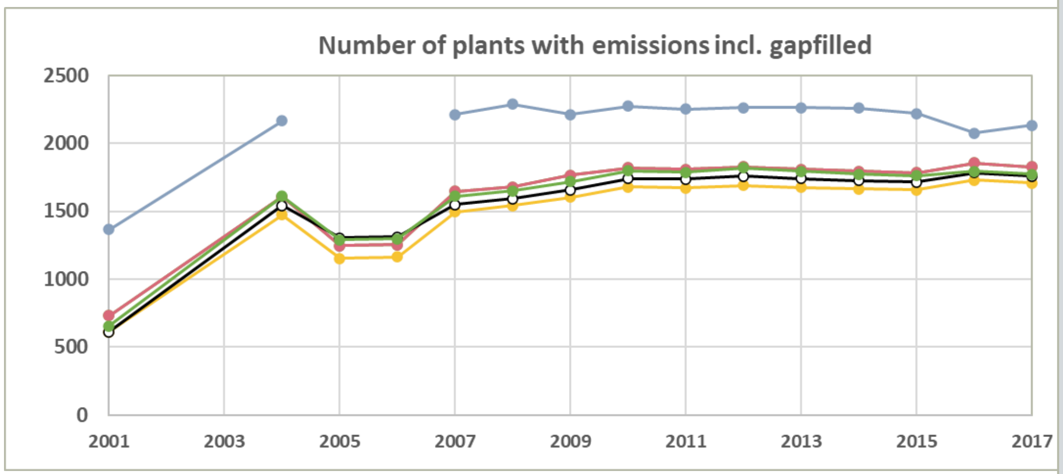
Static threshold value for annual emissions levels (E-PRTR) or plant size (LCP, >50 MWth)

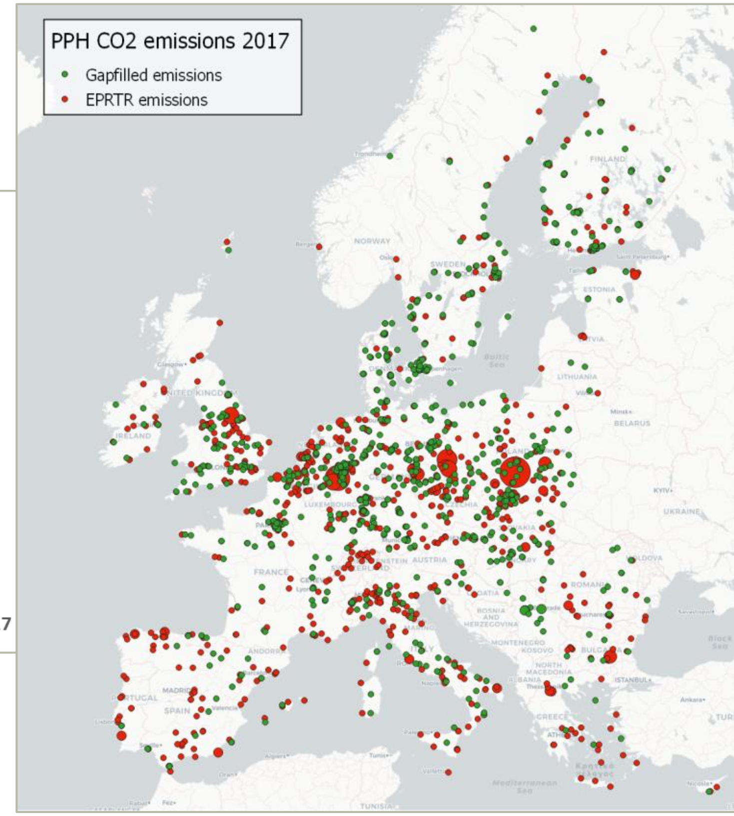
Species	Threshold (tonnes/y)
CO	500
CO2	100,000
NOx	100
PM10	50
SOx	150

INCOMPLETENESS OF CO-EMITTED SPECIES



RESULTS: MORE COMPLETE INVENTORY





- **Number of PPH point sources for CO2 is almost doubled → more smaller point sources!**
- Includes fuel type info
- But no solution yet for small plants that are outside of the reporting datasets
- If plant does not report any emissions in a year, no gapfilling is performed

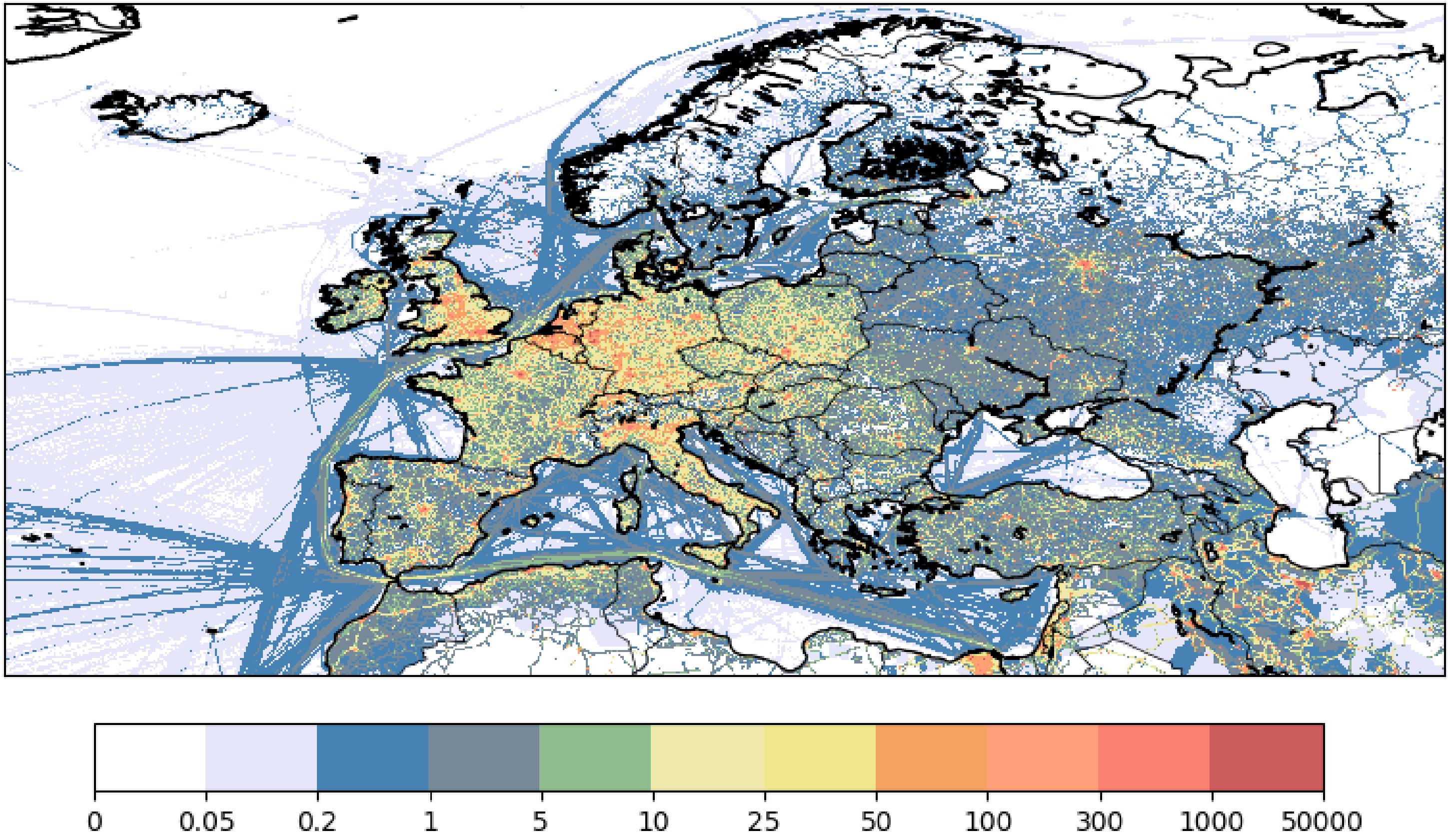
Need to have! - co-emitted species is critical for attribution.

- Reporting could be better!
- Importance of this is picked-up and moved forward in CoCO2

GRIDDED EMISSION TIMESERIES 2005-2020

- 2005-2018 based on and in line with official reporting (D2.3)
- 2019+2020 based on a methodology to derive yr-1 and yr-2 (D2.6)

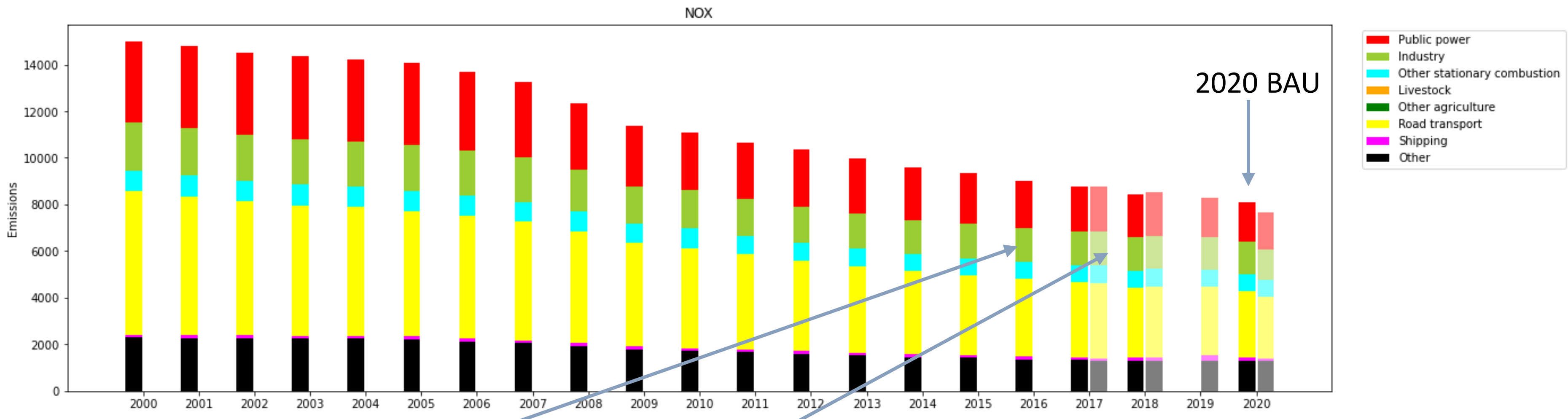
Total (2018)



GHG Emission CO2_FF [kTon/yr]

Annual updates – adding a new year + revision: Final deliverables D2.3 & D2.6

HOW TO DEAL WITH COVID-19?
ESTIMATED EMISSIONS 2020 VS. 2020 "BAU"

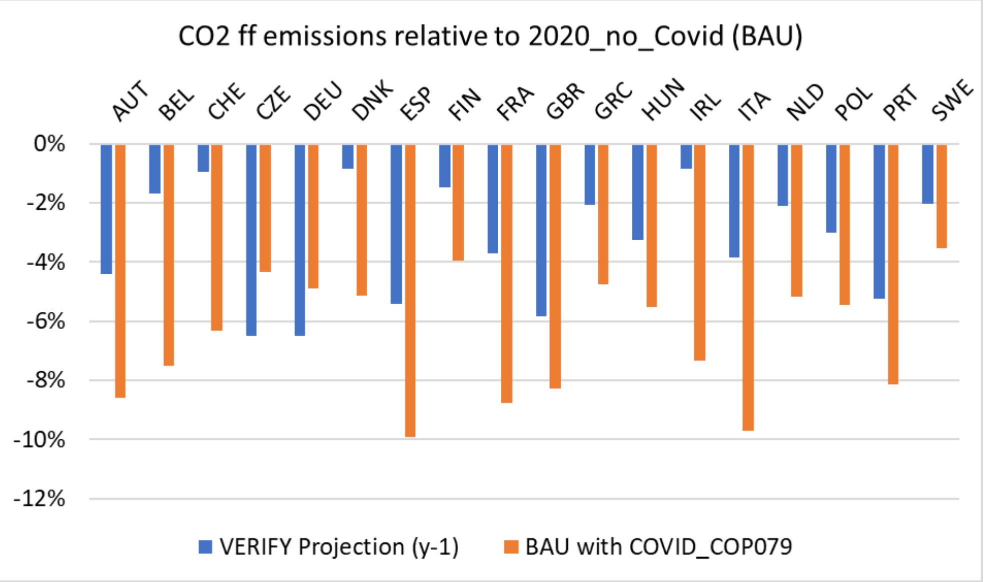


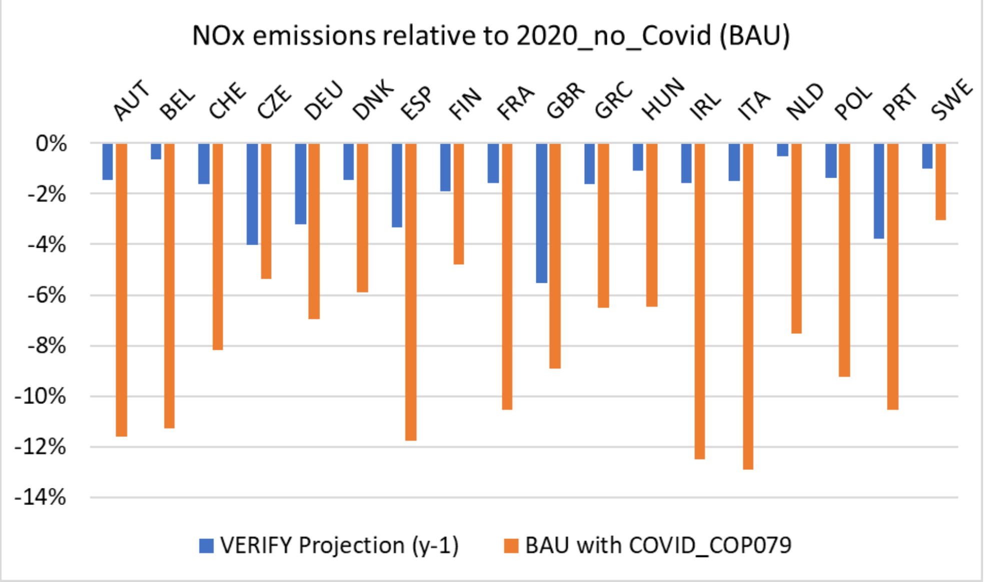
Dark bars 2000-2018: VERIFY TNO_GHGco v3;
Light bars 2017-2020: predicted emissions; Dark bar 2020: BAU

- Prediction of yr-1 and yr-2 uses trend info, activity data and emission modelling
- No COVID-19 in 2019: our estimated 2019 (yr-2) emission is reliable
- Public power good proxy data for 2020; both our BAU and predicted 2020 is good
- Residential combustion – our climatic information is accurate; both are probably good
- Road transport, aviation, shipping, industry – our proxies underestimates impact but BAU good

2020 (YR-1) EMISSION DATA SET FOR VERIFY

- The projection method works but not for acute disruptions
- By collaborating with e.g. CAMS a good 2020 estimate was made
- Complete VERIFY 2005-2020 emission data set avaible for the modelling in T2.3





More info on the Covid reduction factors In Guevara et al., : Time-resolved emission reductions for atmospheric chemistry modelling in Europe during the COVID-19 lockdowns, Atmos. Chem. Phys., 21, 773–797, https://doi.org/10.5194/acp-21-773-2021 , 2021.

Example of novel method testing in VERIFY WP2

ST PETERSBURG CAMPAIGN (EMME)

- Russian VERIFY partners (St. Petersburg State University SPBU + Ural State University) supported by IUP Bremen and KIT.
- **April 2019: campaign for observing the St. Petersburg city emissions** using COCCON (Collaborative Carbon Column Observing Network) spectrometers (CO_2, CO) and other instrumentation (e.g. NO_2)

Ring roadway observations of NO2 tropospheric column - St. Petersburg NO2 plume

03.04.2019
1A-3B

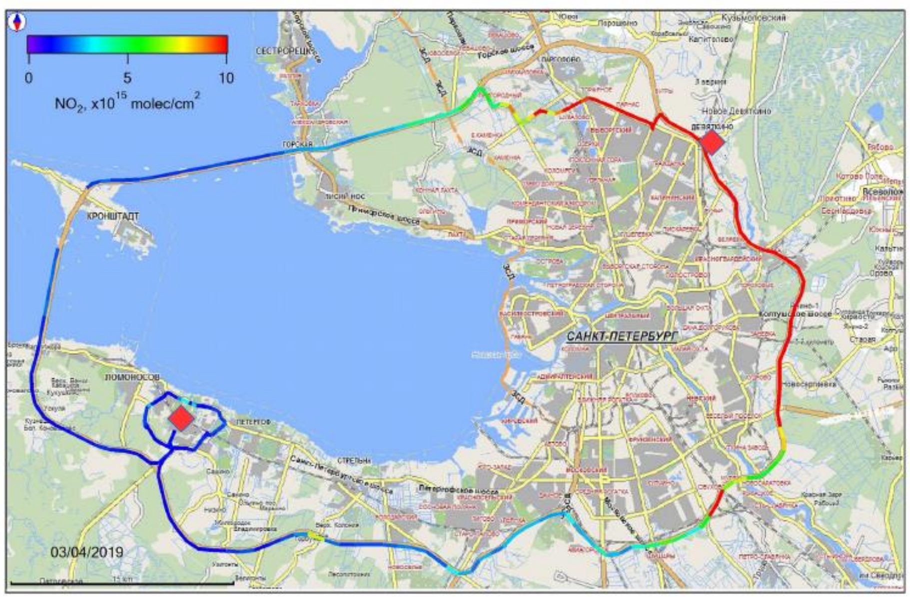


Figure courtesy of SPBU

https://doi.org/10.5194/amt-2020-87
Preprint. Discussion started: 22 April 2020
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Atmospheric Measurement Techniques
Discussions

Emission Monitoring Mobile Experiment (EMME): an overview and first results of the St. Petersburg megacity campaign-2019

Maria V. Makarova[1], Carlos Alberti[2], Dmitry V. Ionov[1], Frank Hase[2], Stefani C. Foka[1], Thomas Blumenstock[2], Thorsten Warneke[3], Yana A. Virolainen[1], Vladimir S. Kostsov[1], Matthias Frey[4], Anatoly V. Poberovskii[1], Yuri M. Timofeyev[1], Nina N. Paramonova[6], Kristina A. Volkova[1], Nikita A. Zaitsev[1], Egor Y. Biryukov[1], Sergey I. Osipov[1], Boris K. Makarov[5], Alexander V. Polyakov[1], Viktor M. Ivakhov[6], Hamud Kh. Imhasin[1], Eugene F. Mikhailov[1]

[1] Department of Atmospheric Physics, Faculty of Physics, St. Petersburg State University, Russia
[2] Institute of Meteorology and Climate Research IMK-ASF, Karlsruhe Institute of Technology, Karlsruhe, Germany
[3] University of Bremen, Germany
[4] National Institute for Environmental Studies, Japan
[5] Institute of Nuclear Power Engineering, Peter the Great St. Petersburg Polytechnic University, Russia
[6] Voeikov Main Geophysical Observatory, St. Petersburg, Russia

https://www.atmos-meas-tech-discuss.net/amt-2020-87/

Was presented as a highlight at VERIFY GA 2020 (a different world….)

