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Materials Science and Technology

From Atmospheric Observations to Validation of Greenhouse Gas Emission Inventories

Provide Actionable Data on Policy-Relevant Scales

Stephan Henne
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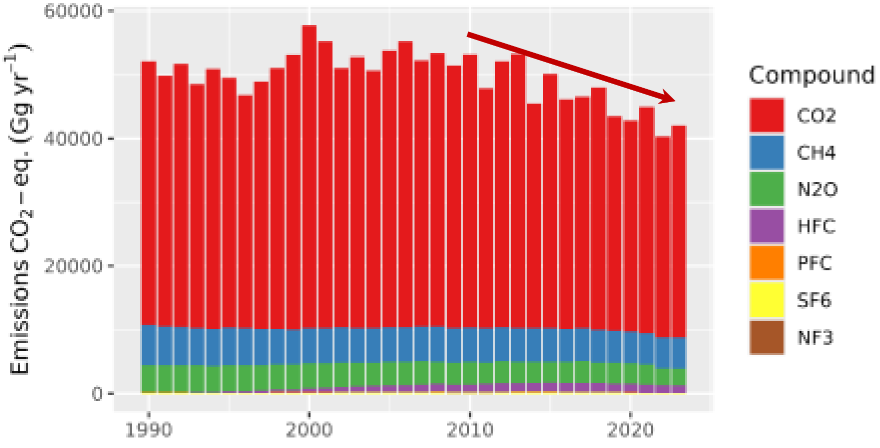
Empa, Swiss Federal Laboratories for Materials Science and Technology

The Bottom-Up Approach

- Annex I countries report their GHG emissions yearly to the United Nations Framework Convention on Climate Change (UNFCCC)
- Tracking compliance with national legislation and international reduction pledges

- Reports are mostly based on activity data and emission factors
- Evolving use of process models

- How robust are totals and reported trends?
- Are there missing sources/sinks?



Trend of total Swiss GHG emissions incl. LULUCF

LULUCF 2023: 1'299 CO_2-eq. (Gg)

Total reduction since 1990: 19.8 %

Source: Swiss CRT submission 2025

Image: NASA Goddard Space Flight Center

Observations and inverse modelling can provide independent, observation-based GHG flux estimates at different scales.

The atmosphere cannot be deceived!

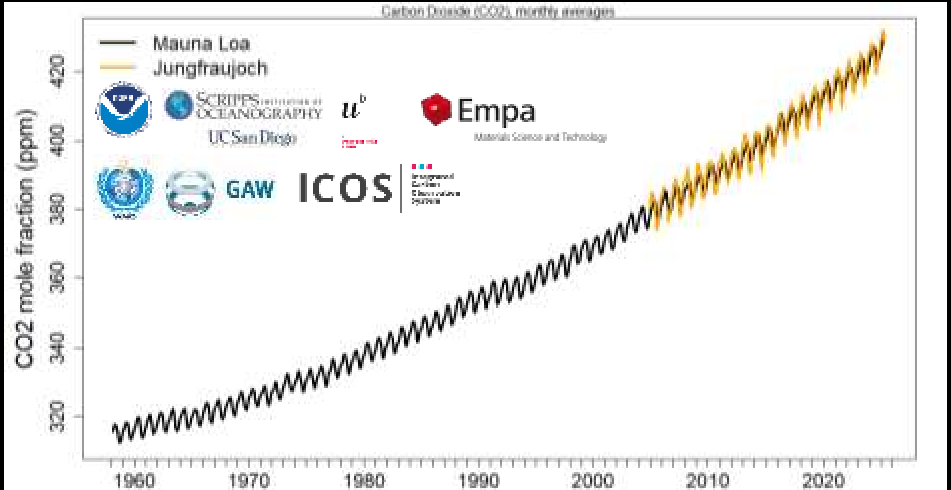


Image: Martin Steinbacher, GAW, Empa

Elements of Top-Down Inverse Modelling of GHG Fluxes on the Regional Scale

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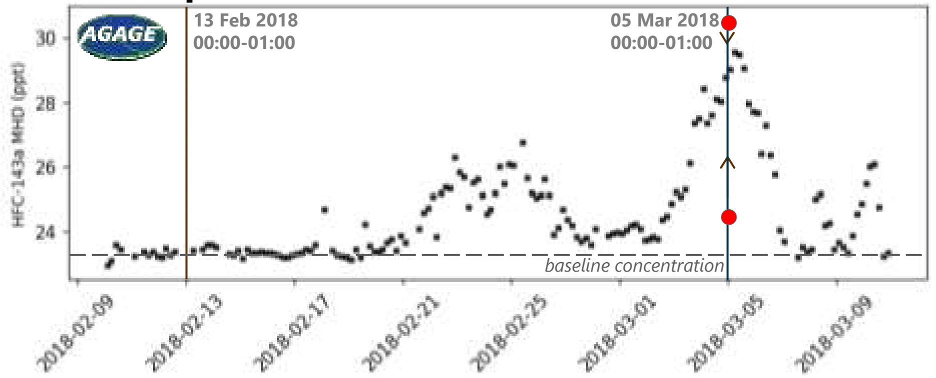
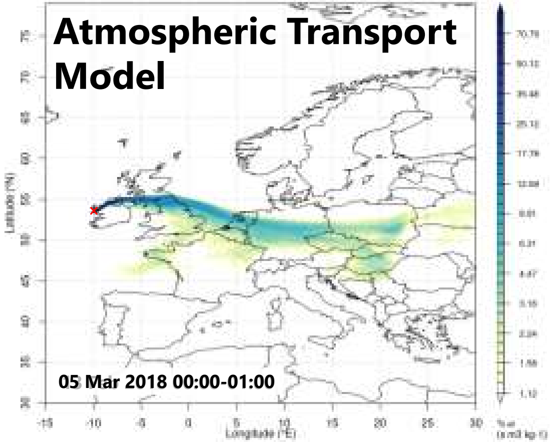
Atmospheric Observations

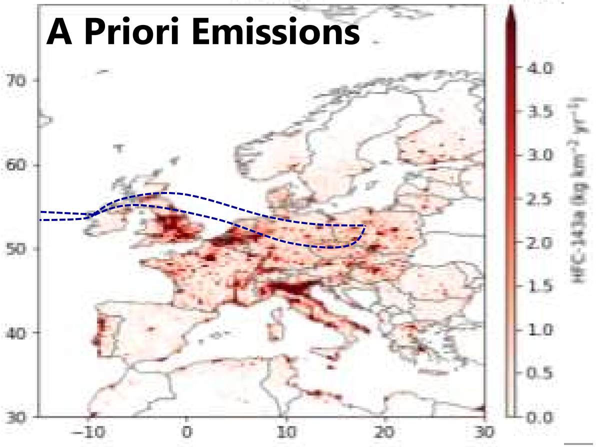




time-reversed Lagrangian particle dispersion model (LPDM): source sensitivity (concentration footprint)

Optimisation

Prior emissions are modified so that the modelled concentrations are in agreement with the measured values.



Bayesian Inverse Modelling

Bayes theorem

y: observation vector
x: state vector
Forward model

$$y = F(x) + \varepsilon_0$$

observation given x   *a priori*

$$P(x|y) = \frac{P(y|x)P(x)}{P(y)}$$

a posteriori

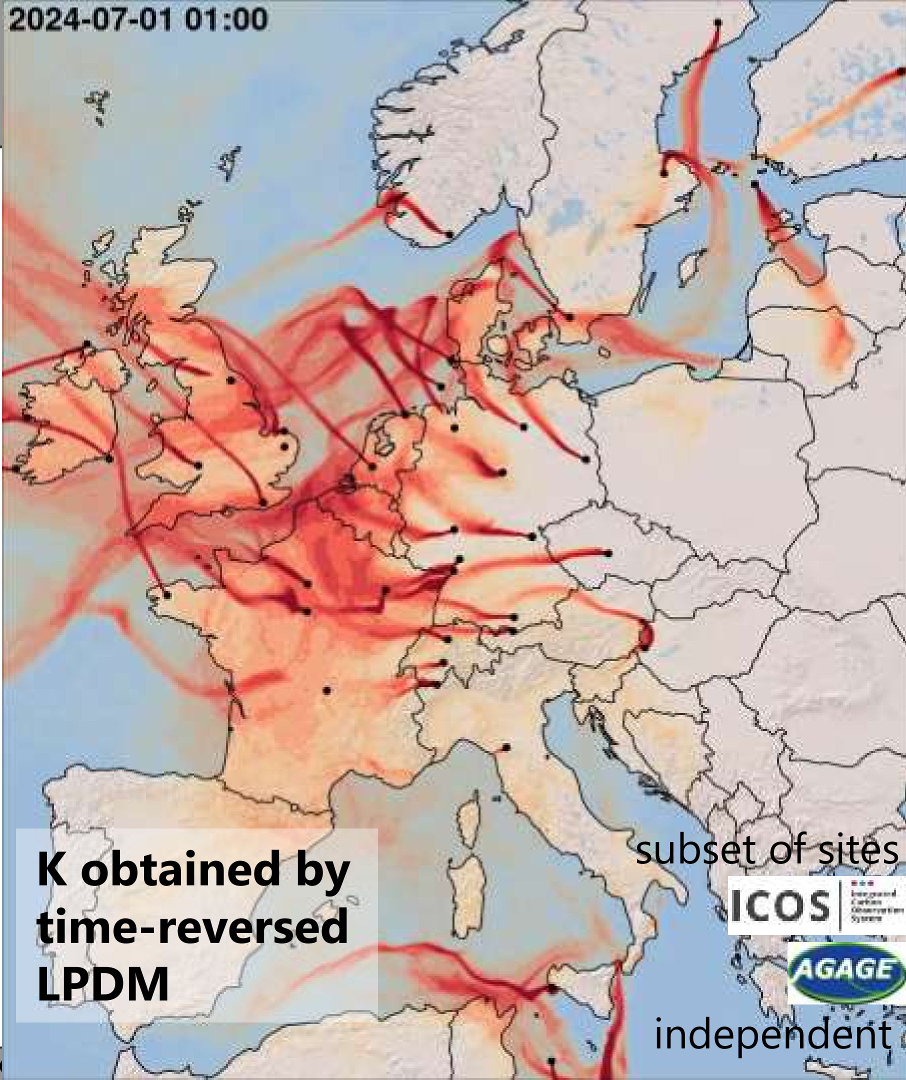
Maximum of $P(x|y)$ for Gaussian probability distributions at minimum of J

$$J(x) = \frac{1}{2}(x - x_b)^T \mathbf{B}^{-1}(x - x_b)$$ *a priori misfit*

$$+\frac{1}{2}\left(\chi_o - \mathrm{F}(x)\right)^T \mathbf{R}^{-1}\left(\chi_o - \mathrm{F}(x)\right)$$ *observation misfit*

Analytical minimisation of cost function with linear/linearised model

$$\mathbf{K} = \nabla_x \mathrm{F}(x) \rightarrow \mathrm{F}(x) = \mathbf{K}x$$



Promoting Observation-Based Validation

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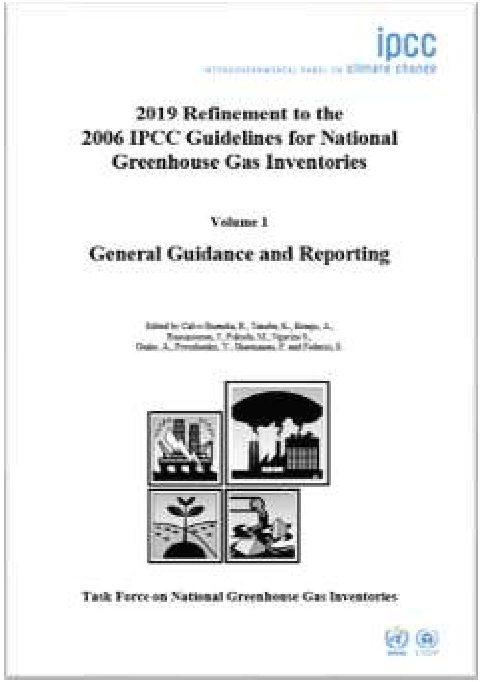
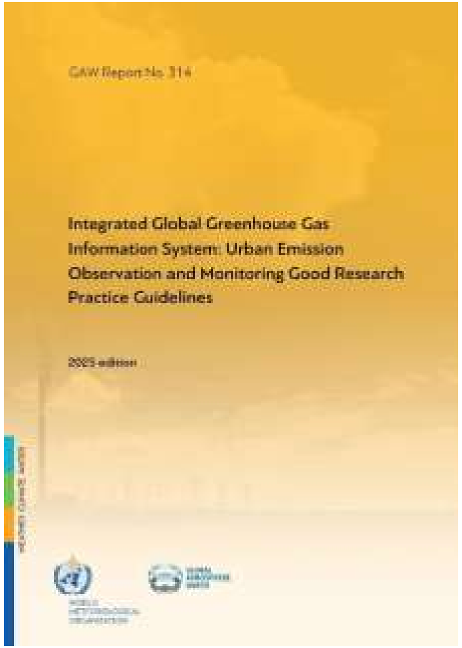
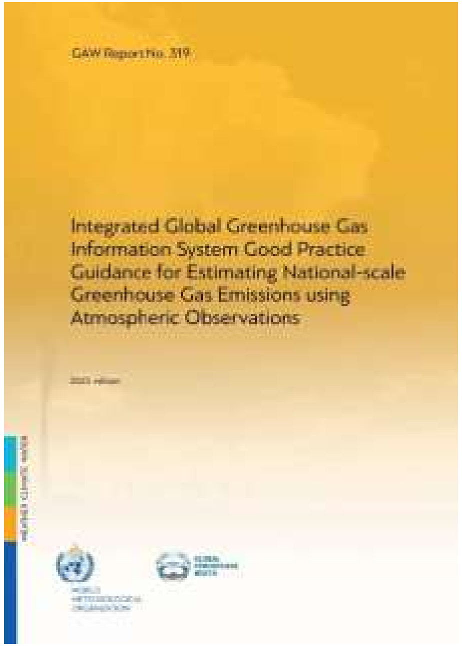


Volume 1, Chapter 6



Urban guidance



National guidance

GLOBAL ATMOSPHERE WATCH

IG3IS Integrated Global Greenhouse Gas Information System

IG3IS Stakeholder Consultations
20-22 April 2026, Geneva

Inverse Modelling in Support of the Swiss National Inventory Document (NID)

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- Annual update of Annex 6 in Swiss NID
- Empa Lagrangian Regional Inversion System (Henne et al., 2016; Katharopoulos et al., 2023)
- Continuous development/improvements (observations, a priori, inversion system)

- Started with **CH_4** estimates (for year 2013)
- Transport model (FLEXPART) developments
  - Higher resolution (COSMO-7 to COSMO-1)
  - New NWP (ICON)
  - @ 7 km resolution 2013 – 2021
  - @ 1 km resolution 2017 onwards
- Including **N_2O** from 2017 onwards
- **Halogenated** compounds: tracer ratio, campaign-based inversions

National Inventory Document of Switzerland 2025 555

Annex 6 Additional information on verification activities

A6.1 Independent verification of the National Greenhouse Gas Inventory for F-gases

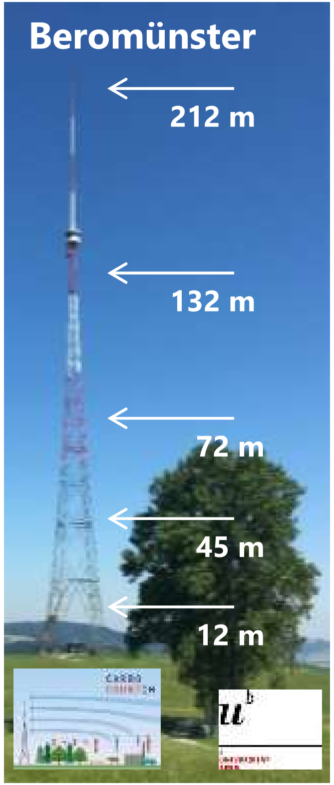
Introduction

Since 2000, the Swiss Federal Laboratories for Materials Science and Technology (Empa) performs continuous measurements of halogenated greenhouse gases at the high-Alpine site of Jungfraujoch (3'580 m a.s.l.). These measurements are used for estimating emissions of fluorinated greenhouse gases (HFCs, SF_6, PFCs) from Switzerland and neighbouring countries. The information can be used for an independent assessment of Swiss inventory data of these greenhouse gases. The independent emission estimate is not used directly for deriving data for the inventory. Data is used, however, to identify either consistency in support of the inventory or discrepancies, which could lead to a reassessment for identifying sources for disagreement and options for improvements.

