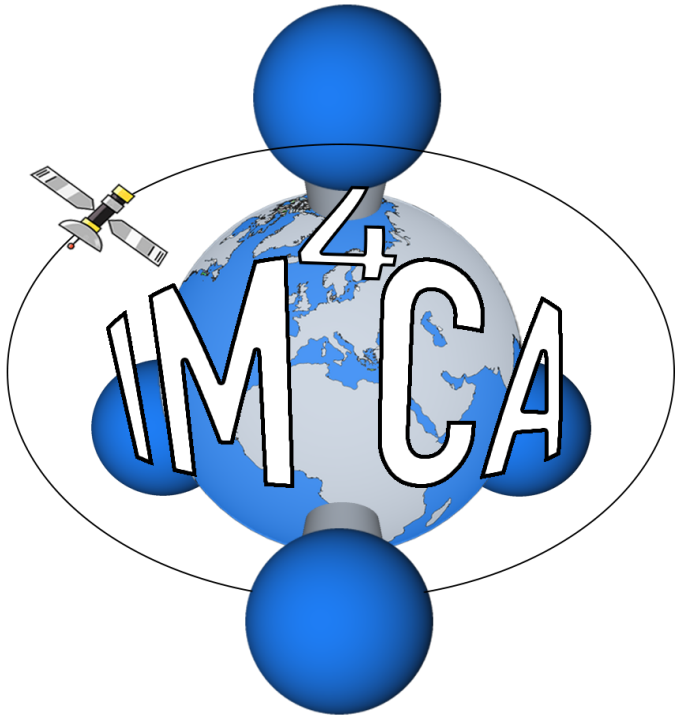


WP4: EU emission trends

Andreas Stohl, Hugo Denier van der Gon and WP4 team
(UniVie, TNO, IIASA, FMI, MPI-BGC, AGH, INOE, EMPA, SRON, SP, UU, VUA)



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Introduction and status

Main objectives of WP4:

- Reconcile and improve bottom-up emission inventories via enhanced process understanding. (T4.1 & 4.2)
- Enhance the ICOS network in Eastern Europe and extend the whole network with methane isotopes. (T4.3)
- Integrate European observational data using inverse modeling at high spatial and source sector resolution. (T4.4)
- Determine and reconcile European methane trends since 2005 with focus on 2020 2025. (T4.5)

Period M1-18: T4.1 & 4.2 started in M1 and T4.3 & 4.4 started at M17; T4.5 has not started yet

Deviation: In T4.3 a delay occurred due to delayed acquisition and subsequent installation of the new Isotope Ratio Mass Spectrometer, but this has been mitigated within IM4CA with the help of UU (see details in T4.3).

During the M1-M18 period, the following deliverables and milestones were due and completed:

- M4.1: First data set of EU methane emissions (T4.1)
- D4.5a: Synthesis of European emission trends v1 (natural fluxes) (T4.2)

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4.1 Emission inventories and sectoral trends

Goal

Analysis of CH4 emissions

- UNFCCC, GAINS, EDGAR, TNO/CAMS
- Methodological changes
- Main CH4 emission sources

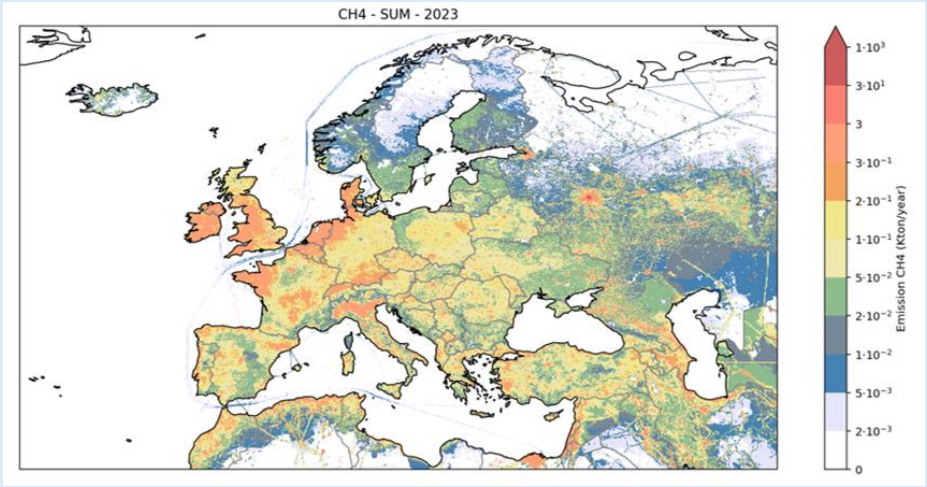
- Preparation of spatially gridded emissions, including time profiles and uncertainty

MS4.1 First gridded dataset (June 2026)