RESULTS OF THE VERIFY ST. PETERSBURG CITY CAMPAIGN

(EMME: Emission Monitoring Mobile Experiment)

Based on the analysis of two observational campaigns significantly higher CO2 emission from the megacity of St Petersburg compared to the data of municipal inventory,

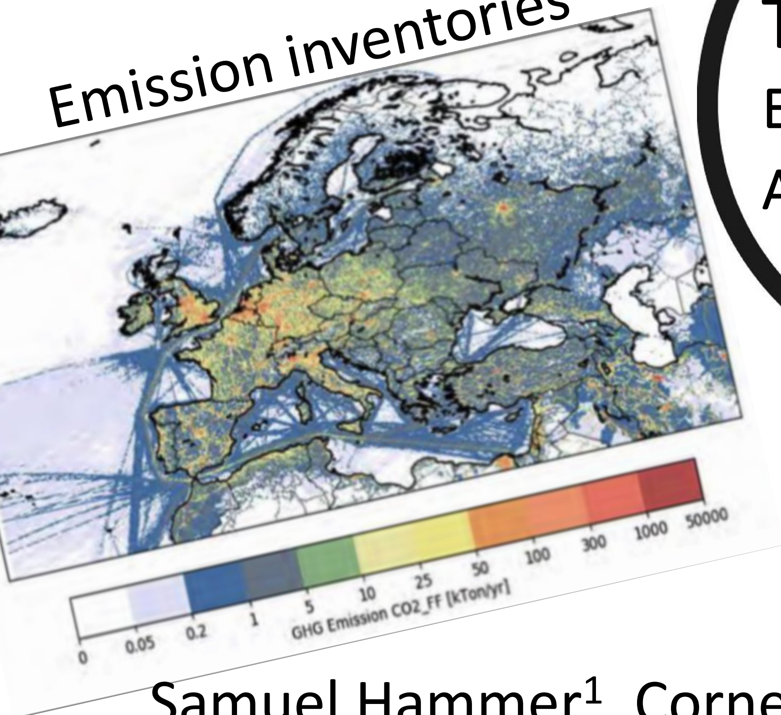
~75800 ± 5400 kt yr−1 for 2019
~68400 ± 7100 kt yr−1 for 2020 versus **~30 000 kt yr−1 reported by official inventory.**

Impact COVID-19 lockdown in 2020 suggests – 10% in emissions *(but tricky to compare 2019 & 2020 directly)*

- **We can do this!** (and we need more of this for cities outside of EU)
- Some methods are suitable for city / sub-national scale
- Connection to national scale is not trivial

Ionov, D. V., Makarova, M. V., Hase, F., Foka, S. C., Kostsov, V. S., Alberti, C., Blumenstock, T., Warneke, T., and Virolainen, Y. A.: The CO_2 integral emission by the megacity of St Petersburg as quantified from ground-based FTIR measurements combined with dispersion modelling, Atmos. Chem. Phys., 21, 10939–10963, https://doi.org/10.5194/acp-21-10939-2021 , 2021.

Emission inventories



T2.2: Verifying emission ratios and trends

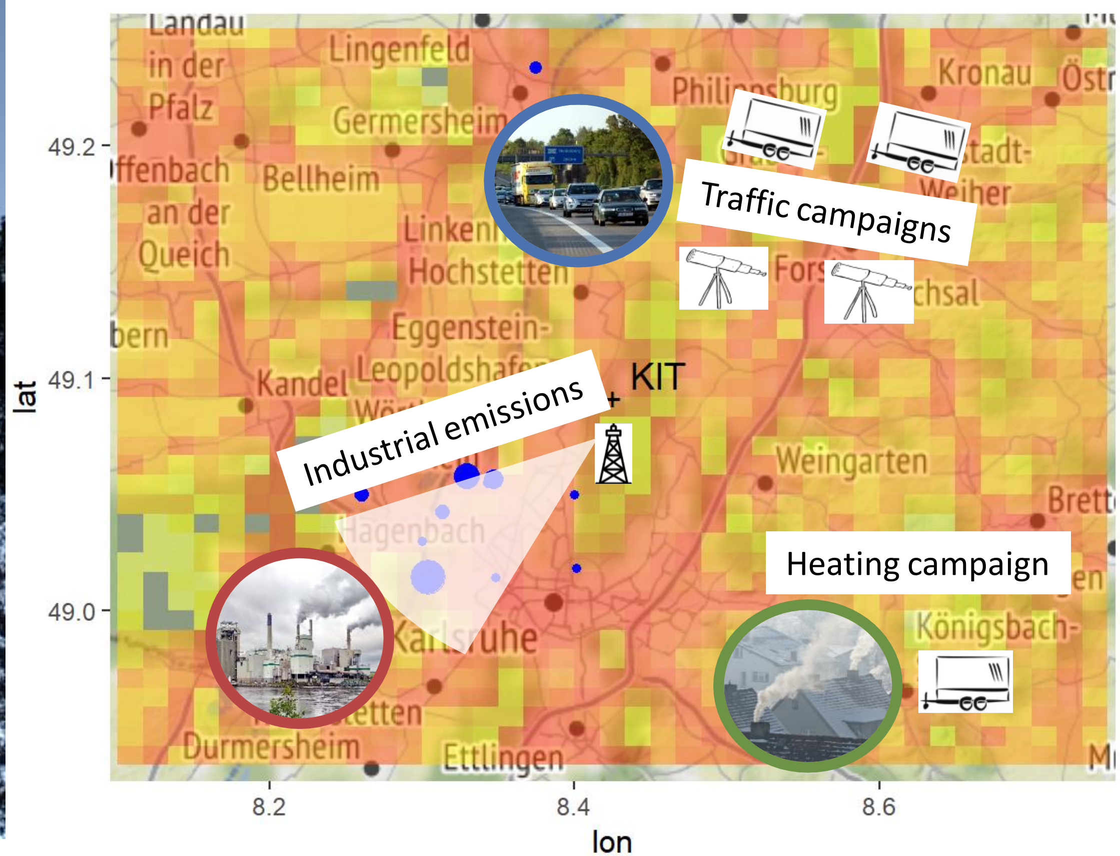
Data users & modellers

Samuel Hammer[1], Cornelia Jäschke[1], Carlos Alberti[2], Claudius Rosendahl[1], Fabian Maier[1] and Frank Hase[2]

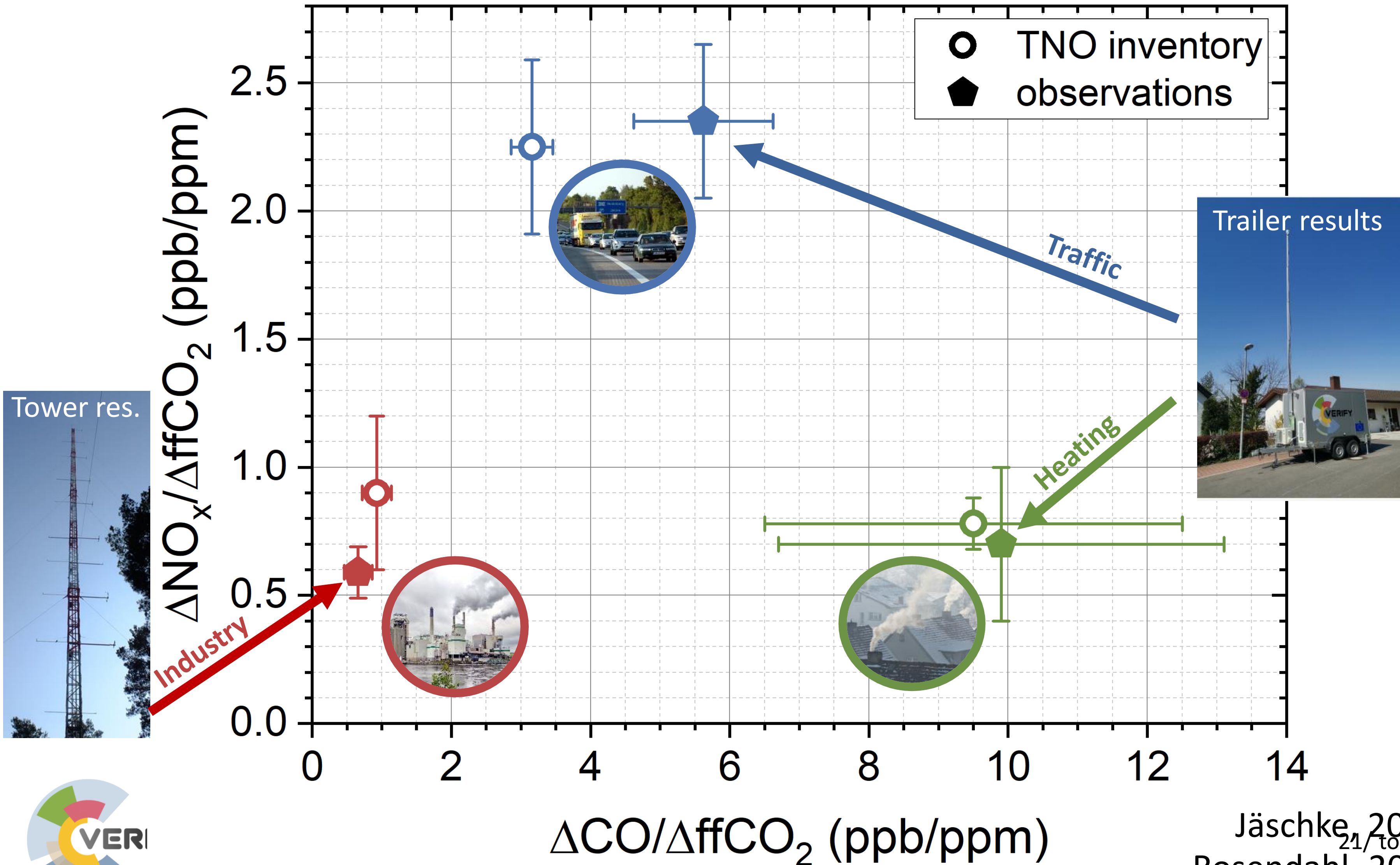
[1]Institut für Umweltphysik, Heidelberg University
[2]IMK-ASF, Karlsruher Institut für Technologie

VERIFY GA meeting | May 9th -11th , 2022 | Paris

VERIFYING ATMOSPHERIC PROXY/FFCO_2 RATIOS (SECTOR SPECIFIC)

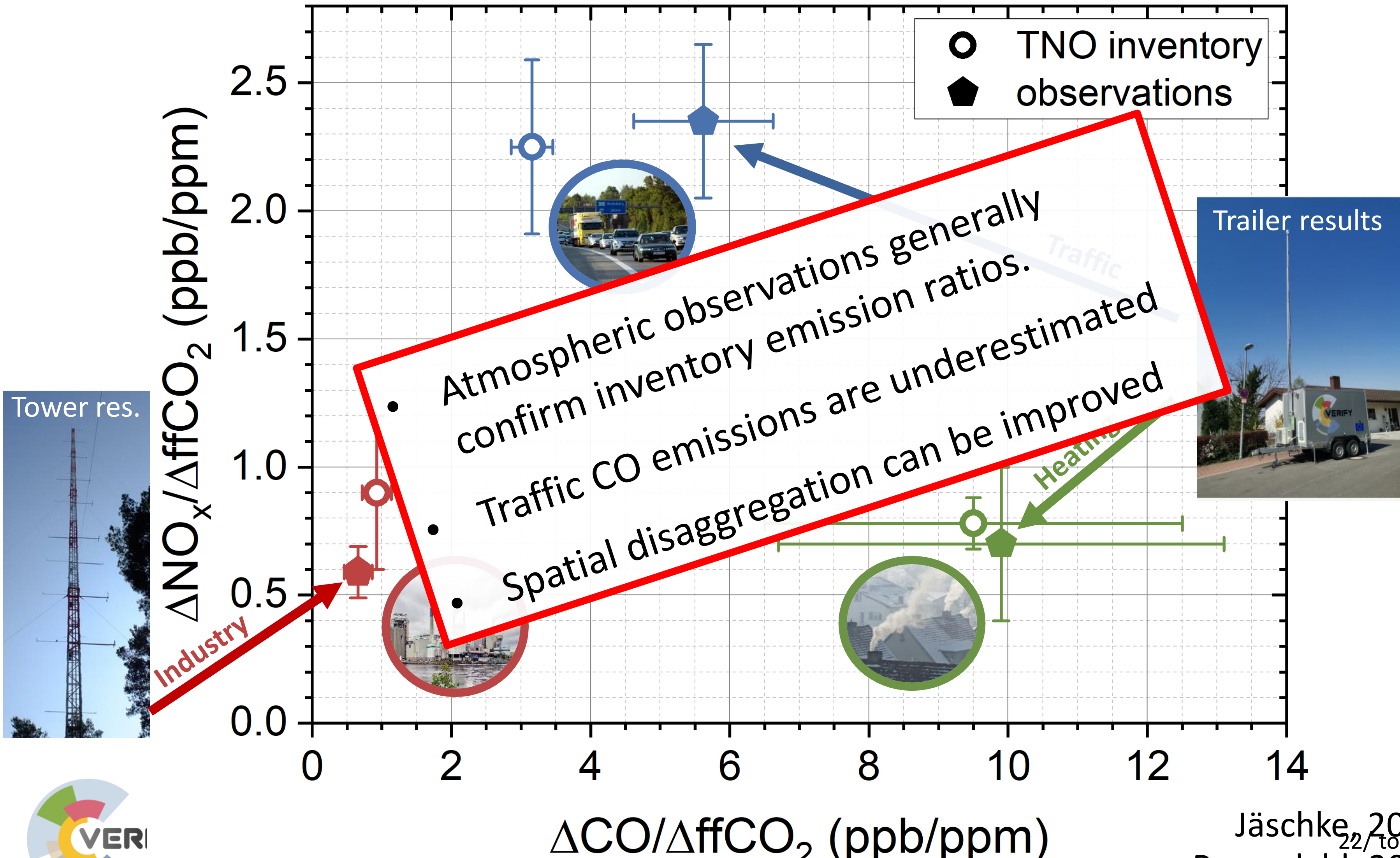


CO AND NO_X DOUBLE-RATIO PLOT



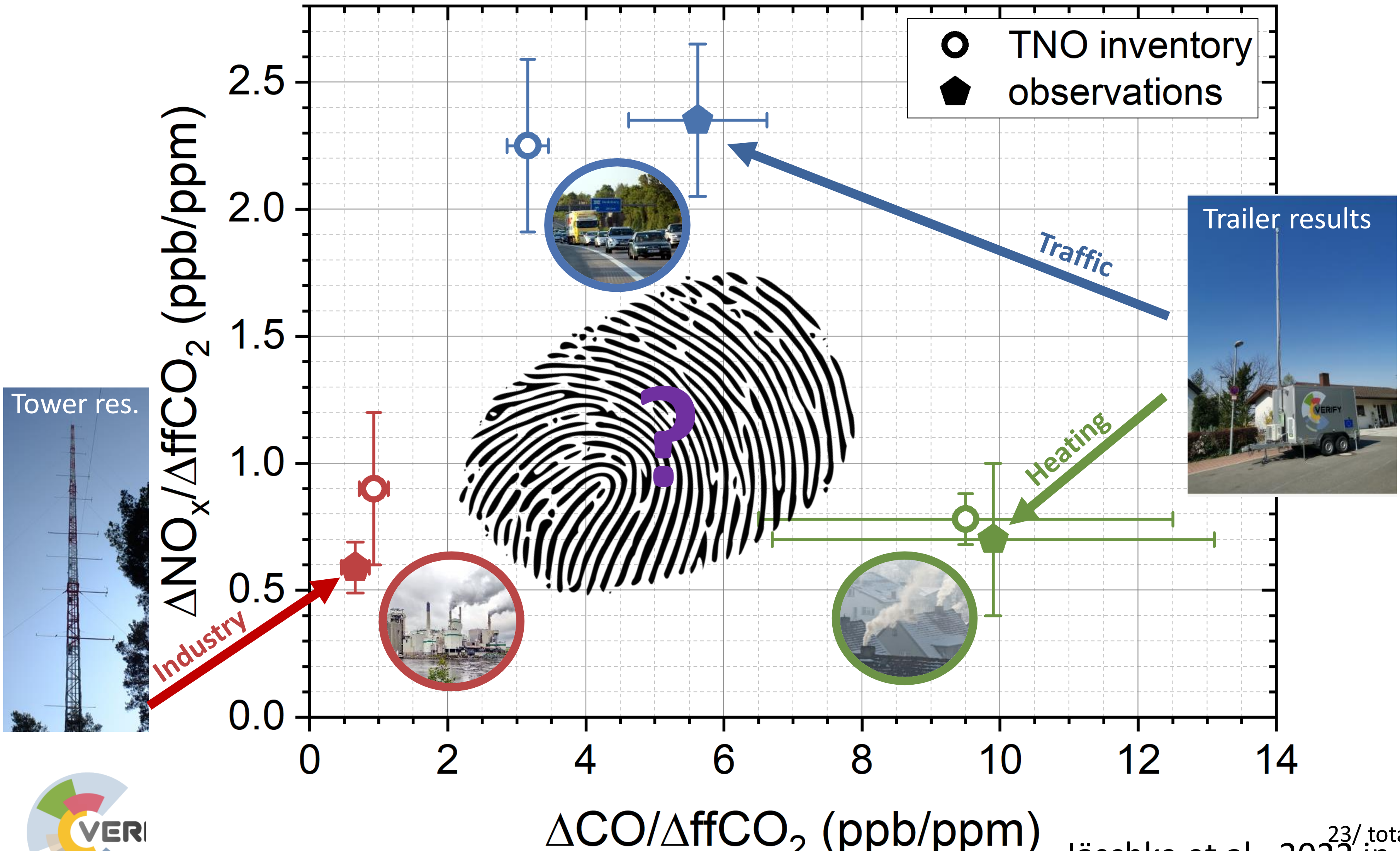
Jäschke, 2021
Rosendahl, 2022

CO AND NO_X DOUBLE-RATIO PLOT



Jäschke, 2021
Rosendahl, 2022

CO AND NO_X DOUBLE-RATIO PLOT

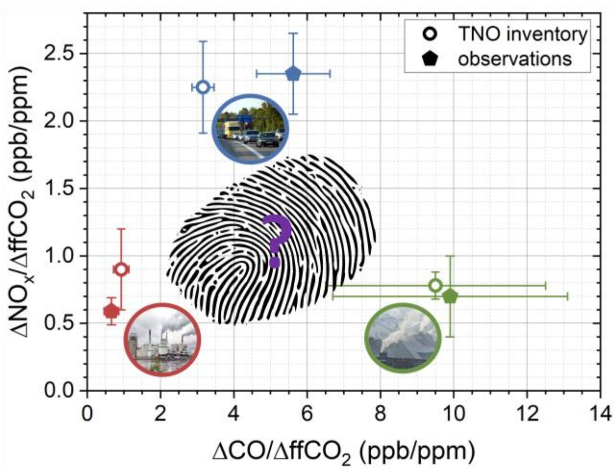


Jäschke et al., 2022 in prep.