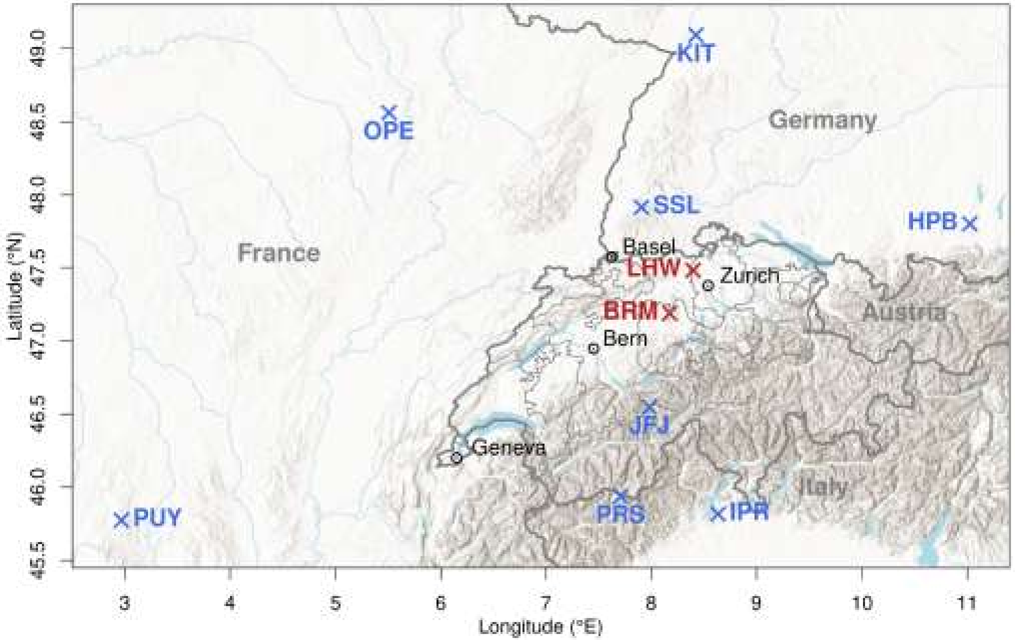
For the independent assessment of fluorinated greenhouse gas emissions from Switzerland the so-called tracer-ratio method is applied, where Swiss pollution events of HFCs and SF_6, arriving at Jungfraujoch, are scaled to concurrent pollution events of carbon monoxide (CO) and then multiplied by the Swiss CO emission inventory (see Figure A – 2 for a graphical illustration of the method). Similar approaches are also used for the independent verification of greenhouse gas emissions in the United Kingdom (UK MetOffice – using atmospheric observations from Mace Head (Ireland) combined with atmospheric transport models), in Australia (CSIRO – using the tracer-ratio method with measurements from Cape Grim, Tasmania) and in the US (NOAA – using a combination of airborne and ground-based samples).

BAFU project HALCLIM, CLIMGAS-CH

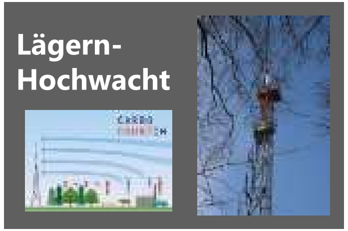
Swiss GHG Concentration Observations



CO_2, CH_4, N_2O, CO, $^{13}CO_2$, $^{14}CO_2$, $^{13}CH_4$, $^{14}CH_4$



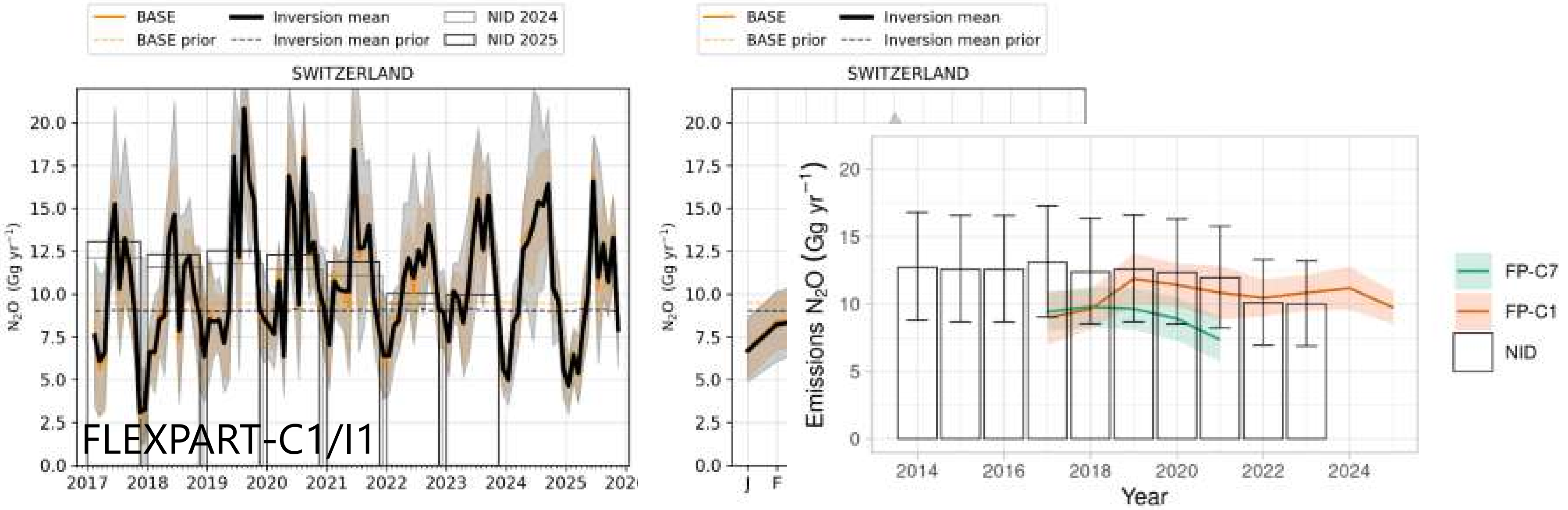
Swiss boundary layer sites
ICOS atmospheric sites



CO_2, CH_4, CO

CO_2, CH_4, N_2O, halogenated GHG, CO, O_2/N_2, Rn, $^{13}CO_2$, $^{14}CO_2$, $^{13}CH_4$, $^{14}CH_4$

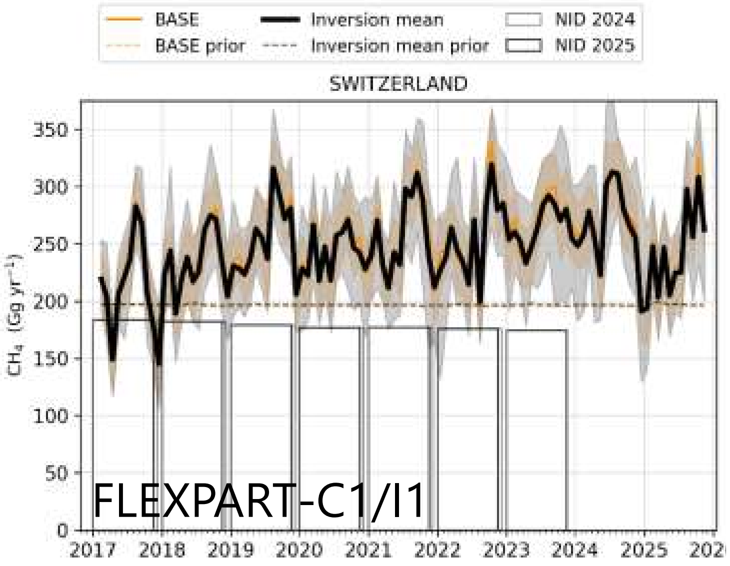
Annex to Swiss NID: N_2O

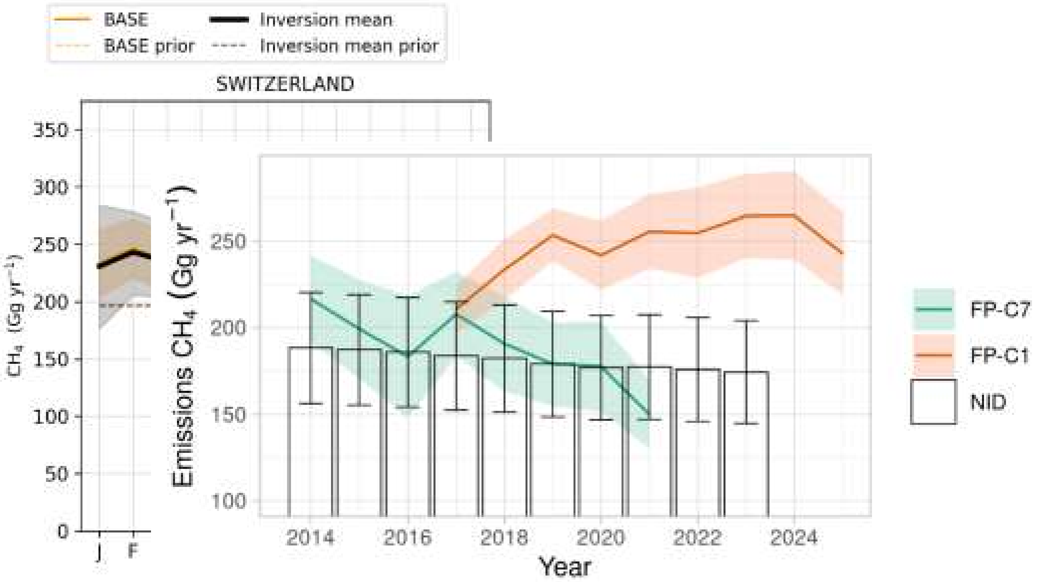


- Inverse estimate consistent with inventory
- Pronounced spring/summer maximum
- Results relatively consistent for different transport model resolution

to be submitted to UNFCCC April 2026

Annex to Swiss NID: CH_4





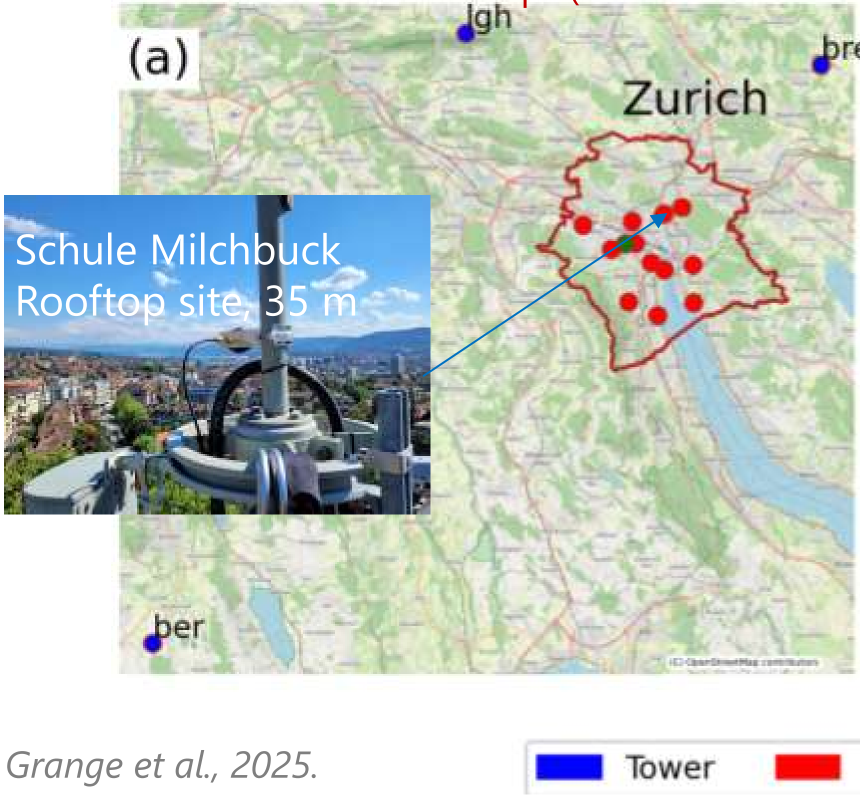
- Inverse estimate considerably larger than inventory
- Moderate late summer maximum
- Results **not** consistent for different transport model resolution

to be submitted to UNFCCC April 2026

Observations over Zurich and Paris

Mid-cost CO_2 sensor network in Zurich

13 NDIR sensors on rooftops (16 Sensors in total)



Cost: 5’000 – 10’000 CHF
Sensor 1h RMSE: 1.0 (0.46 – 1.5) ppm

Grange et al., 2025.

ICON-ART CTDAS

Anthropogenic & biospheric fluxes

- TNO-GHGco inventory (EU, 5 km)
- + Swiss national & Zurich inventories over Zurich (100 m)
- Biospheric fluxes from Veg. Photosynthesis and Respiration Model (VPRM)

ICON-ART offline nested simulations

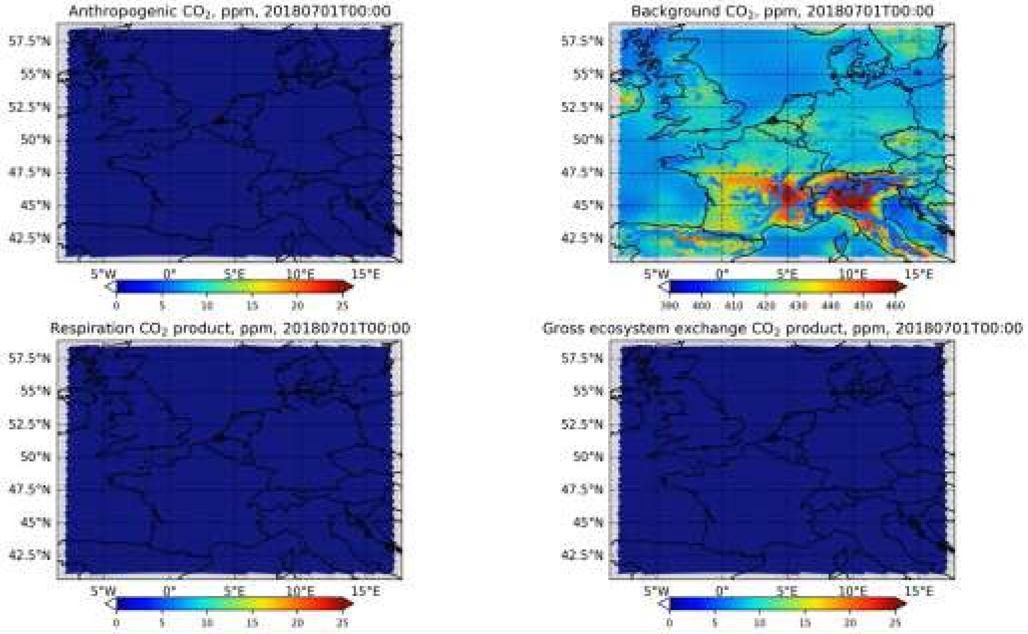
- Europe @ 6.5 km resolution
- Zurich domain @ 0.5 km

Initial and boundary conditions

- Meteorology from ECMWF ERA5
- CO_2 from CAMS global inversion

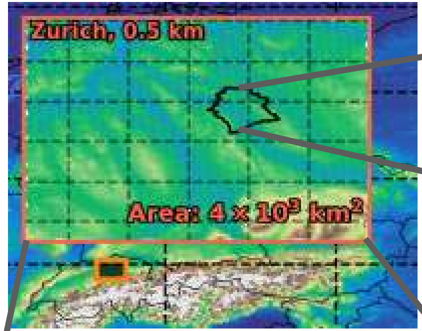
Flux optimisation

- Carbon Tracker Data Assimilation Shell (CTDAS)
- Ensemble Square Root Smoother



Ponomarev et al., 2026.