Spatially gridded CH4 emissions 2005-2023 at 0.1° x 0.05° resolution

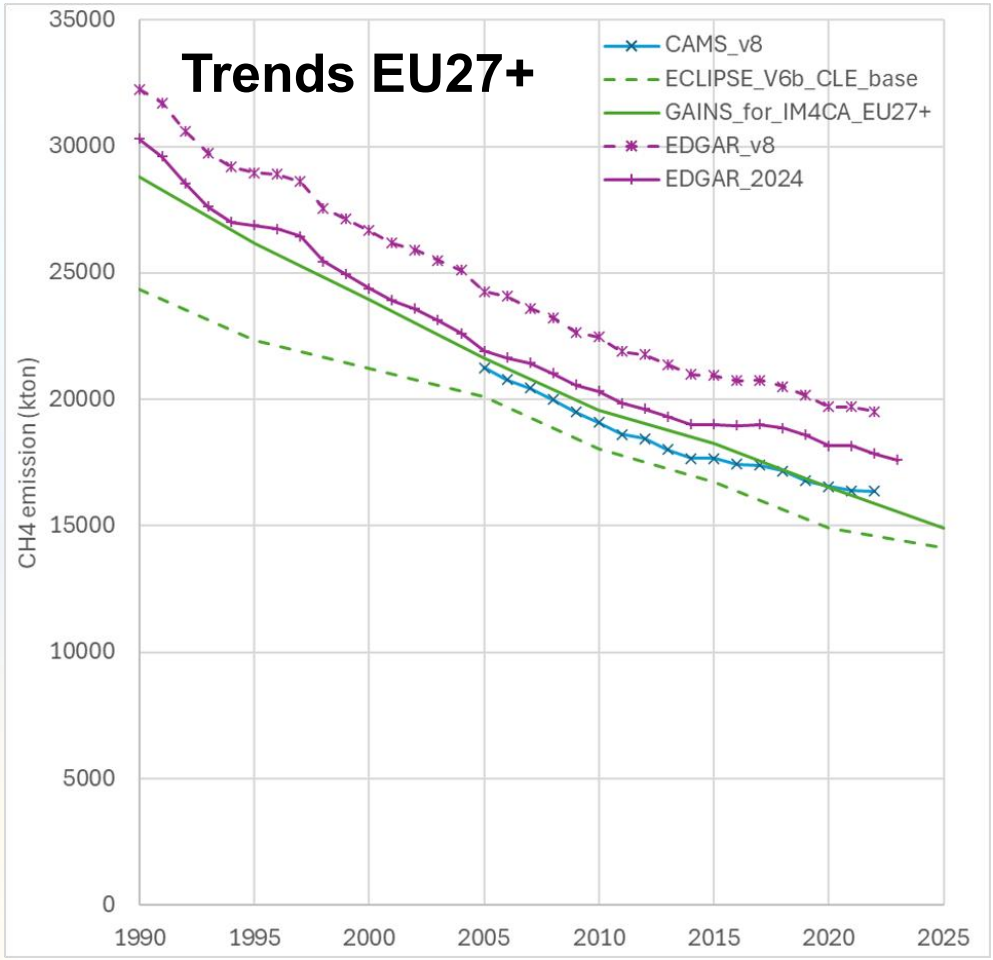
- Time profiles
- Milestone report, describing analysis of CH4 emissions and updates included in the spatially gridded dataset

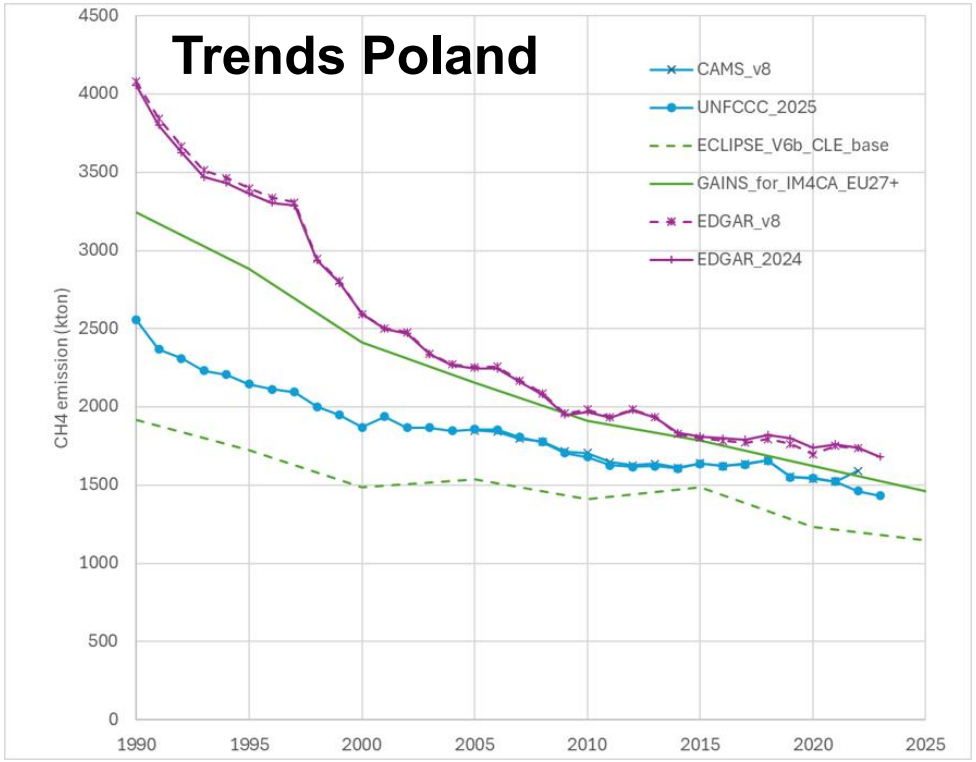
- Dataset 2023 available on ICOS carbon portal
- Complete time series available on the project fileshare for project partners