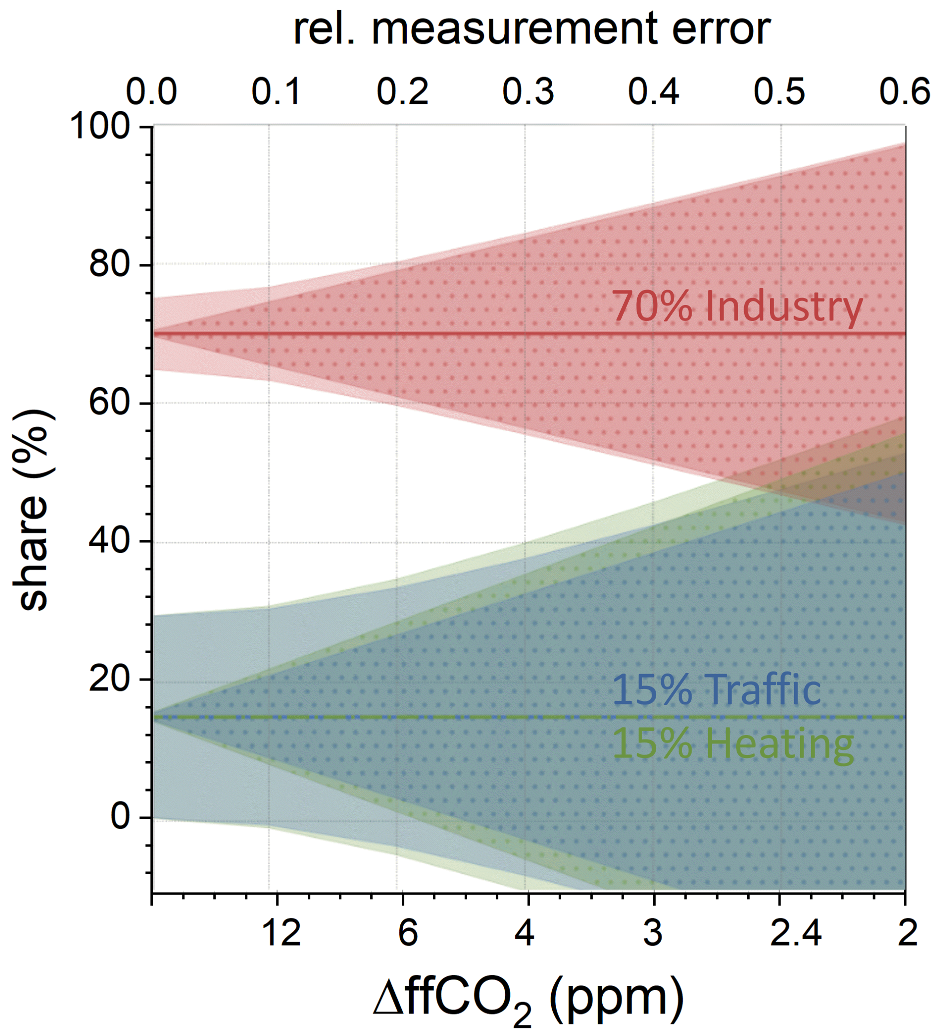
Multi Proxy Source Attribution Approach

Source attribution uncertainty depends on:

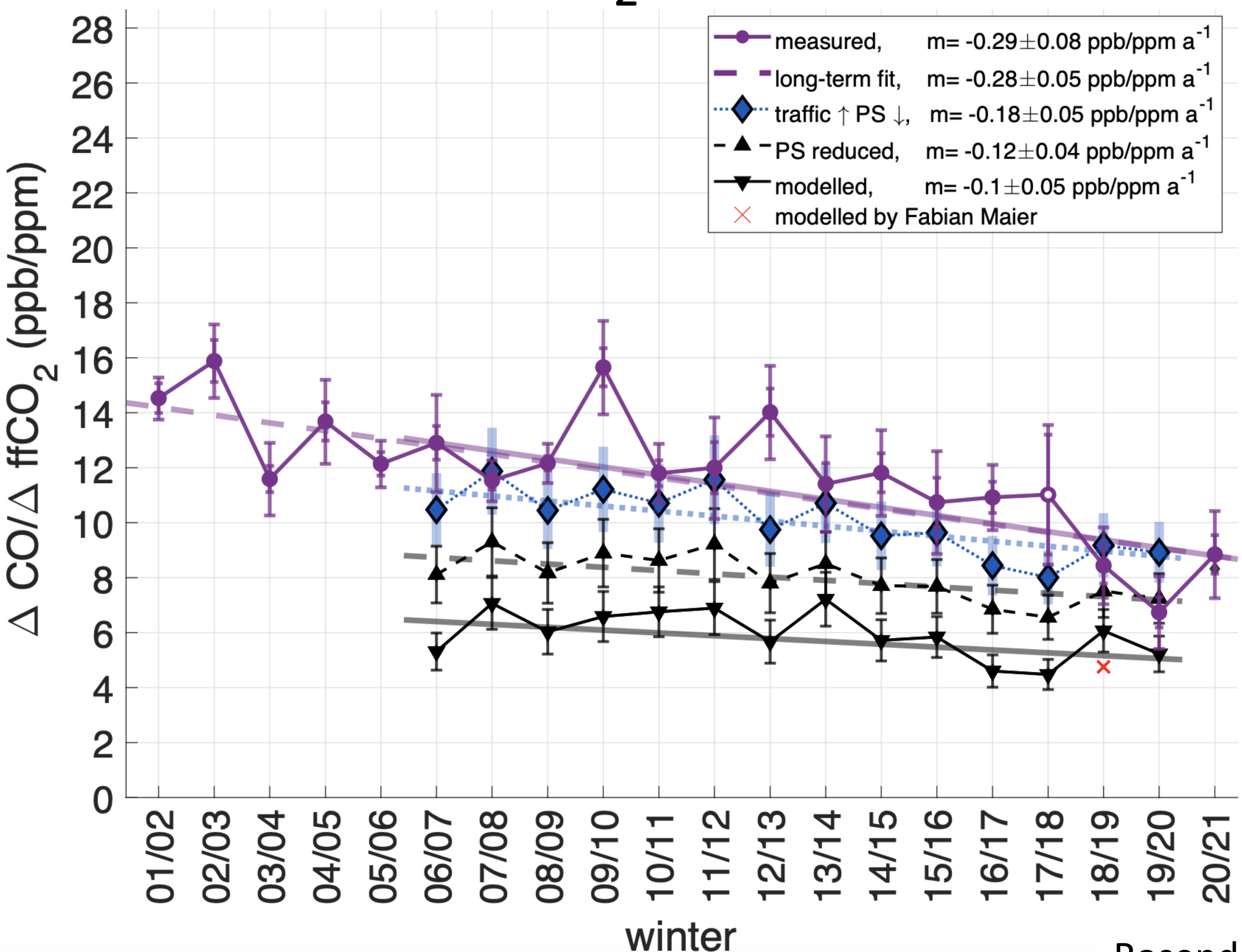
- signal strength
- source mix
- emission ratio uncertainties



Jäschke et al., 2022 in prep.



LONG-TERM EMISSION RATIO TREND $\Delta CO/\Delta ffCO_2$ FOR HEIDELBERG



Rosendahl, 2022

T2.2 Conclusions

- atmo. observations are generally consistent with the TNO inventory emission ratios
- CO emissions from the "Traffic" sector are underestimated in TNO -> Talk by C. Rosendahl
- observed atmo. $\Delta CO/\Delta ffCO_2$ long-term trend is steeper compared to the TNO trend
- experimental Multi-Proxy Source Attribution is possible for large (> 6 ppm) $ffCO_2$ signals

ICOS Cities

Jäschke C., (2021): Potentials and Limitations of Proxy to Fossil Fuel CO_2 Ratios – a Case Study at the ICOS Station near Karlsruhe, (master's thesis, Heidelberg University)

Jäschke et al.,(2022): Multi-Proxy Source Attribution Approach, in preparation

Rosendahl C., (2022): Proxy to fossil-fuel CO_2 emission ratios: in-situ versus inventory data, (Phd thesis, Heidelberg University)

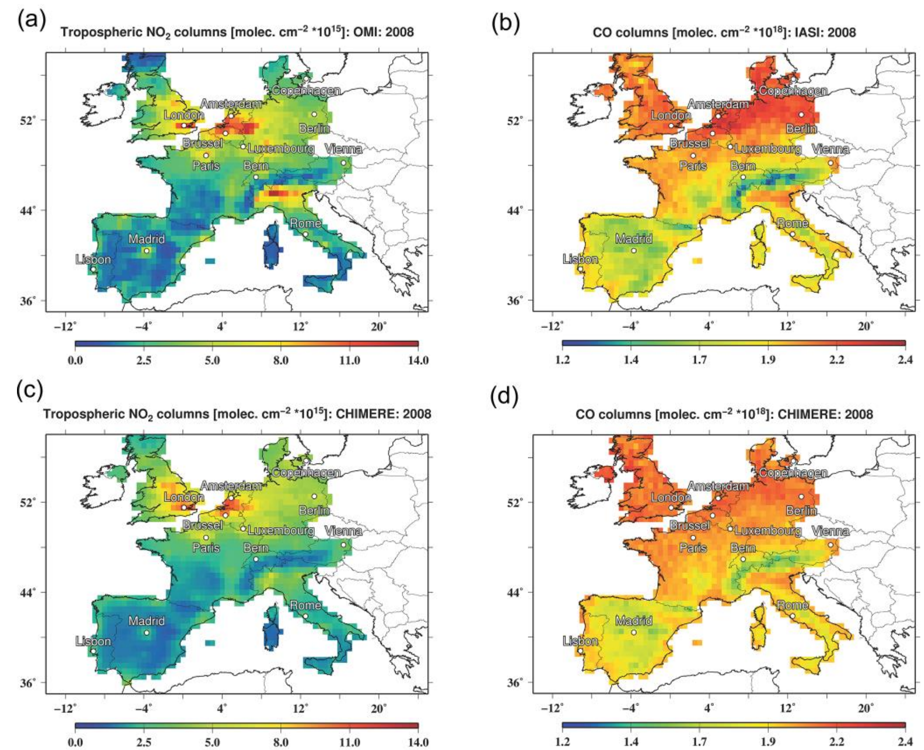
T2.3 Annual to monthly budgets of fossil CO2 emissions at the national scale across Europe using CO and NOx satellite data

M1-M48 / Lead LSCE, Involved Partners: WU, TNO, UEDIN, subcontracting of RSA

Inversion targeting national / 1-month budgets of emissions with a distribution by large sectors of activity

- Analysis over 2005 – present year-1: annual updates
- Use of the most adapted and consistent datasets over the last 15 years: satellite CO and NO_x data
- ➢ Need for converting the information on the co-emitted species into information about the FFCO2 emissions
- ➢ Legacy from Konovalov et al., 2016, ACP

See deliverables : D2.10, D2.11, D2.12 and the VERIFY synthesis



Annual mean of OMI NO_2 and IASI CO retrievals vs. CHIMERE at 0.5° res

Konovalov et al., 2016

T2.3 Annual to monthly budgets of fossil CO2 emissions at the national scale across Europe using CO and NOx satellite data

1) Fast-track inversion : report Konovalov and Lvova (2018), D2.10

- Extending the computations of Konovalov et al. (2016) for 2008 to 2012-2015
- Few control parameters: quantification of annual budgets of EU10+UK+Switzerland for 2 large aggregated sectors
- Results used for the VERIFY synthesis (see Petrescu et al., 2021, ESSD)

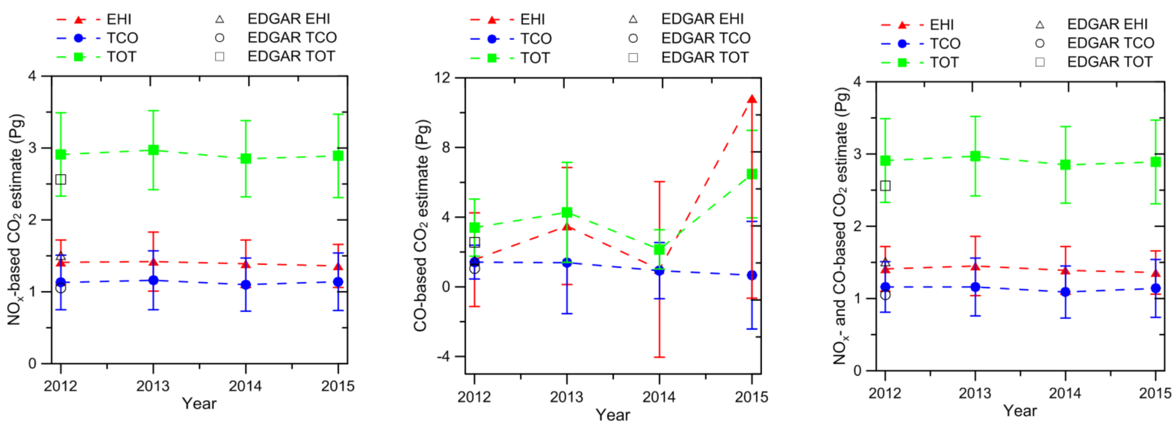


Figure 2. Hybrid estimates of the annual fossil-fuel CO_2 emissions from the study region in comparison with the data of the EDGARv.4.3.2 inventory. The hybrid estimates are based on either (a) only OMI NO_2 measurements, (b) only IASI CO measurements or (c) both NO_2 and CO satellite measurements.

2) 15+ year re-analysis using NOx and CO variational inversions at 0.5° / 1-day resolution

→ see the specific presentation by Fortems-Cheiney et al. (& D2.11, D2.12)

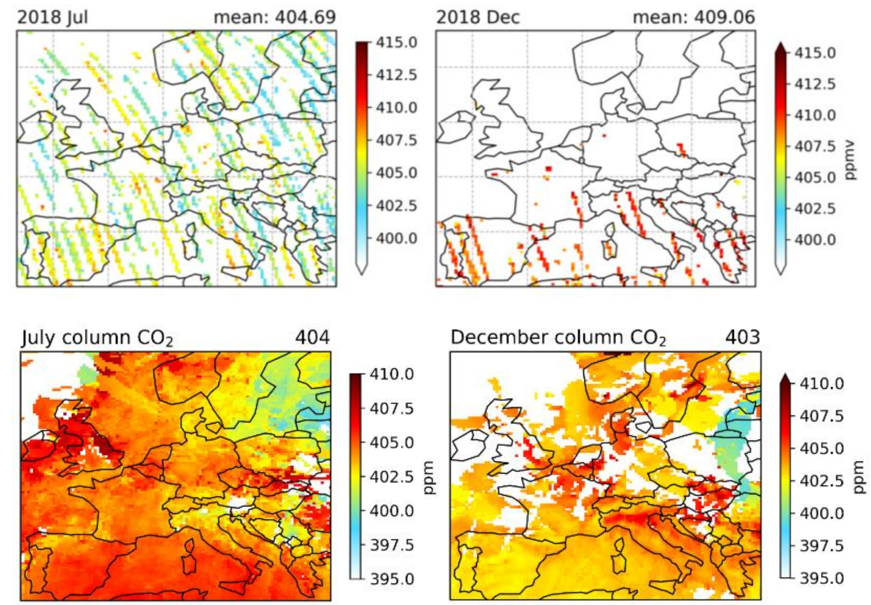
T2.4 Exploring the potential of new data, upcoming instruments, and new methods to improve the pre-operational ffCO2 estimation system

M12-M48 / Lead UEDIN, Involved Partners: ULUND, WU, LSCE

Dovetailing existing and anticipated space-borne measurements of CO2 and reactive trace gases to improve source attribution of ffCO2.

- Reactive trace gases (observed by satellites) are co-emitted with CO2 during combustion.
- How do we use that information to determine ffCO2? (cf T2.3)
  - What can we achieve using current instruments
  - What is the theoretical potential of upcoming space-borne sensors?

See deliverables : D2.14, D2.15,



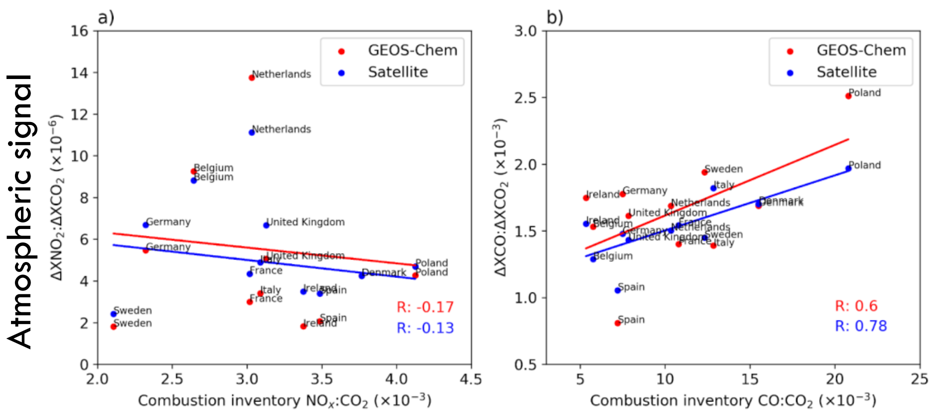
Distribution of clear-sky CO2 data from (top) OCO-2 and (bottom) CO2M

Deliverable D2.15

HOW DO WE HARNESS INFORMATION FROM SATELLITE OBSERVATION TO QUANTIFY FFCO2?

T2.4 explores this using two approaches.