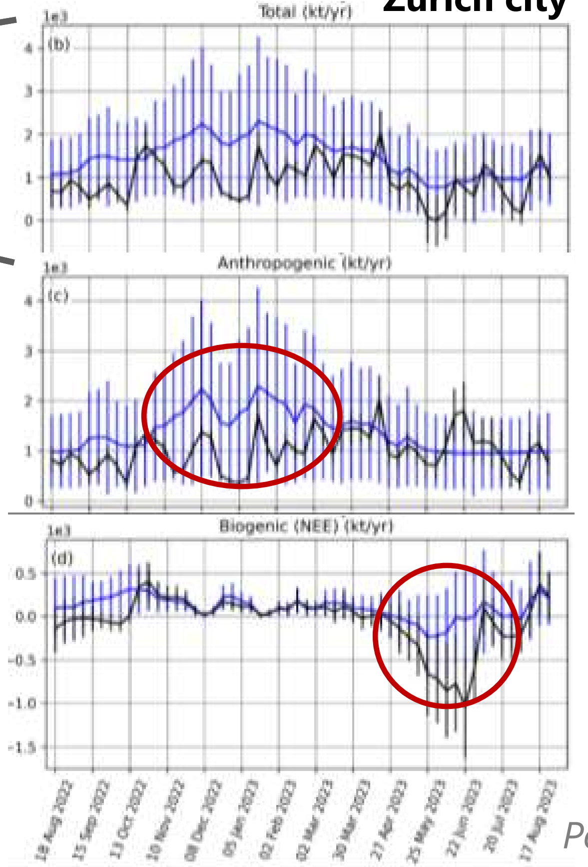
A priori and Optimised Fluxes



a priori
a posteriori

Zurich domain

Zurich city

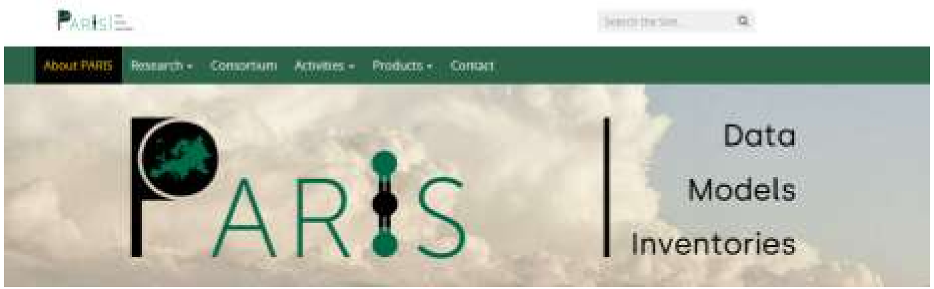


Total

Anthropogenic

Biogenic

Ponomarev et al., 2026



horizoneurope-paris.eu

Funded by the European Union

Verification and reconciliation of GHG emissions estimates in Europe 2022-2026

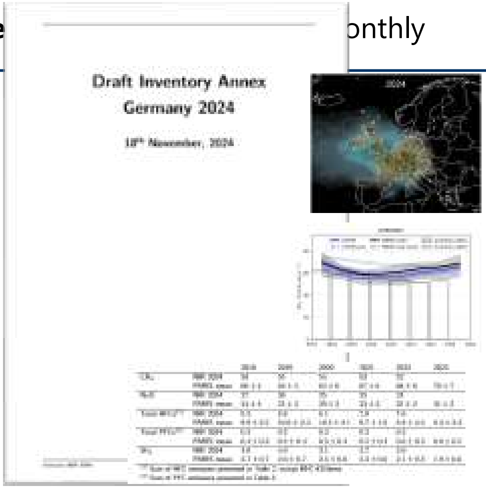
PARIS Inversion Results

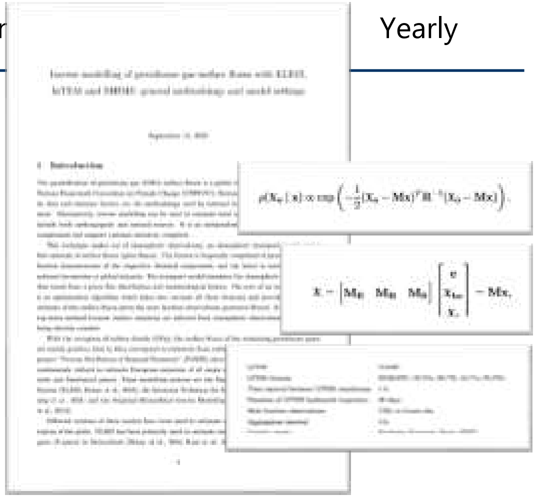
Default inversion results

Time window	2016 – 2024 InTEM HFCs: 2008 -
Species	CH_4, N_2O (monthly) 11 HFCs 4 PFCs SF_6, NF_3 (yearly: HFCs, PFCs, SF_6, NF_3)
Inversion systems	InTEM RHIME ELRIS DWD ITMS-D (CH_4)

	CH_4	N_2O	HFCs	PFCs, NF_3, SF_6
Number of sites	40	29	11	10/6/26
Transport	NAME FLEXPART ICON-ART	NAME FLEXPART	NAME FLEXPART	NAME FLEXPART
Prior emissions	EDGAR 8 + WetCHARTs	EDGAR 8	EDGAR 8 or uniform	Uniform over each country
Te	onthly	Mor		Yearly

- Harmonised netcdf output @ ICOS CP: flux (spatial & country), mole fractions https://doi.org/10.18160/GR1Q-6SK4
- Draft annex + model documentation
- Consultations with inventory teams
- Results in Dutch and Irish NID 2026

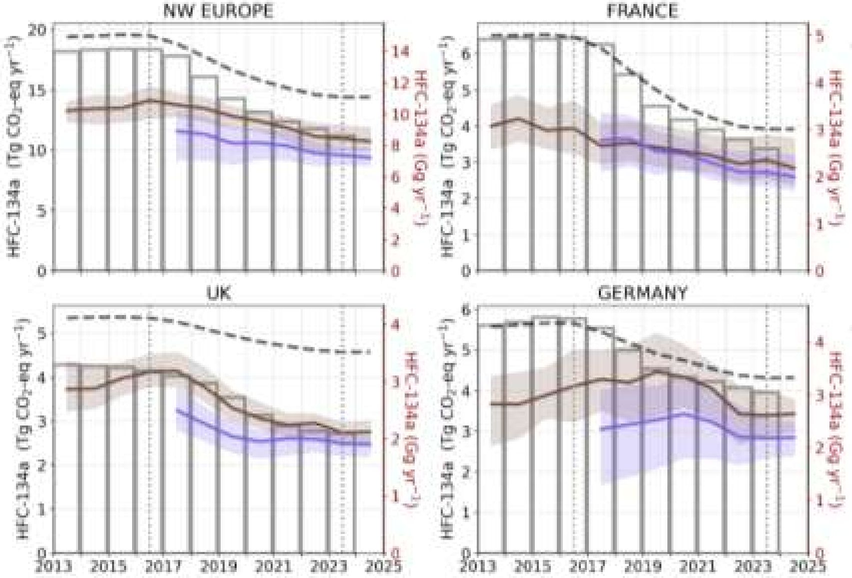




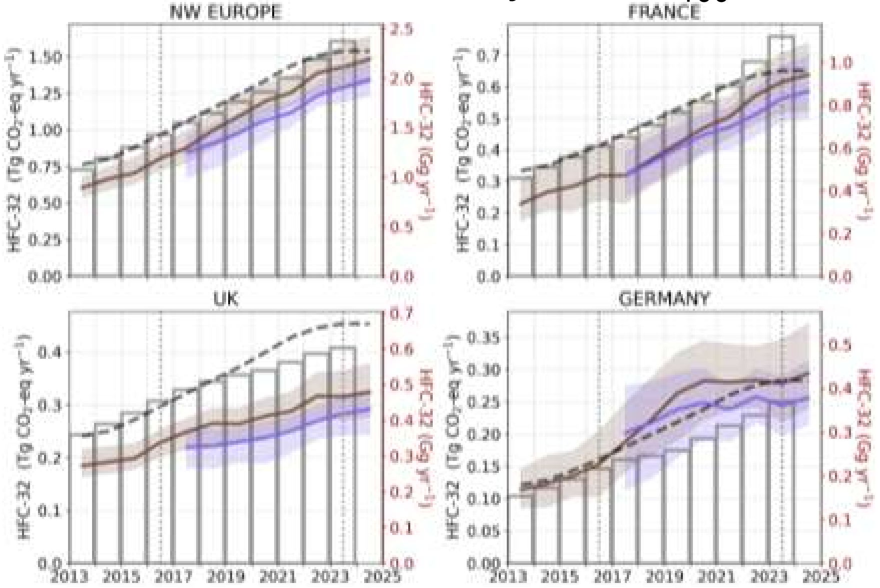
European HFC Trends

HFCs emssions targeted by European F-gas regulation
Phase-down depending on GWP

HFC-134a; lifetime: 14 yr; GWP_{100}: 1430

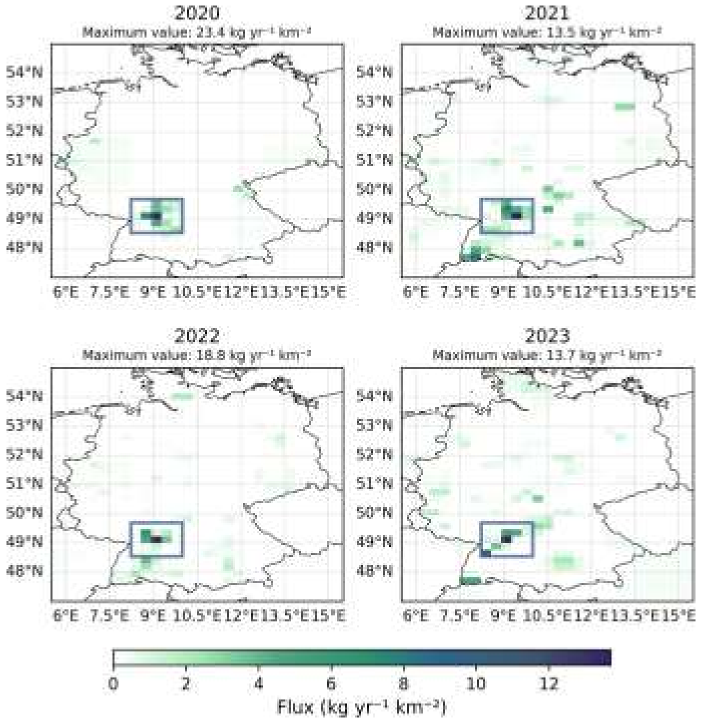


HFC-32; lifetime: 4.9 yr; GWP_{100}: 675



De Longueville et al., 2026

German SF_6 Emission Hot-Spot



SF_6 a posteriori emission estimate

Meixner et al., 2025

88 WISSEN DER SPIEGEL

Wolke von Bad Wimpfen

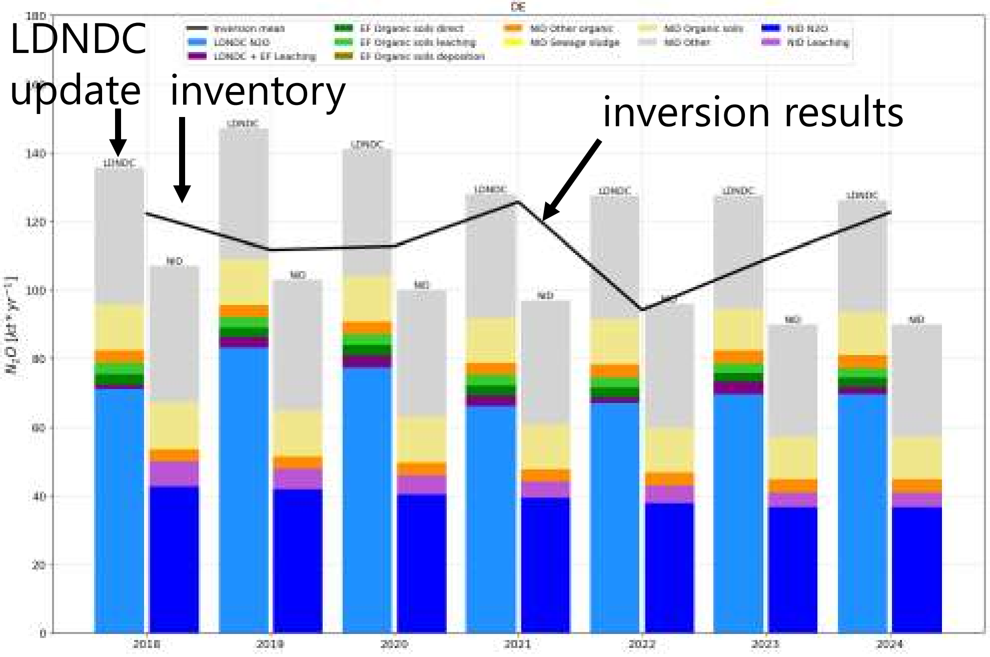
Umweltschutz: Aus einer Chemiefabrik in Baden-Württemberg entweicht wohl tonnenweise extrem klimaschädliches Gas. Das grün geführte Umweltministerium in dem Bundesland weiß davon, unternimmt offenbar aber wenig.

Point source emissions

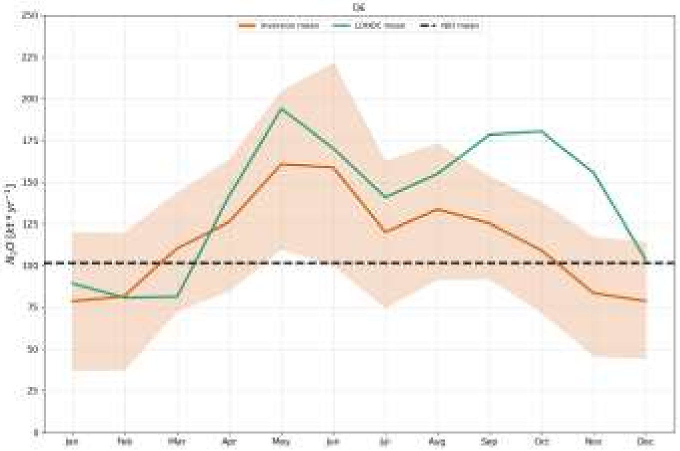
Reported: ~50 kg yr^{-1}

Inversions: ~40 t yr^{-1}

Sector Attribution of German N_2O Emissions



German N_2O emissions by sector
LandscapeDNDC: soil process model



PARIS inverse model mean
LandscapeDNDC plus

Weber et al. (in prep.)