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4.1 Emission inventories and sectoral trends

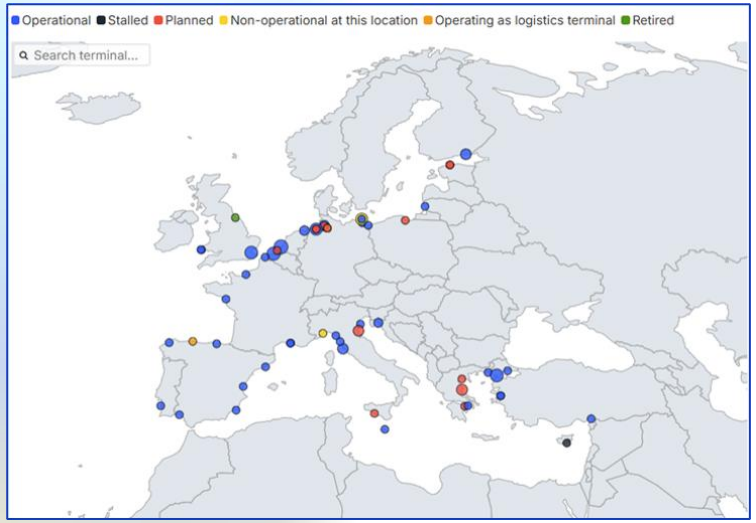




- Overall EU27+ trend similar, at country level significant discrepancies
- To understand trends and support T4.4 we build and compile a modified inventory for EU27+

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4.1 Summary updates for specific sectors in the first emission dataset

