Universität Bremen

Institut für Umweltphysik

Fachbereich 01
Physik/Elektrotechnik

Stanford | Doerr School of Sustainability

UNIVERSITY OF MICHIGAN

IWGGMS-21

21st International Workshop on Greenhouse Gas Measurements from Space (IWGGMS-21), 9-12 June 2025, Takamatsu, Japan

Methane emission estimates of localized sources from Sentinel-5 Precursor, PRISMA, EnMAP and EMIT using a cross-sectional-flux method

Michael Buchwitz, Oliver Schneising-Weigel, Stefan Noël, Maximilian Reuter, Michael Hilker, Jonas Hachmeister, Heinrich Bovensmann, Hartmut Boesch

University of Bremen, Institute of Environmental Physics, Germany

Frances Reuland, Adam Brandt

Department of Energy Science and Engineering Doerr School of Sustainability, Stanford University, CA, USA

Taylor Adams, Eric A. Kort

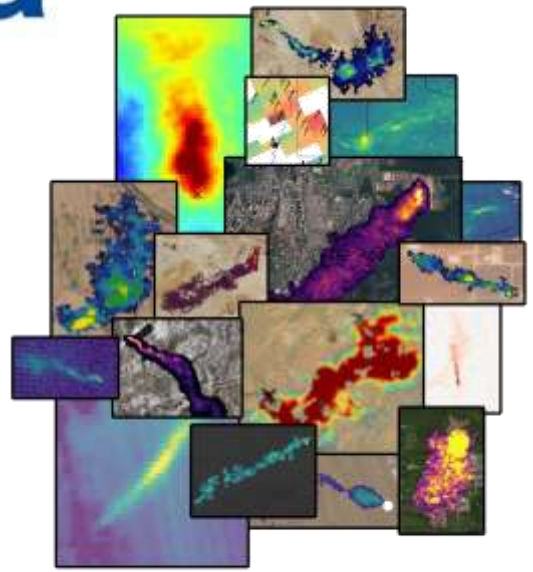
Department of Climate and Space Sciences and Engineering, University of Michigan, Ann Arbor, MI, USA

v2, 2-June-2025

IUP-UB: Funding through various projects

esa

ghg cci



SRON · Universitat Politècnica de València · KAYRROS · GHGSAT · Universität Bremen · University of Leicester

Methane Emissions Detection Using Satellites Assessment (MEDUSA)

SMART-CH4

copernicus
Europe's eyes on Earth

Climate Change Service
climate.copernicus.eu

Atmosphere Monitoring Service
atmosphere.copernicus.eu

EYE-CLIMA
Verifying emissions of climate forcers

NILU

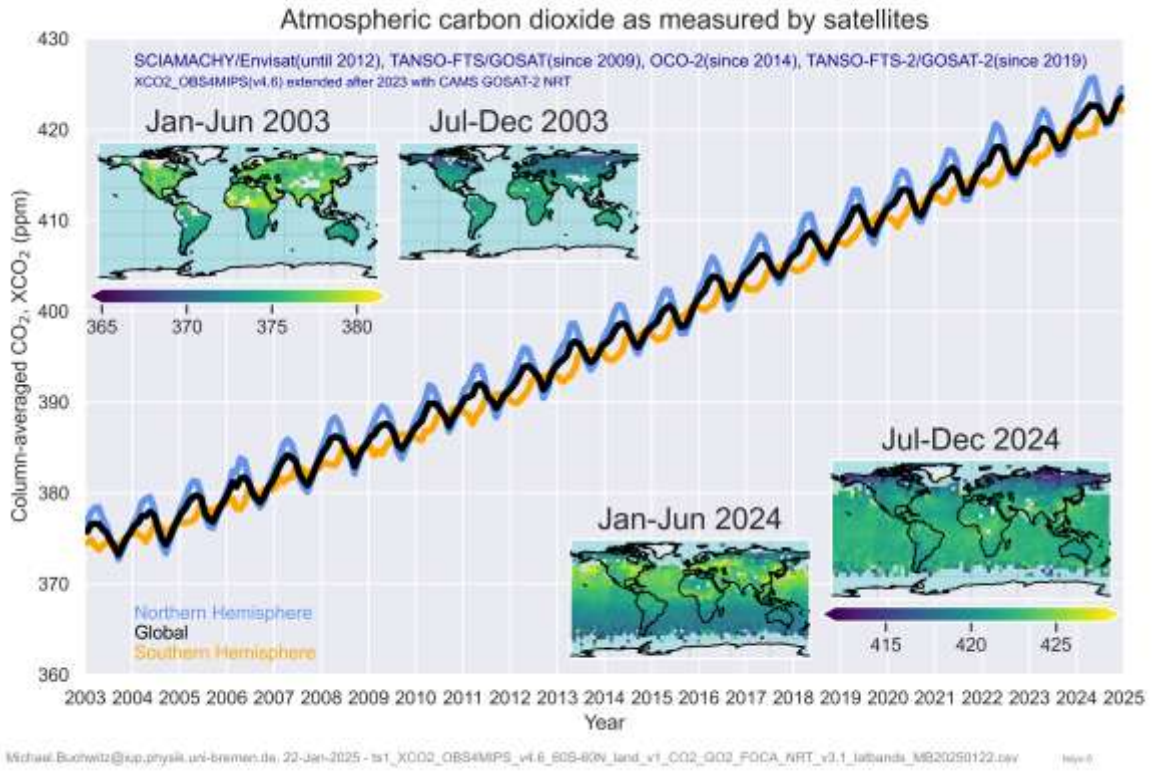
ITMS
INTEGRATED GREENHOUSE GAS MONITORING SYSTEM

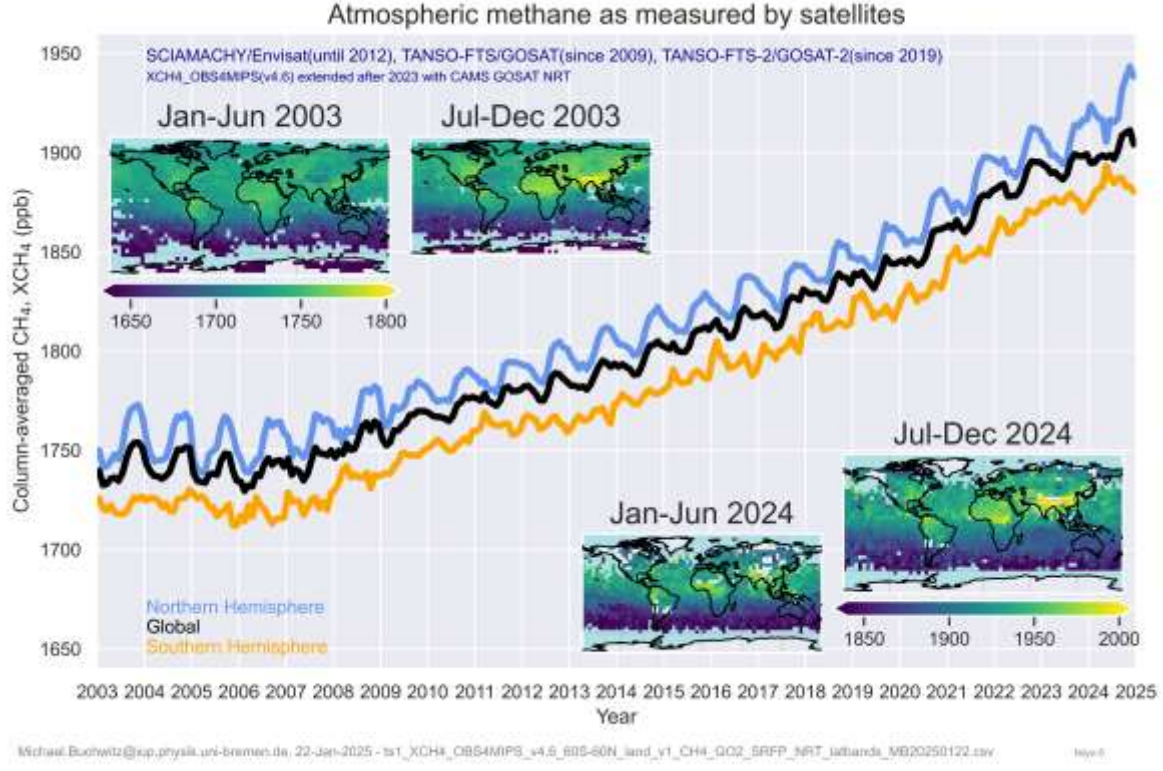
Bundesministerium für Bildung und Forschung

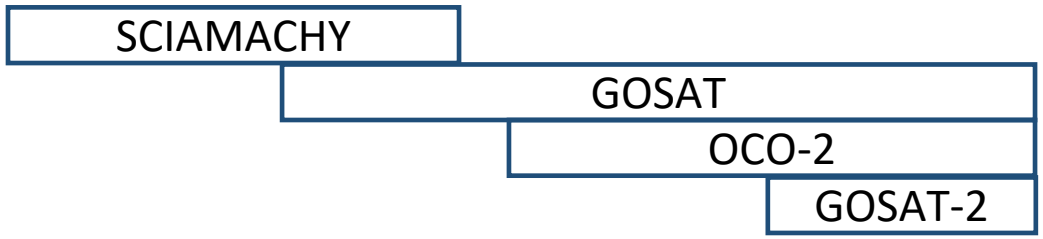
Deutscher Wetterdienst
Wetter und Klima aus einer Hand
DWD