Use of Isotopes and Co-emitted Tracers for Regional Inverse Modelling

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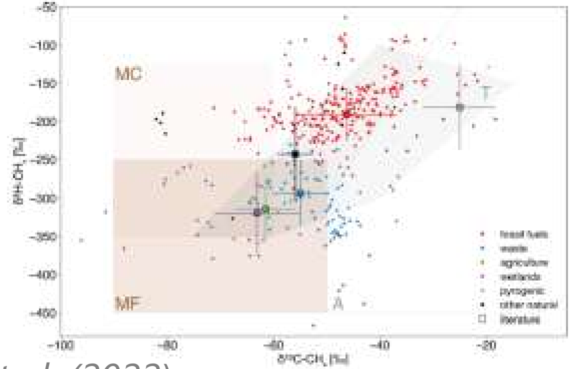
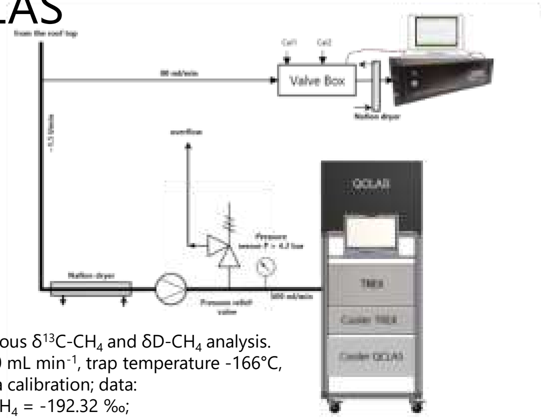


Menoud et al. (2022)

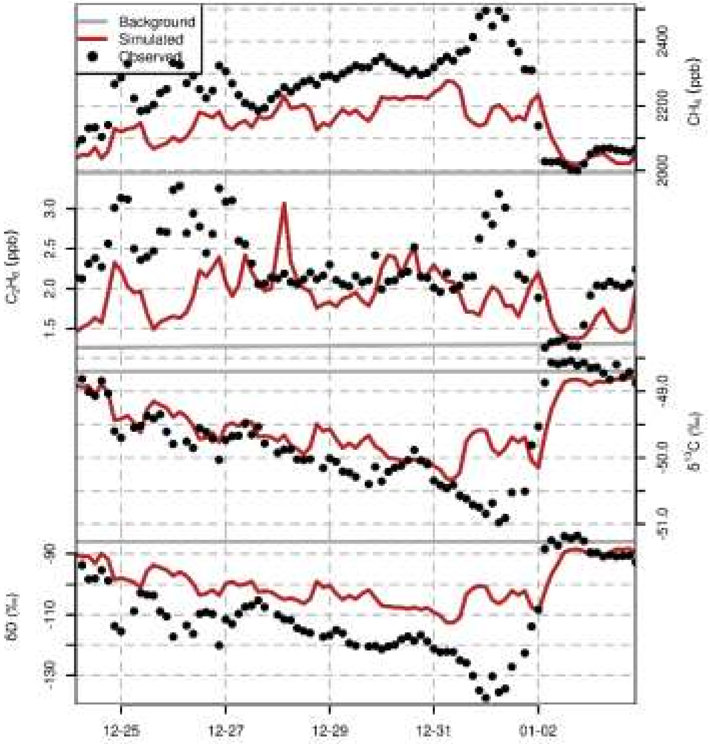
TREX / Aerodyne QCLAS
δ^{13}C- and **δD-CH$_4$**

AERIS MIRA ULRA
CH_4 and **C_2H_6**

@Empa Dübendorf

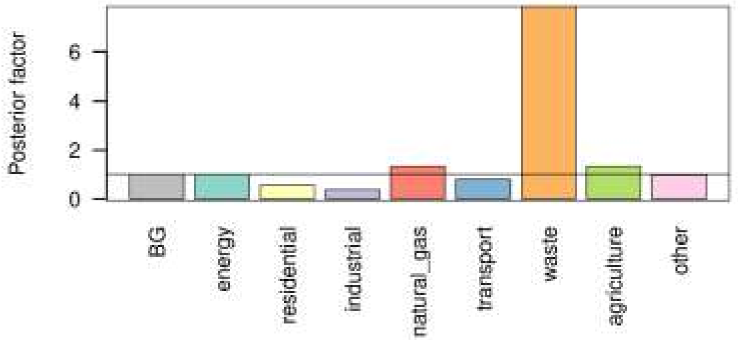


Setup applied for continuous C_2H_6/CH_4 and semi-continuous δ^{13}C-CH$_4$ and δD-CH$_4$ analysis.
Operation conditions of TREX III: adsorption flow rate 500 mL min^{-1}, trap temperature -166°C, desorption gas N_2, 1h cycle time. QCLAS: two-point delta calibration; data:
Cal1: c(CH$_4$)= 2040 ppm, δ^{13}C-CH$_4$ = -46.75 ‰ and δD-CH$_4$ = -192.32 ‰;
Cal2: c(CH$_4$)= 587 ppm, δ^{13}C-CH$_4$ = -57.13 ‰ and δD-CH$_4$ = -319.19 ‰.



Observations: Kerstin Zeyer, Joachim Mohn
Simulation: FLEXPART-ICON

Use of Isotopes and Co-emitted Tracers for Regional Inverse Modelling



TREX / Aerodyne QCLAS
$\delta^{13}C$- and **δD-CH_4**

AERIS MIRA ULRA
CH_4 and **C_2H_6**

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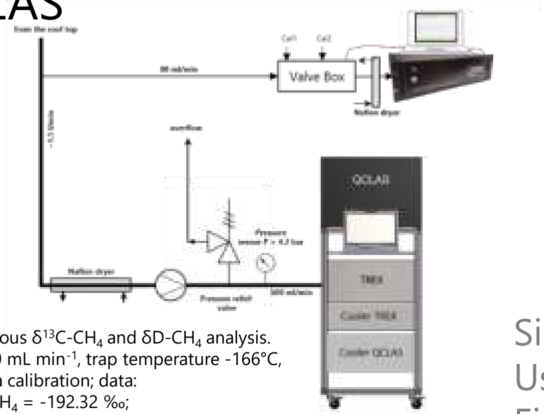

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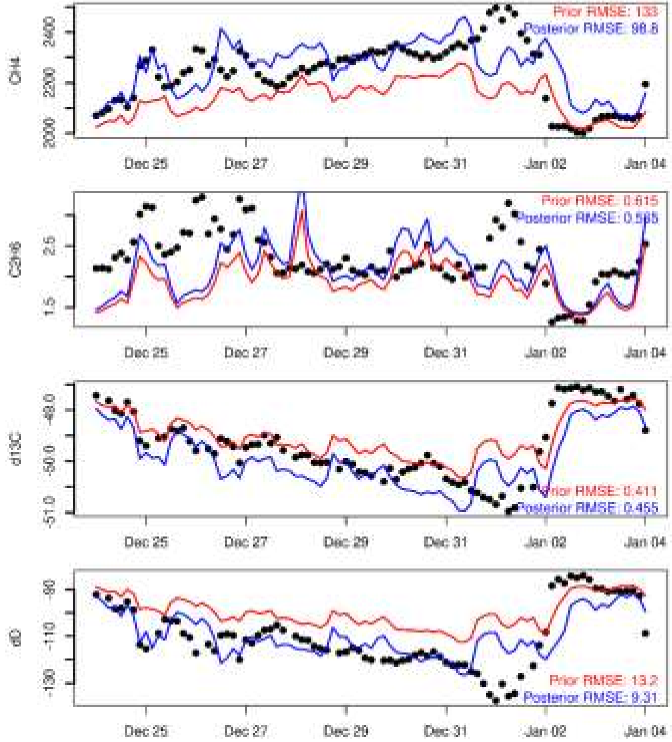

Simple Bayesian inversion: one factor for each sector
Using all observations: CH_4, C_2H_6, δD, $\delta^{13}C$
Fixed source signatures and emission ratio

SMART-CH4 TROPOMI CH_4 Inversion Romania

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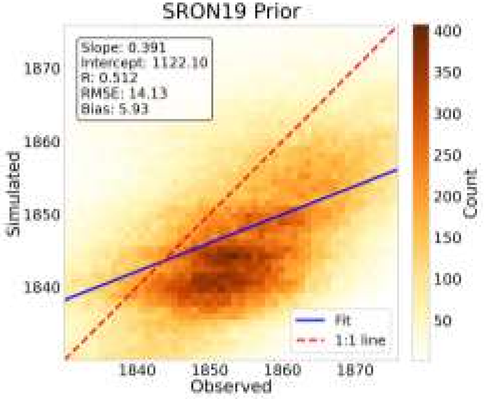
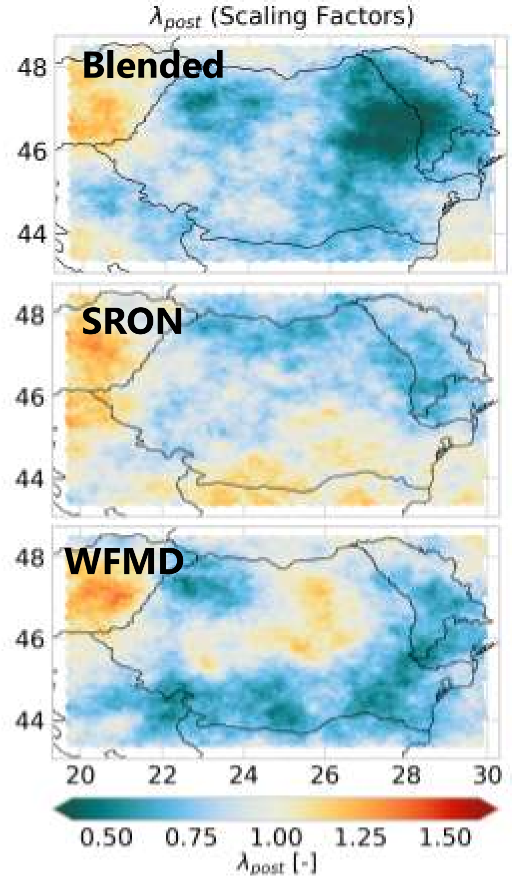
- Inversions with ICON-ART + CIF Ensemble Square Root Filter
- High-resolution simulations
  (3 km, compatible with TROPOMI)
- Assimilation of 3 different TROPOMI CH4 products
  - Blended: Harvard
  - SRON: Operational product
  - WFMD: Univ. Bremen, improved version 2
- Optimization fluxes and lateral boundary conditions

Model vs. observations (example for SRON)



Riess et al., in preparation



SMART-CH4 TROPOMI CH_4 Inversion Romania

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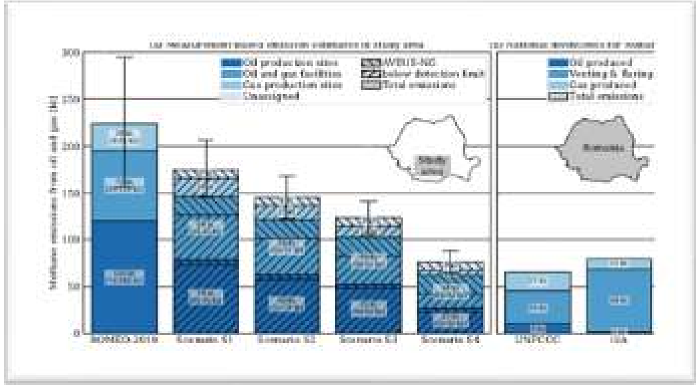
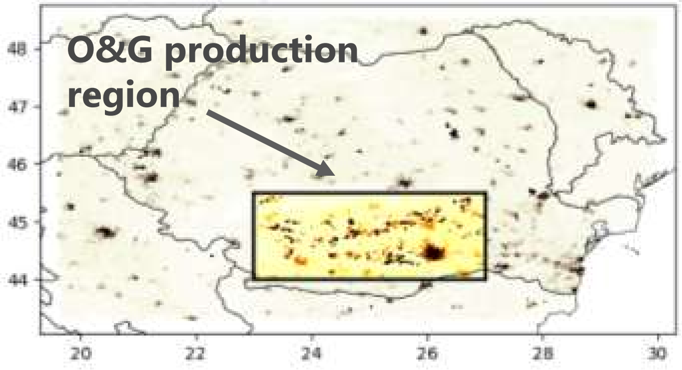
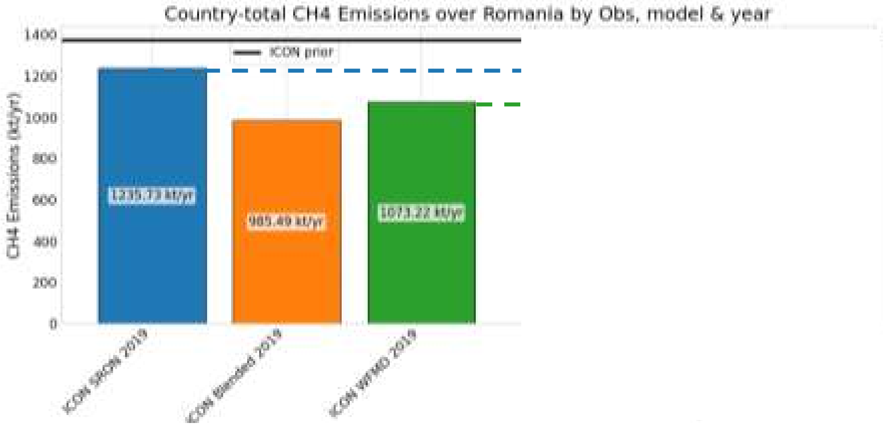
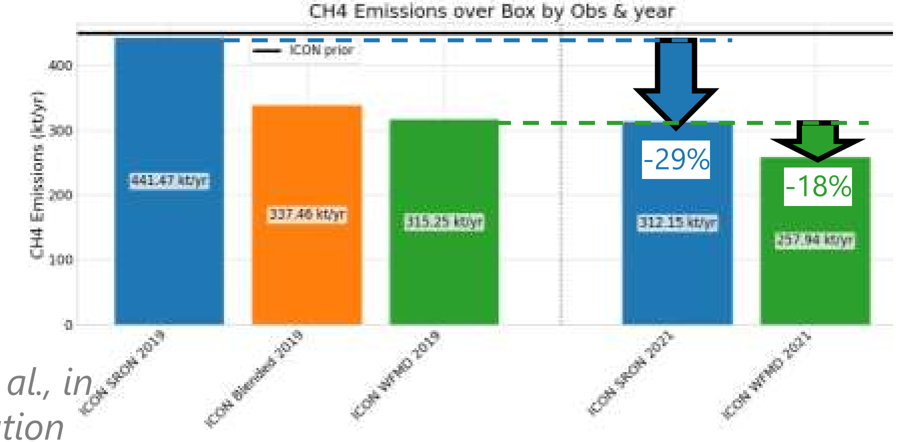


Kuhlmann et al. (2025): Emissions from O&G likely decreased by >20% from 2019 to 2021







Riess et al., in preparation

Regional-Scale Inverse Modelling Requirements & Solutions

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Requirements for meaningful inverse modelling of GHG fluxes

- Unbiased transport modelling at appropriate resolution
- Unbiased and traceable (high-precision) observations at appropriate locations
- Longterm stability of monitoring system to detect trends

- Multi-model inversions for a more complete description of uncertainty
- Direct interaction with inventory community/local experts to allow feedback

Near-routine service

- Western European **non-CO_2** GHGs based on surface observations
- Routine observation (ICOS) and modelling data flows
- Interoperable data formats
- Traceability and open data

- Emerging community tools: CIF, fluxie, …
- Countries with atmospheric validation in NID: **GBR, CHE, NLD, IRL**, DEU, ESP, **AUS**, KOR, CAN, IDN, **NZL**, **(USA)**, …

Regional Inverse Modelling
Open Questions & Challenges

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National/sub-national scale

- Are we on track? (i.e., national/sub-national legislation, Nationally Determined Contributions)
- How will carbon sink in forests develop?
- How accurate are bottom-up estimates for agriculture, organic soils, waste, fossil fuel sectors?
- Are there unknown sources or unexpected changes in known sources & sinks?

Global scale

- How will CO_2 uptake by land biosphere & oceans evolve in warming climate?
- How will thawing permafrost soils and warming wetlands/oceans affect CH_4 (& CO_2) fluxes?
- How will deforestation and other land use changes evolve?