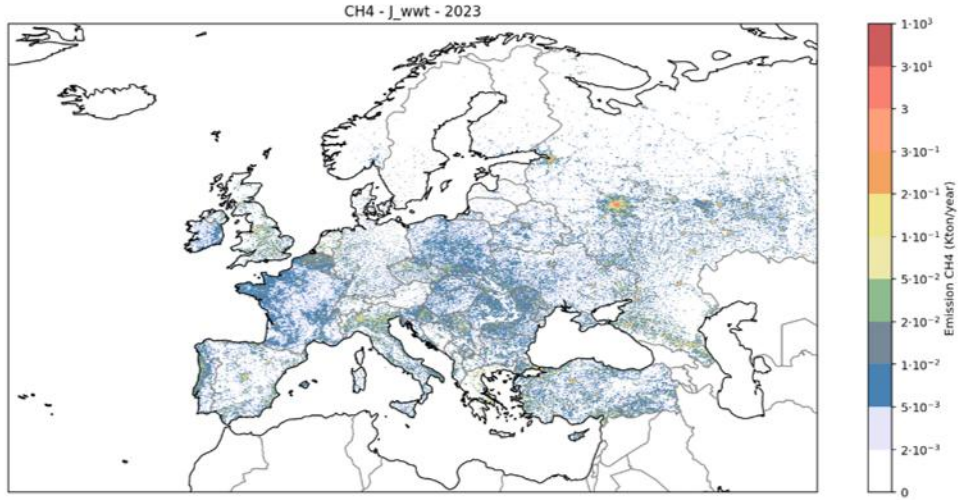


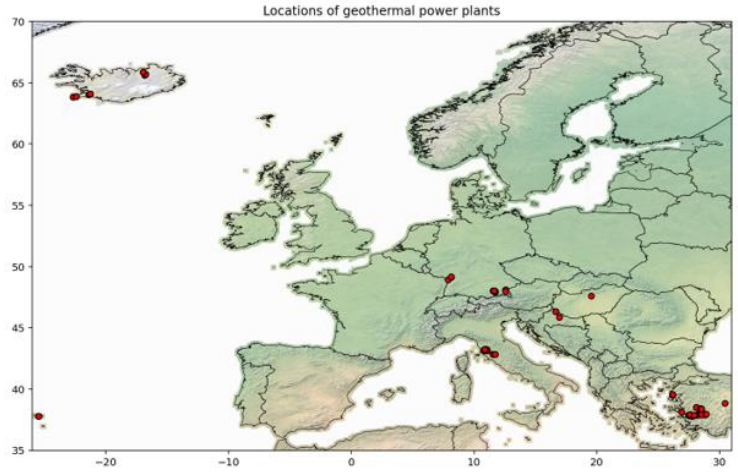
LNG terminals

- Increasing importance of LNG import, and not reported by all countries
- Emissions calculated for all countries

Waste water treatment

- Measurements suggest that these emissions might be underestimated
- Partly related to UNFCCC 2019 refinements
- Emissions and gridding updated





Geothermal power plants

- Emissions calculated for all countries (except Iceland, Italy who report already)
- Spatial distribution based on point sources

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4.1 Next steps

Deliverable 4.1: Final gridded dataset (December 2026)

High-resolution EU methane emission inventory

- Spatially distributed emissions
- Time profiles
- Uncertainty

Analysis and/or updates for specific sectors in deliverable 4.1:
(Additional to the sectors in MS 4.1)

- Solid waste disposal
- Oil & gas production
- Small combustion
- Biogas production
- Ditches and freshwater systems
- Urban sewage systems

Key points of attention:

- Investigate inclusion of satellite-based point source emissions
- Provide analysis overlap / double counting / missing emissions between Anthropogenic (T4.1) and Natural (T4.2) emissions especially semi-natural waterbodies

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4.2 Trends in (semi-)natural methane sources

- **Objectives:** Estimate biospheric CH4 fluxes from pristine and rewetted peatlands in Europe with the JSBACH-HIMMELI ecosystem model for the past decades at daily resolution, including fluxes in wet and dry mineral soils. Combine with CH4 emissions from lakes, reservoirs and rivers

- **M1-18: Implementation update:** Model simulations have been made and land fluxes and freshwater emissions analysed and processed for years 1990 to 2025.
  - **Deliverable of D4.5a**: Synthesis of European emission trends v1 (M18) has been prepared. Data and report have been delivered.