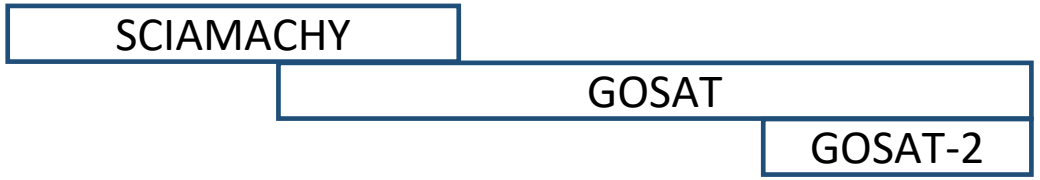
DLR

Satellite XCO2 and XCH4 retrievals …





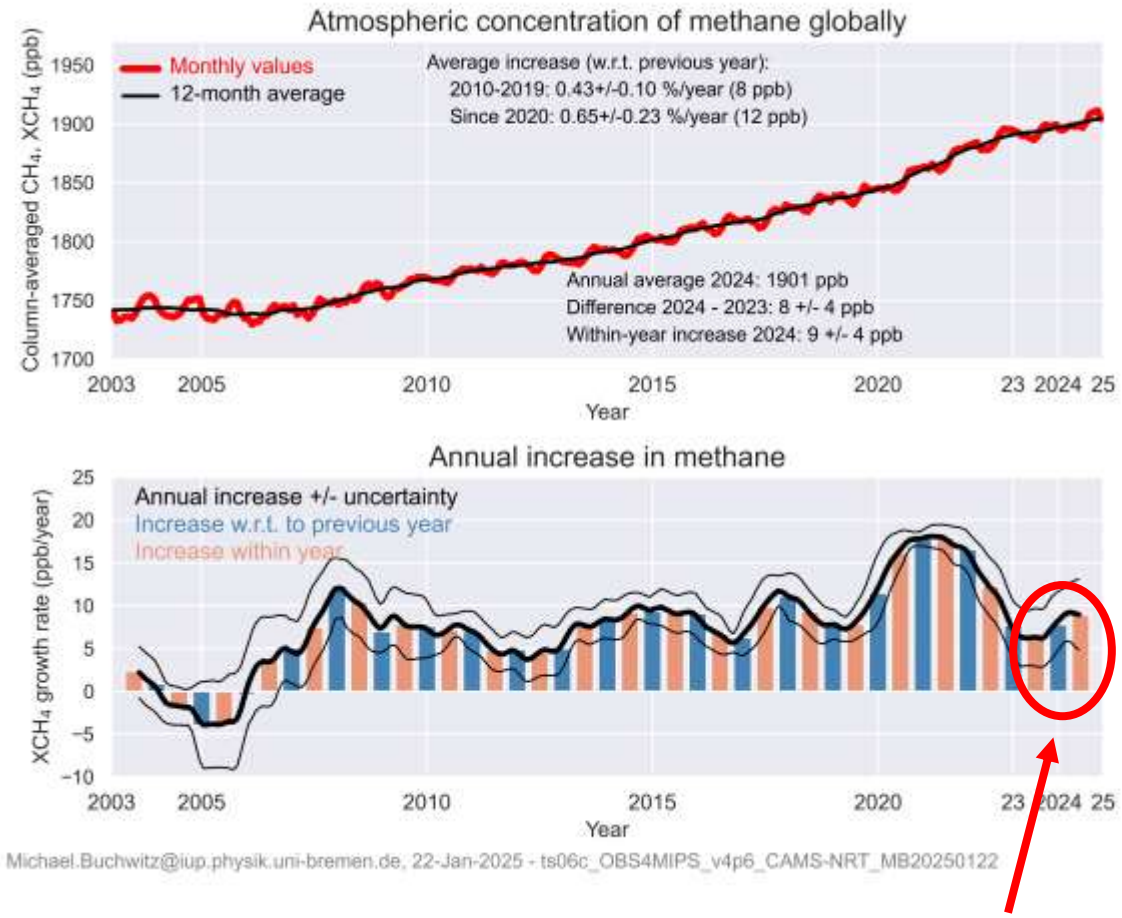


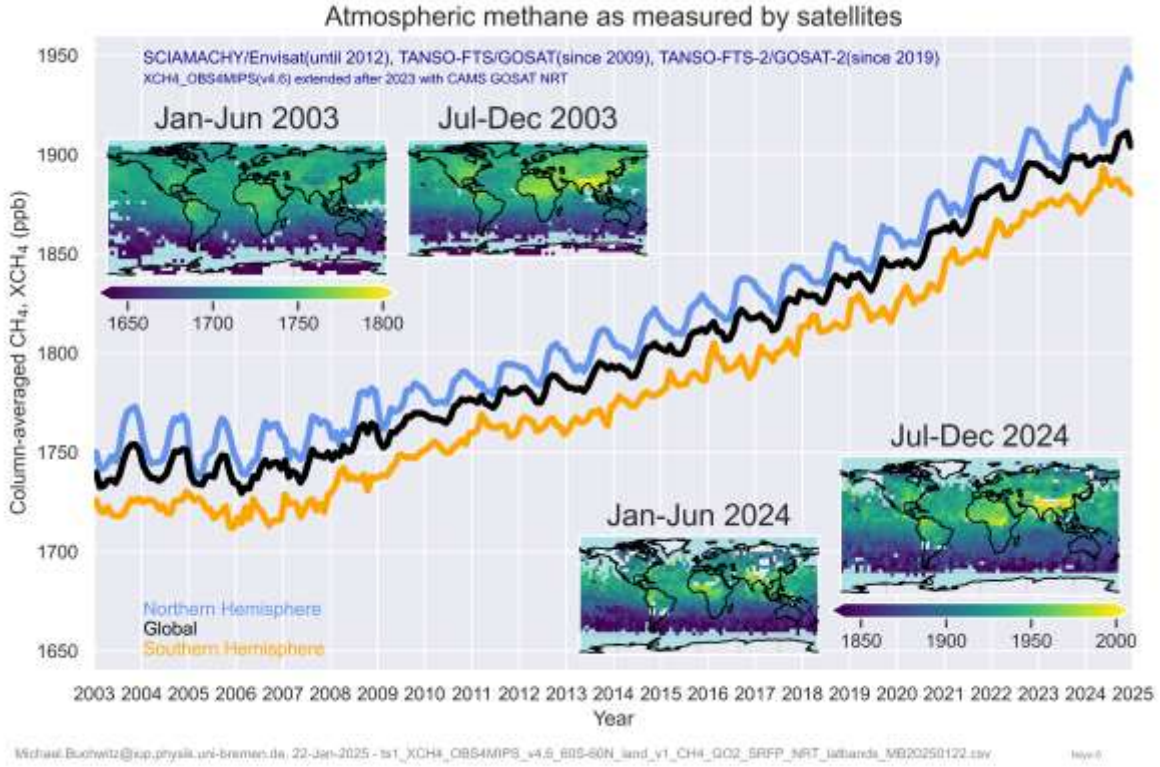


+ TROPOMI/S5P, PRISMA, EnMAP, EMIT, …
+ future S5, GOSAT-GW, CO2M, …

See also: https://climate.copernicus.eu/esotc/2024/trends-climate-indicators

Satellite XCH4 retrievals …





Methane growth rate in 2024 high (~ 8 ppb) but not record high

SCIAMACHY

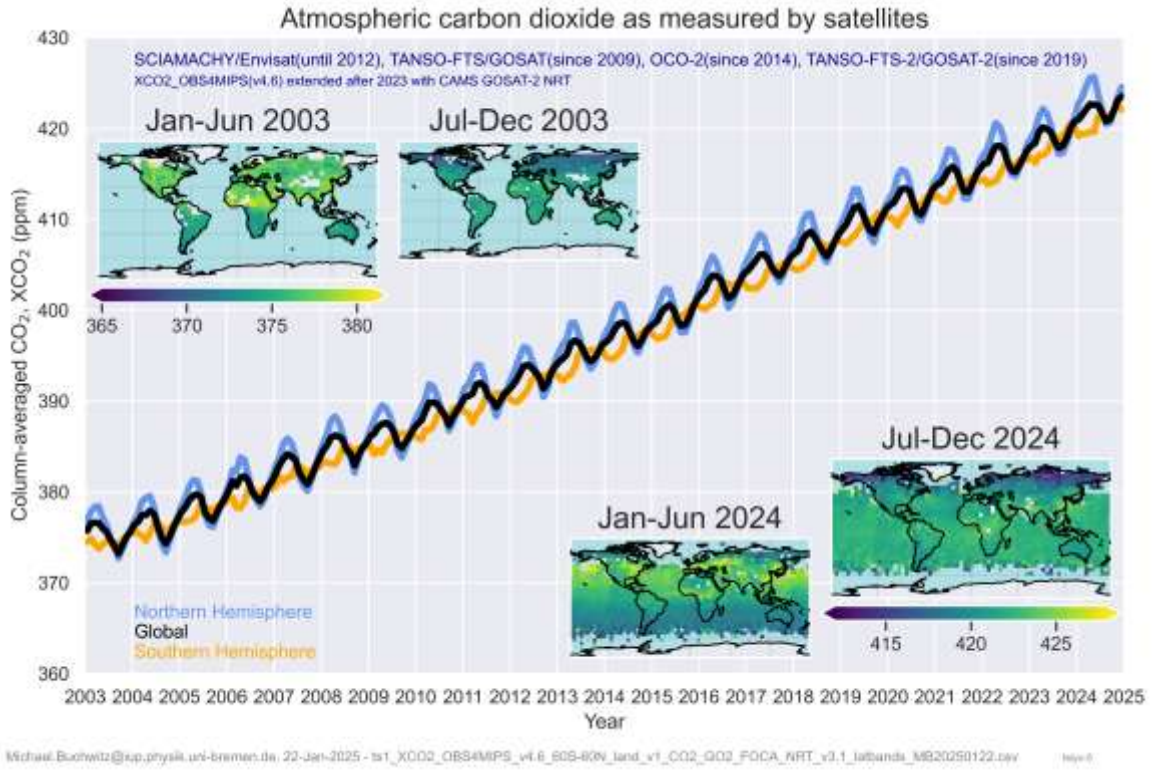
GOSAT

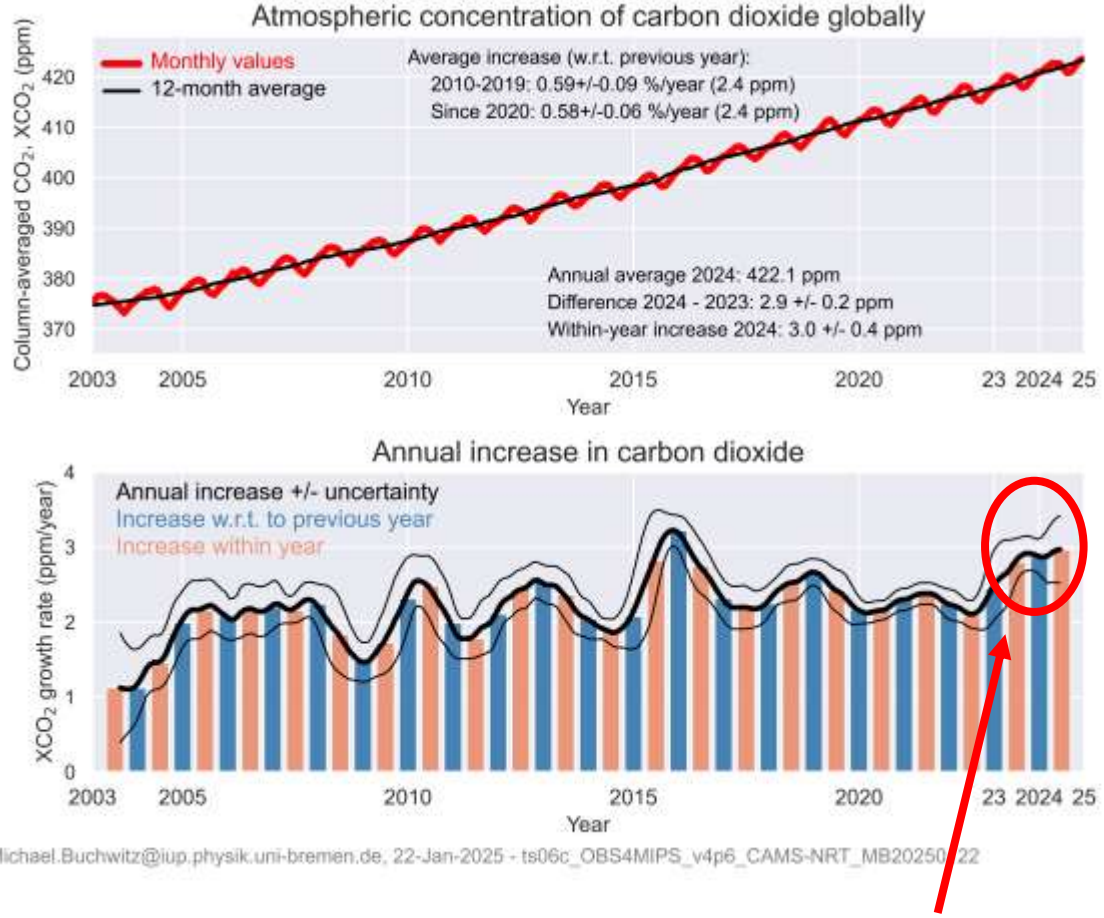
GOSAT-2

+ TROPOMI/S5P, PRISMA, EnMAP, EMIT, …
+ future S5, GOSAT-GW, CO2M, …

See also: https://climate.copernicus.eu/esotc/2024/trends-climate-indicators

Satellite XCO2 retrievals …





- SCIAMACHY
- GOSAT
- OCO-2
- GOSAT-2

XCO2 growth rate very high in 2024: ~ 3 ppm !