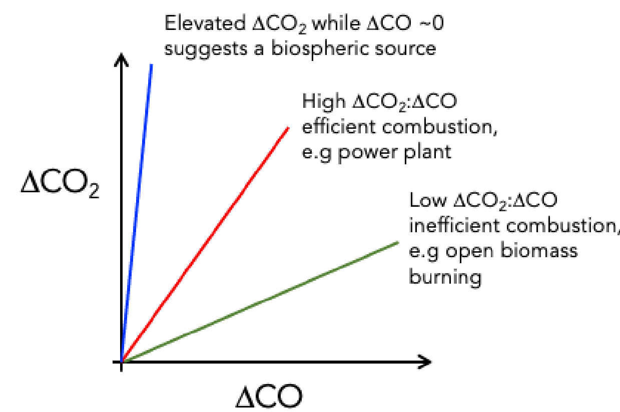
1) use observed and model CO and NO_2 as proxies for combustion CO_2 to test inventories



Emission inventory

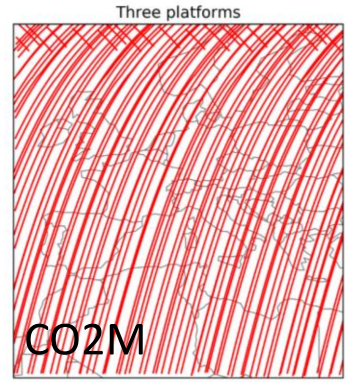
We use GEOS-Chem driven by TNO inventories over Europe and UK

2) Bayesian inversion: use CO to constrain combustion CO_2



CO_2:CO correlations (and their uncertainties) due to the combustion process & atmospheric transport

REAL DATA VS (SYNTHETIC) FUTURE DATA

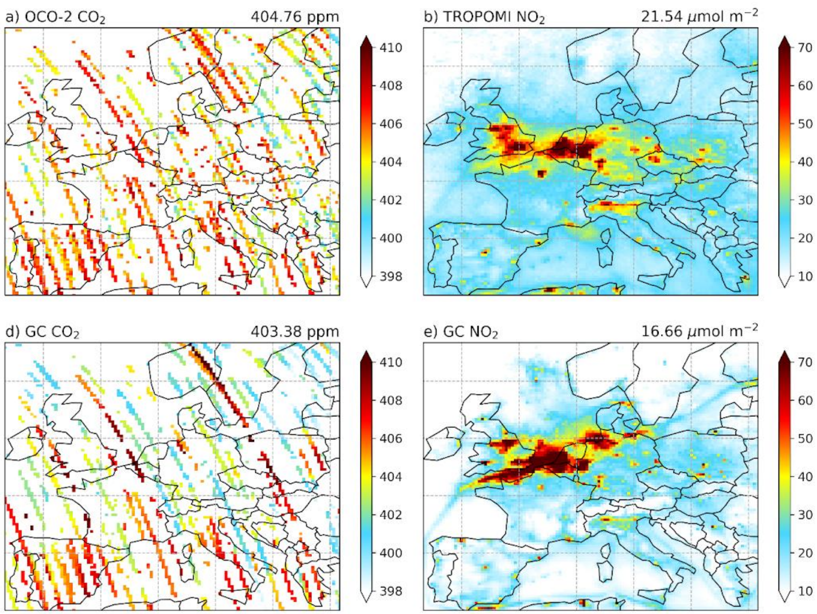


+ realistic clear-sky filter & nominal averaging kernel

Orbits (3 satellites) c/o Dr Ruedinger Lang

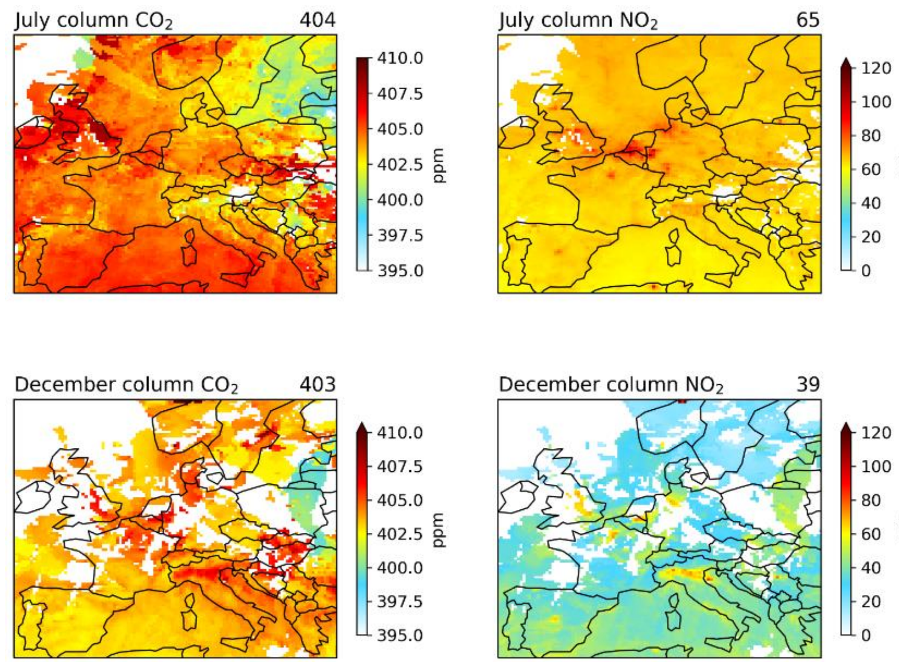
Real data: July 2018

OCO-2 TROPOMI



OCO-2 data during winter is too sparse to be an effective constraint on ffCO2: $\Delta NO_2:\Delta CO_2$

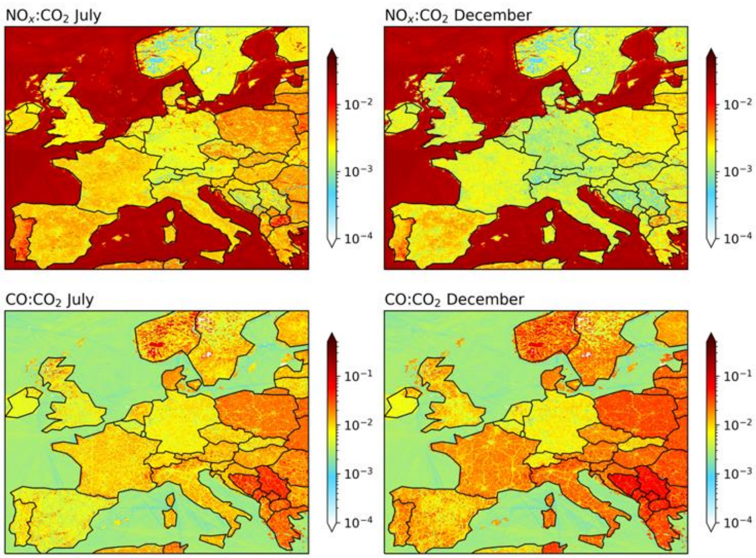
Resulting clear-sky data coverage

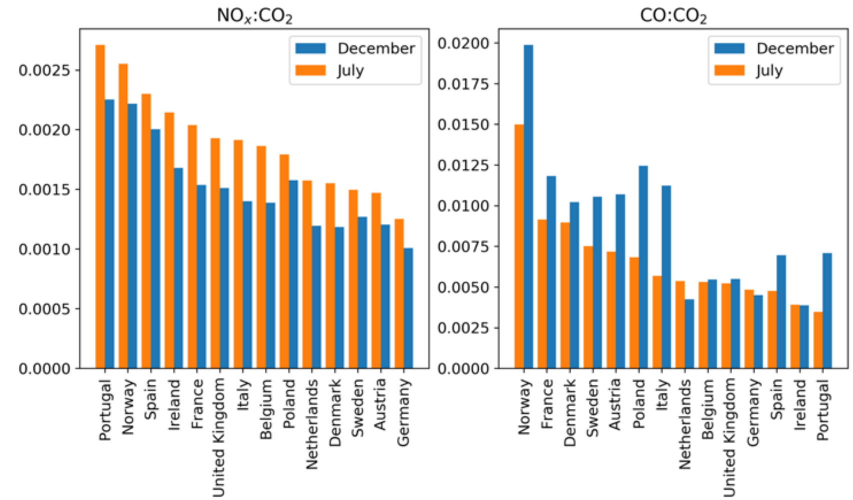


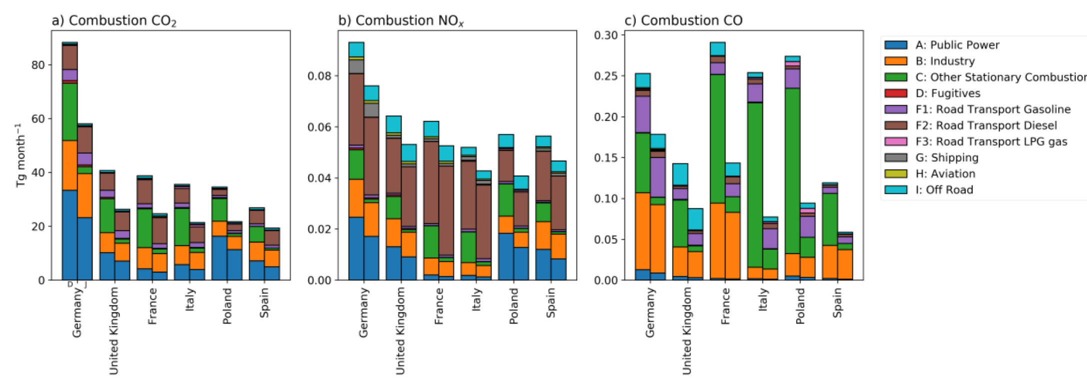
GOSAT-GW has comparable coverage for CO2 and CO (D2.15)

INVENTORY DETERMINANTS OF FFCO2

TNO inventory T2.1

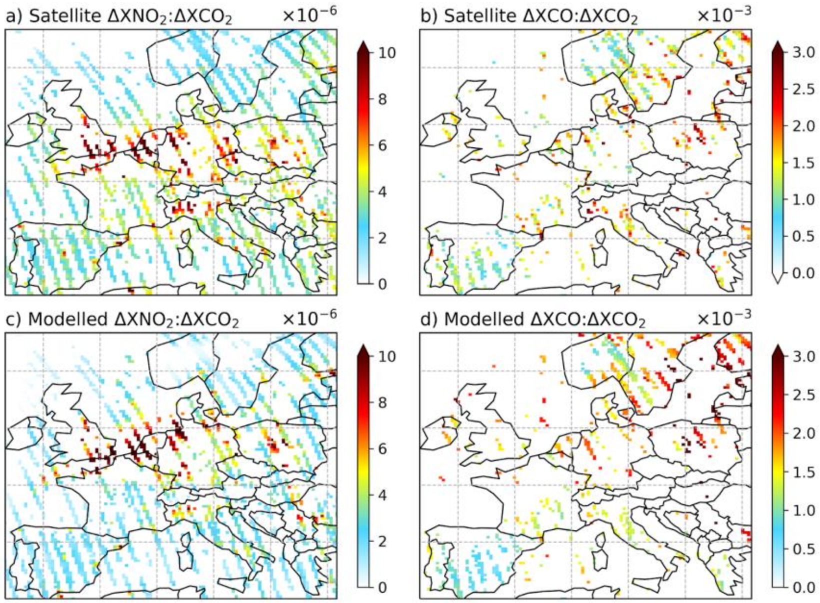




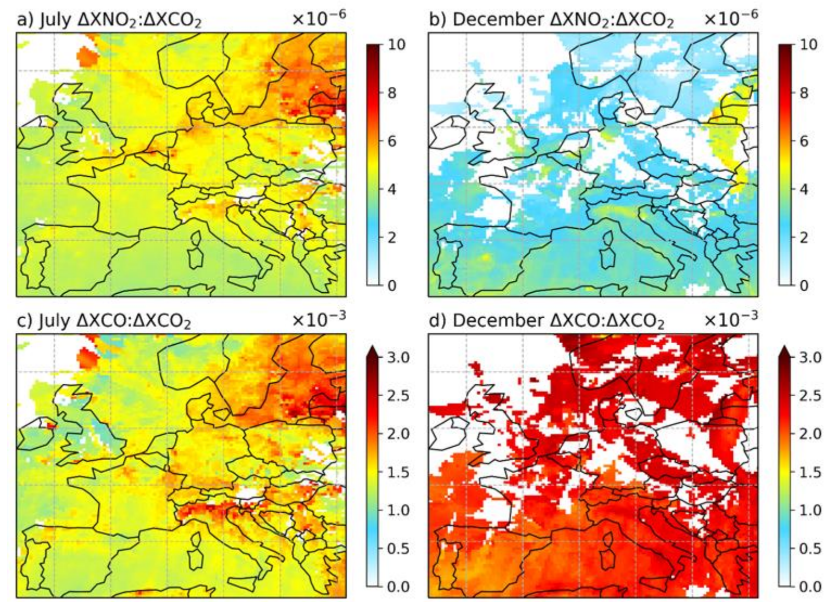


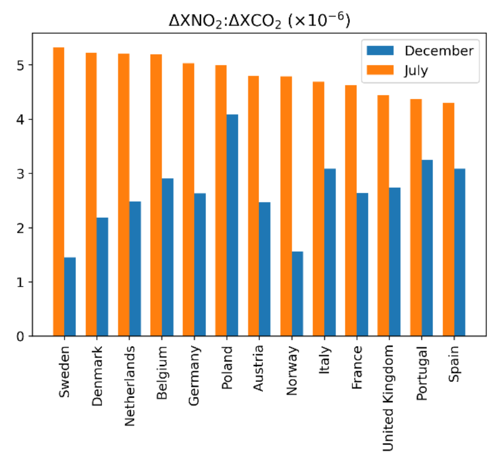
ATMOSPHERIC DETERMINANTS OF FFCO2

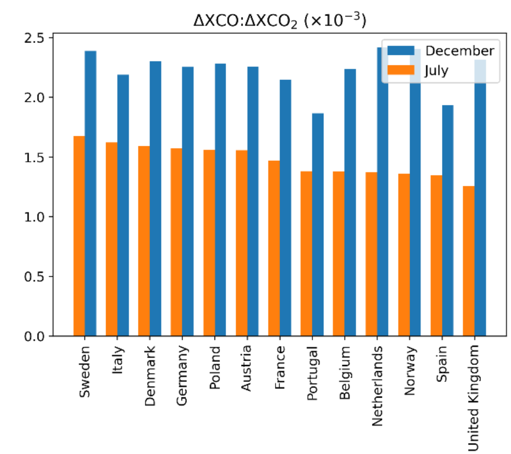
Real July 2018 data: OCO-2 & TROPOMI



Future data: CO2M (NO_2) & GOSAT-GW (CO)





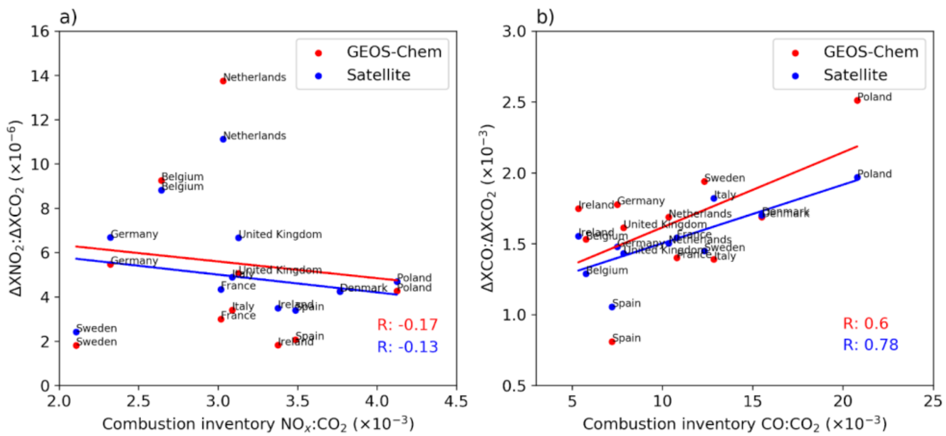


Δ determined from subtracting “remote” Atlantic background

Different sector contributions to CO_2 from different countries also responsible for national variations in $\Delta CO:\Delta CO_2$ and $\Delta NO_2:\Delta CO_2$

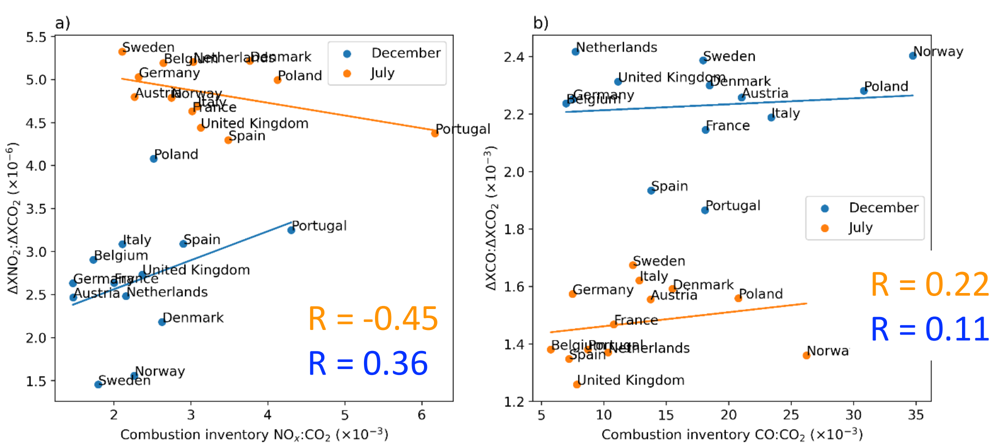
RECONCILING INVENTORY AND ATMOSPHERIC DETERMINANTS OF FFCO2

GEOS-Chem and Real data: OCO-2 & TROPOMI



- Using this approach, CO appears to be the better proxy for combustion CO_2 emissions.
- Negative slope suggests strong non-linearity between NOx emissions and NO_2 columns. Likely due to photochemistry.