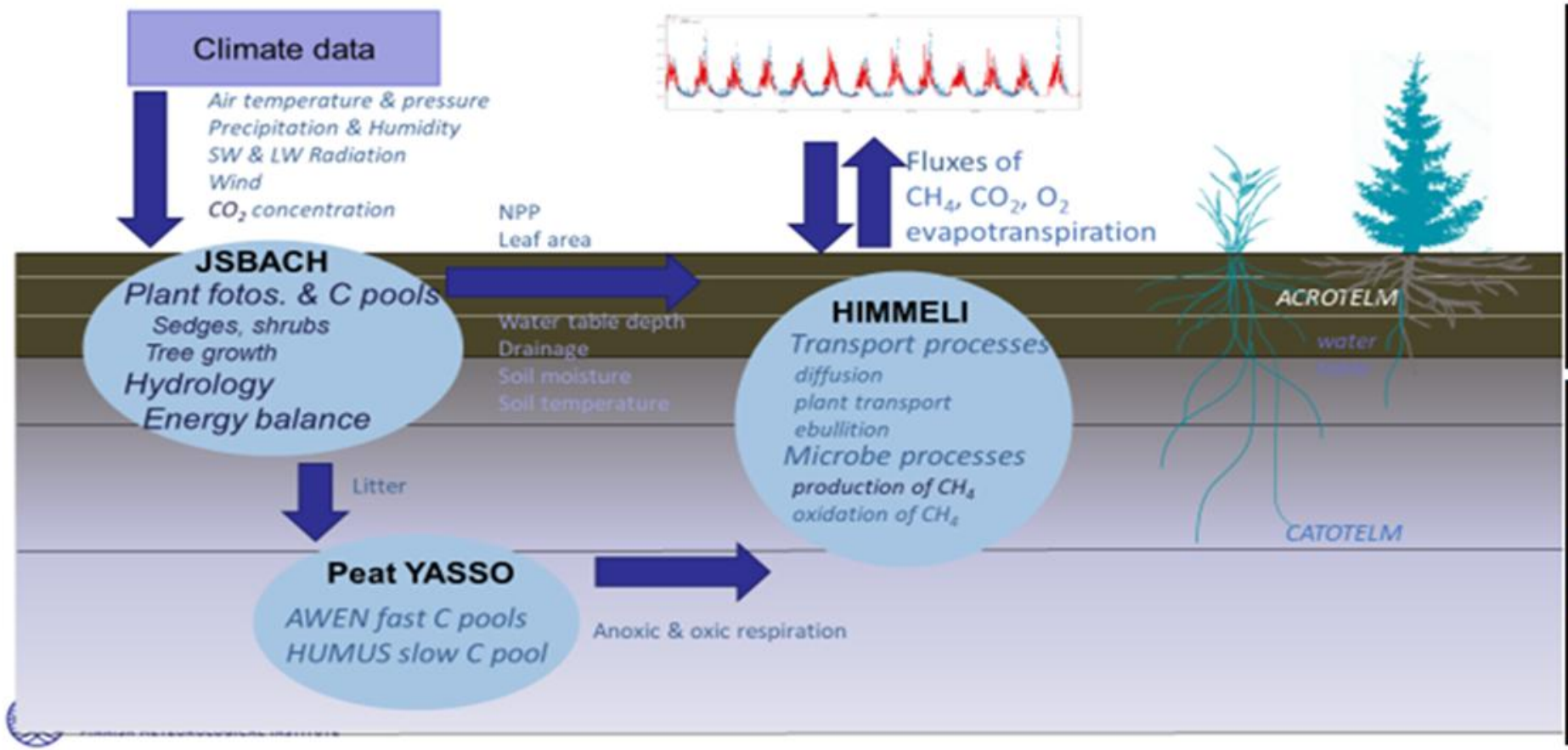
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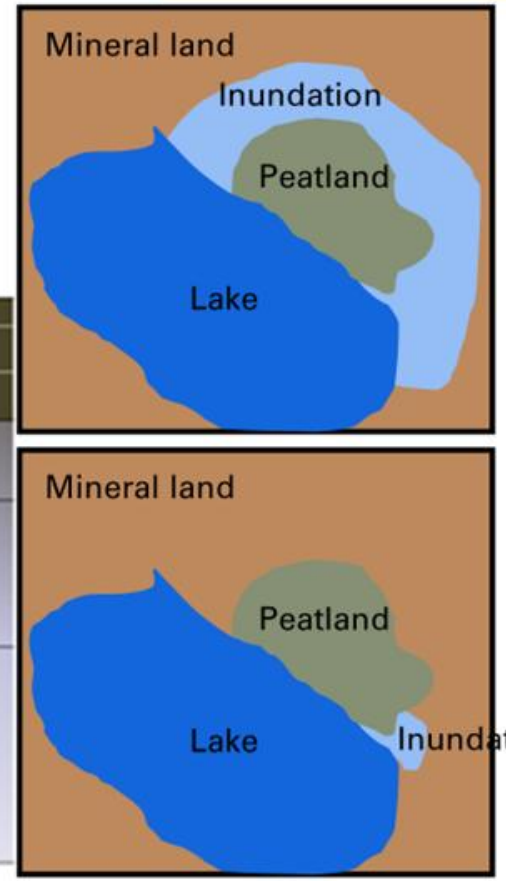
T4.2 JSBACH peatland and mineral land methane fluxes (FMI)

- Peatlands (F_{pe}): JSBACH-PeatYASSO ecosystem model coupled with HIMMELI methane model
- Mineral land emissions (F_{me}): JSBACH-PeatYASSO: R_{hetero}, Soil moist, temp & emission factor
- Mineral land uptake (F_{mu}): JSBACH-PeatYASSO: Soil moist, temp & Curry et al parametrization
- Inundated lands (F_{in}): JSBACH-YASSO: R_{hetero} & emission factor & WAD2M inundation map