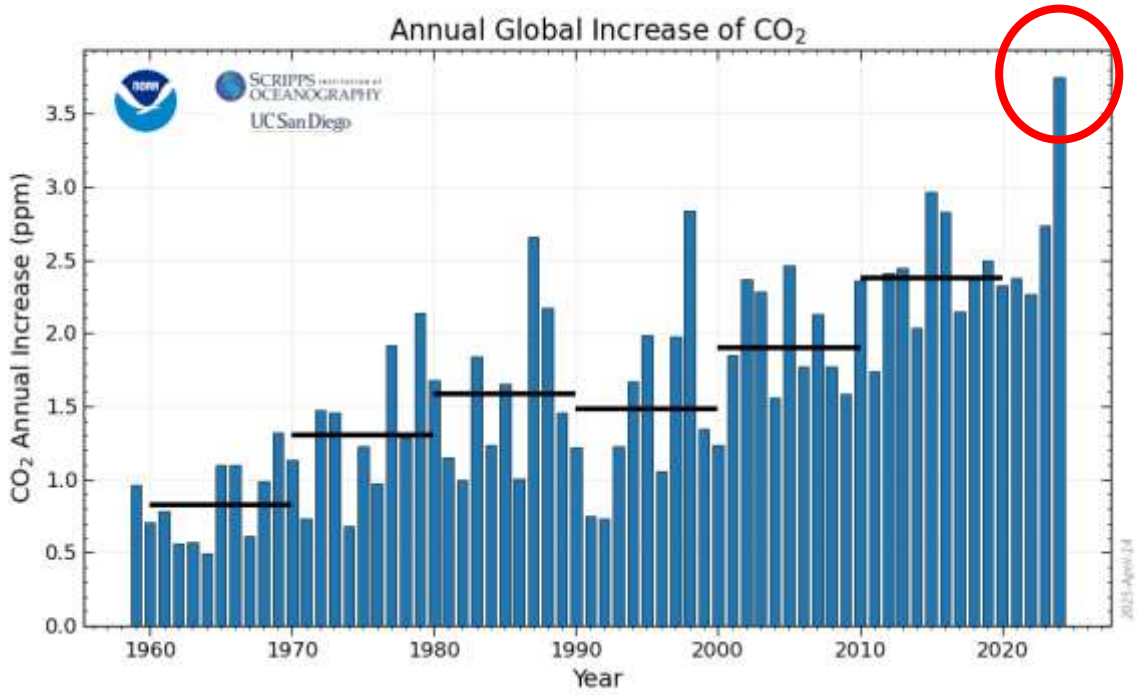
See also: https://climate.copernicus.eu/esotc/2024/trends-climate-indicators

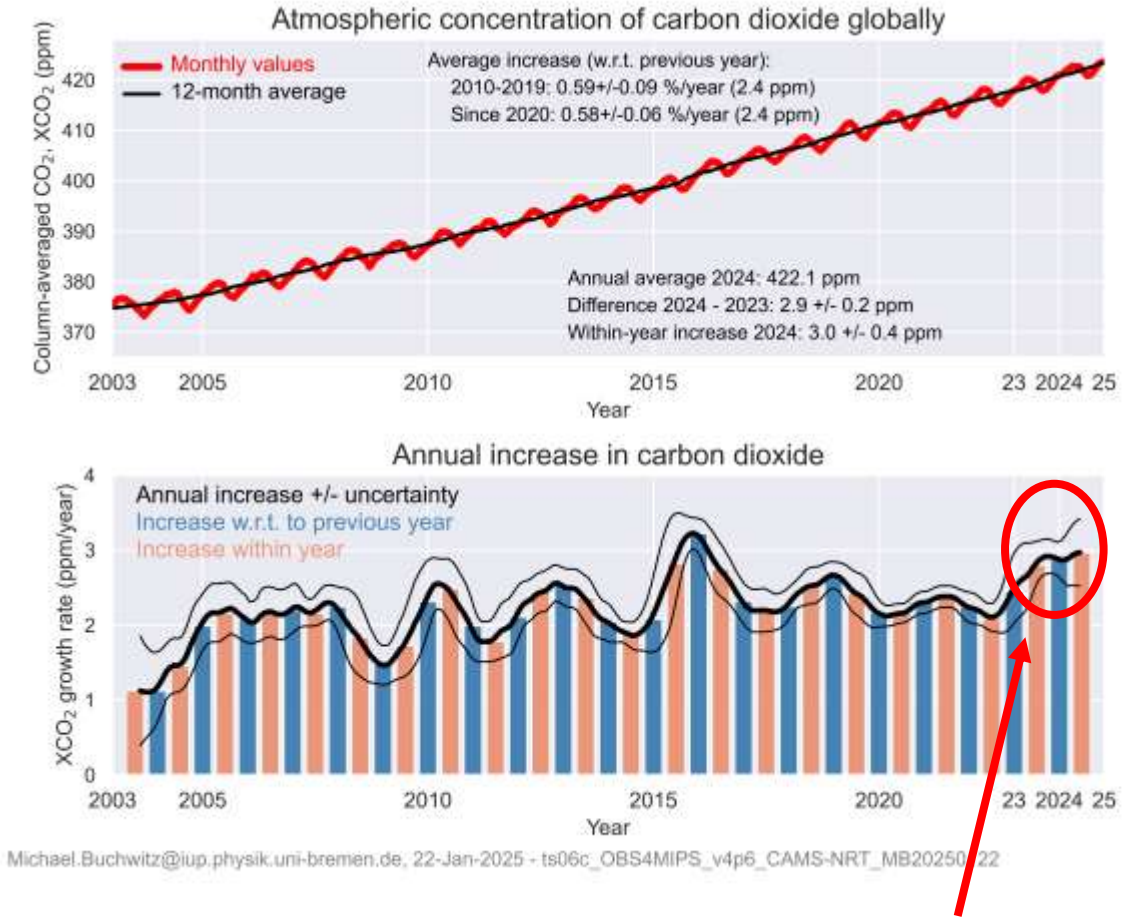
XCO2 and surface CO2 growth rates …

CO2 surface data:

3.75 ppm (global)

3.33 ppm (Mauna Loa)

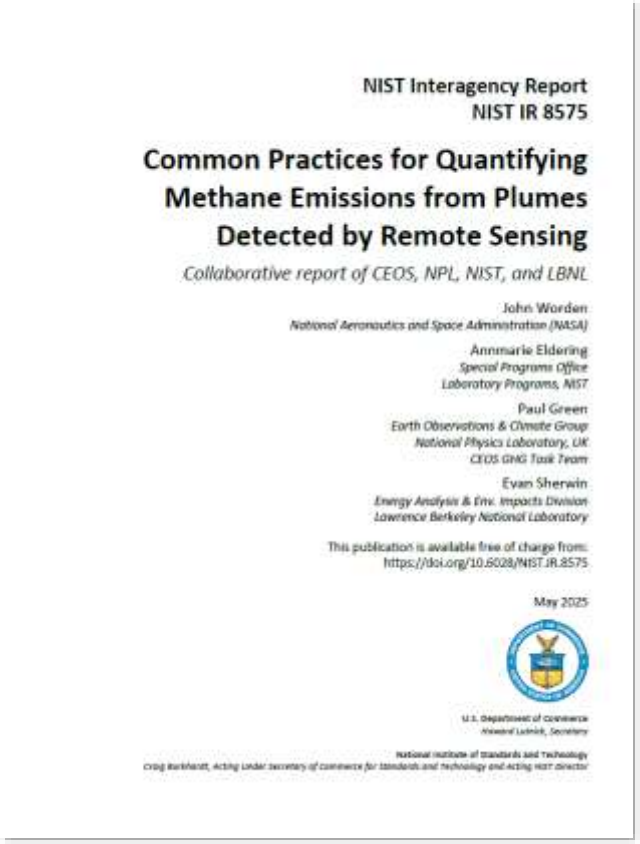




XCO2 growth rate very high in 2024: ~ 3 ppm !

See also: https://climate.copernicus.eu/esotc/2024/trends-climate-indicators

Emission estim. algos for localized sources


NIST Interagency Report
NIST IR 8575

Common Practices for Quantifying Methane Emissions from Plumes Detected by Remote Sensing

Collaborative report of CEOS, NPL, NIST, and LBNL

John Worden
National Aeronautics and Space Administration (NASA)

Annmarie Eldering
Special Programs Office
Laboratory Programs, NIST

Paul Green
Earth Observations & Climate Group
National Physics Laboratory, UK
CEOS GHG Task Team

Evan Sherwin
Energy Analysis & Env. Impacts Division
Lawrence Berkeley National Laboratory

This publication is available free of charge from:
https://doi.org/10.6028/NIST.IR.8575

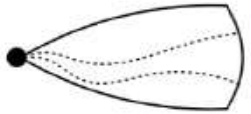
May 2025

U.S. Department of Commerce
Howard Lutnick, Secretary

National Institute of Standards and Technology
Craig Burkhardt, Acting Under Secretary of Commerce for Standards and Technology and Acting NIST Director

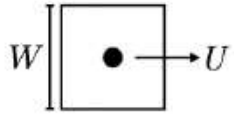
https://doi.org/10.6028/NIST.IR.8575

Gaussian Plume



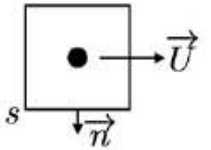
$$Q = U\Delta\Omega(x,y)\left(\sqrt{2\pi}\sigma_y(x)e^{\frac{y^2}{2\sigma_y(x)^2}}\right)$$

Local mass balance



$$Q = UW\Delta\Omega$$

Gauss's theorem

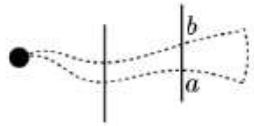


$$Q = \oint_s \Omega(s)\vec{U}\cdot\vec{n}\,ds$$

Integrated mass enhancement (IME)

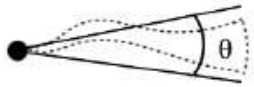
$$Q = U_{\text{eff}}\,\text{IME}/L$$

Cross-sectional flux (CSF)



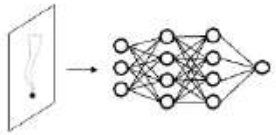
$$Q = U\int_a^b \Delta\Omega(x,y)dy$$

Angular width



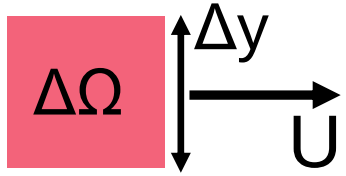
$$Q = f(\text{IME},\theta)$$

Computer vision



$$Q = \text{NN}(\text{Plume image})$$

Integration of column enhancements times wind speed along transects perpendicular to wind / plume direction



$Q[t/h] = \Delta\Omega[t/km^2] * \Delta y[km] * U[km/h]$

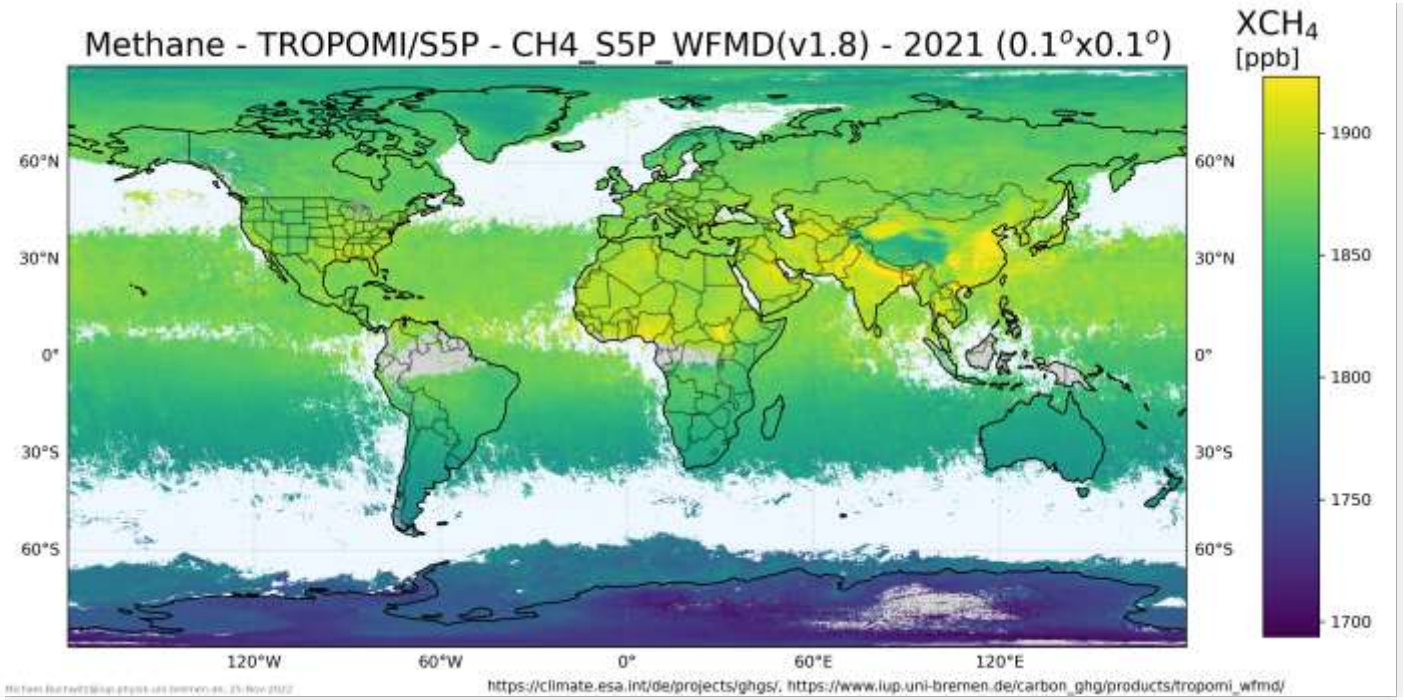
Emission ~ Column enhancement * Wind speed