Future data: CO2M (NO_2) & GOSAT-GW (CO)



- Using CO2M and GOSAT-GW we have sufficient data to study July and December
- Differences in slope signs for NO_2 support seasonal changes in photochemistry
- Correlations better for CO2M $\Delta NO_2:\Delta CO_2$ but worse for GOSAT-GW $\Delta NO_2:\Delta CO_2$

CO:CO2 INVERSION COMPROMISED BY WEAK NATIONAL-SCALE CO:CO2 ERROR CORRELATIONS

Mass of fuel consumed/country/yr

Mass of gas emitted/ (mass of fuel consumed/country/yr)

Emissions = Activity Data x Emission Factor

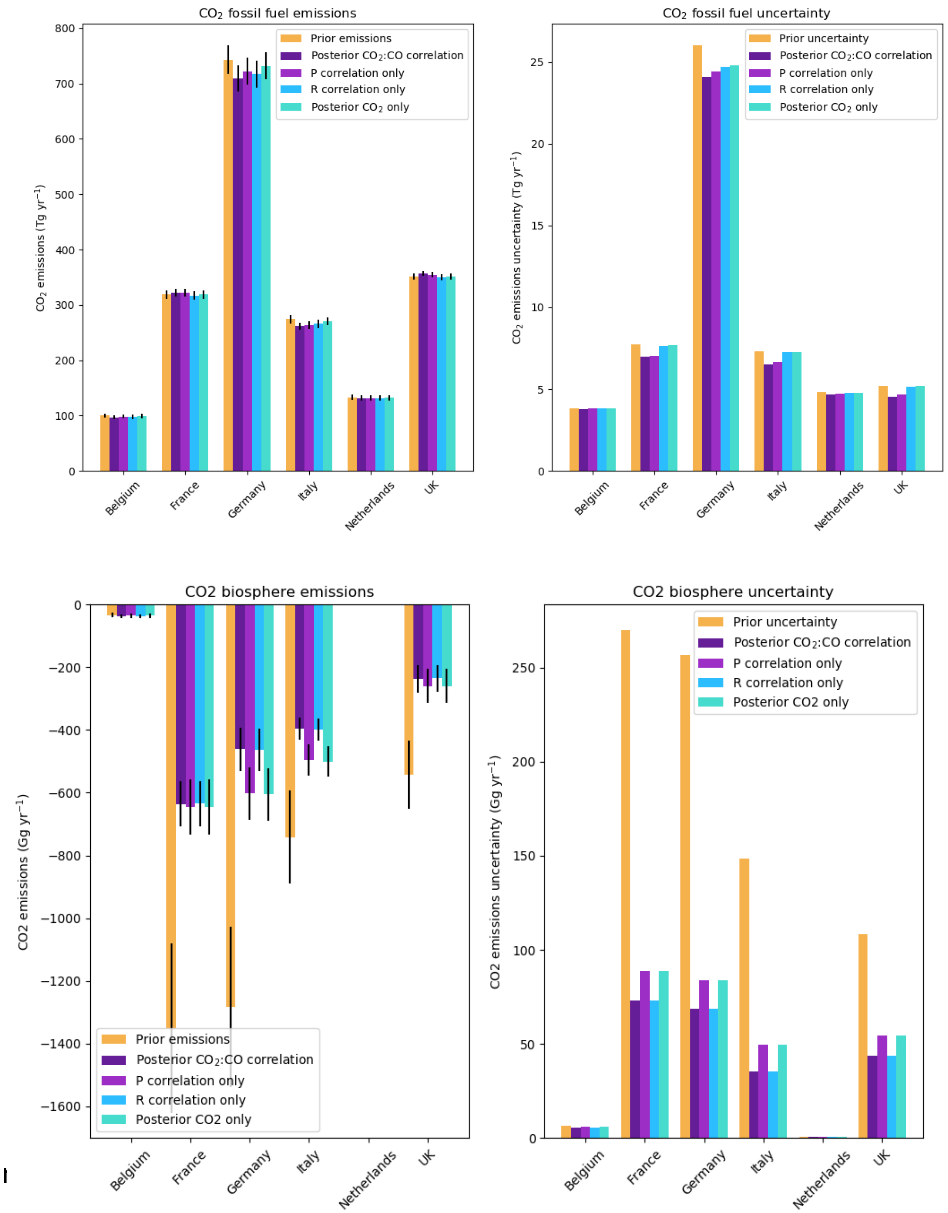
Common to CO_2 and CO

Anticorrelated between CO and CO_2 via combustion efficiency

$$Emis_i = (AD + \sigma_{AD})\times(EF + \sigma_{EF})$$

Country	Prior CO_2:CO error correlation
Belgium	-0.10
France	-0.42
Germany	-0.23
Italy	-0.43
Netherlands	-0.25
United Kingdom	-0.49

- Prior CO_2:CO correlations help split apart combustion and biospheric CO_2 fluxes
- Atmospheric transport error CO_2:CO correlations determined by meteorology analyses at different spatial resolutions also plays a role.
- Results over Europe encouraging even though knowledge of emissions is good.

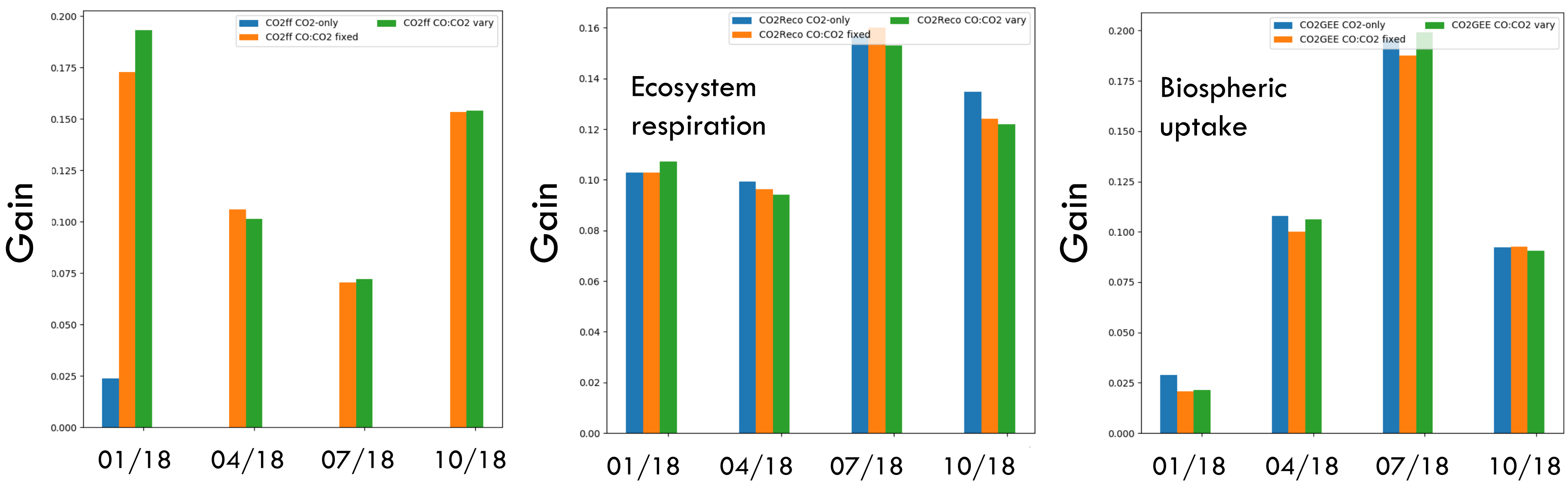


ESTIMATION OF FFCO2 USING SYNTHETIC DATA IS MARGINAL

$$Gain = 1 - \frac{\sum |x_{true} - x_{post}|}{\sum |x_{true} - x_{ap}|}$$

Value of 0 = no improvement
Value of 1 = perfect retrieval of true values

NW Europe (UK, Ireland, France, Germany, Belgium, Netherlands)



Inv1. CO_2-only: Only CO_2 data used to estimate $ffCO_2$

Inv2. $CO:CO_2$ fixed: CO data used in addition to constrain $ffCO_2$. The relationship is assumed to be direct, and a common scale factor was used for both gases.

Inv3. $CO:CO_2$ variable: the $\mathbf{E_R}$ term (which applies only to ffCO) was also included within the inversion in addition to a common scale factor for ffCO and $ffCO_2$.

Conclusions

- Value in satellite observations of reactive trace gases to infer ffCO2.
- Current instruments limit the analysis (by CO2) to late Spring – early Autumn months.
- CO2M and GOSAT-GW will radically change our ability to infer ffCO2.

- **However:**

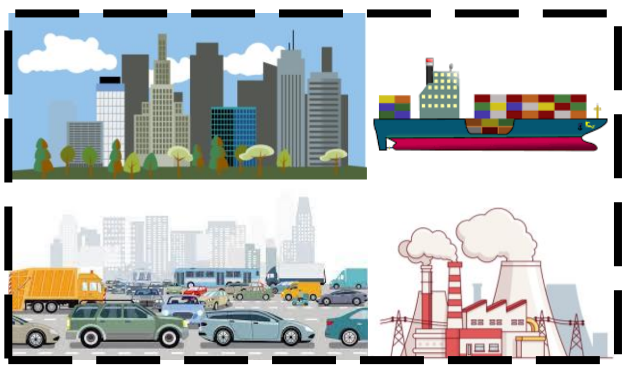
→ Reconciling inventory and atmospheric CO:CO2 and NOx:CO2 require knowledge of photochemistry (shorter lived gases) and atmospheric transport (longer-lived gases)

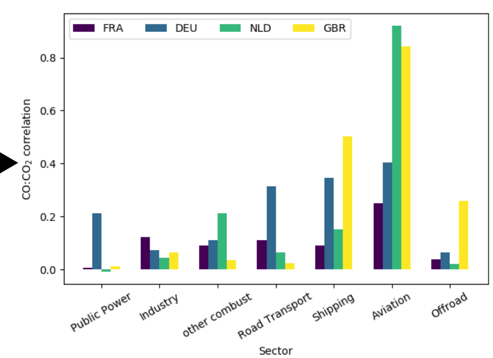
CoCO2
Prototype system for a Copernicus CO_2 service

→ National inventory values reveal relative importance of different sectors (T2.3)

→ Bayesian inversions requires stronger CO:CO2 error correlations from inventories for CO to be a useful constraint for ffCO2. Currently limited by national scale statistics that aggregate regional/local sectors

Reality: spatially-resolved sectors with strong and weak ΔCO2:ΔCO emission ratios





Inventories: National-scale statistics dilute richness of spatial (and temporal) information

SCIENCE HIGHLIGHTS

- Verifying proxy ffCO2 emission ratios: a highway measurement campaign
  - Claudius Rosendahl et al (U. Heidelberg)
- Quantifying ffCO2 using inversions of NO2 and CO
  - Gregoire Broquet on behalf of Audrey Fortems-Cheiney (LSCE)

VERIFYing proxy/$ffCO_2$ emission ratios: a highway measurement campaign

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Julian Della Coletta[#], Mahshid Homayou[#],

Armin Jordan[§],

Hugo Denier van der Gon[†], Stijn Dellaert[†], Ingrid Super[†]

Wolfram Knörr[&],

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INSTITUT FÜR UMWELTPHYSIK

ICOS INTEGRATED CARBON OBSERVATION SYSTEM

Karl Otto Münnich ^{14}C Laboratory

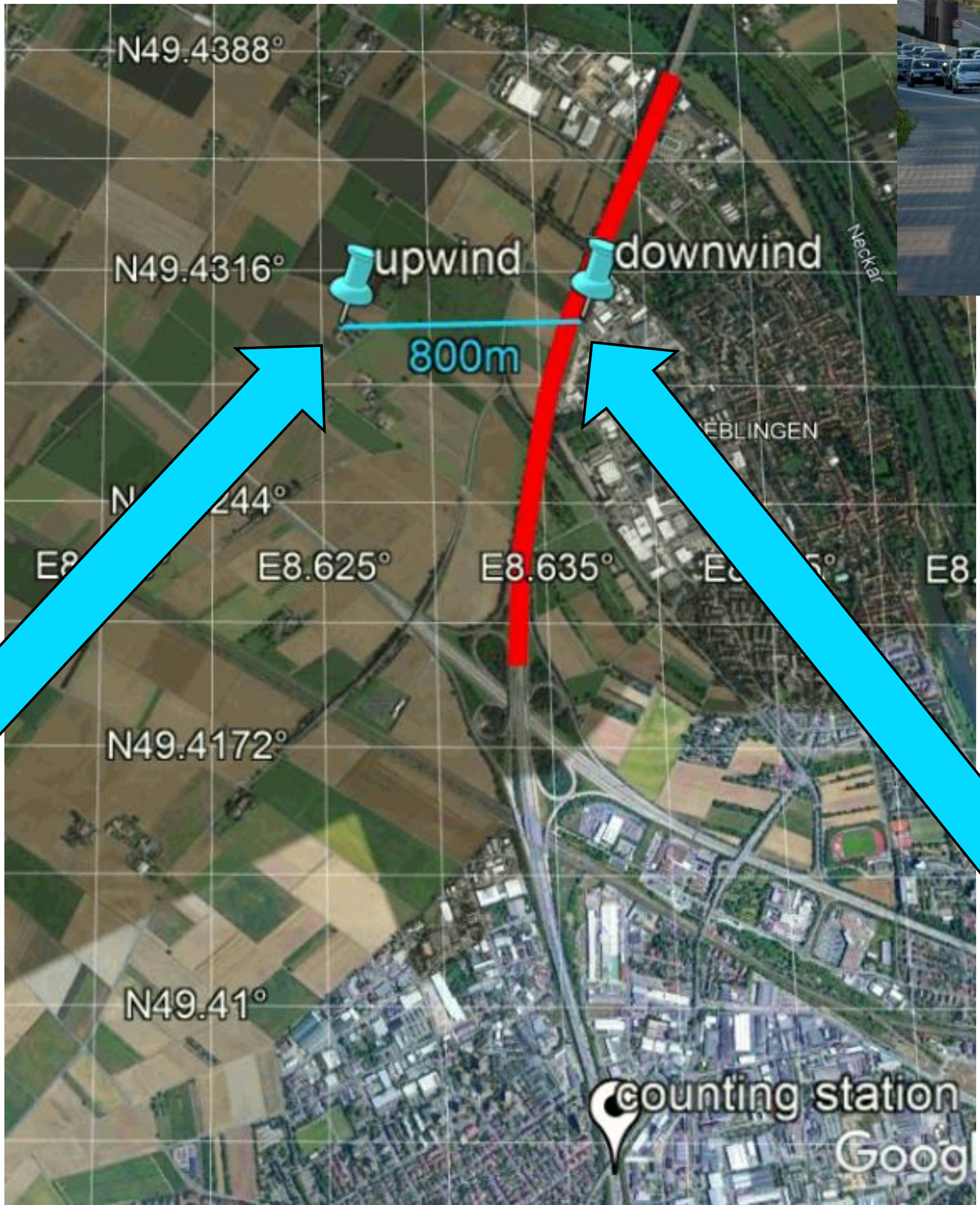
Goals

- Proxy/ffCO_2 emission ratios: used to estimate ffCO_2
- Emission inventories: provide sector-specific emission ratios

Are the sector-specific emission ratios correct?

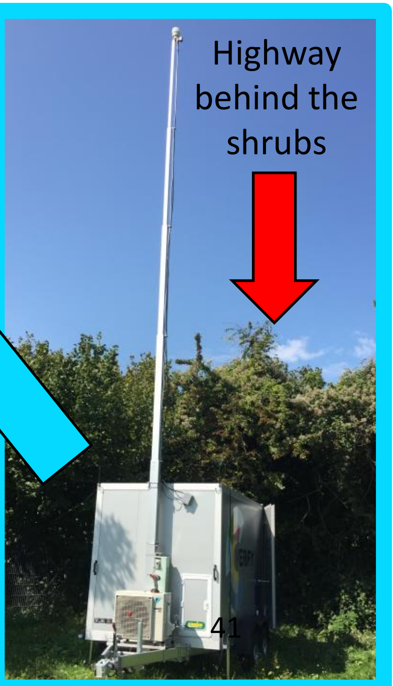
→ Measurements as independent validation tool