Challenges and continued research efforts

- Sector attribution (CH_4, N_2O)
- Fossil vs. biogenic separation/estimation (CO_2)

- Use of co-tracers for sector attribution
  - Stable isotopes
  - Radiocarbon
  - Oxygen/nitrogen ratio
  - Currently strongly limited by data availability

- Satellite remote sensing observations
- Promise improved observational coverage in data-sparse regions
- Precision and accuracy requirements high

Acknowledgements

- Empa CLIMGAS-CH
  - Stefan Reimann, Martin Vollmer, Martin Steinbacher Lukas Emmenegger, Dominik Brunner
- PARIS
  - Empa: Daniela Brito Melo, Kerstin Zeyer, Joachim Mohn
  - University of Bristol: Hélène De Longueville, Alexandre Danjou, Joseph Pitt, Brendan Murphy, Matthew Rigby, Anita Ganesan
  - UK MetOffice: Alison Redington, Alice Ramsden, Peter Andrews, Alistair Manning
- All European scale inversions rely on atmospheric measurements provided by the Advanced Global Atmospheric Gases Experiment (AGAGE) and the Integrated Carbon Observation System (ICOS).

Funding

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- Financial support by Federal Office for the Environment (FOEN) & Federal Office of Meteorology and Climatology (MeteoSwiss) in the framework of the GAW-CH programme

Schweizerische Eidgenossenschaft
Confédération suisse
Confederazione Svizzera
Confederaziun svizra

Federal Office for the Environment FOEN

Federal Office of Meteorology and Climatology MeteoSwiss

- Contributing national research projects: CarboCount-CH, IHALOME

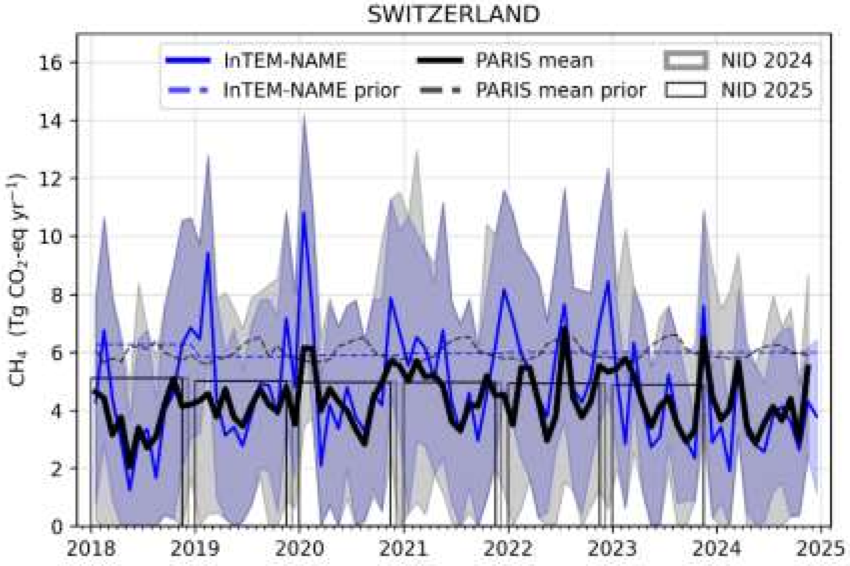
FNSNF
FONDS NATIONAL SUISSE
DE LA RECHERCHE SCIENTIFIQUE

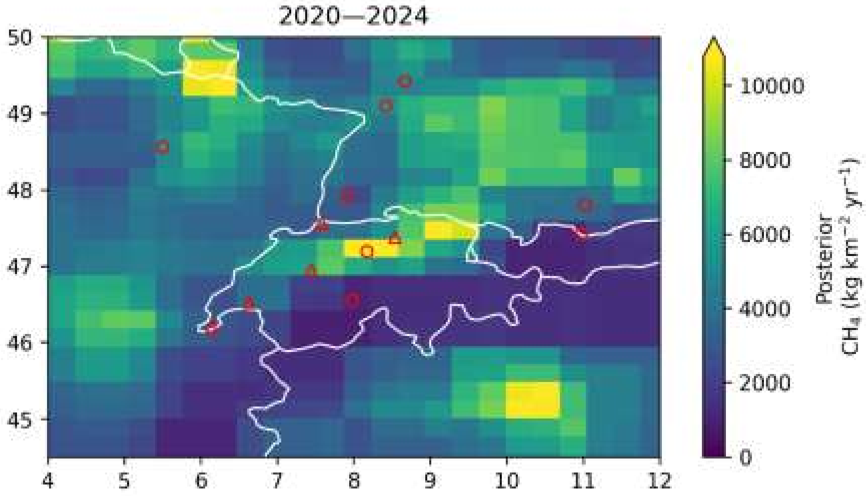
- PARIS is funded by the European Union under the Grant Agreement number 101081430.

PARIS | DATA MODELS INVENTORIES

https://horizoneurope-paris.eu/

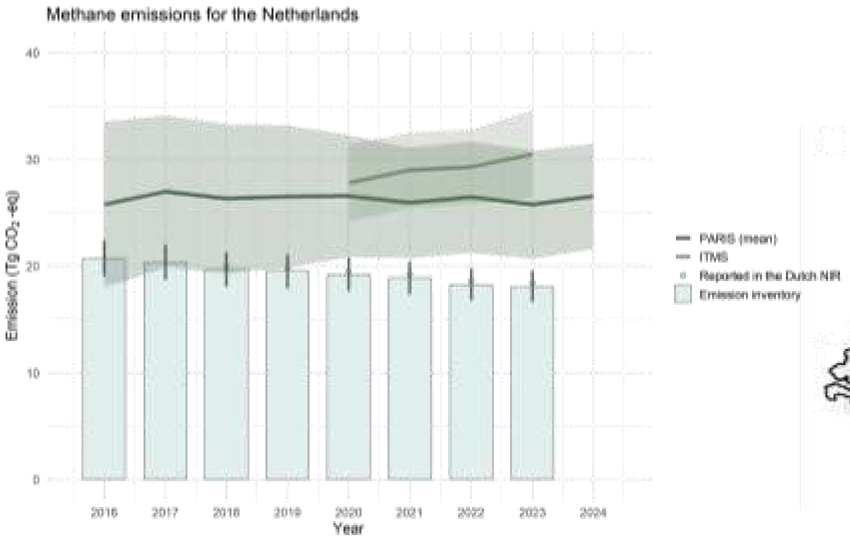
PARIS Results for Switzerland

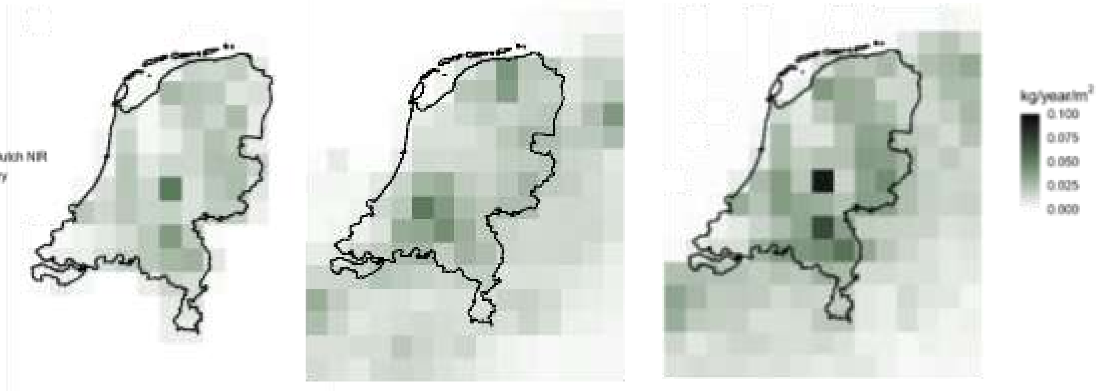




- Current PARIS transport and inversion models lack resolution required for complex terrain
- But much closer agreement with inventory as for high-resolution inversions

CH_4 Emissions in Dutch NID Annex



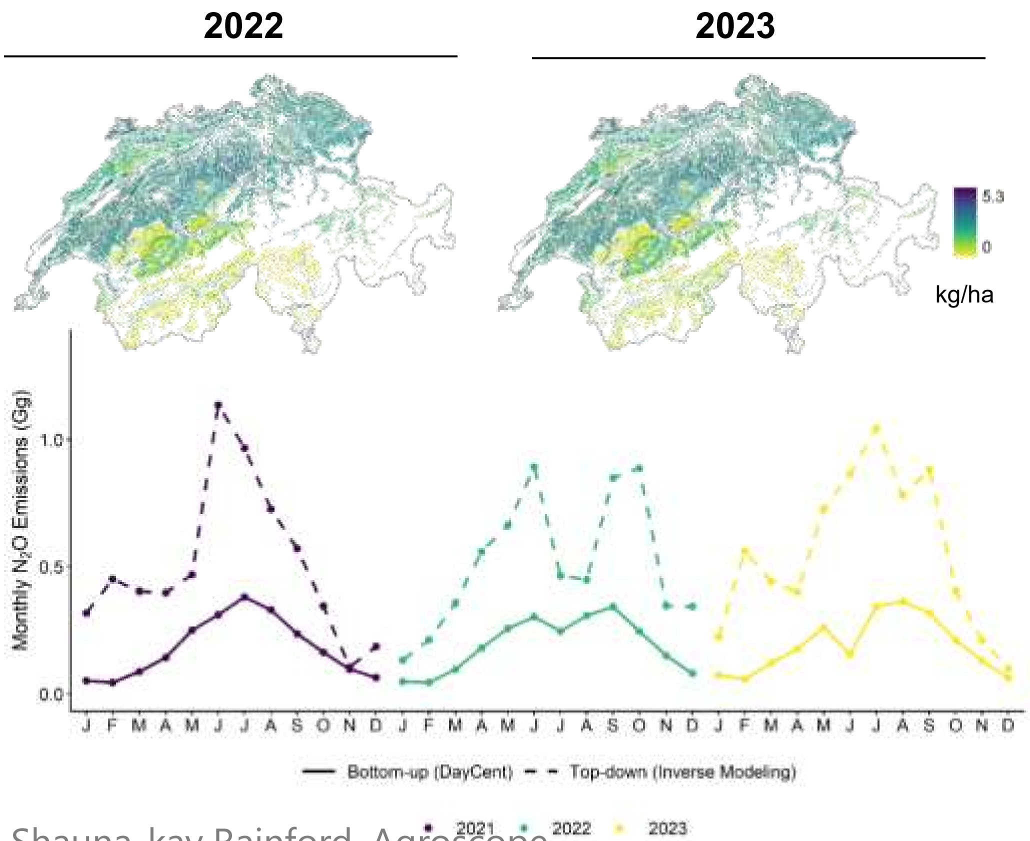


Inventory PARIS – 6 models ITMS-D

- Models higher than inventory (40-66% higher)
- NID keeps six runs (InTEM, RHIME, ELRIS) separate to ITMS-D inversion
- Combines uncertainty weighted by uncertainties of individual models
- No clear conclusion as to why estimates differ (natural gas, organic soils, inland waters?)

Swiss N_2O: Tier 3 Process Model (preliminary)

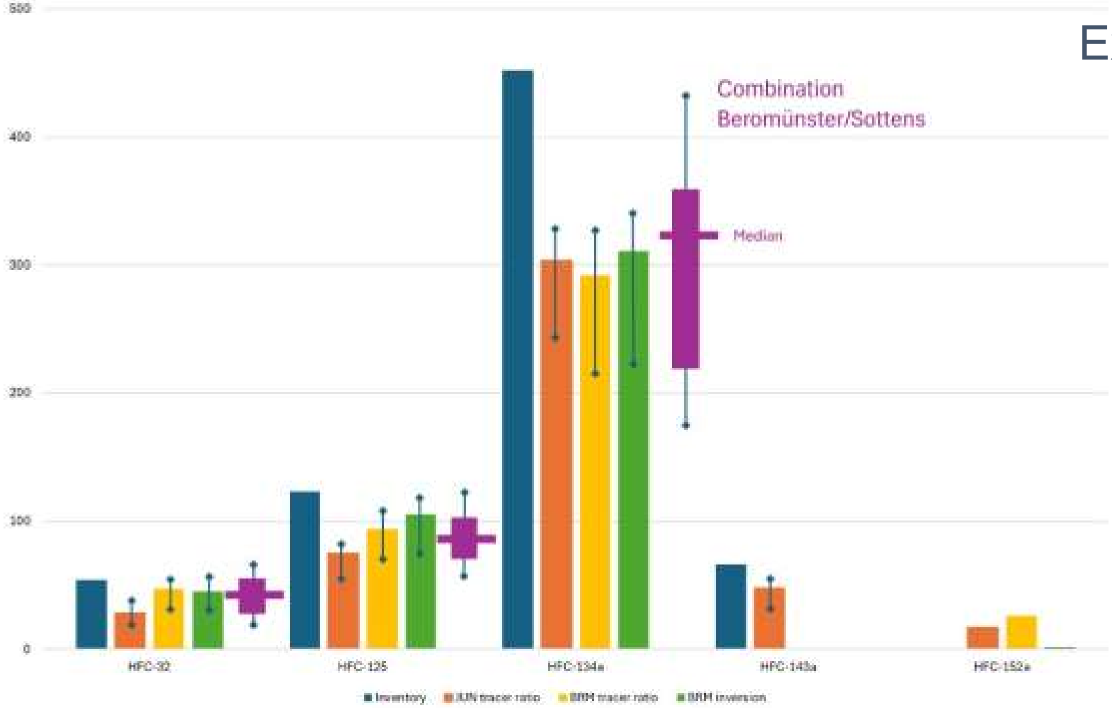
Empa
Materials Science and Technology



Shauna-kay Rainford, Agroscope

- DayCent soil process model for arable land
- Top-down estimates include additional sources that can explain difference
- Bottom-up estimates reflect only direct emissions from managed soils
- Both approaches show similar year to year changes in monthly N_2O emissions

Swiss Emissions of Halogenated Compounds

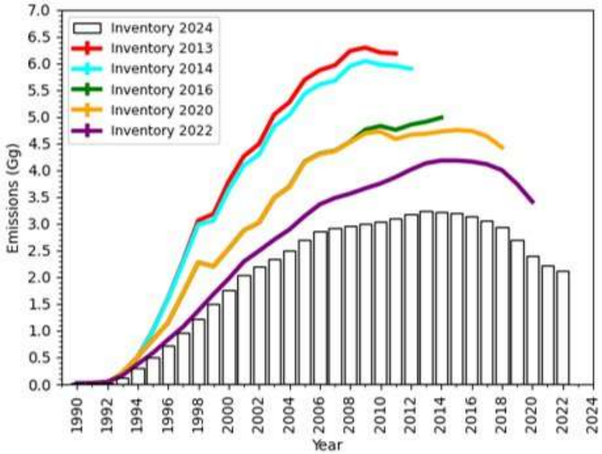


PBL campaign 2019/2020, Beromünster, Sottens

Rust et al., 2022.

Katharopoulos et al., 2023.

Example from the UK for HFC-134a



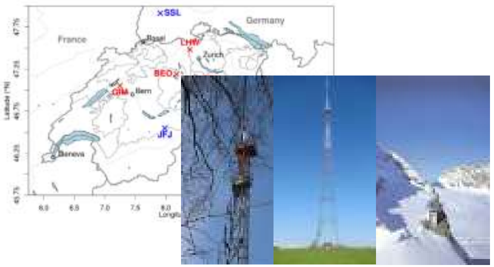
Revisions to e.g. refill rate and market penetration

Ultimately new MAC model adopted

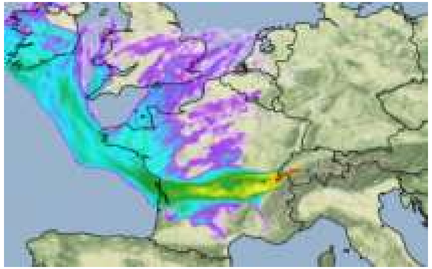
Expert reviews triggered by *top-down* results

Courtesy of Alistair Manning, UKMO.
Do not re-distribute!