TROPOMI/S5P XCH_4 & methane emissions

Schneising et al., AMT, 2023

Advances in retrieving XCH_4 and XCO from Sentinel-5 Precursor: improvements in the scientific TROPOMI/WFMD algorithm

Oliver Schneising, Michael Buchwitz, Jonas Hachmeister, Steffen Vanselow, Maximilian Reuter, Matthias Buschmann, Heinrich Bovensmann, and John P. Burrows



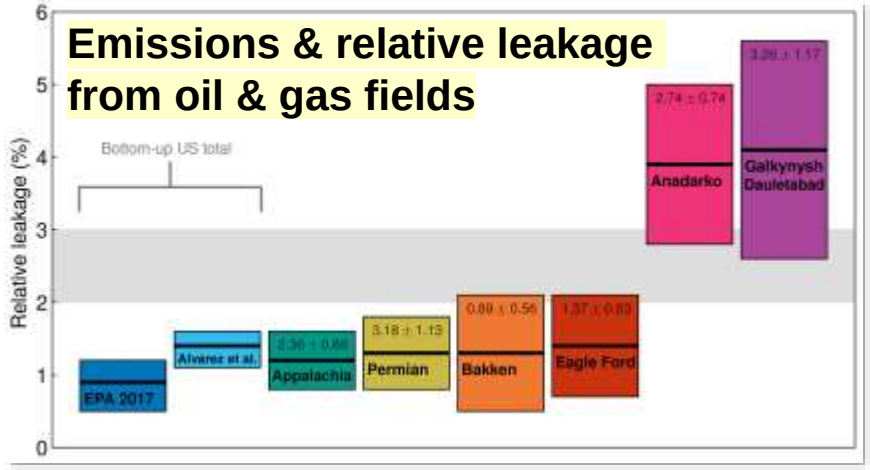
Schneising et al., ACP, 2020

Remote sensing of methane leakage from natural gas and petroleum systems revisited

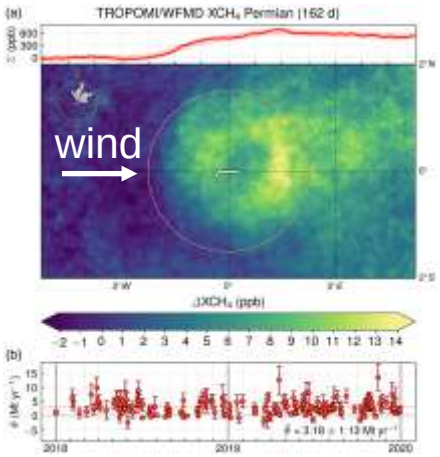
Oliver Schneising, Michael Buchwitz, Maximilian Reuter, Steffen Vanselow, Heinrich Bovensmann, and John P. Burrows

Institute of Environmental Physics (IUP), University of Bremen FB1, Bremen, Germany

Emissions & relative leakage from oil & gas fields



Emission estimates via Cross-Sectional-Flux (CSF) method for 2018-2019

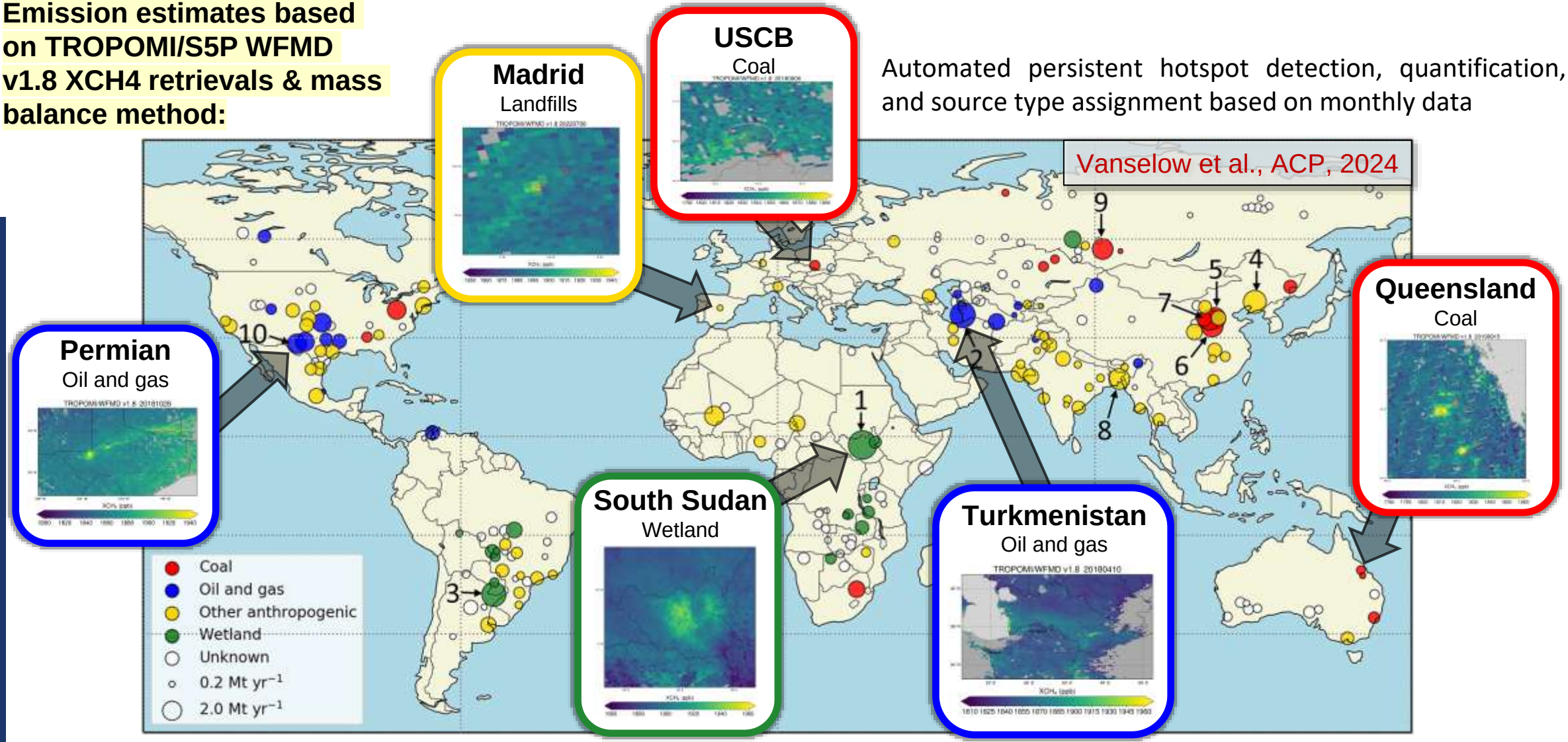


Available from:
https://www.iup.uni-bremen.de/carbon_ghg/products/tropomi_wfmd/
https://climate.esa.int/en/projects/ghgs/
https://catalogue.ceda.ac.uk/

Potential persistent emission hotspots

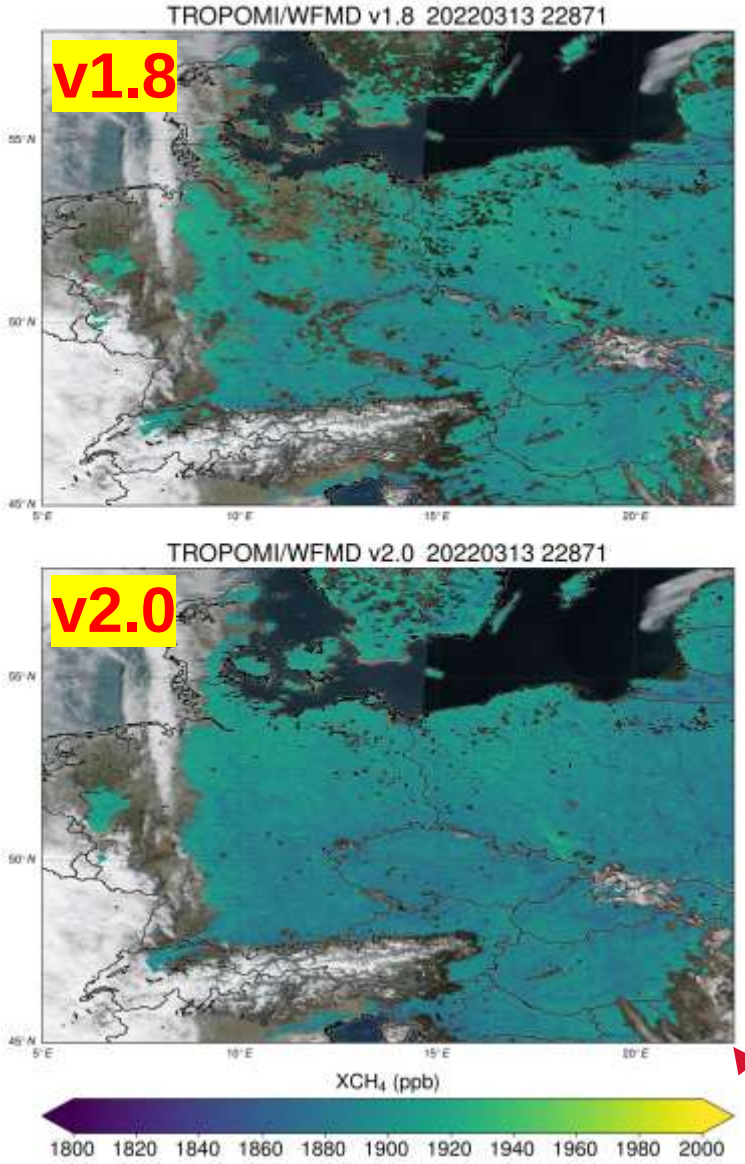
Emission estimates based on TROPOMI/S5P WFMD v1.8 XCH4 retrievals & mass balance method:

Automated persistent hotspot detection, quantification, and source type assignment based on monthly data