Setup at A5 highway

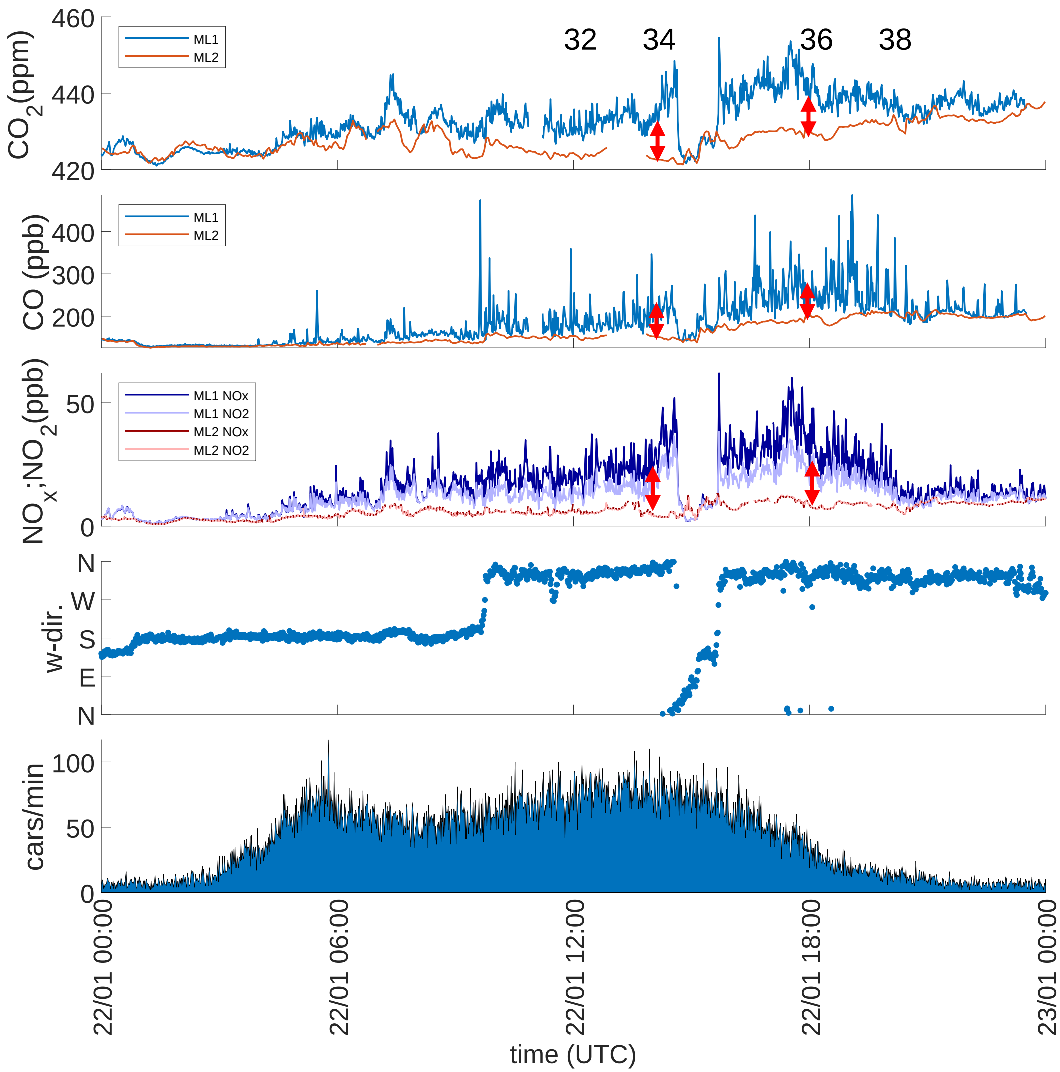


background

signal



Setup at A5 highway



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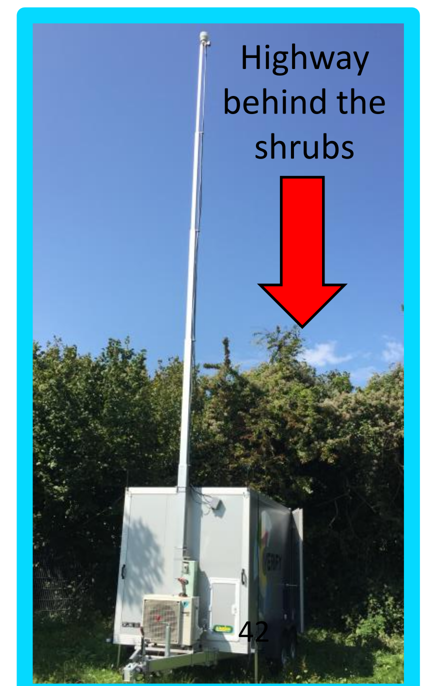
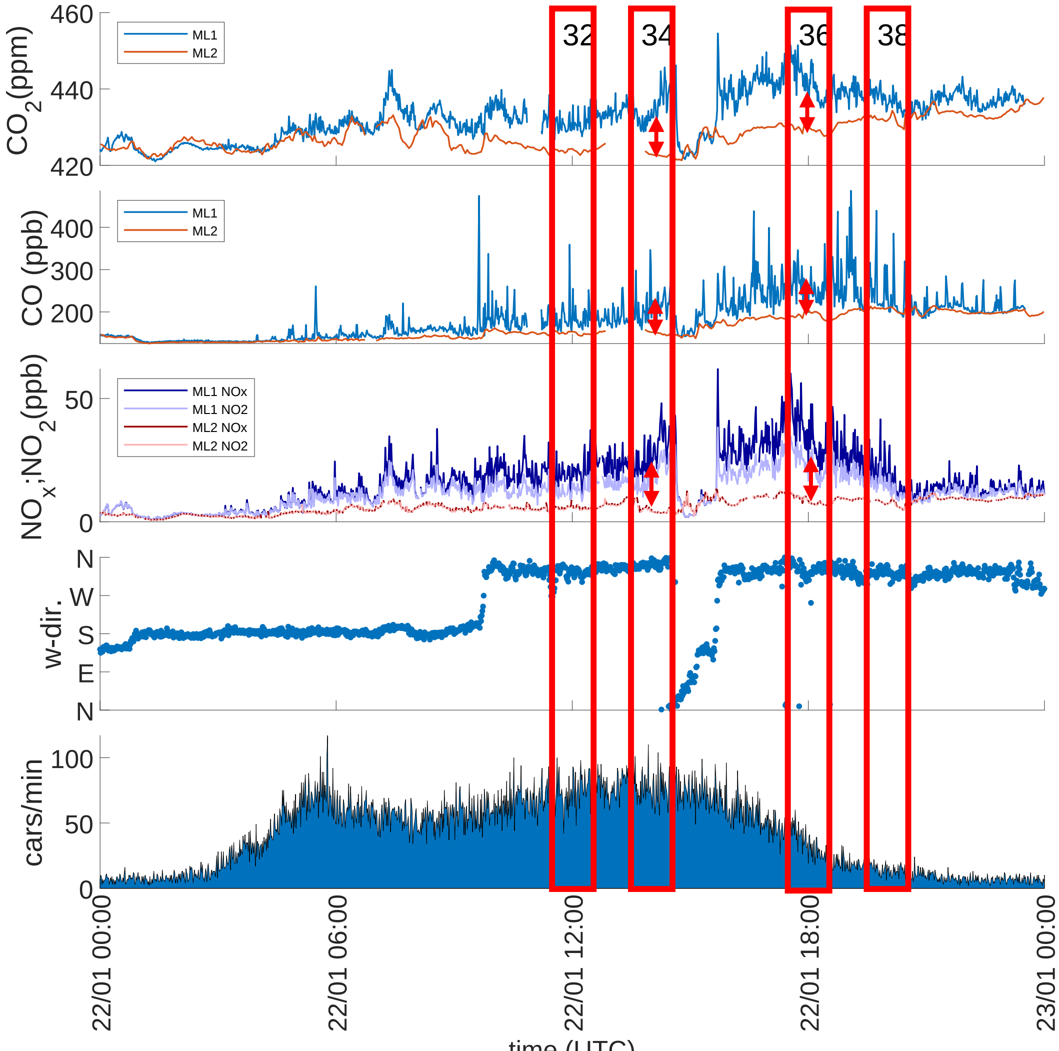


Setup at A5 highway



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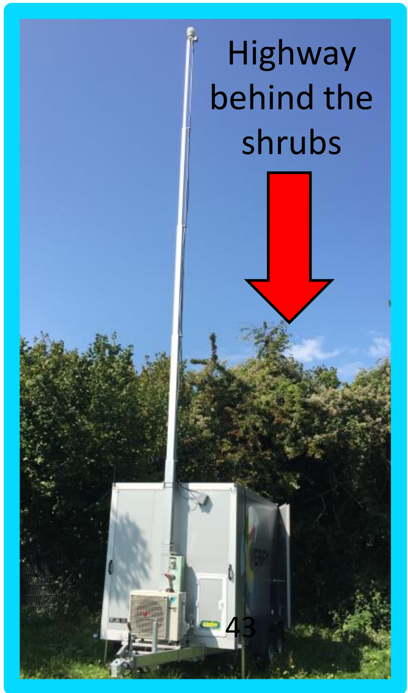
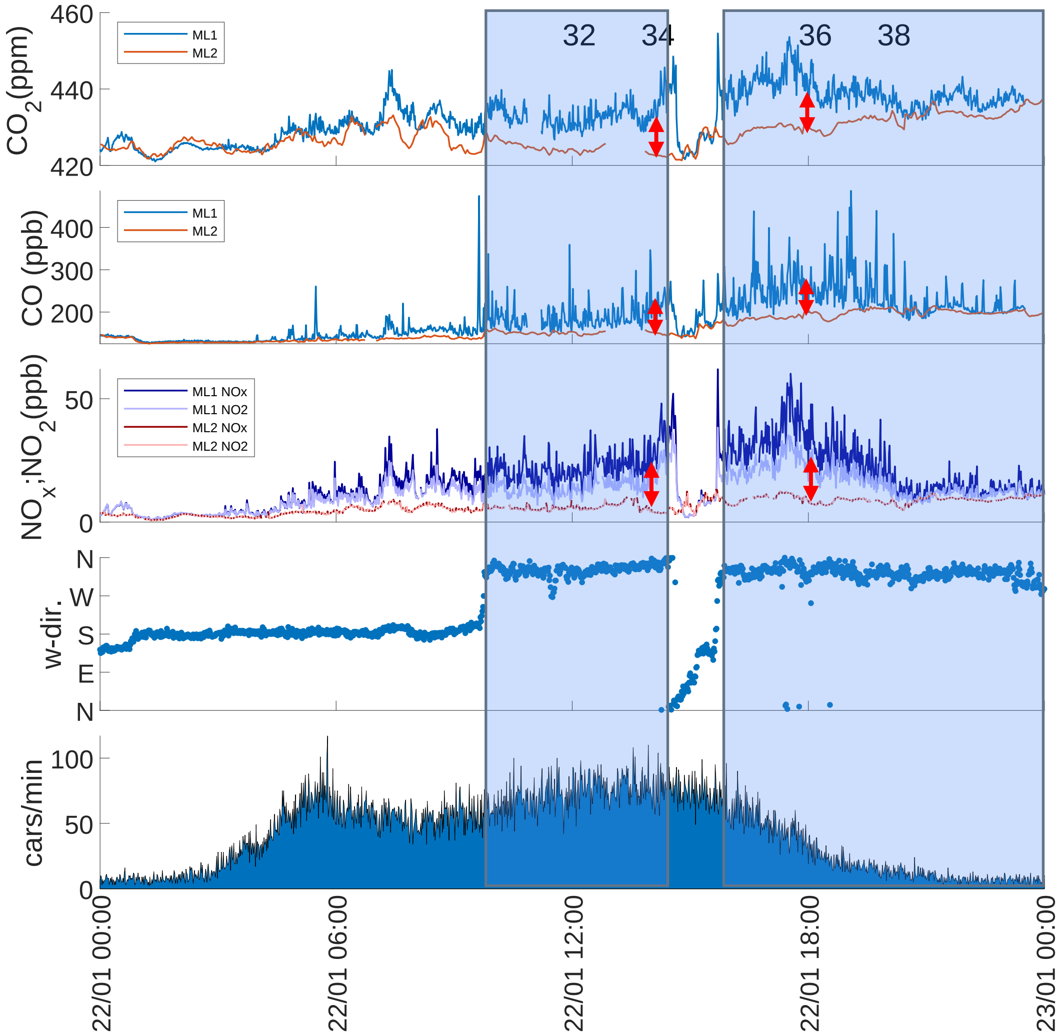


Setup at A5 highway

Virtual flasks



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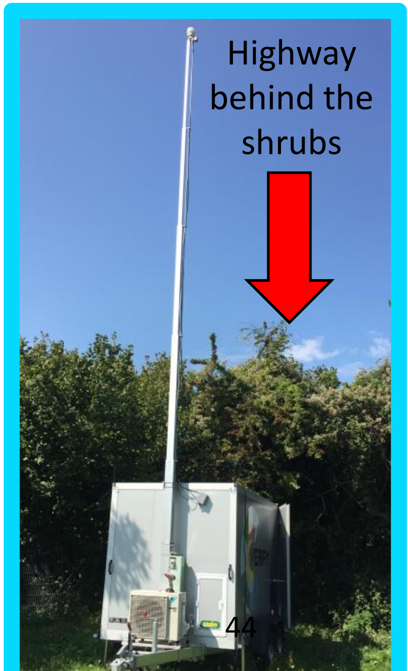
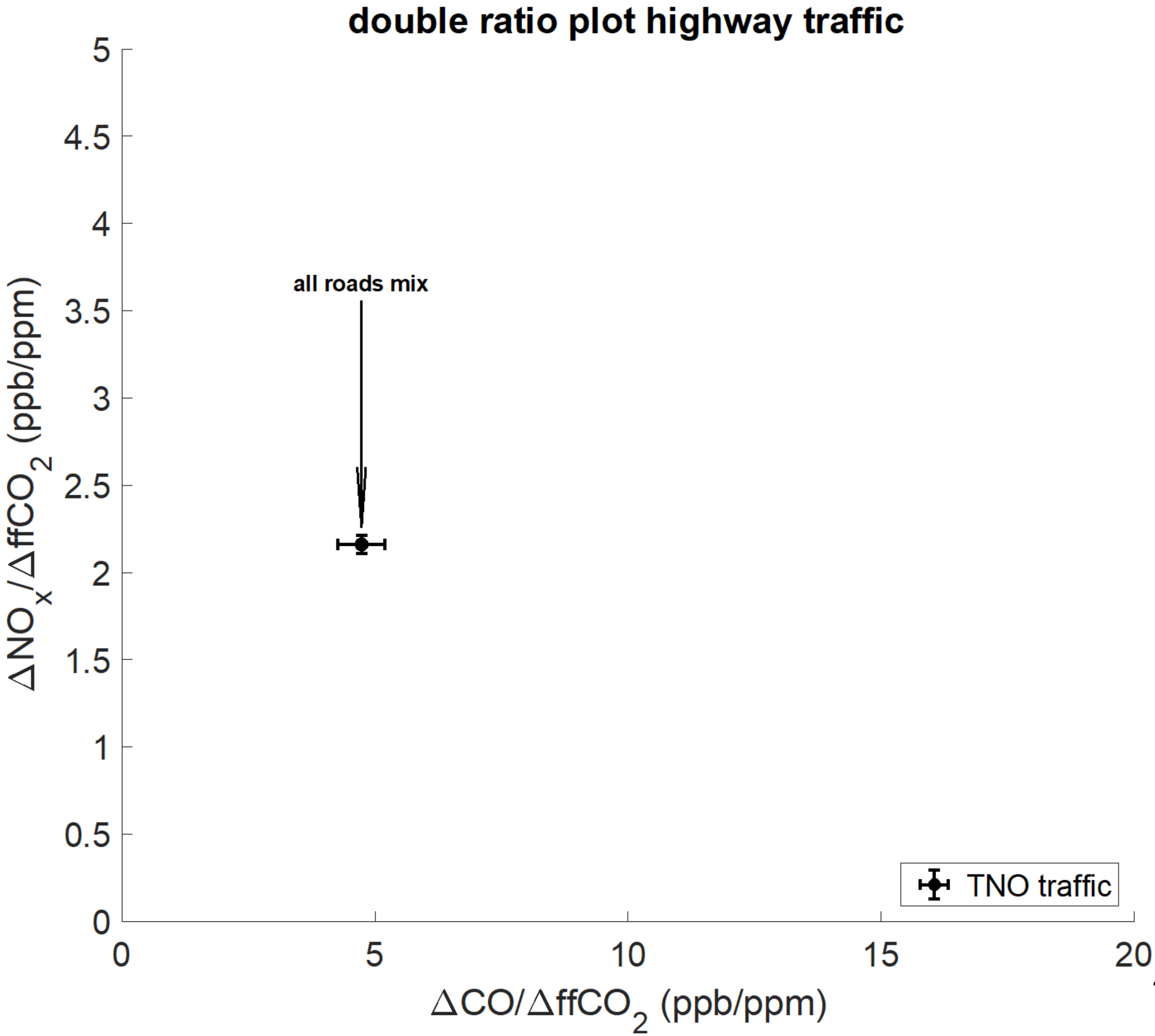
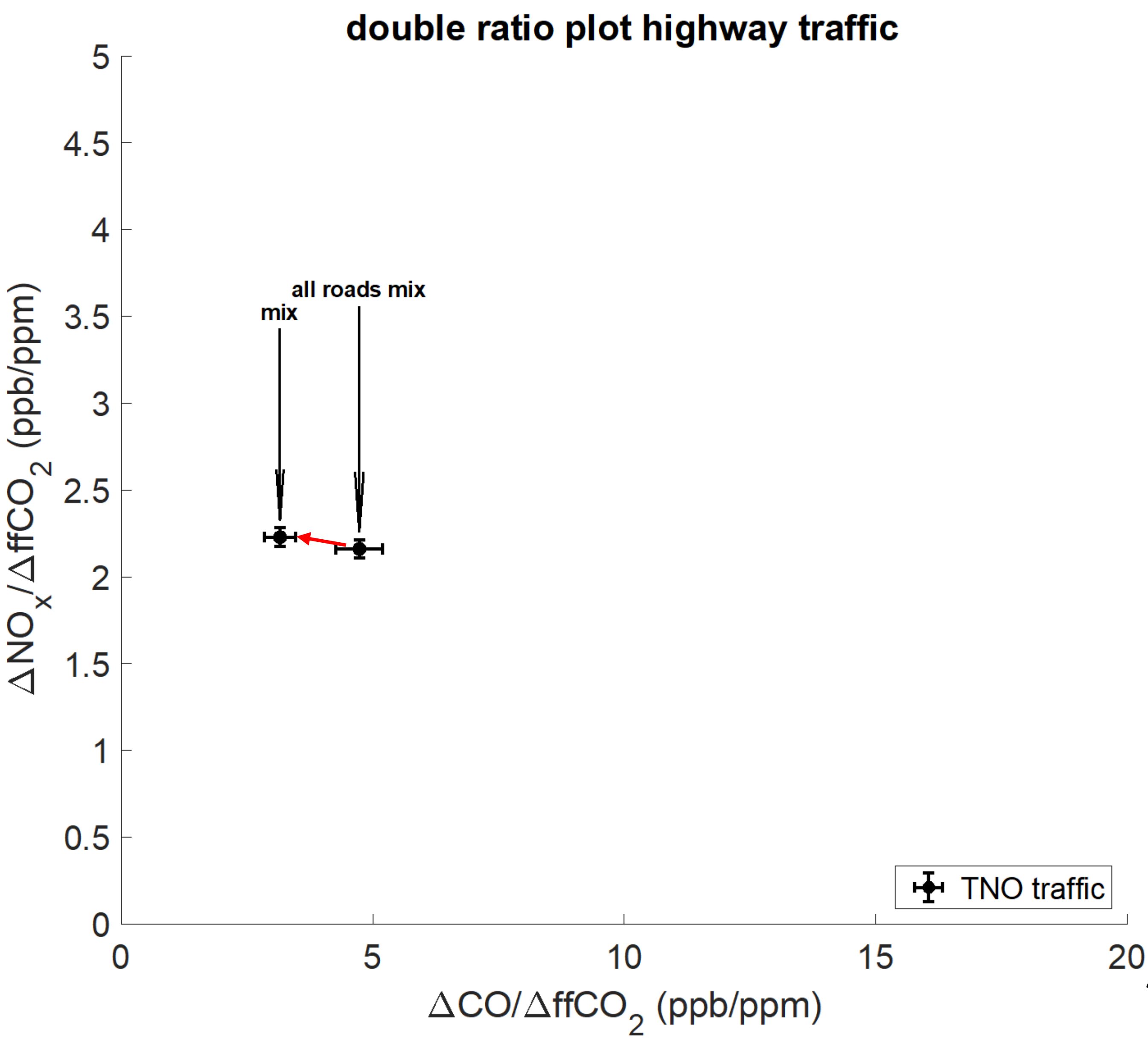