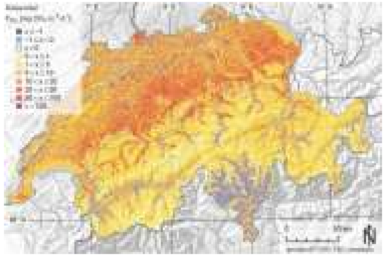
Elements of Top-Down GHG Monitoring



Observations

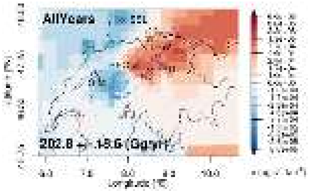


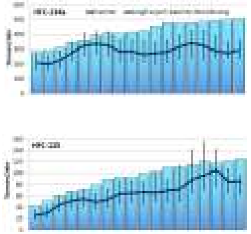
Atmospheric Transport Model
FLEXPART IFS/COSMO/ICON



A priori Emissions
National/EDGAR/TNO

Top-down methods
ELRIS: Empa Lagrangian Regional Inversion System
TRM: Tracer ratio method

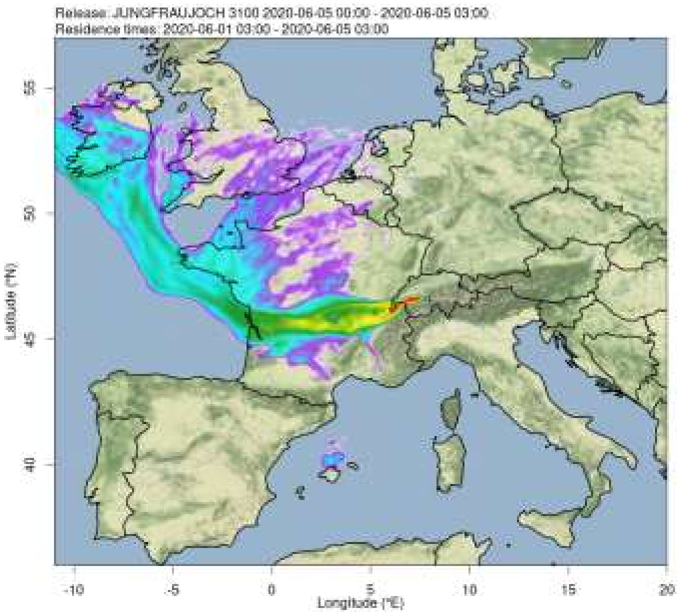




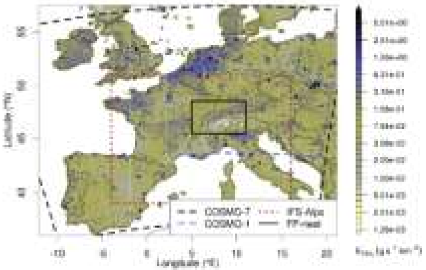
Top-down emissions (national total, spatio-temporal attribution)

Lagrangian Particle Dispersion Simulation

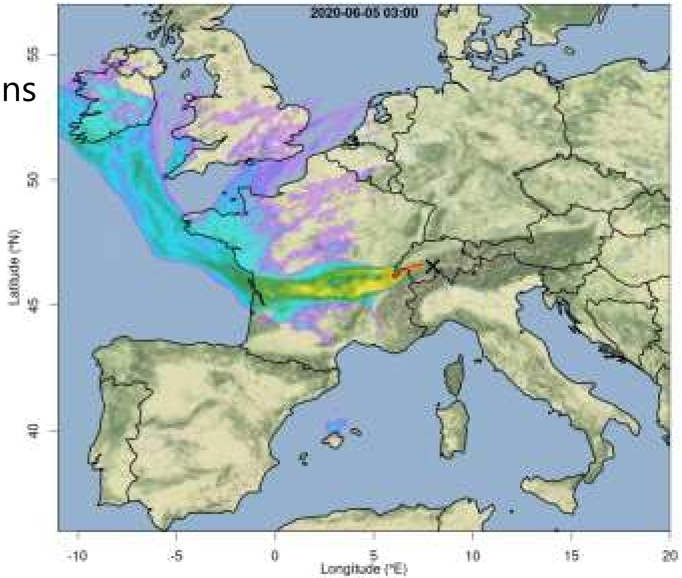
Empa
Materials Science and Technology

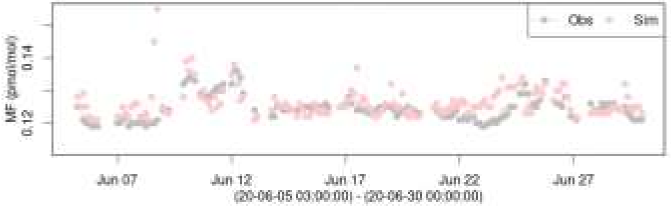


Multiplication with emissions



$$\chi = \underbrace{\sum_{i,j} m_{i,j} E_{i,j}}_{\chi_p} + \underbrace{\frac{1}{K}\sum_{k}^{K} \chi_k}_{\chi_b},$$





Release O(1x10^4) particles per hour
Trajectory integration ~1 week
Turbulence/convection stochastic process
Make use of archived analysis fields
Surface source sensitivities (footprints), *m*

Concentration at receptor

Simulated concentration time series

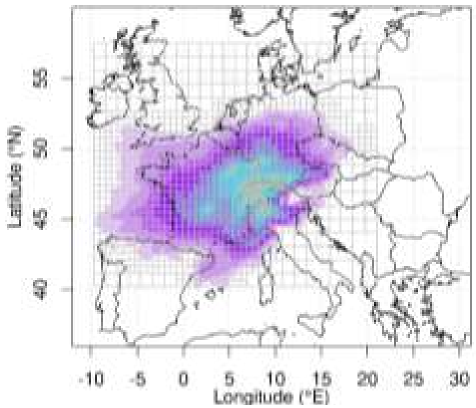
Empa Lagrangian Regional Inversion System (ELRIS)

Empa
Materials Science and Technology

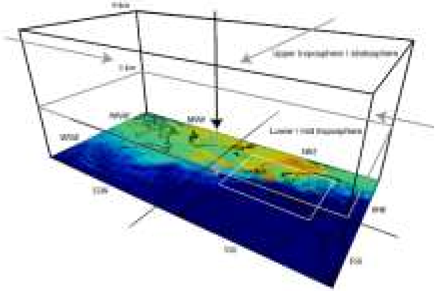
- Employing source and boundary sensitivities as calculated by LPDM
- Linear model of mole fractions with respect to emissions and boundary conditions

$$\chi = \begin{bmatrix} \mathbf{M}_E & \mathbf{M}_B \end{bmatrix} \begin{bmatrix} \mathbf{e} \\ \chi_{bc} \end{bmatrix} = \mathbf{M}\mathbf{x},$$

- Analytical Bayesian kernel
- Reduced inversion grid
- Different ways of baseline treatment
  - By site [Stohl et al., 2008]
  - By boundary interfaces [Ganesan et al., 2015]
- Enforce positive a posteriori emissions [Stohl et al., 2008; Thacker 2007]
- First employed to halocarbons in China [Vollmer et al, 2009]
- Main reference: Henne et al. (2016)
- R package

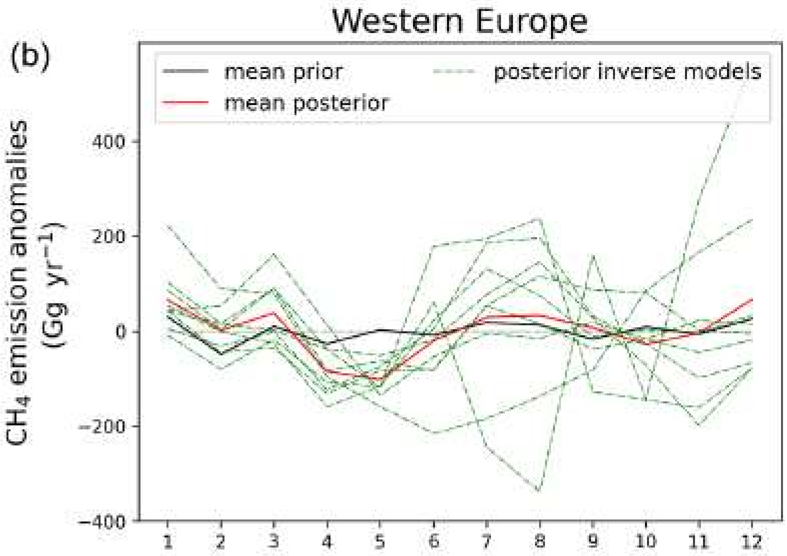


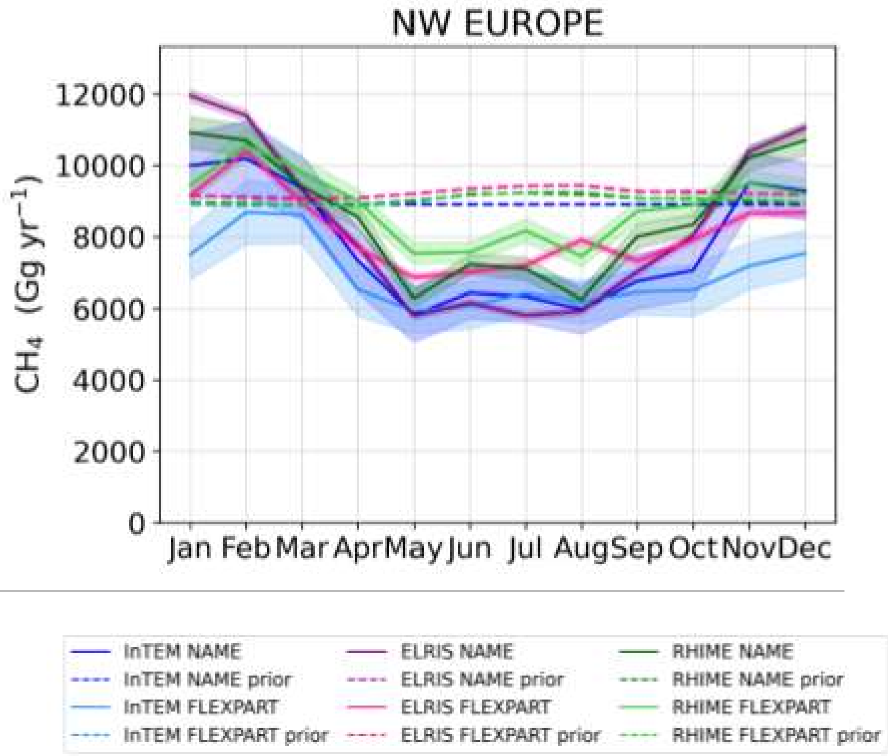
Reduced inversion grid for Swiss CH_4 inversion



Boundary interfaces as in Ganesan et al., 2015

PARIS vs. Recent TRANSCOM CH_4 Comparison





Setups and periods differ
Western Europe = NW Europe + CHE + AUT
PARIS yields very different seasonality
PARIS seasonality driven by NLD, FRA, DEU

Source: Ioannidis et al., 2026

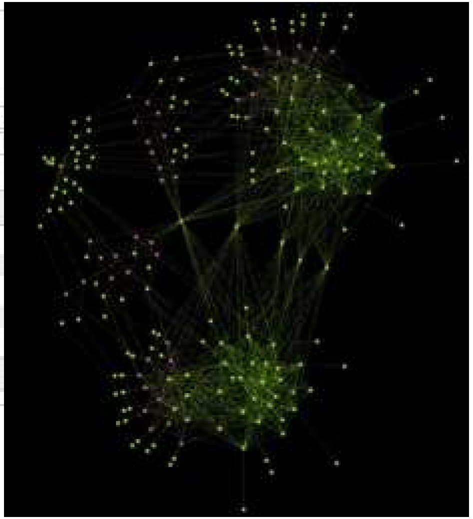
Source: PARIS2026NID

Reproducibility, data provenance and sharing

- NID based on rigorous reporting framework
- Internationally audited
- Common data format
- High level of detail in NID

- Inverse estimates should follow similar principles
- Open data and version control
- More complex and dynamic codes development
- Stricter code versioning and provenance documentation
- Common data formats required

Workflow manager (incl. HPC)
GUI interface
Data provenance



Simplified provenance graph of one week of FLEXPART simulations

Spatially Resolved National Inventory

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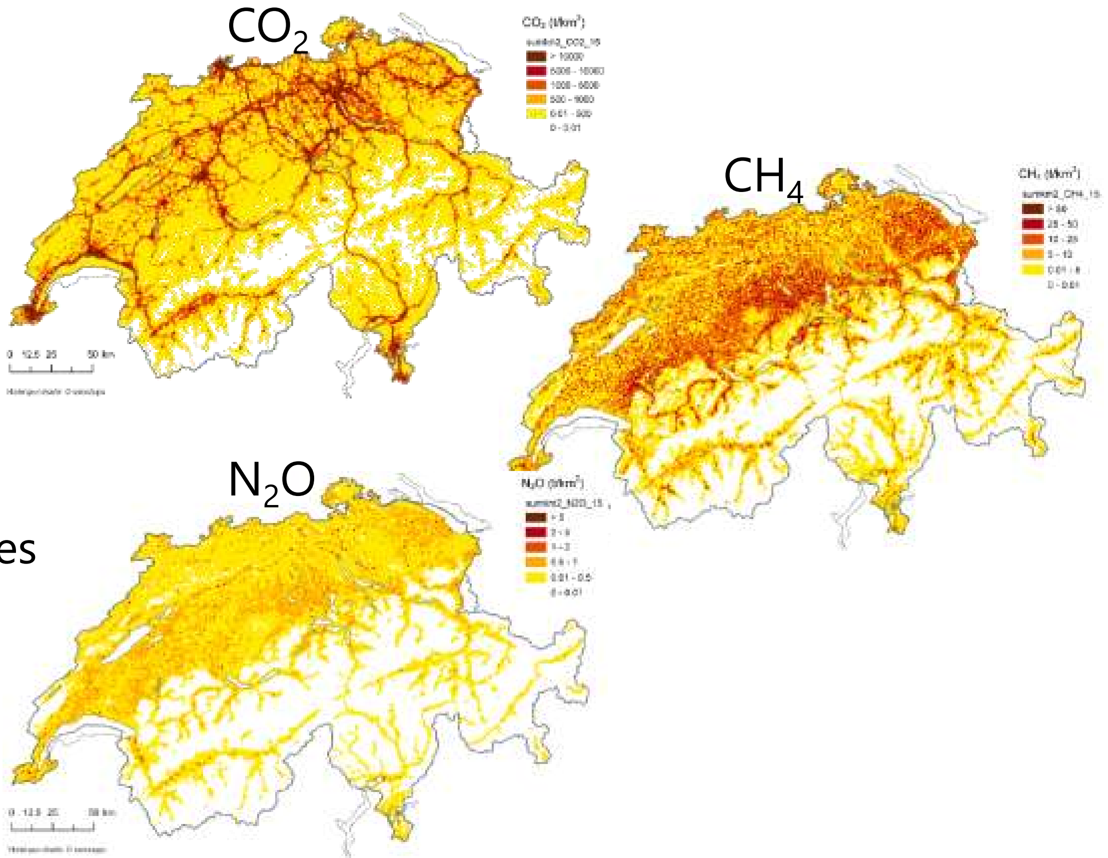
Materials Science and Technology

- Gridded inventory at up to 100 m x 100 m resolution
- Available for air pollutants (NO_x, CO, SO_2, NH_3, PM) and greenhouse gases (CO_2, CH_4, N_2O)
- Detailed emissions by sector
- Total amount consistent with officially reported data
- Spatial mapping using representative geostatistical proxies (from Swiss Arealstatistik) per sector