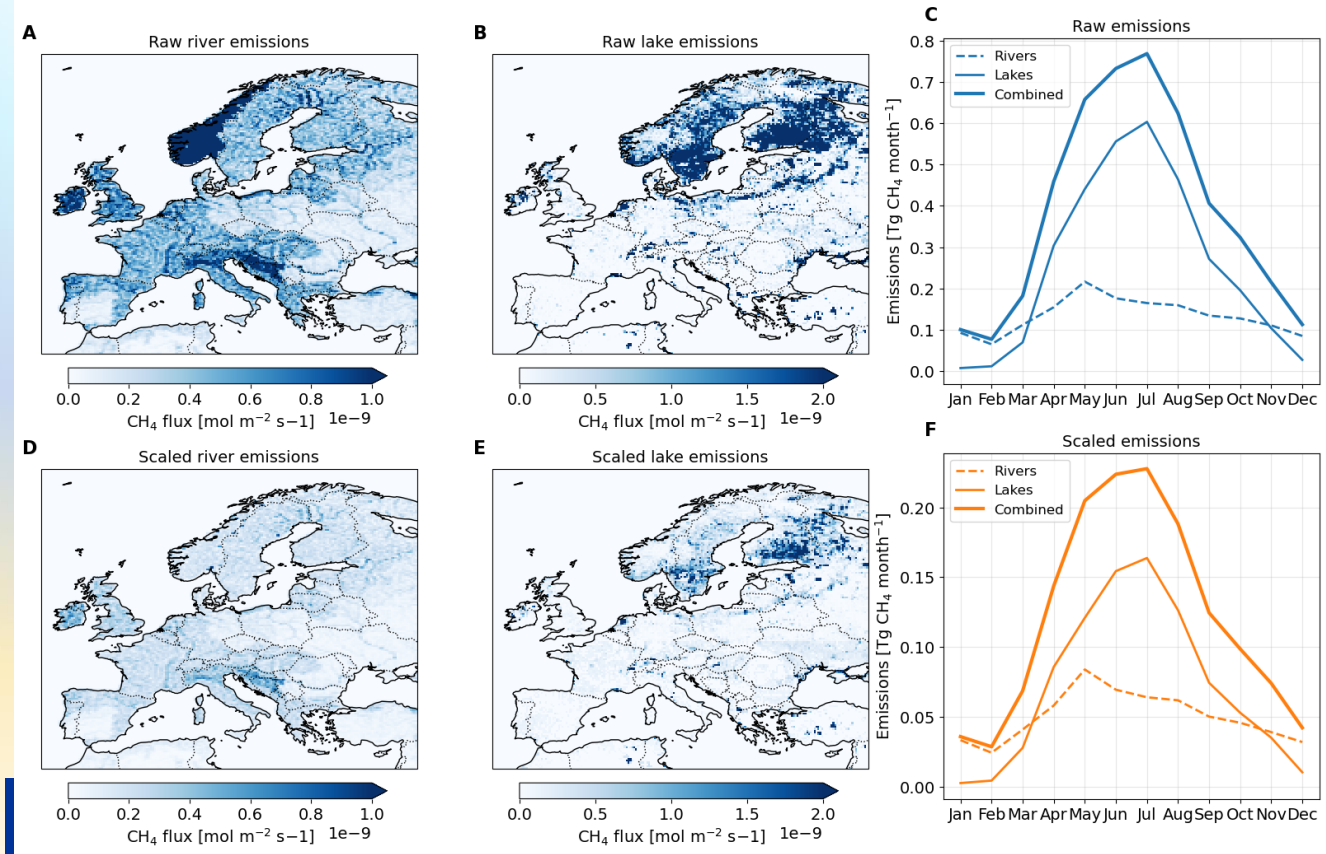
⟹ Net flux in a grid cell i

$$F_{CH4,i} = f_{pe,i} \cdot F_{pe,i} + f_{m,i} \cdot (F_{me,i} - F_{mu,i}) + f_{in,i} \cdot F_{in,i}$$