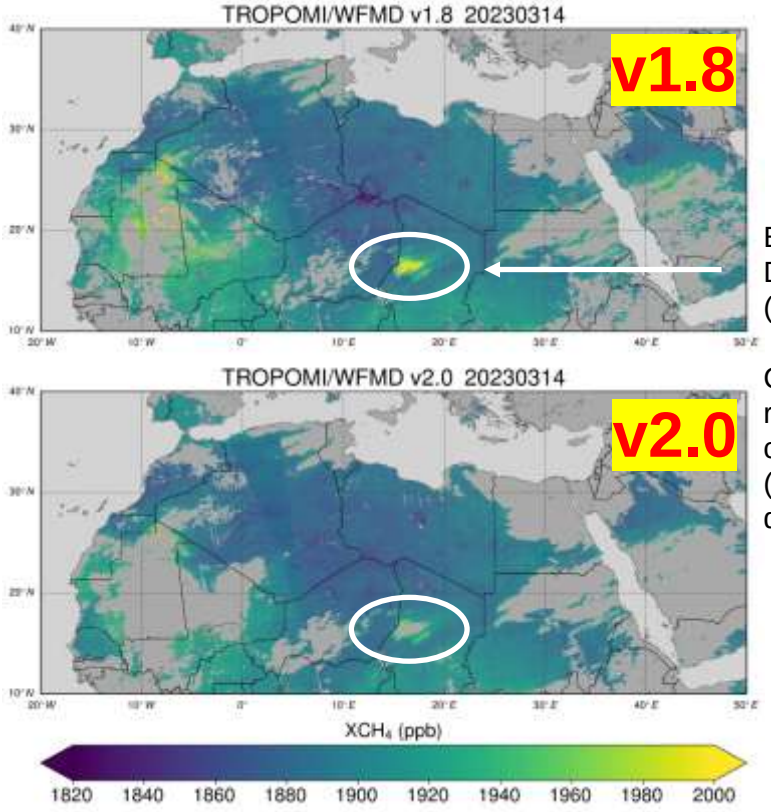


217 Potential Persistent Source Regions (PPSRs) detected (2018 - 2021)

TROPOMI/S5P XCH_4 WFMD v2.0



New v2.0



Bodélé Depression (Chad)

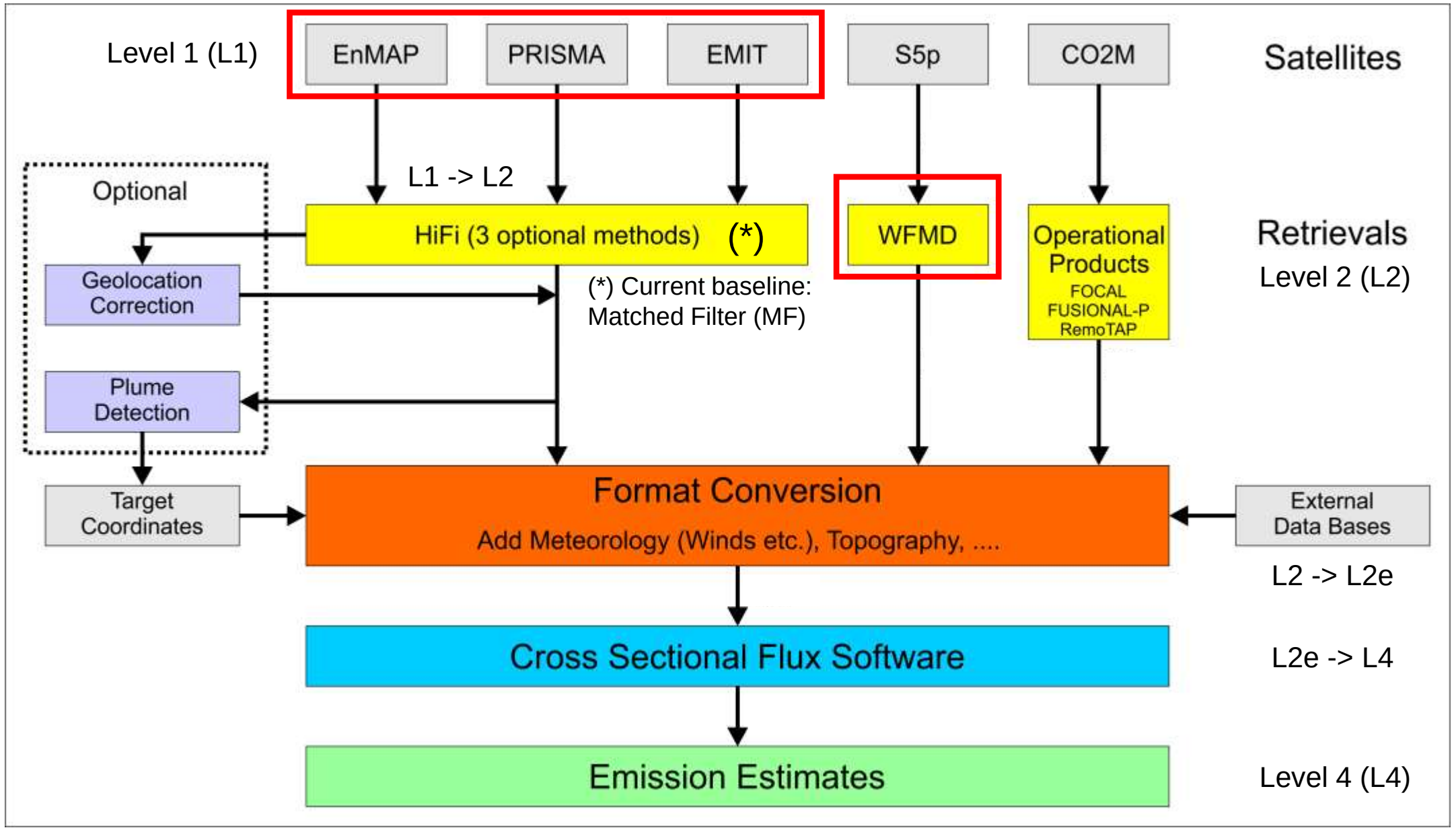
Challenging retrieval conditions (surface + dust storms)

TROPOMI/WFMD v2.0

- Better resource efficiency due to reduced memory consumption of machine learning quality filter
- Improved accuracy and precision according to validation with TCCON
- More rigorous filtering of specific aerosol events over bright surfaces
- Otherwise, higher data yield, especially for mid and high latitudes

Available from: https://www.iup.uni-bremen.de/carbon_ghg/products/tropomi_wfmd/

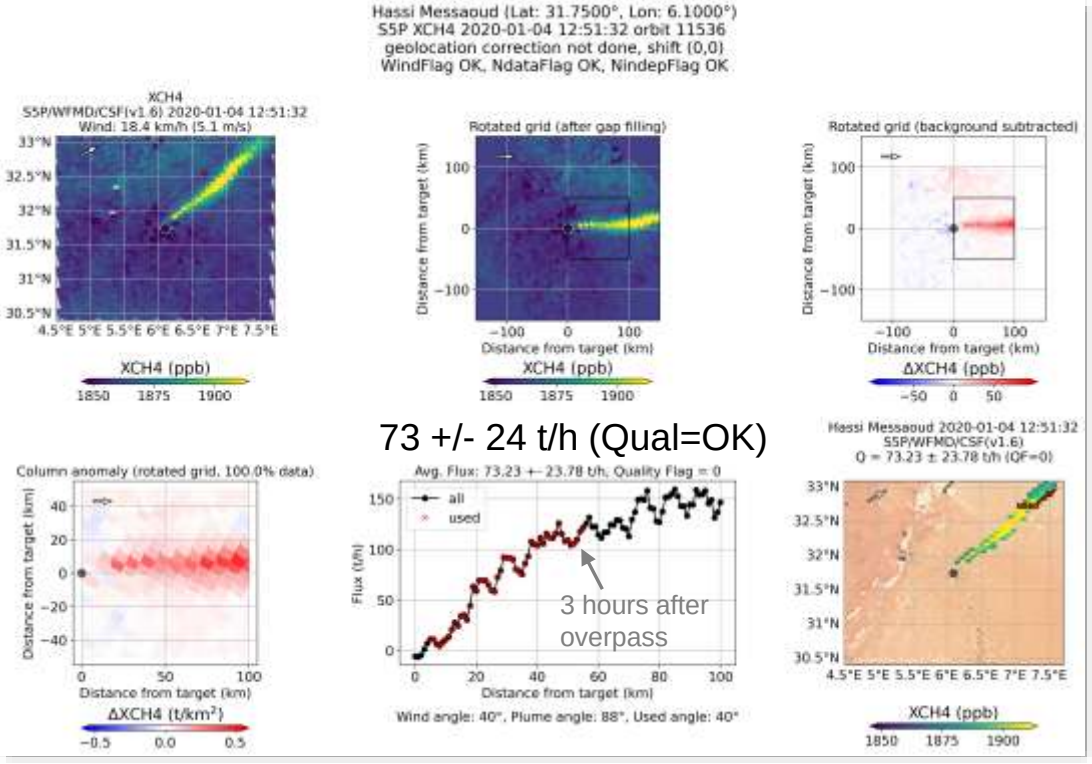
Emissions: Cross-Sectional-Flux (CSF) algo



Methane emission estimates: CSF method

TROPOMI/S5P (CSF v1.6)

Input: Level 2: XCH4 WFMD v1.8



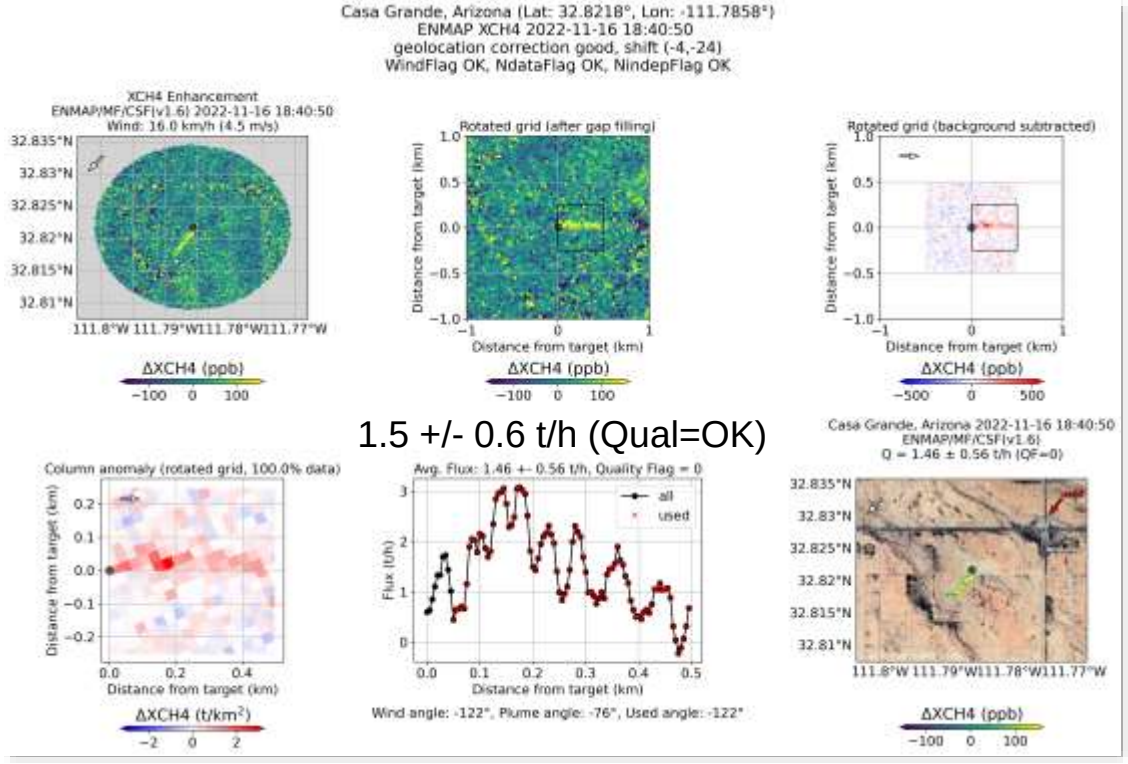
73 +/- 24 t/h (Qual=OK)

Box size (default): 100 x 100 km^2
Wind: PBL average (ERA5)

Uncertainty (1-sigma): Several terms added quadratically:
(i) Stddev of emissions per cross-section,
(ii) wind (variability + 0.5 m/s), (iii) other (20%)