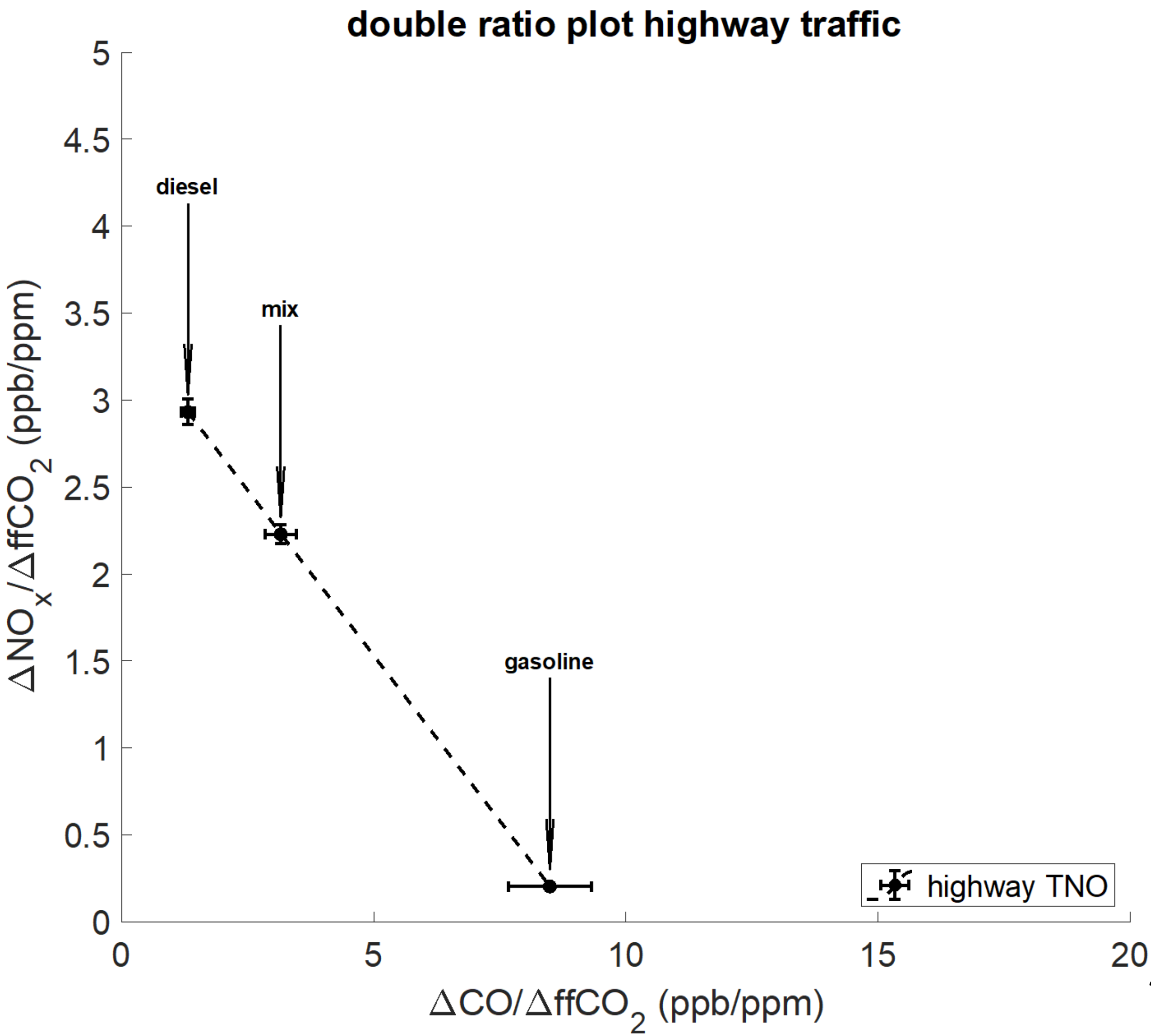
Results: double ratio plot



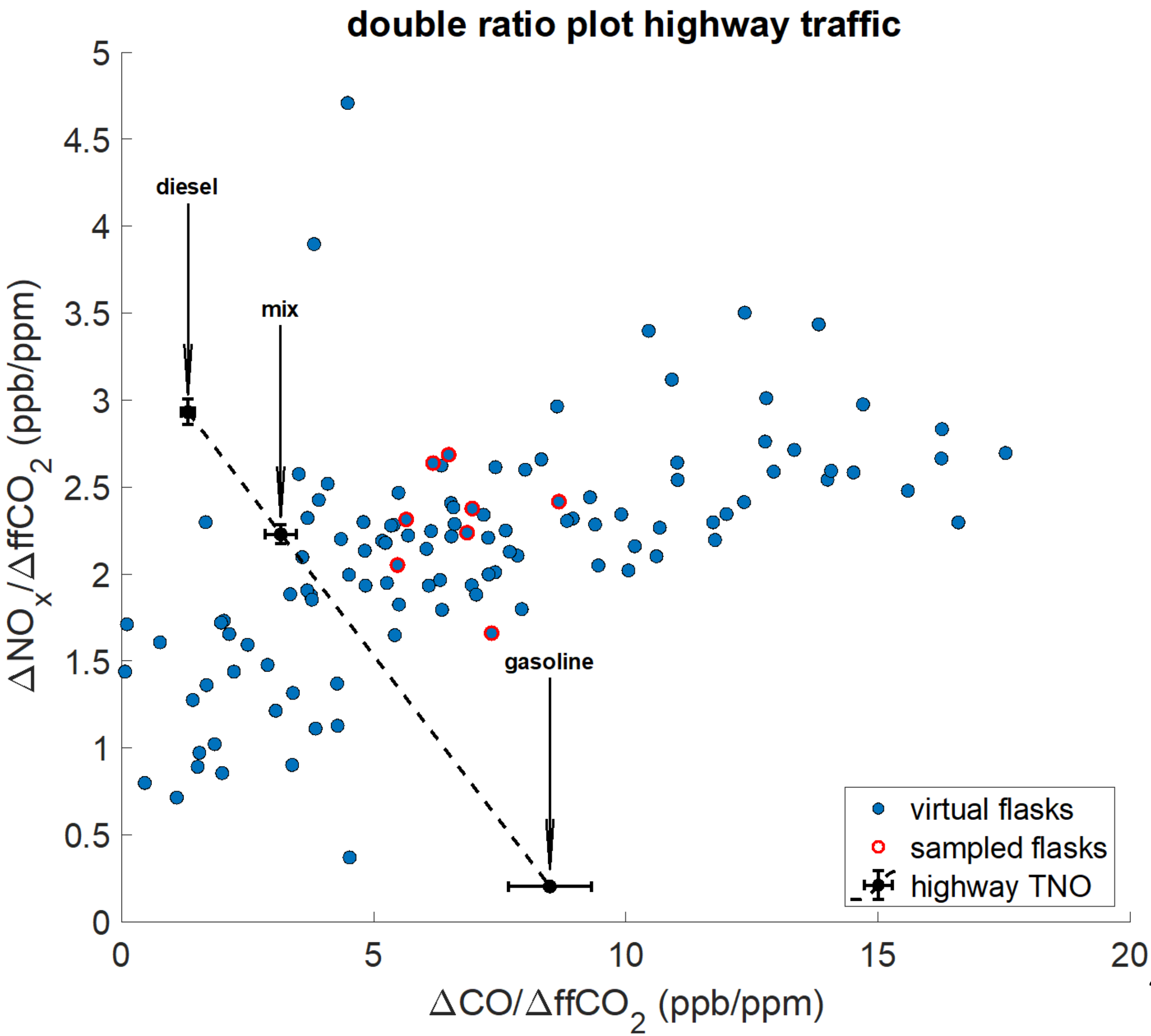
Results: double ratio plot



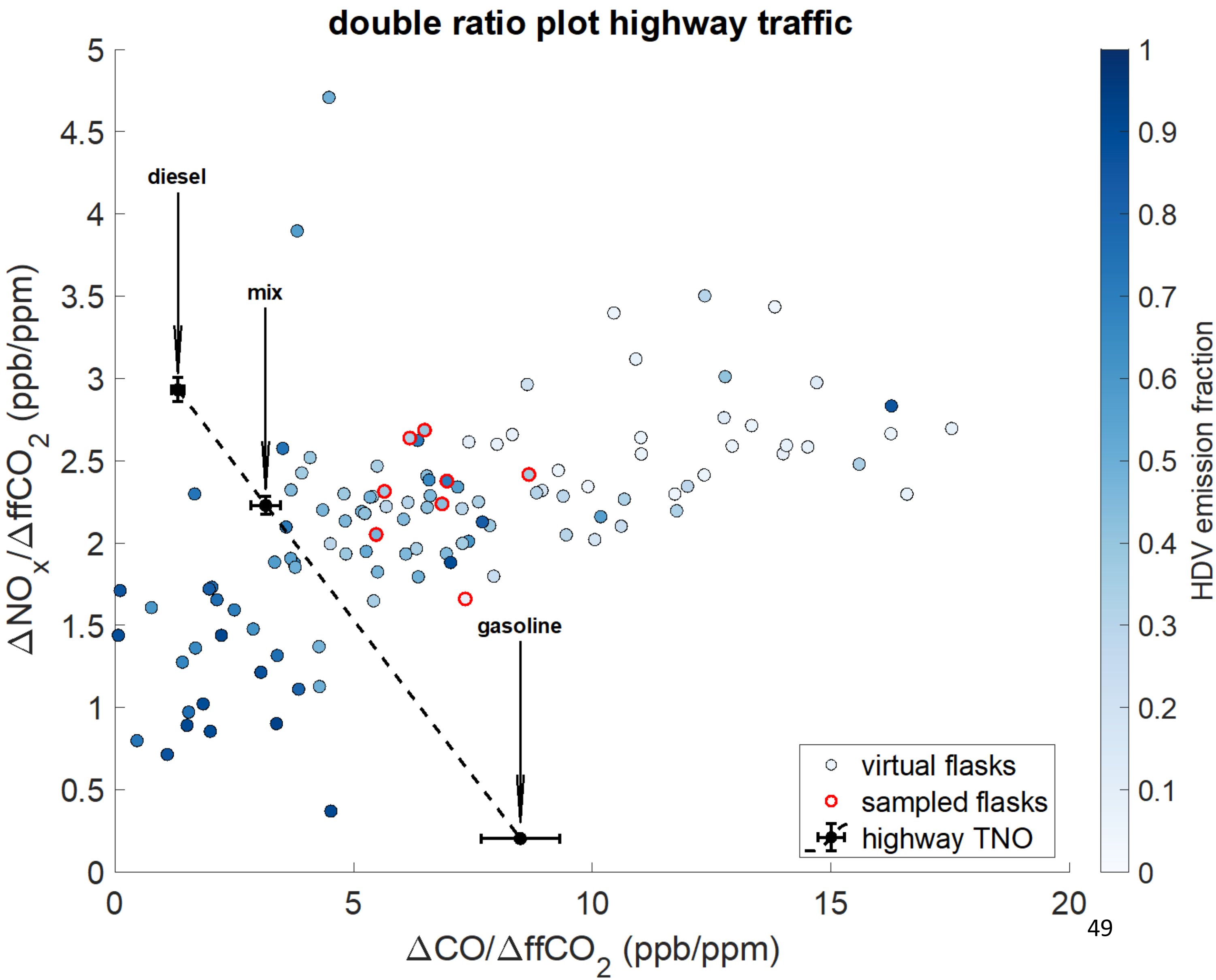
Results: double ratio plot



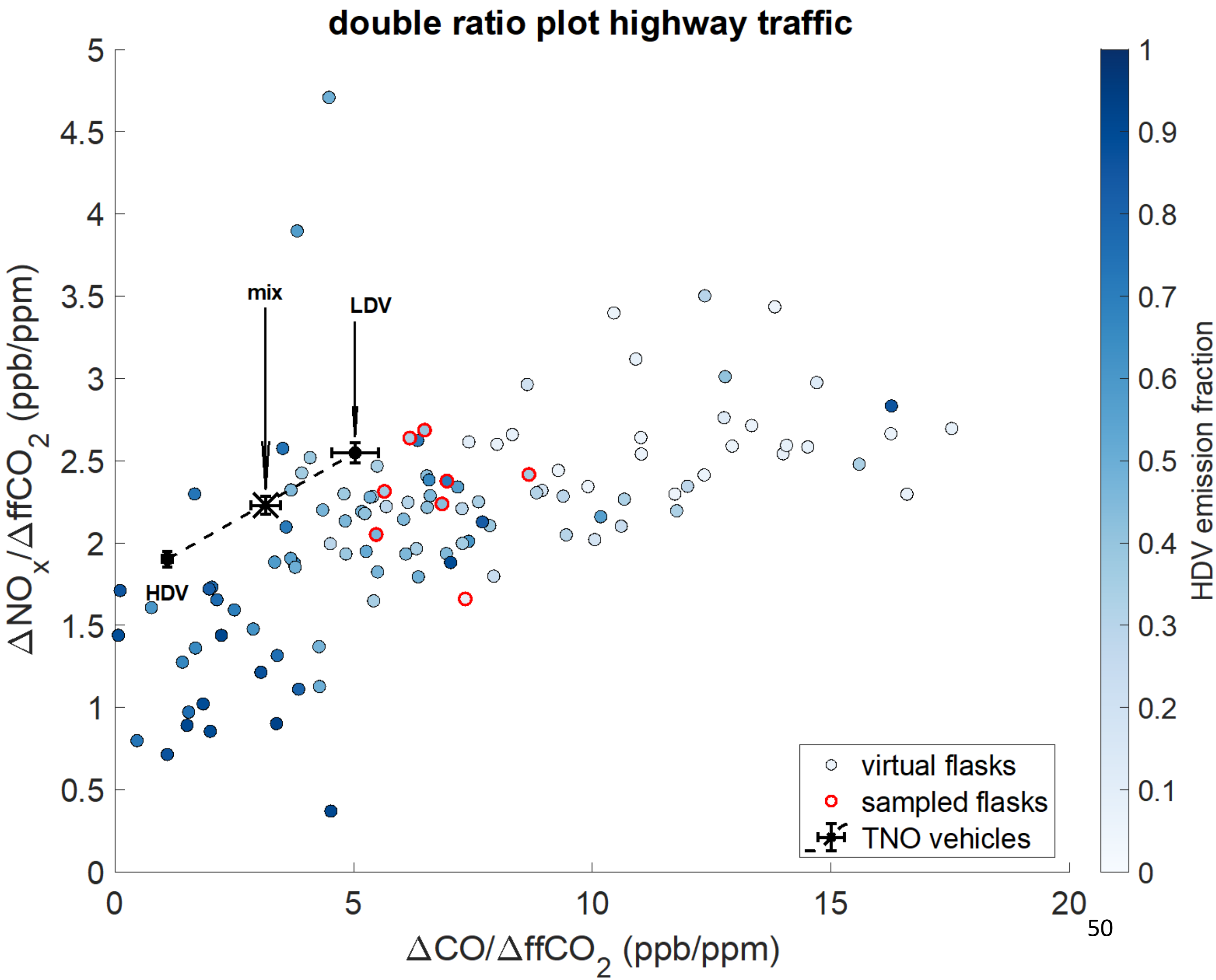
Results: double ratio plot



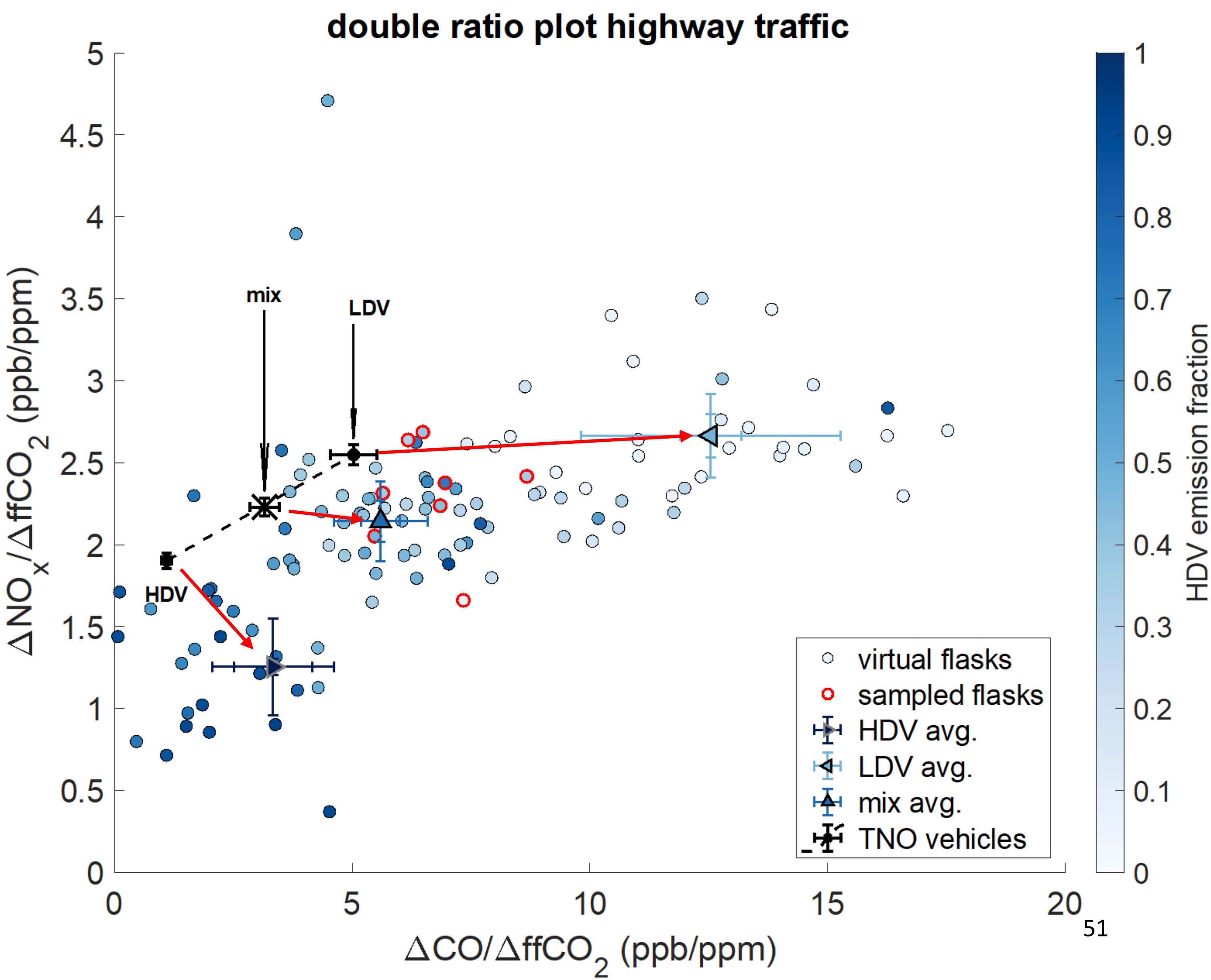
Results: double ratio plot



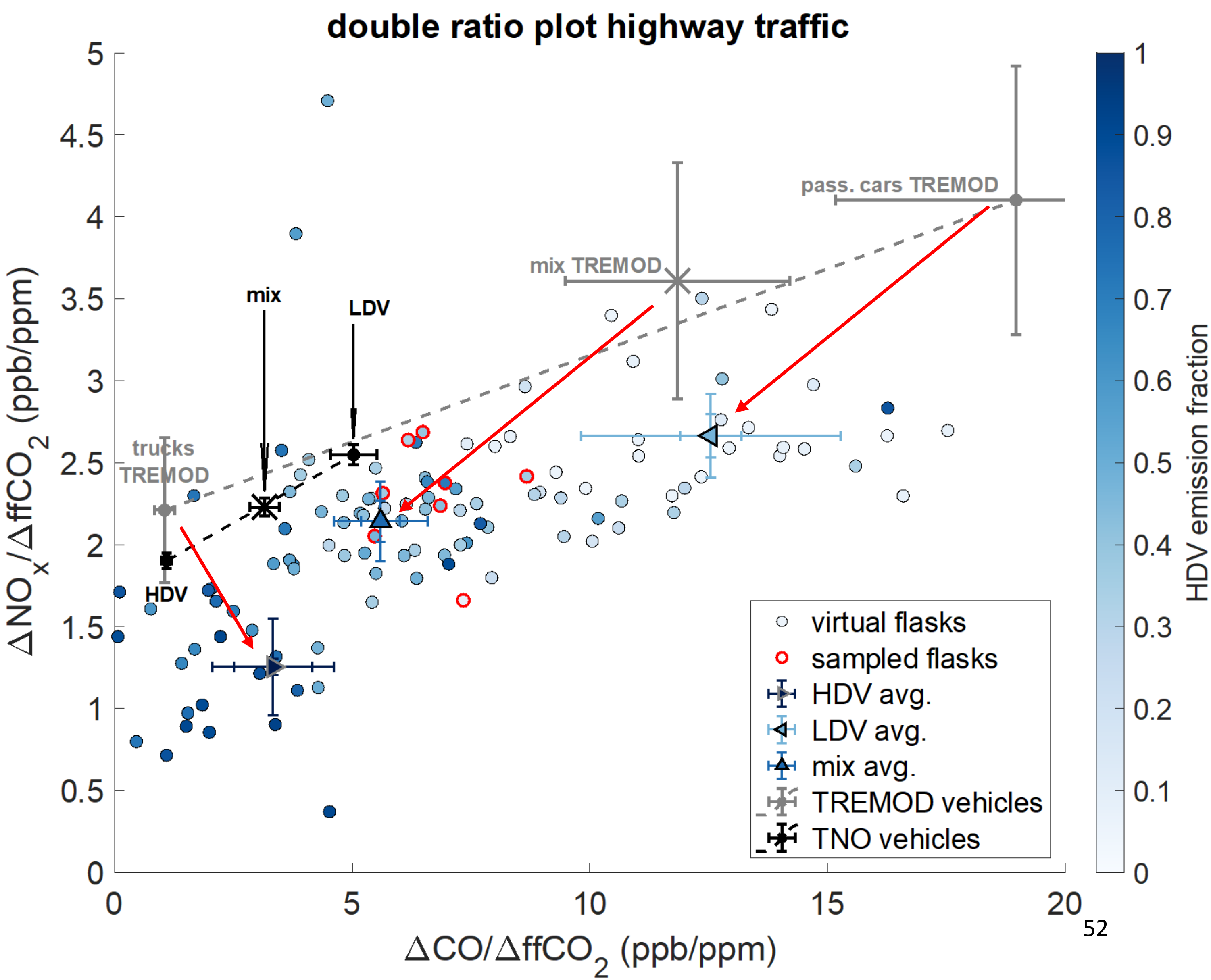
Results: double ratio plot



Results: double ratio plot



Results: double ratio plot



Summary

(1) Measurements of effective atmospheric emission ratios for the traffic sector possible with this setup
(2) Variability of emission ratios is caused by changes in traffic composition
  a) Variability in CO emission ratio predicted by TREMOD
  b) NO_x emission ratio is overestimated
(3) Highway emission factors for LDV and HDV must be re-evaluated
(4) Independent check of inventory emission ratios is possible