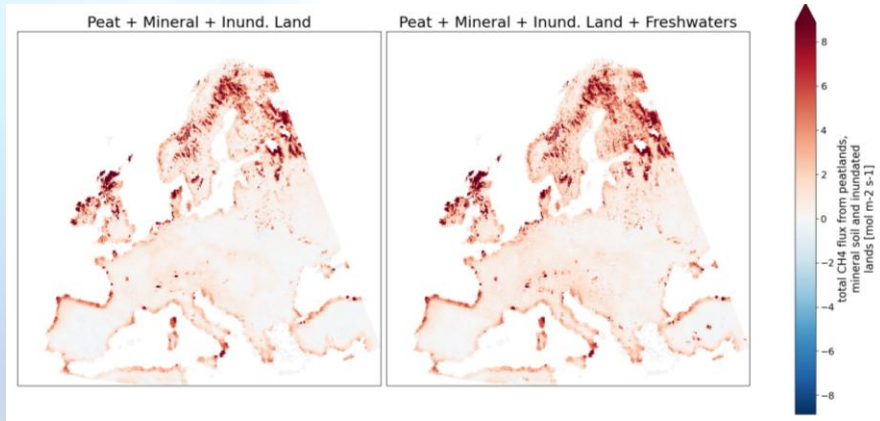
4.2 Freshwater emissions

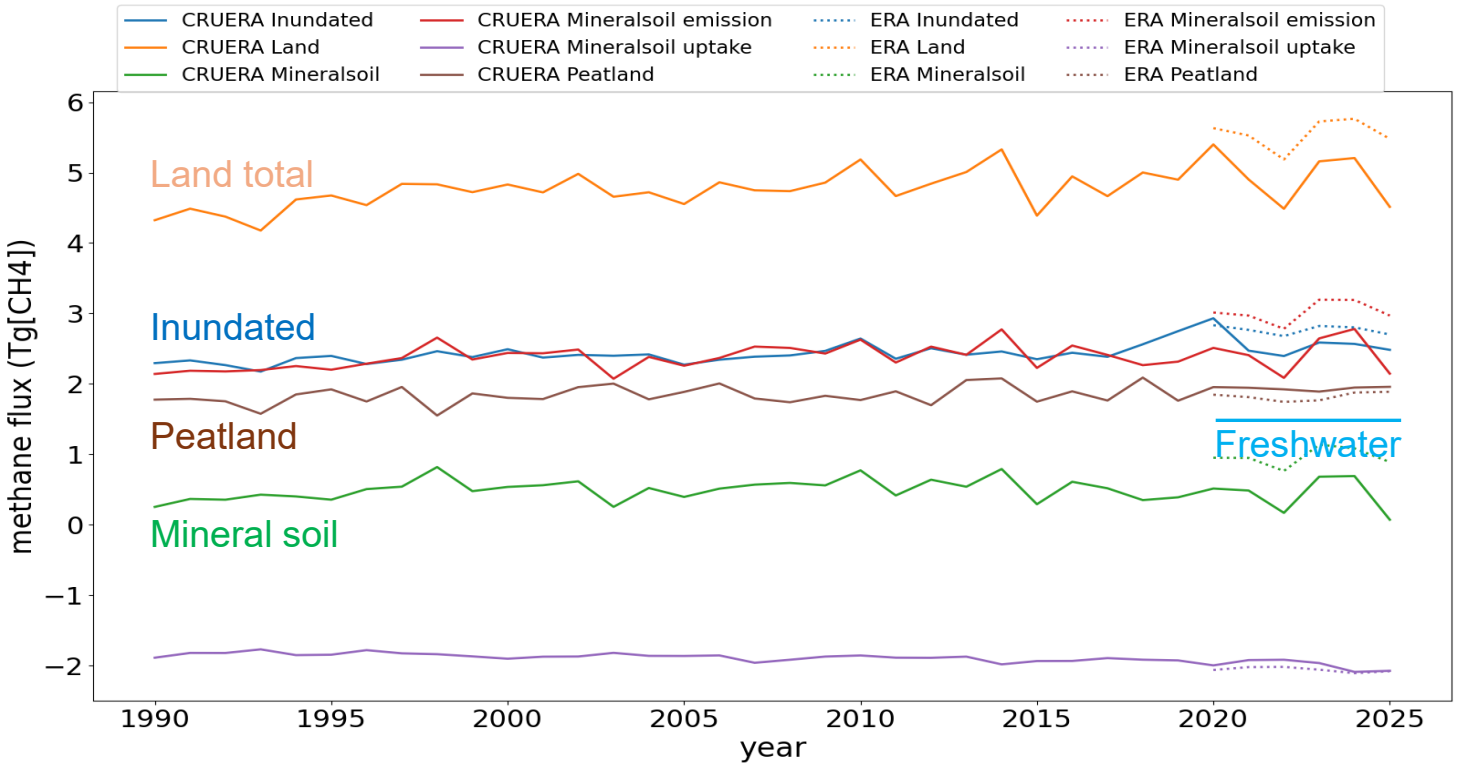


- Freshwater emissions were obtained from Rocher-Ros et al 2023 and Johnson et al, 2022. Large lakes and anomalous river emissions were scaled down.
- Freshwater emissions were remapped to spatial resolution of 0.1°×0.1° used in JSBACH (HILDA+ land cover). The freshwater dataset is climatological with daily temporal resolution.
- The resulting annual emissions for the European domain are 0.6 Tg/yr for rivers and 0.86 Tg/yr for lakes, a combined total of 1.46 Tg/yr.

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4.2 Land fluxes





- The largest methane emissions are in peatland abundant areas and in areas with seasonal inundation. The net mineral soil flux is relatively small.
- The total net peat, mineral and inundated land flux in Europe exhibits a weak but statistically important increasing trend of +0.014 Tg yr^{-1}.

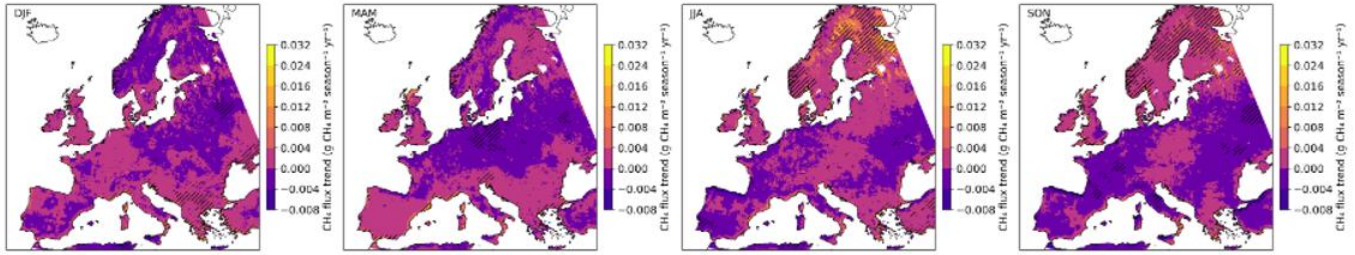
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4.2 Trends in methane fluxes