EnMAP (HiFi-MF & CSF v1.6)

Input: Level 1



1.5 +/- 0.6 t/h (Qual=OK)

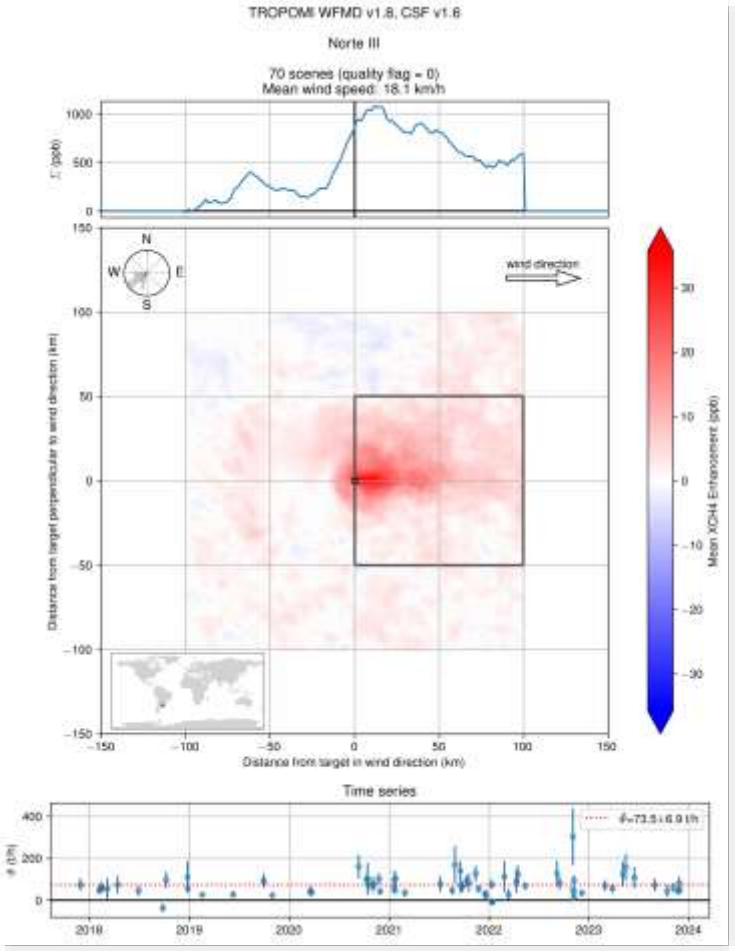
Box size (default): 0.5 x 0.5 km^2
Wind: 10 m (ERA5)

Released: 1.1 t/h (Sherwin et al., 2022)

Quality flag: Qual=OK (QF=0) means:
- Enough data in box (e.g., > 90% of area covered)
- Wind not too low (wind speed > 1 m/s)

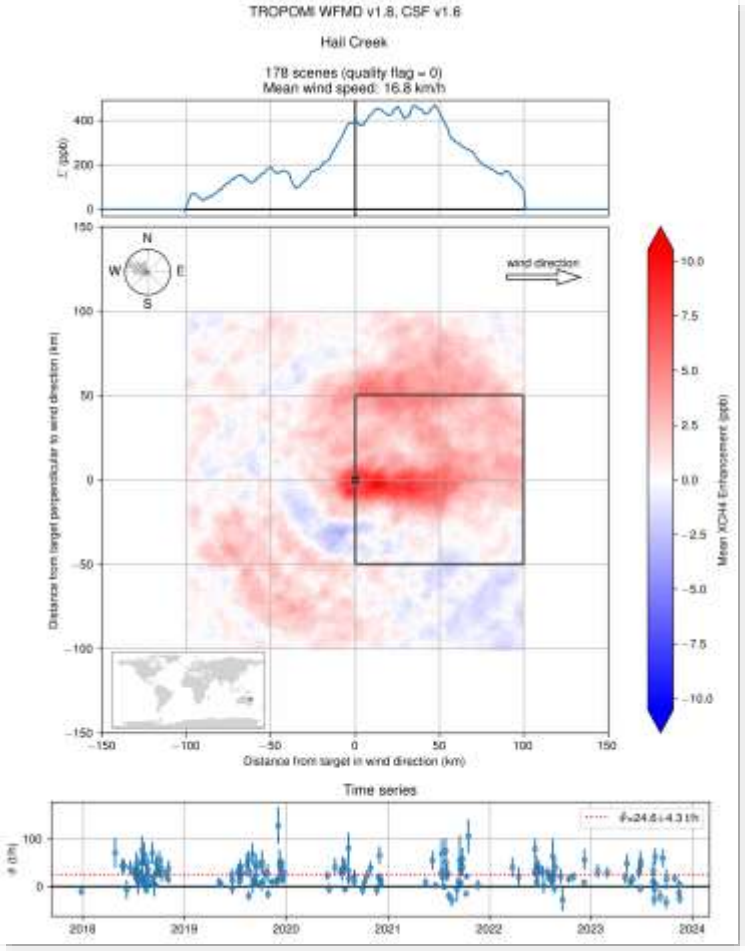
Methane: S5P/WFMD: ΔXCH4 rotat. & avg.

Norte III landfill
Buenos Aires, Argentina



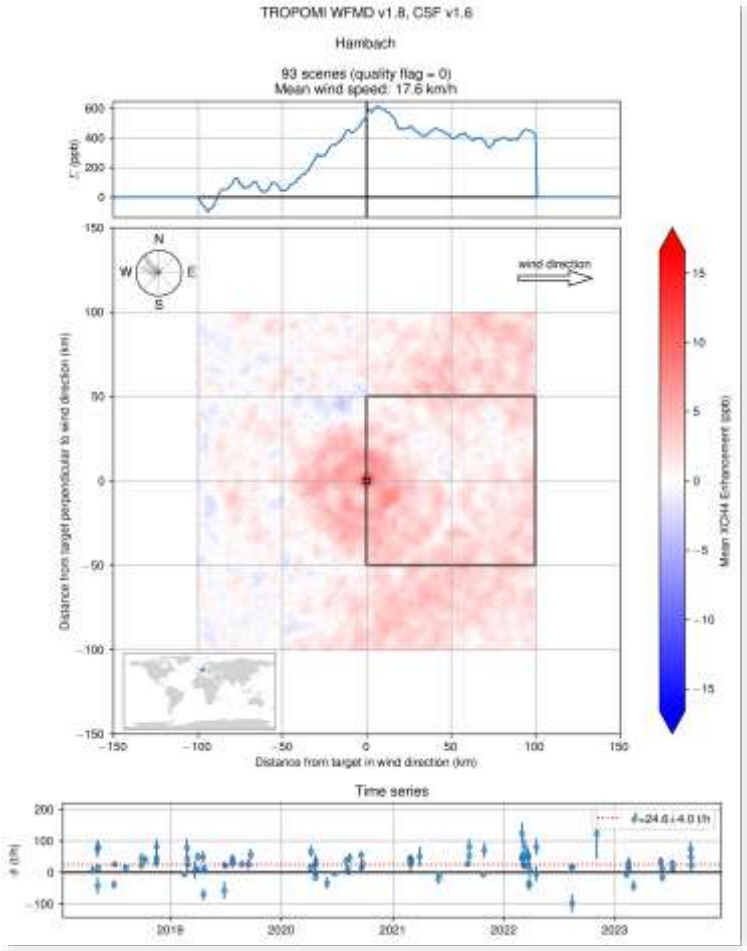
Clear average plume
indicating strong isolated source

Open coal mine
around Hail Creek, Australia



Average plume but also strong
near-by sources

Open coal mine
around Hambach, Germany



No average plume but local
enhancement (challenging conditions)

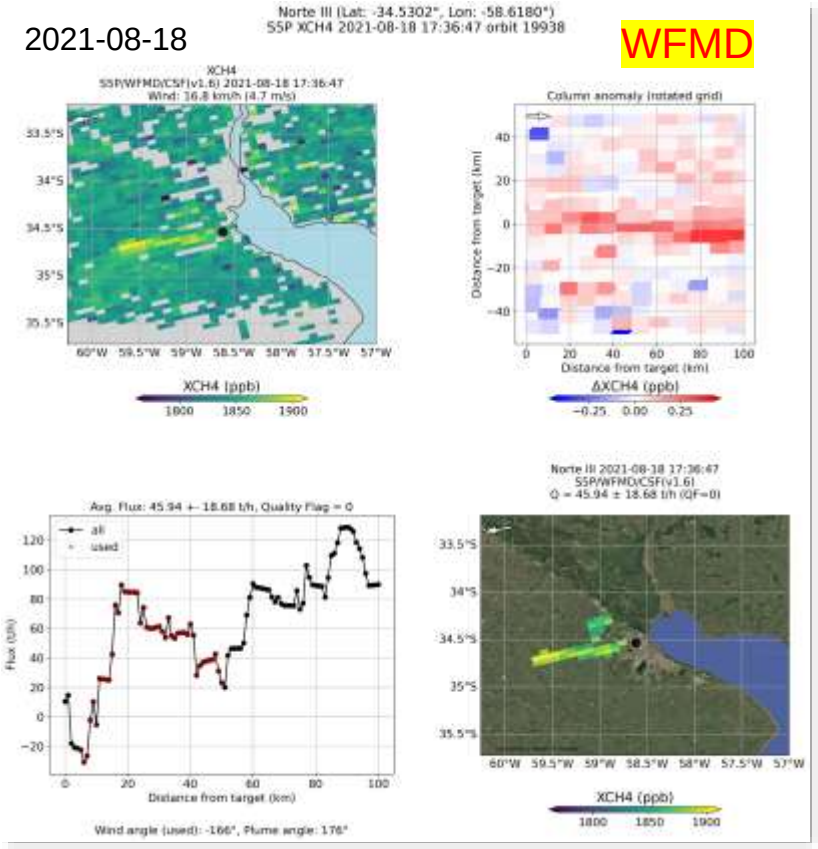
(->talk Julia Marshall)

Methane: S5P/WFMD&OPER/CSF: Norte III

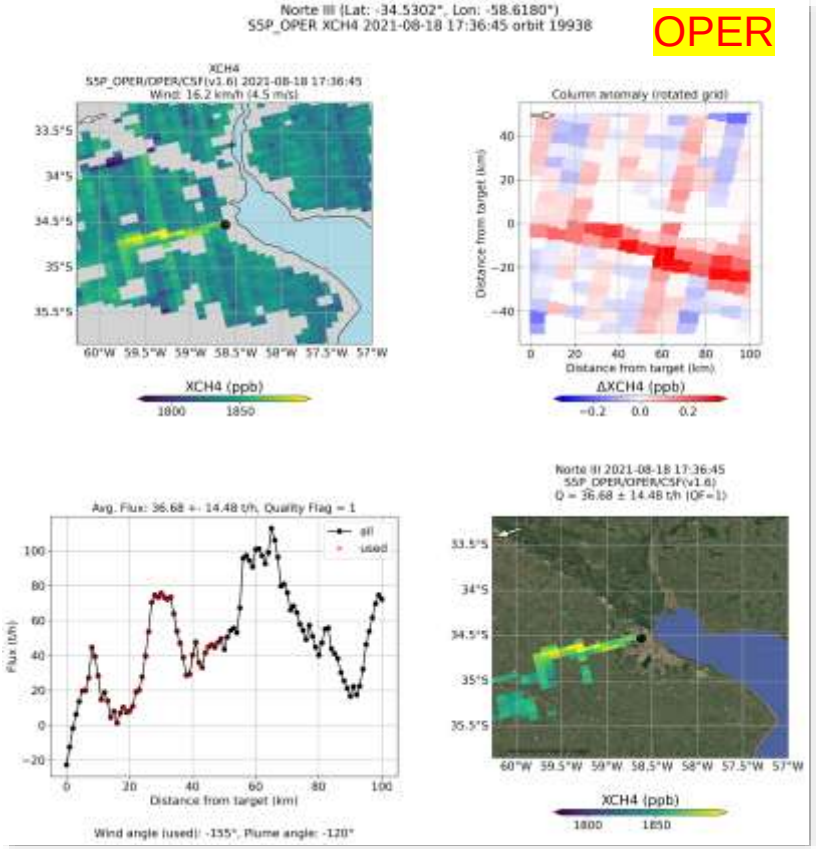
IUP-UB CSF (v1.6) algorithm applied to 2 different XCH4 data products:

- Scientific WFMD v1.8
- OPERational v02

2021-08-18



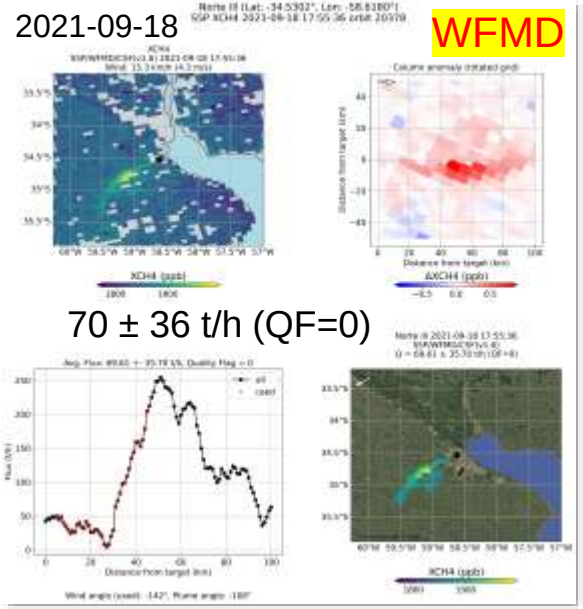
46 ± 19 t/h (QF=0)



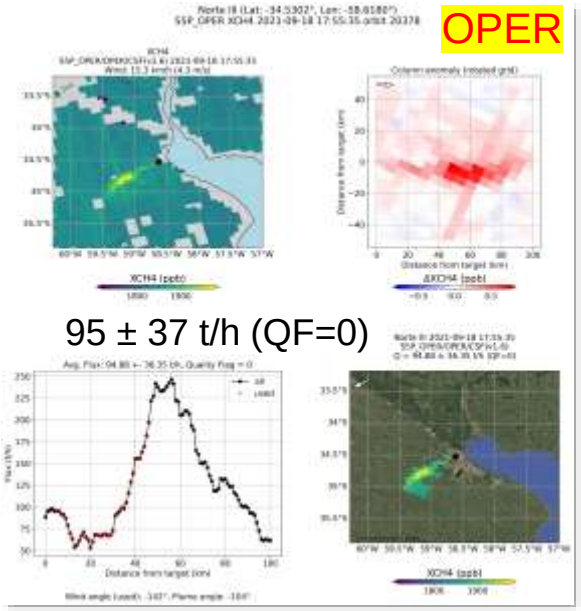
37 ± 15 t/h (QF=1)

OPER product used as is, i.e.,
without correction for striping, etc.

2021-09-18

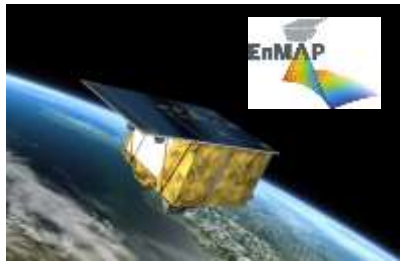


70 ± 36 t/h (QF=0)



95 ± 37 t/h (QF=0)

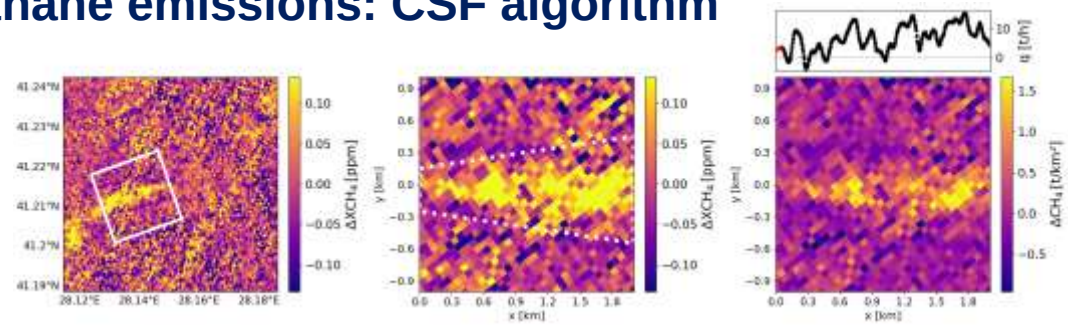
Hyperspectral Imager (HI) @ 30m/60m res.

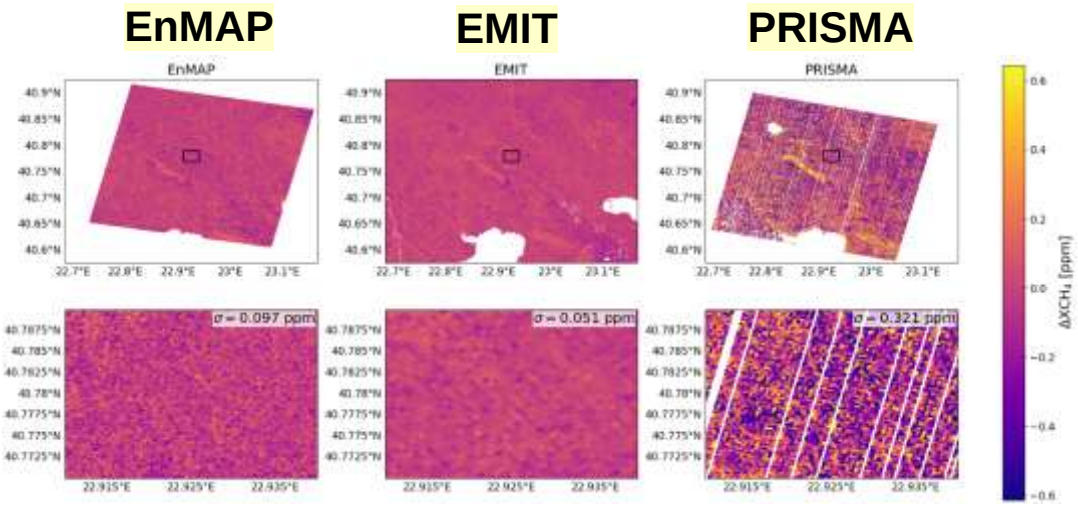


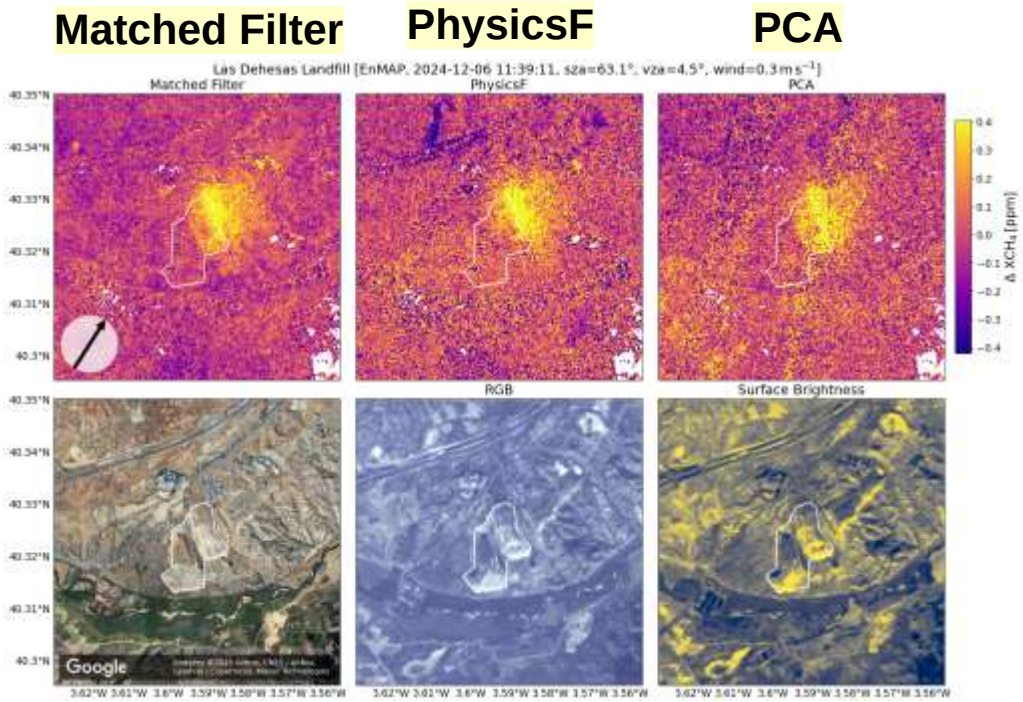
Methane enhancement retrievals:

- Three methods under development („HiFi“)
  - Differ primarily w.r.t. forward model F & measurement error covariance matrix Sε
  - **PhysicsF** (PF) (low order „DOAS polynomial“ e.g. for surface reflectivity, …)
  - Principal Components Analysis (**PCA**) (PCs instead of polynomial)
  - **Matched Filter** (MF) (e.g., no polynomial but Sε from image)