Inferring ffCO2 emissions using satellite observations of NO_2 and CO

WP2.3 - A. Fortems-Cheiney, G. Broquet, I. Pison, A. Berchet, E. Potier, R. Plauchu and the VERIFY WP2 team

LSCE
LABORATOIRE DES SCIENCES DU CLIMAT & DE L'ENVIRONNEMENT

NOx and CO inversions & derivation of FFCO2 emissions in Europe using NO2 and CO satellite data: a 2-step approach

See deliverables : D2.11, D2.12

Objectives:

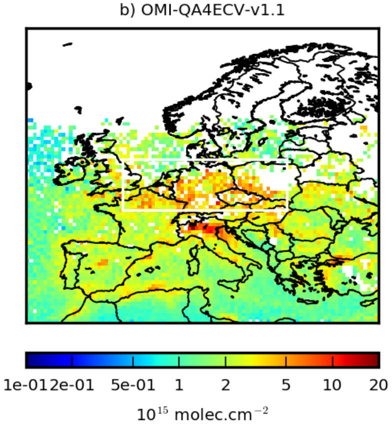
- Testing the capacity of **regional atmospheric inversions to evaluate and improve fossil-fuel CO_2 (FFCO2) budgets** at national scales
- Preparing the **co-assimilation of CO_2 with co-emitted species** to better constrain $FFCO_2$ emission estimates

→ Analysing the **national budgets in Europe over the last 15+ years**

→ Using the most adapted and consistent datasets of atmospheric concentrations connected to anthropogenic fossil fuel combustion over these 15+ years: **NO_2 and CO observations from satellites**

→ Legacy of **Konovalov et al. 2016, ACP & Konovalov and Lvova, 2018 (VERIFY T4.3 FT product, D2.10)**

Monthly mean of NO_2 tropospheric columns in January 2020 from OMI (in 10^{15} molec.cm^{-2})



2-step approach:

- 1) **Variational inversion of the NO_x & CO emissions** at 0.5°/1-day res.
- 2) **Conversion into estimates of $FFCO_2$ emissions** for large sectors of activity at national / 1-month scale using sectoral maps of emissions

→ Longer-term goal: **fully integrated joint NO_x-CO-CO_2 (one-step) inversion framework**

NO_x and CO variational & regional inversions using CIF-CHIMERE

$$J(\mathbf{x})=(\mathbf{x}-\mathbf{x_b})^T\mathbf{B}^{-1}(\mathbf{x}-\mathbf{x_b}) + (H(\mathbf{x})-\mathbf{y})^T\mathbf{R}^{-1}(H(\mathbf{x})-\mathbf{y})$$

Configuration in VERIFY

Variational mode of the **Community Inversion Framework** (CIF; Berchet et al., 2021, GMD)

Prior input $\mathbf{x_b}$
Covariance matrix **B**

NO_x anthropogenic emissions from the **TNO-GHGco-v3 inventory**
NO_x biogenic emissions from MEGAN
*or CO anthropogenic emissions from the **TNO-GHGco-v3 inventory***

H

Regional chemistry-transport model (0.5°x0.5° x 17 vertical levels)
MELCHIOR-2 module for gaseous chemistry
ECMWF meteorological fields

H^T

Adjoint of CHIMERE including adjoint of chemistry

Observation **y**
Covariance matrix **R**

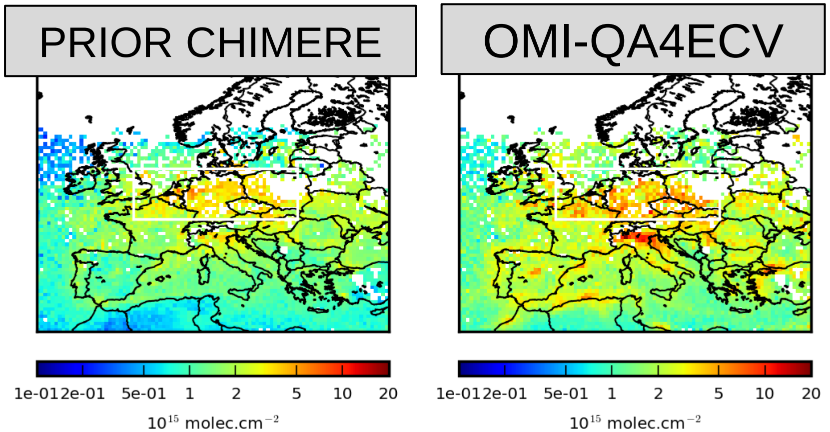
Satellite retrievals of NO_2 from OMI-QA4ECV-v1.1
or satellite retrievals of CO from MOPITT-v8J

Control vector **x**

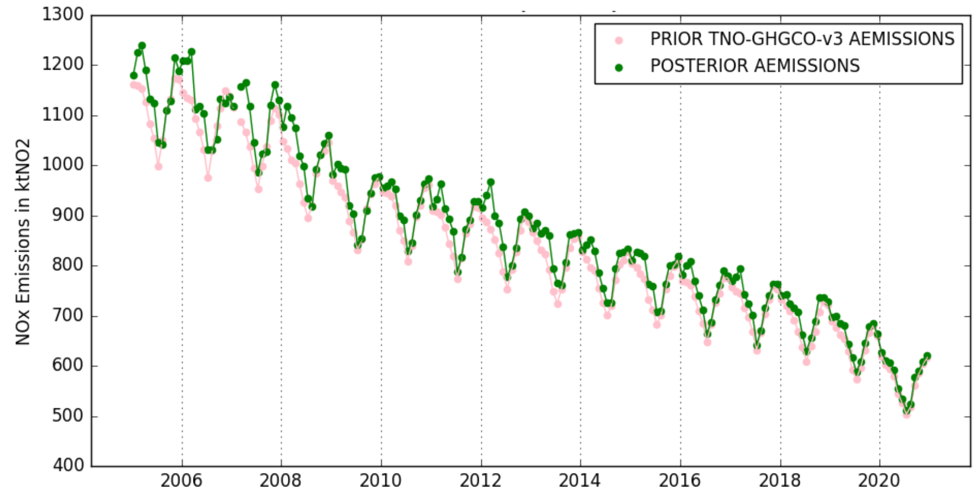
NO_x emissions at a 1-day / 0.5°x0.5° resolution & NO_x initial conditions
or CO emissions at a 1-day / 0.5°x0.5° resolution & CO initial conditions

See Fortems-Cheiney et al. 2021a, GMD & 2021b, GRL

NO_x inversions over 2005-2020



Monthly mean of NO_2 tropospheric columns in January 2020 (in 10^{15} molec.cm^{-2})



Monthly prior and posterior estimates of the NO_x anthropogenic emissions from 2005 to 2020 over continental land (in $ktNO_2$)

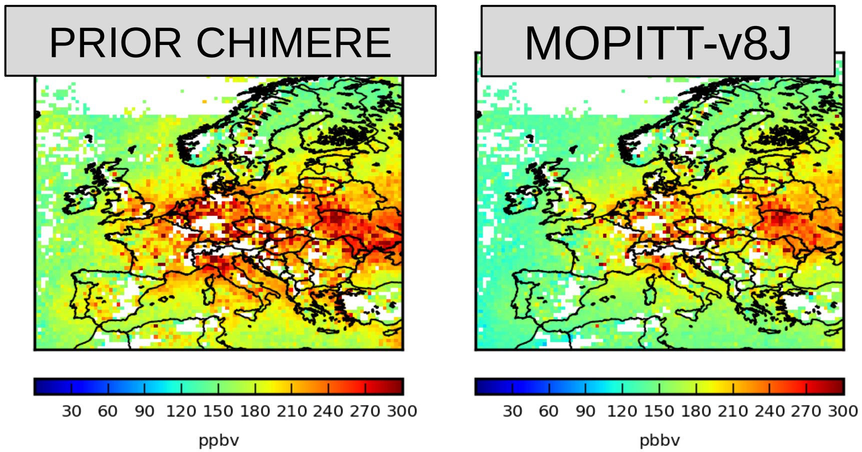
Strong underestimation of the NO_2 simulated TVCDs compared to OMI-QA4ECV observations, seen for all seasons:

- underestimation of prior emissions ?
- biases in the observations ?

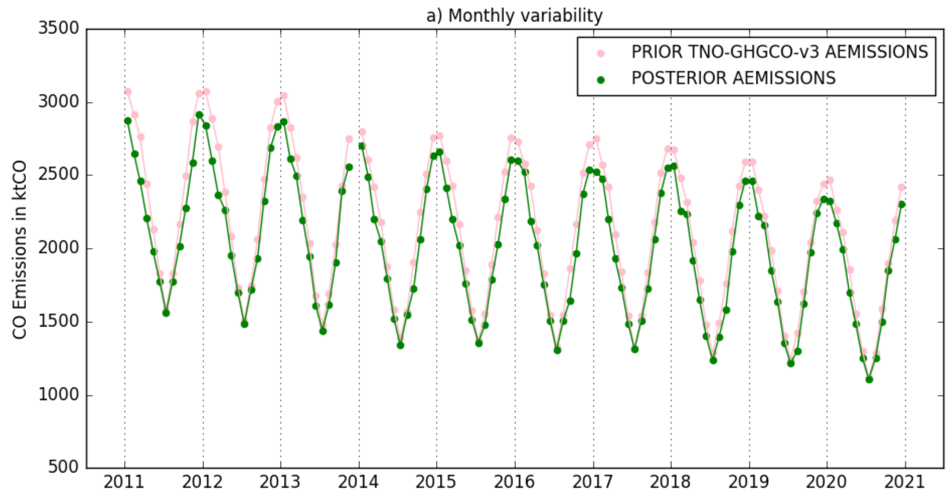
→ Consistent with the literature [e.g., Huijnen et al., 2010; Miyazaki et al., 2017, Visser et al., 2019]

- Slight differences between the inverted NO_x emissions and the prior ones during winter mainly due to the lack of observations
- **The inversion mainly applies positive increments to the prior anthropogenic emissions in spring and in summer**

CO inversions over 2011-2020



Monthly mean of CO « surface » concentrations in February 2015 (in ppbv)



Monthly prior and posterior estimates of CO anthropogenic emissions from 2011 to 2020 over continental land (in ktCO)

Overestimation of the simulated concentrations of CO compared to the MOPITT-v8J data

The inversion mainly applies negative increments to the prior anthropogenic emissions in winter

Conversion from NO_x or CO to $FFCO_2$ emissions (current scheme)

Comparison between
- the sectoral maps of NO_x / CO anthropogenic emissions from TNO-GHGco-v3
vs.
- the maps of total NO_x / CO anthropogenic emissions from the inversion
→ for each month and country

Sectors = energy, industry, residential, road transport and "others" (the rest of the sectors)

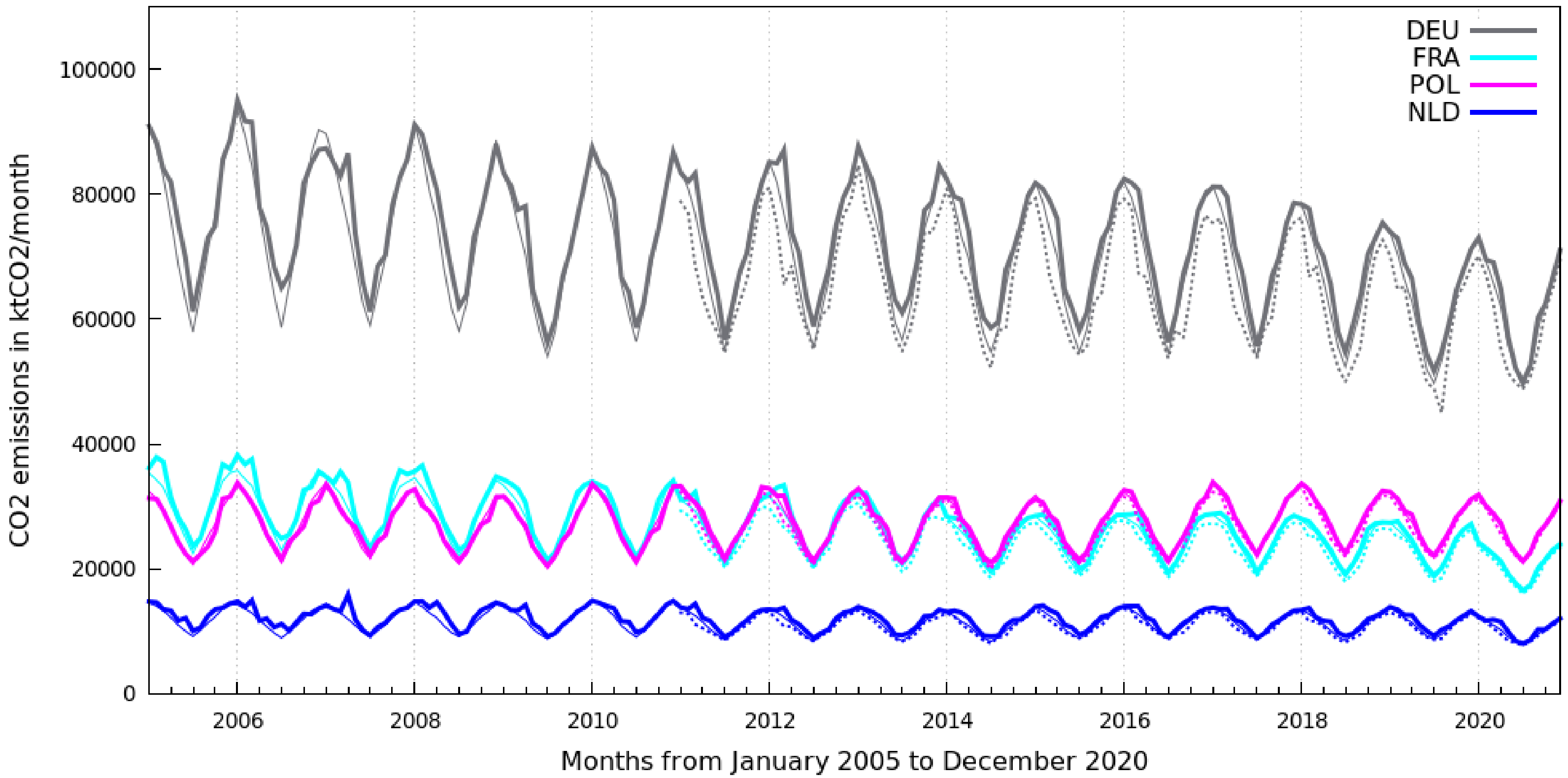
Simple analytical inversion scheme

Optimal scaling of the sectoral maps NO_x or CO anthropogenic emissions from TNO-GHGco-v3
for each month and country

NO_x-to-$FFCO_2$ or CO-to-$FFCO_2$ **sectoral emission ratios** from TNO-GHGco-v3
for each month and country

$FFCO_2$ sectoral emissions

Conversion from NO_x or CO to $FFCO_2$ emissions (current scheme)



Thin line = $FFCO_2$ prior emissions
Bold line=from the NO_x inversions
Dashed line = from the CO inversions

Monthly prior and inversion-based estimates of $FFCO_2$ emissions from 2005 to 2020 for different countries (in $ktCO_2$)

Conclusions

- Inversion based estimates close to the inventory: **general consistency between the inventory and the observations**

- **However, significant residual biases between the simulation and the data, due to**
→ the large nominal errors associated to the satellite retrievals
→ the non-linearity of the chemistry

- **Lack of data in winter** esp. for Northern countries

- $FFCO_2$ emission **estimates from NO_x and CO inversions present contradictory information** regarding the sign of the corrections to be applied to the inventory:
→ highlighting the **weight of uncertainties in emission ratios or biases in the observations ?**

Perspectives

General targets: need to

- **characterize the uncertainties in the estimates**
- **account for uncertainties in the $CO/FFCO_2$ & $NO_x/FFCO_2$ anthropogenic emission ratios**
- **synthetize the information from the different species**
- **co-assimilate CO_2 data (controlling the CO_2 NEE with the anthropogenic emissions)**

Next steps (short-term):

- **Exps with pseudo-data** to characterize the uncertainties in NO_x and CO inversions and first analysis of the uncertainties in the emission ratios:
  - → to derive uncertainties in the $FFCO_2$ estimates
  - → to weight the respective confidence in the NO_x and CO inversions
- Scaling the $FFCO_2$ emission **using both the NO_x and CO inversions**
- Tests with independent prior estimates (e.g. perturbing the TNO inventory) and emission ratios (from different sources)
- **Update of prior uncertainties in the inversion and NO_x/CO-> $FFCO_2$ conversion protocol** based on most recent analysis of the uncertainties in the inventories (in VERIFY & CoCO2)
- Analysis using **TROPOMI** CO & NO_2 data
- **Co-assimilation of NO_2, CO and CO_2 satellite data in a fully integrated joint $CO/NO_x/CO_2$ inversion framework**

DISCUSSION SLIDE

- Nothing is ever easy! Once we dig in, new problems surface (e.g. E-PRTR data not consistent, biomass combustion, natural sources,….)
- Seeing the discrepancy for St Petersburg between "official" and observed – How can we get a bigger pool of such data?

→ Reconciling inventory and atmospheric CO:CO2 and NOx:CO2 require knowledge of photochemistry (shorter lived gases) and atmospheric transport (longer-lived gases)

→ National inventory values reveal relative importance of different sectors (T2.3)

→ Bayesian inversions requires stronger CO:CO2 error correlations from inventories for CO to be a useful constraint for ffCO2. Currently limited by national scale statistics that aggregate regional/local sectors

- Legacy of VERIFY…
  - VERIFY & CHE -> point source data quality -> work in CoCO2
  - ICOScities PAUL project looking into urban GHG budgets (related to measured proxy ratios T2.2)
  - New HEU Climate forcer projects (Wednesday)

Thank you for your attention.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 776810