- Produced by Meteotest & INFRAS



https://www.bafu.admin.ch/bafu/de/home/themen/klima/zustand/karten.html

European Research Projects on Top-Down Emission Estimation

Empa Materials Science and Technology

EU

- CarboEurope (2004-2008) http://www.carboeurope.org/
- GHG-Europe
- NitroEurope (2006-2011)
- InGOS (2011-2015) https://www.ingos-infrastructure.eu/
- **ICOS, ERIC since 2015** https://www.icos-cp.eu

- VERIFY (2018-2022) https://verify.lsce.ipsl.fr/
- CHE (2017-2020) https://www.che-project.eu
- CoCO2 (2021-2023) https://coco2-project.eu
- **CAMS** (European Monitoring and Verification Support Capacity as part of the Copernicus programme) https://atmosphere.copernicus.eu/

ESA

- GlobEmission https://www.globemission.eu/
- World Emission https://www.world-emission.com/

New HORIZON projects

HORIZON-CL5-2022-D1-02-01: Verification and reconciliation of estimates of climate forcers

- AVENGERS (2023-2026)
  - Lead: M. Scholze, U. Lund
  - aerosols, future capabilities
- EYE-CLIMA (2023-2026)
  - Lead: R. Thompson, NILU
  - attribution, high resolution sat. data
- PARIS (2023-2026)
  - Lead: T. Röckmann, U. Utrecht
  - Co-Lead: A. Ganesan, U. Bristol
  - attribution, isotopes, halogenated species, national reporting

Top-Down Support of Swiss NIR

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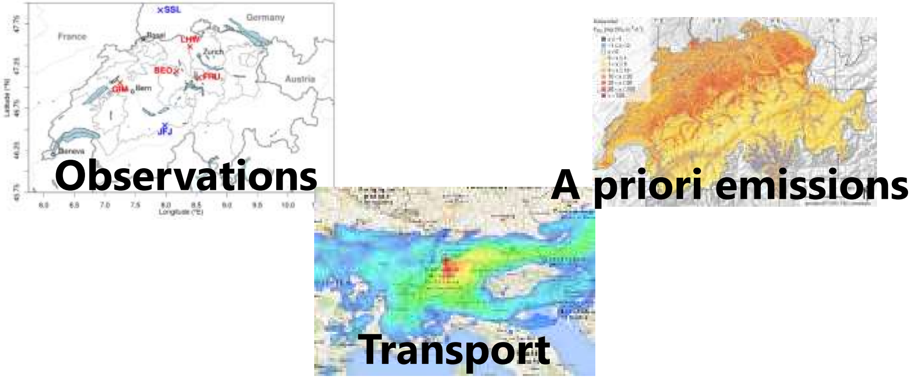
Materials Science and Technology



Inverse methods
Bayesian inverse modelling: CH_4, N_2O
Tracer ratio method: Synthetic gases

Supported through FOEN project CLIMGAS

- In-situ observations of CH_4, N_2O, and halogenated species
- High-resolution a priori inventory (CH_4, N_2O)
- Lagrangian transport model: FLEXPART-COSMO at 7/1 km resolution
- Direct Bayesian inversion (CH_4, N_2O), tracer ratio (halogenated species)
- Annual reporting to FOEN; key results reported as Annex to NIR (<NIR>/<from>)
  - halogenated: 2012/2001
  - CH_4: 2016/2013
  - N_2O: 2019/2017
- Additional research projects to advance system (model resolution, observations, inverse method)

Emissions Based On Jungfraujoch Observations (Tracer Ratio Method)

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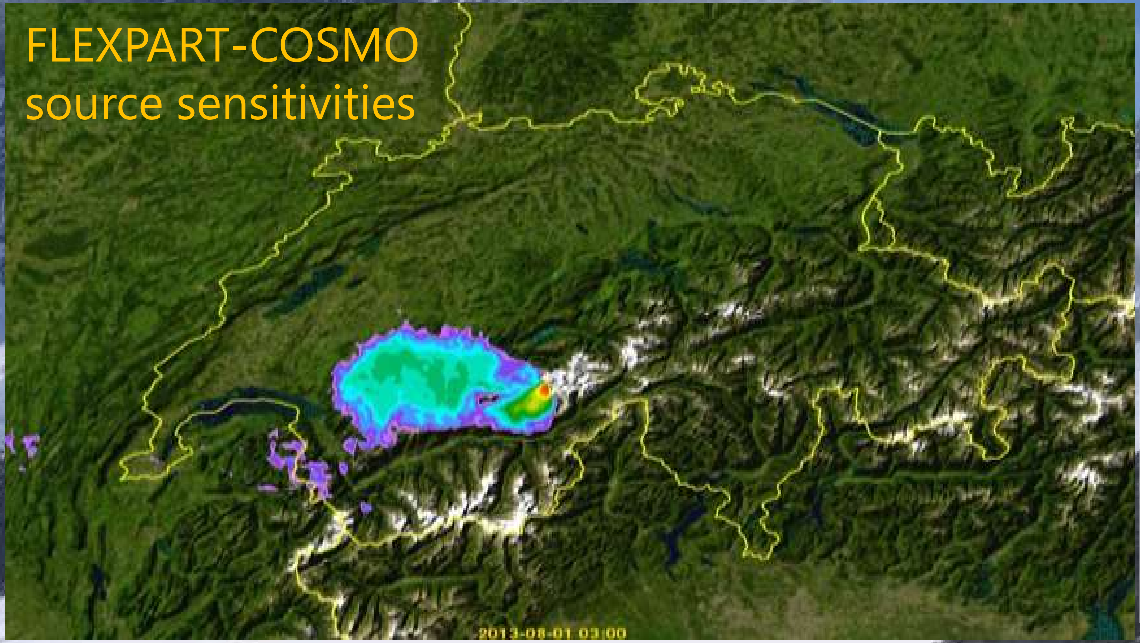
$$E_{target}\ (\text{CH}) = E_{CO}\ (\text{CH Inventory})\ \frac{\Delta \text{target (observed)}}{\Delta \text{CO (observed)}}$$

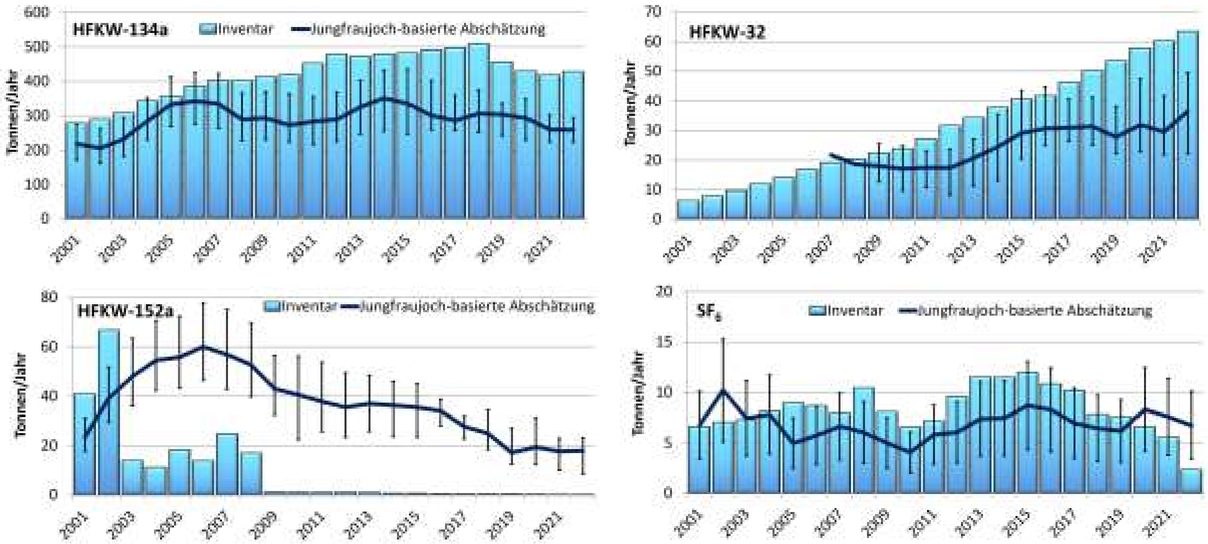


Select weather conditions with strong export from Swiss PBL to Jungfraujoch:
large relative source sensitivties

Swiss Emissions of Halogenated Gases

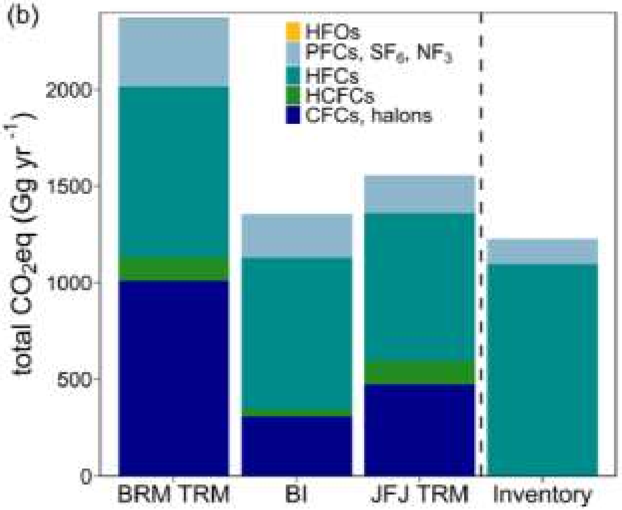
Empa
Materials Science and Technology

CO tracer-ratio-based estimates using measurements at Jungfraujoch



[Swiss NIR, 2024]

Inversion-based estimates for 2019/2020 with additional measurements at Beromünster (28 compounds)



[Rust et al., 2022]

Transport Model Switzerland

Input Meteorology: COSMO @ MeteoSwiss

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COSMO-7

- Boundary conditions from IFS
- 6.6 km, 60 levels
- 3 x 72 h forecast per day

COSMO-2/COMO-1

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- 2.2 km, 60 levels, 1.1 km 80 levels
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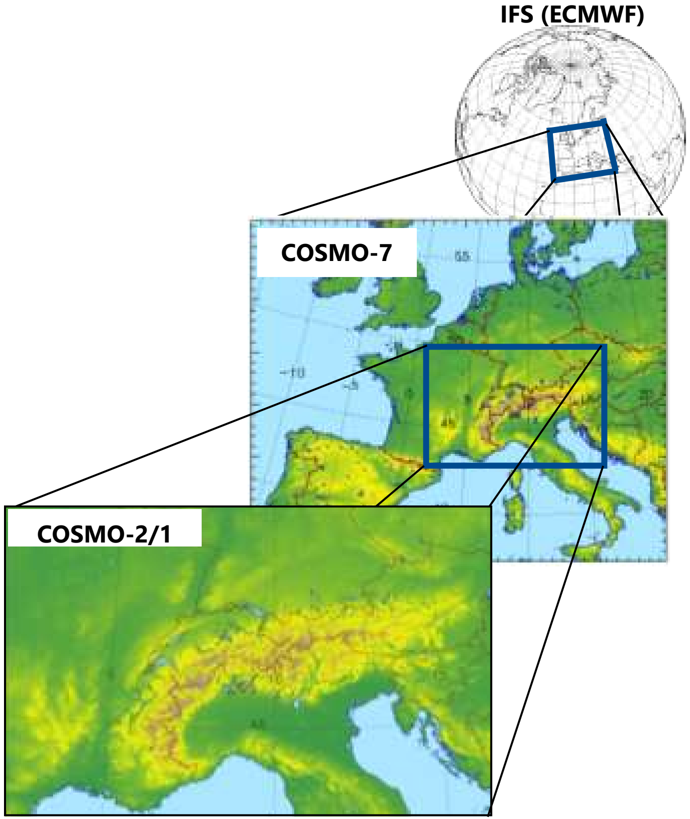
Data Assimilation

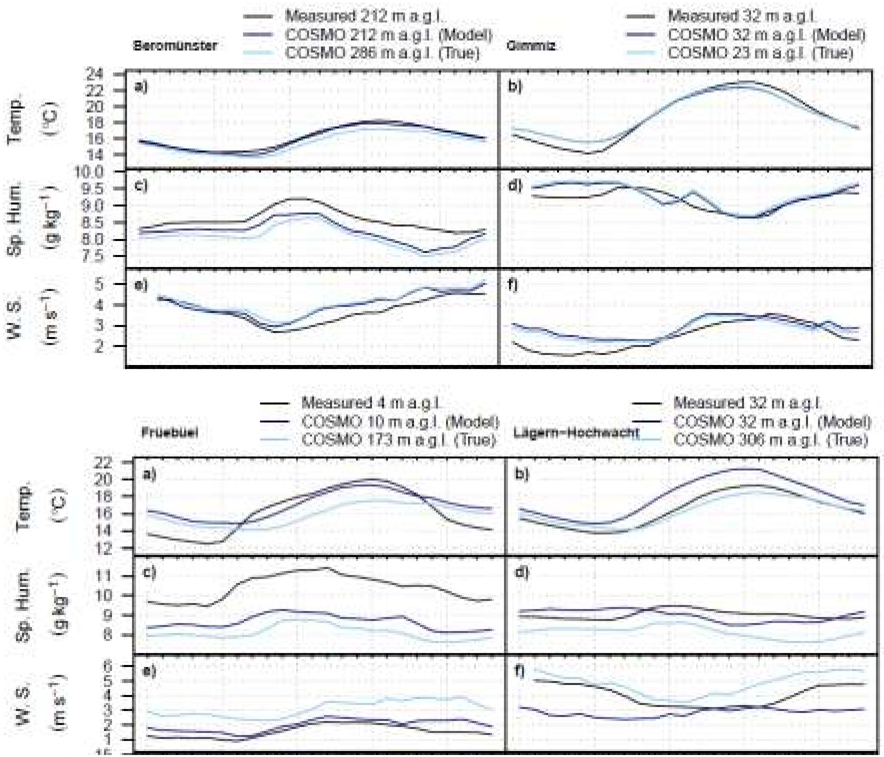
- Ensemble Kalman Filter (KENDA)
- Synop/ship/buoy measurements (PS, RH2, FF10, DD10)
- temp/pilot data (FF, DD, TT, RH)
- profilers (FF, DD, TT)
- In COSMO-2/1: Latent Heat Nudging

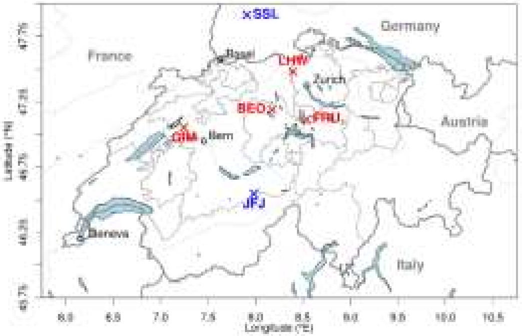
Hourly analysis fields available for FLEXPART



COSMO Model Validation

- Validation of COSMO forecast/analysis products is part of operational MeteoSwiss process
- Additional validation
  - Wind at GHG observing sites
  - PBL height at MeteoSwiss super site Payerne





[Oney et al., 2015]