Methane emissions: CSF algorithm



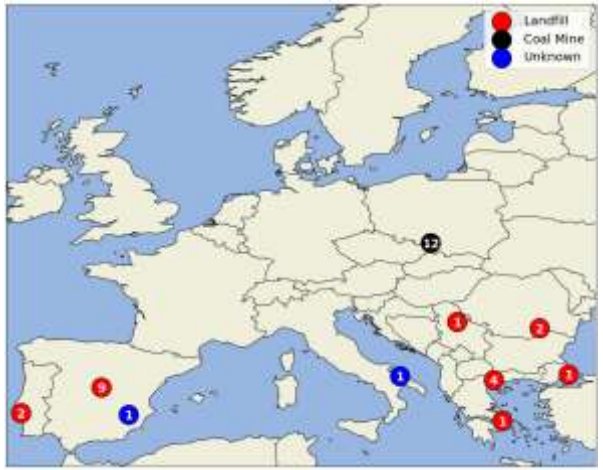


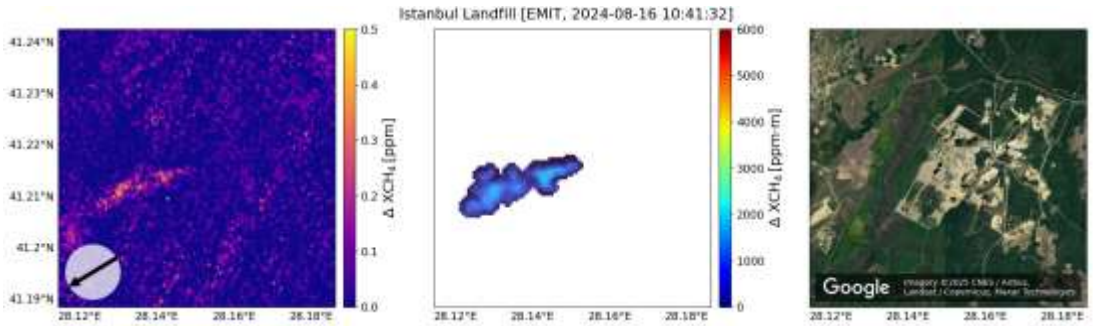


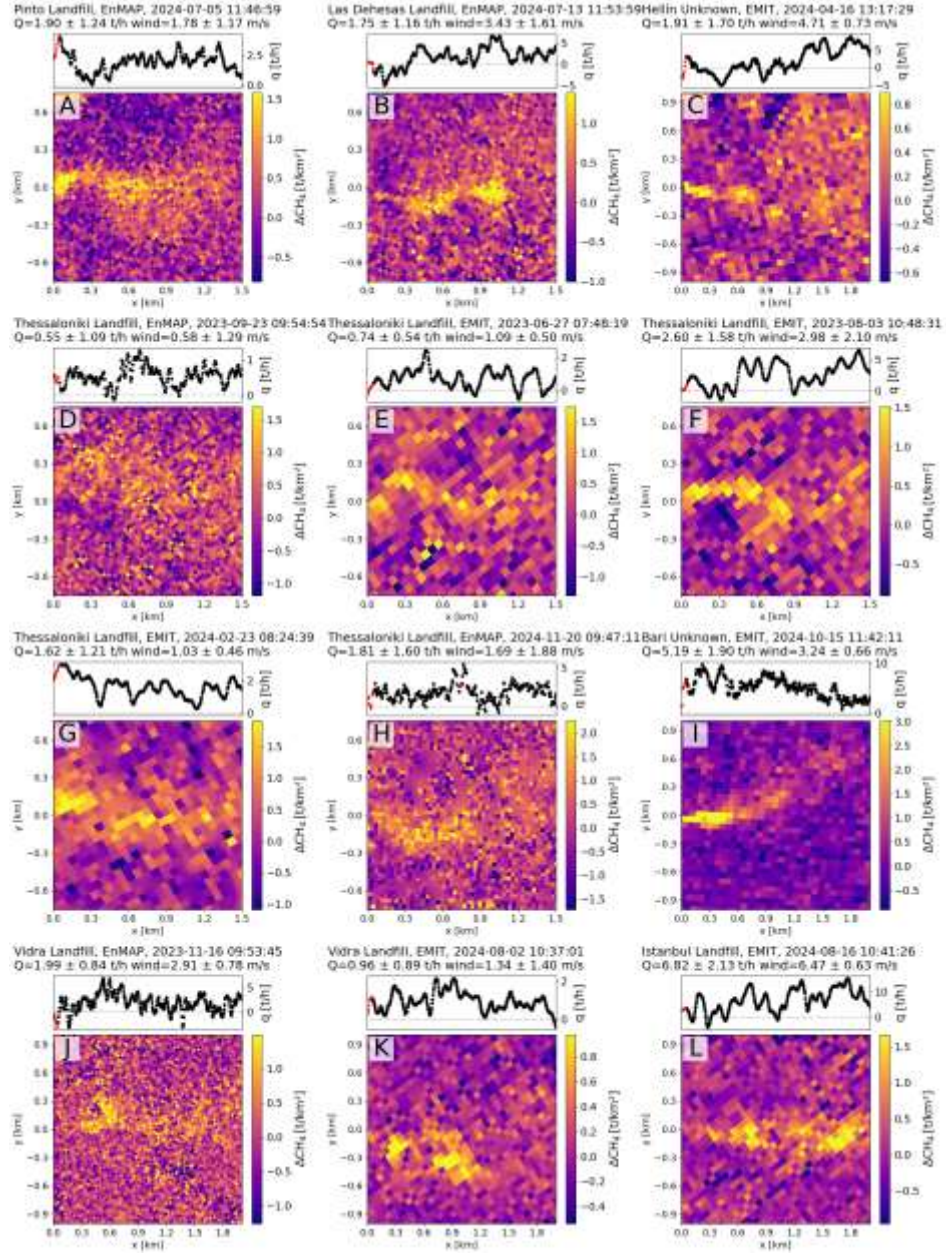
European localized emission sources

https://eyeclima.eu/

CSF method applied to EnMAP and EMIT



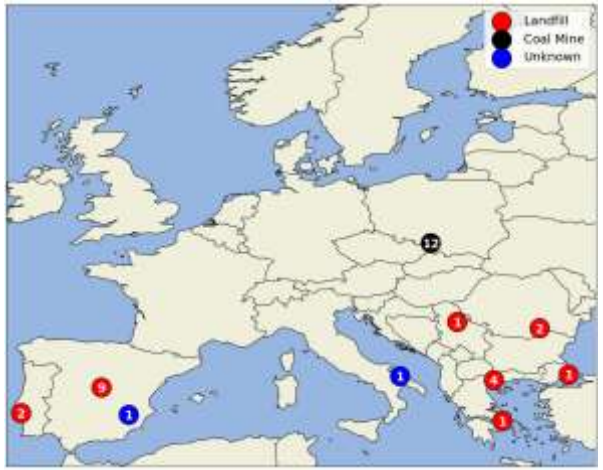


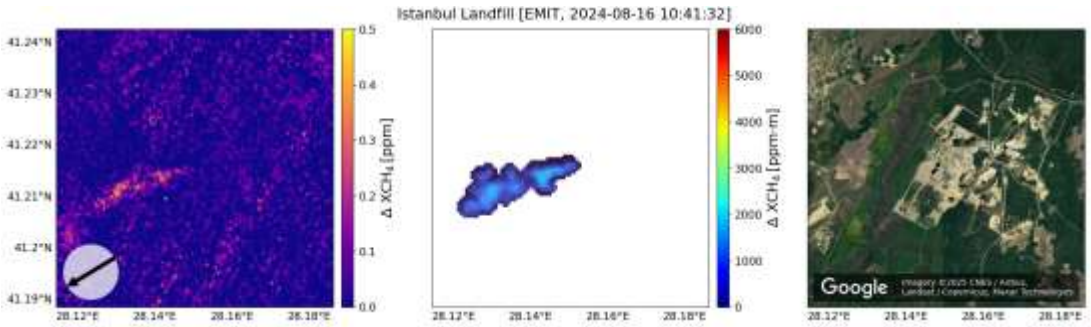


European localized emission sources

https://eyeclima.eu/

CSF method applied to EnMAP and EMIT





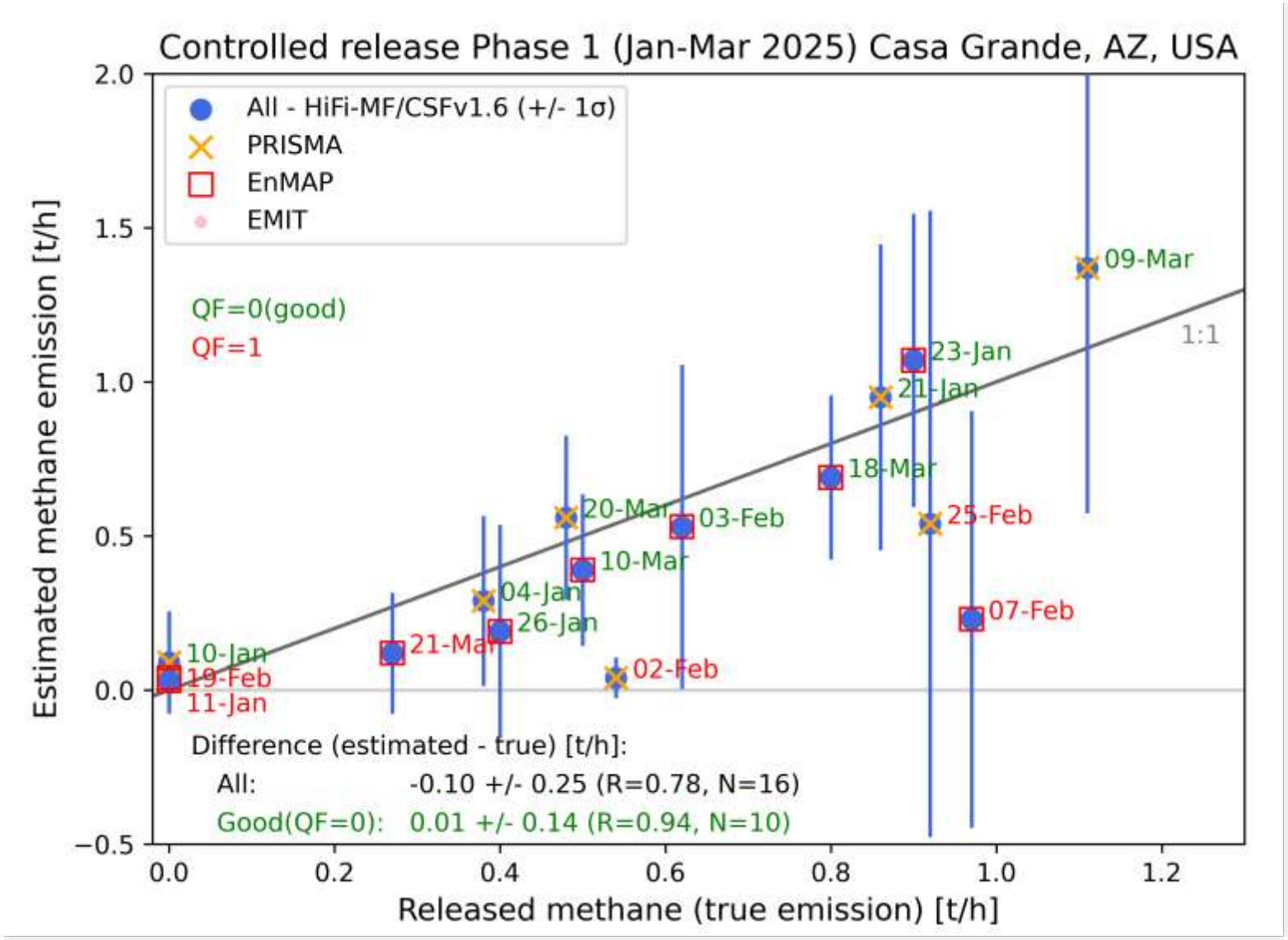
Comparisons of landfill emission estimates:

Location	Scene	Emission rate [t/h]				
		HiFi (Our study)	Carbon Mapper (EMIT) (§)	Carbon Mapper (Tanager)	GHGSat (2021 - 2022)	E-PRTR 2022
Pinto Landfill	EnMAP_20240705T114659	1.90±1.24 (0.44)	-	1.28±0.37	4.48±0.57	0.04
Las Dehesas Landfill	EnMAP_20240713T115359	1.75±1.16 (0.94)	-	1.77±0.74	2.98±0.42	0.17
Hellín Unknown	EMIT_20240416T131729	1.91±1.70 (1.66)	2.09±0.15	-	-	-
Thessaloniki Landfill	EnMAP_20230923T095454	0.55±1.09 (0.13)	-	1.83±0.56	2.91±0.99	0.68
	EMIT_20230627T074819	0.74±0.54 (0.20)	-			
	EMIT_20230803T104831	2.60±1.58 (0.82)	2.31±0.61			
	EMIT_20240223T082439	1.62±1.21 (0.38)	1.62±0.32			
	EnMAP_20241120T094711	1.81±1.60 (0.43)	-			
Bari Unknown	EMIT_20241015T114211	5.19±1.90 (1.35)	4.93±0.42	-	-	-
Vidra Landfill	EnMAP_20231116T095345	1.99±0.84 (0.58)	-	-	2.15±0.58	0.05
	EMIT_20240802T103701	0.96±0.89 (0.23)	0.62±0.06			
Istanbul Landfill	EMIT_20240816T104126	6.82±2.13 (1.94)	3.57±0.49	-	7.21±0.99	-

(§) https://data.carbonmapper.org/

Same EMIT scene

Stanford-Michigan Controlled Releases



2024 – 2025 Methane Controlled Releases

Single-blind test:
- Satellite-derived emissions submitted in April 2025
- „True emission“ information provided in May 2025

Summary & conclusions

- TROPOMI/S5P WFMD XCH_4 data product:
  - WFMD v1.8 product (Schneising et al., 2023) used to identify emission hotspots (Vanselow et al., 2024)
  - Improved WFMD v2.0 XCH4 and XCO product available (https://www.iup.uni-bremen.de/carbon_ghg/products/tropomi_wfmd/)
- Methane emission estimates via S5P and Hyperspectral Imagers:
  - Cross-Sectional-Flux (CSF) algorithm
  - First results from S5P, PRISMA, EnMAP, EMIT
  - Emission estimates European localized sources (EYE-CLIMA)
  - Detailed comparisons within MEDUSA (ongoing)
  - Participation Stanford-Michigan Controlled Releases 2024/25