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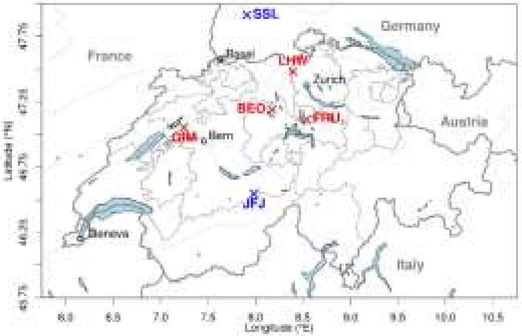
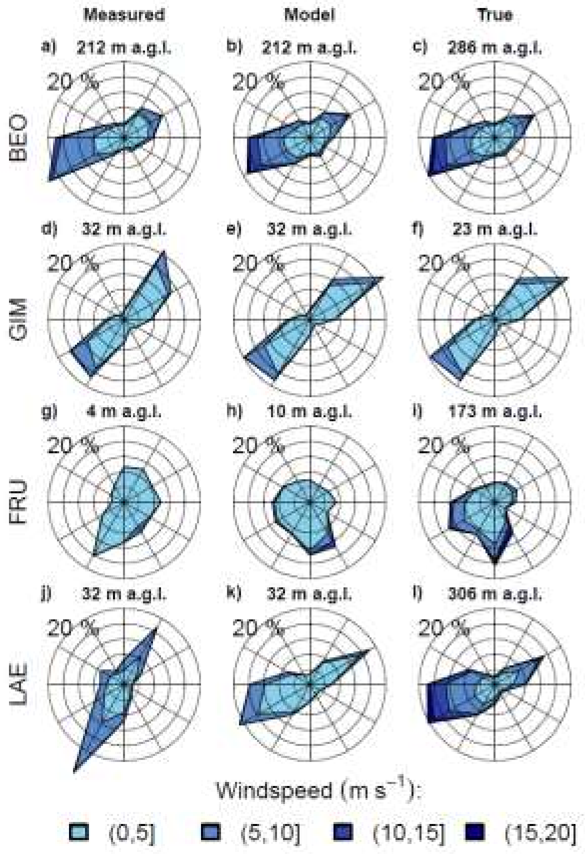


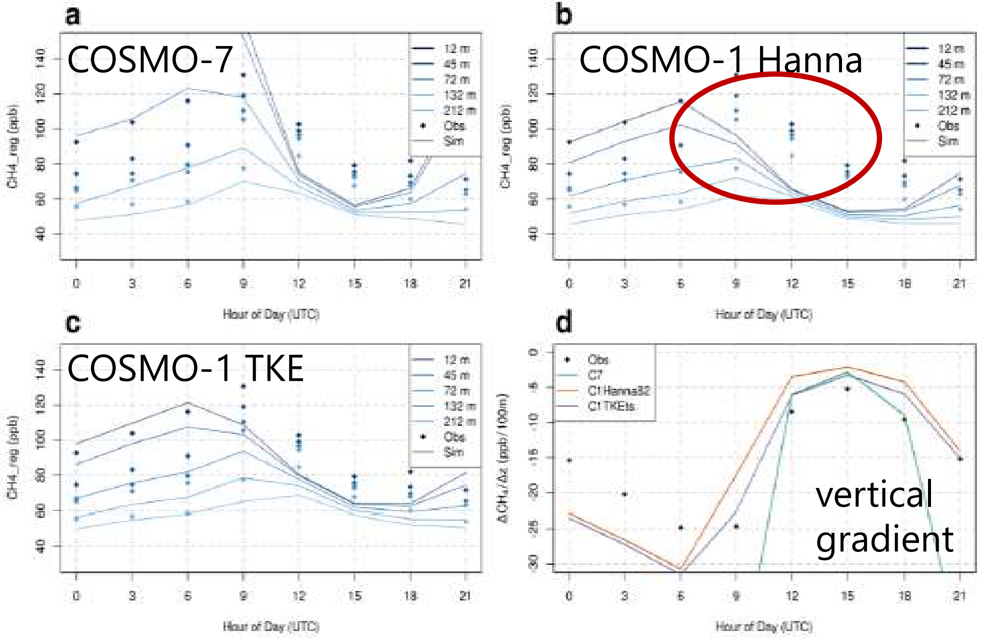
[Oney et al., 2015]



Challenge of elevated sites

FLEXPART-COSMO Resolution Dependence

- FLEXPART-COSMO operated at 1 km resolution (COSMO-1) gave considerably different mole fractions than at 7 km resolution
- Coupling to FLEXPART-IFS
- Re-tuning of FLEXPART turbulence parameterisation against COSMO-simulated TKE
- Validation against CH_4 observations at BRM



Diurnal cycle at different inlet heights

Source: Katharopoulos et al., 2022

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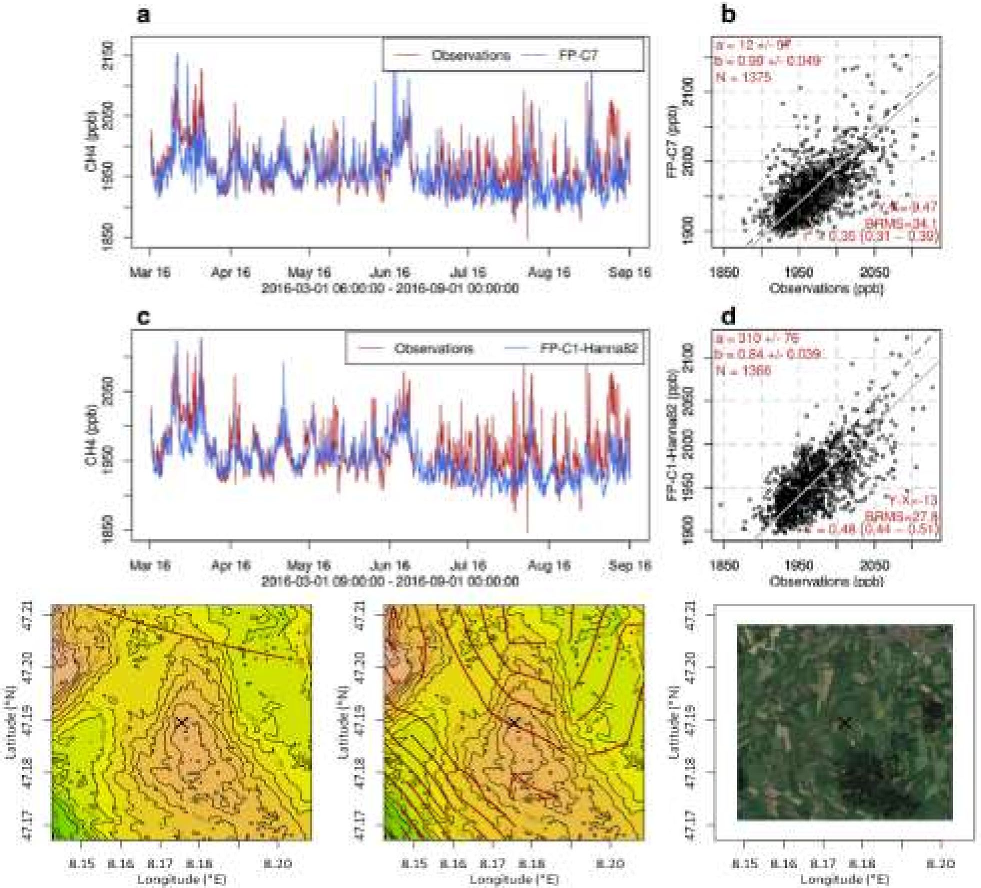
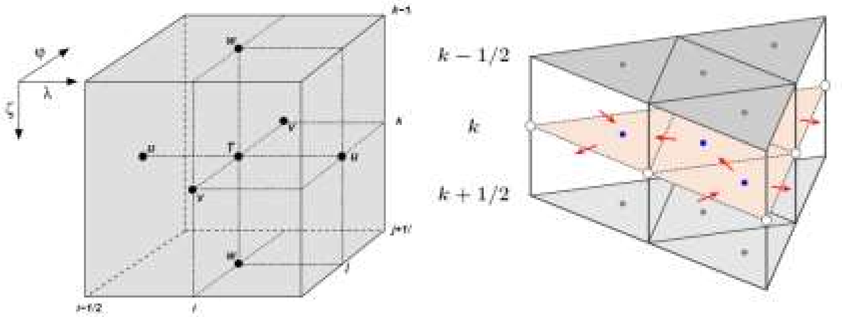
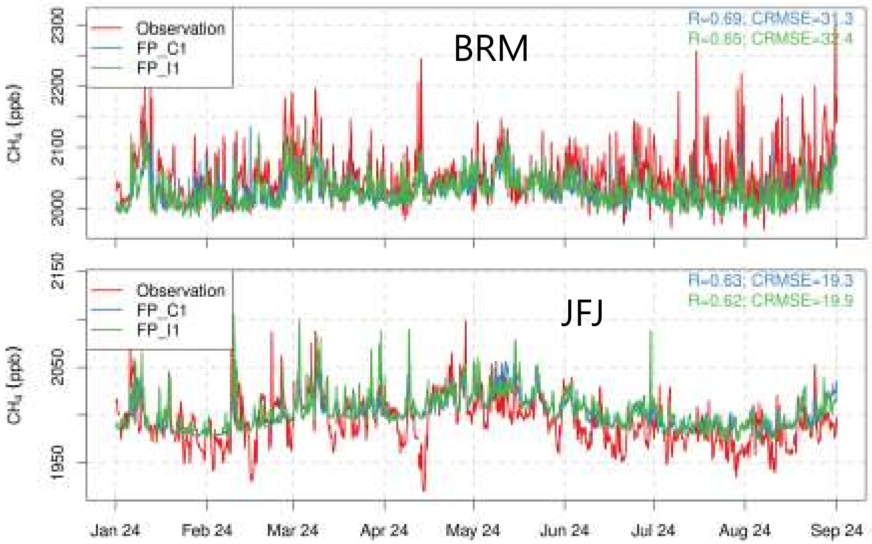


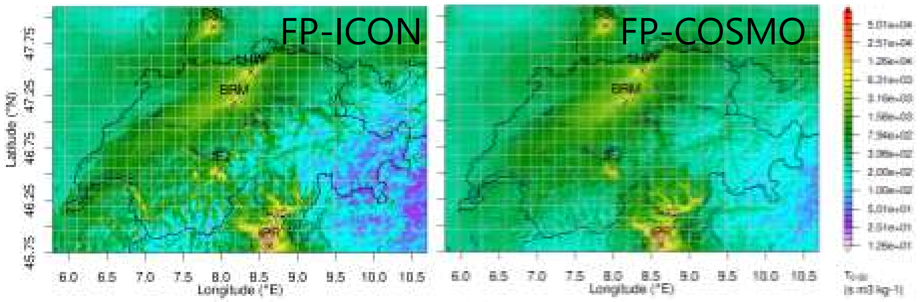
Source: Katharopoulos et al., 2022

FLEXPART-COSMO Transition to FLEXPART-ICON

- COSMO replaced at MeteoSwiss by ICON
- ICON operates on triangular grid
- Re-write of FLEXPART-COSMO to interpolate directly from native grid

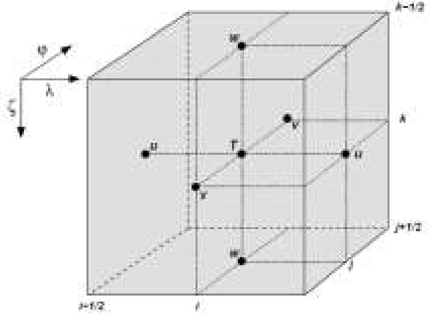




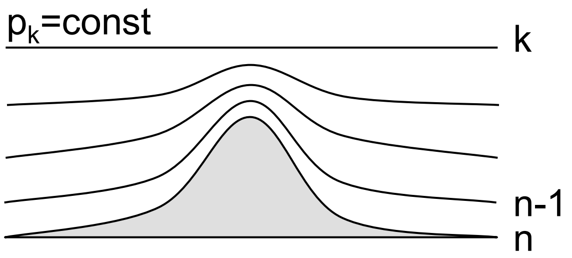


Transport Model: FLEXPART-COSMO

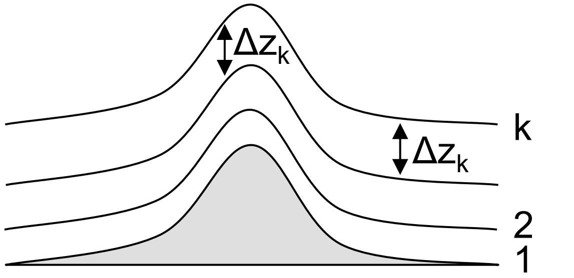
- Standard FLEXPART developed for input from ECMWF-IFS
  - Pressure-based hybrid coordinate, interpolated to fixed terrain following
  - Regular long/lat grid
- COSMO NWP
  - Hybrid z grid
  - Limited area rotated pole grid
- FLEXPART-COSMO: directly using output on COSMO staggered grid



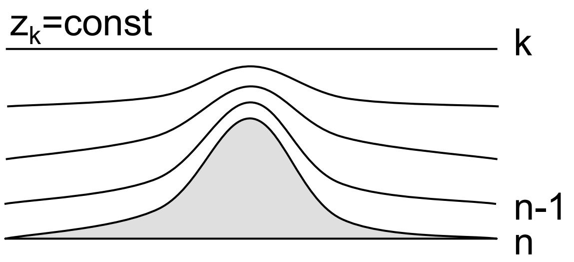
ECMWF:
Terrain following
hybrid pressure
levels



FLEXPART-IFS
(until version10):
Terrain following
constant Δz levels

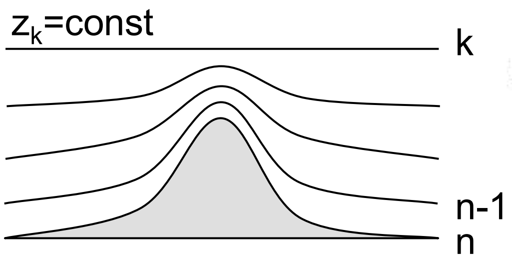


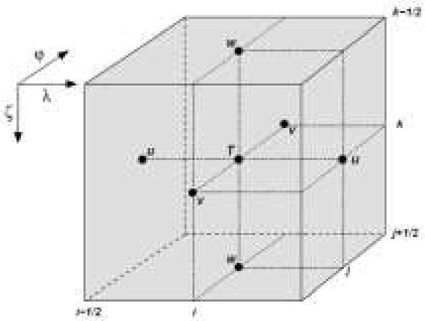
COSMO &
FLEXPART-COSMO:
Terrain following
hybrid z levels



Lagrangian Transport Model: FLEXPART-COSMO

- Standard FLEXPART developed for input from ECMWF-IFS
  - Pressure-based hybrid coordinate, interpolated to fixed terrain following (<v11)
  - Regular long/lat grid
- COSMO NWP
  - Hybrid z grid
  - Limited area rotated pole grid
- FLEXPART-COSMO: directly using output on native COSMO grid (staggered, hybrid z levels)





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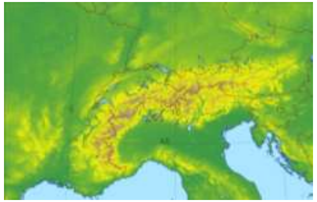

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- profilers (FF, DD, TT)
- In COSMO-2/1: Latent Heat Nudging

Hourly analysis fields available for FLEXPART

Summary and Research Questions

- Inverse modelling requires unbiased transport modelling (esp. in complex terrain)
- Inverse modelling estimates for Western European non-CO_2 GHGs based on surface observations reaching maturity
  - Multi-model estimates
  - Community tools (CIF, fluxie)
  - Routine observation and modelling data flows
  - Traceability
  - Emerging Tier 3 approaches may improve NID
  - Countries with atmospheric validation in NID: GBR, CHE, NLD, IRL, DEU, ESP, AUS, KOR, CAN, NZL, (USA), …
- Sector attribution (CH_4, N_2O) and biosphere separation (CO_2) remains challenging
- Use of co-tracers and isotopes emerging (limited by data availability)
- Satellites promise improved observational coverage
- Precision and accuracy requirements high

National/sub-national scale

- Are we on track? (i.e., national/sub-national legislation, Nationally Determined Contributions)
- How will carbon sink in forests develop?
- How accurate are bottom-up estimates for agriculture, organic soils, waste, fossil fuel sectors?
- Are there unknown sources or unexpected changes in known sources & sinks?

Global scale

- How will CO_2 uptake by land biosphere & oceans evolve in warming climate?
- How will thawing permafrost soils and warming wetlands/oceans affect CH_4 (& CO_2) fluxes?
- How will deforestation and other land use changes evolve?