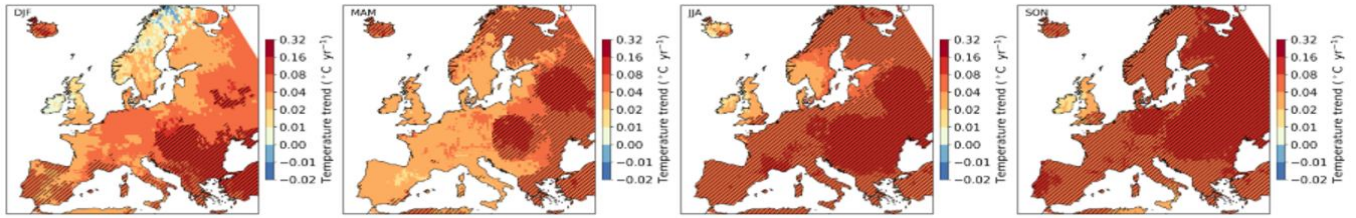
- Widespread and significant positive trends in summertime CH_4 emissions across the northern part of the domain.
  - Positive temperature trends during summer and autumn
  - Increasing precipitation trends in the north but not in the south
- Increase in the inundated land emissions and peatland emissions in northern Europe.
- Decline in peatland and mineral land emissions across eastern Europe

Winter spring summer autumn

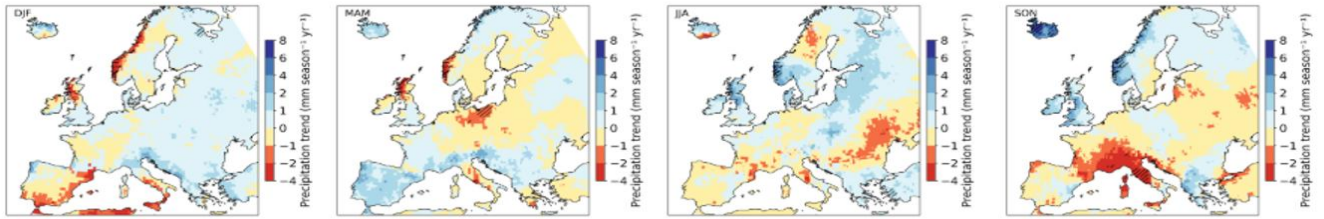
Total emissions



Daily maximum temperature



Precipitation



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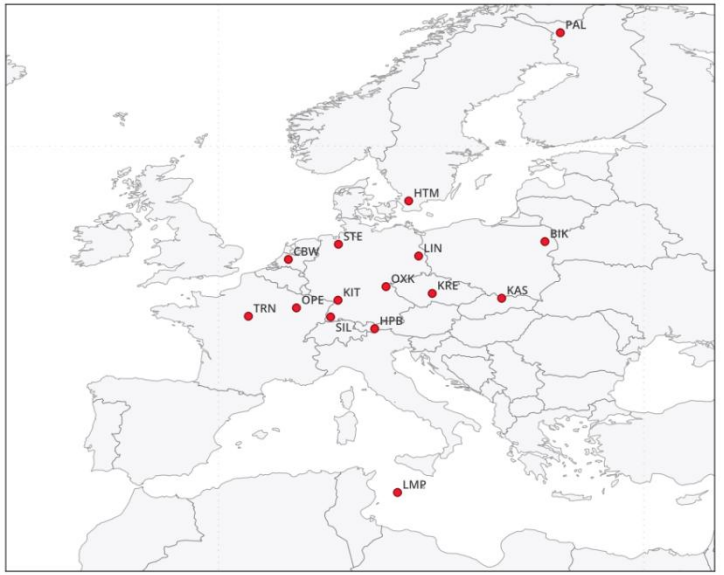
4.3 Extension of ICOS CH_4 monitoring capabilities

- **Objectives:**
  - Establish a high-precision measurement capability for CH_4 stable isotopes ($\delta^{13}C$ and $\delta^{2}H$) within the ICOS network to create a sustainable long-term dataset
  - Provide isotope data for Task 4.4 inverse modelling



- **Implementation update:**
  - Isotope Ratio Mass Spectrometer (IRMS) installation and automation required an adjustment to the implementation timeline

- **A temporary measurement approach to maintain data delivery for WP4 activities:**
  - Two targeted ~60-day campaigns in Summer and Winter
    - Flask samples collected from 15 sites across Europe
    - Summer campaign: started 1 July 2026
    - All samples analyzed by University of Utrecht (UU)



Sampling sites for the two target campaigns

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4.3 Extension of ICOS CH_4 monitoring capabilities

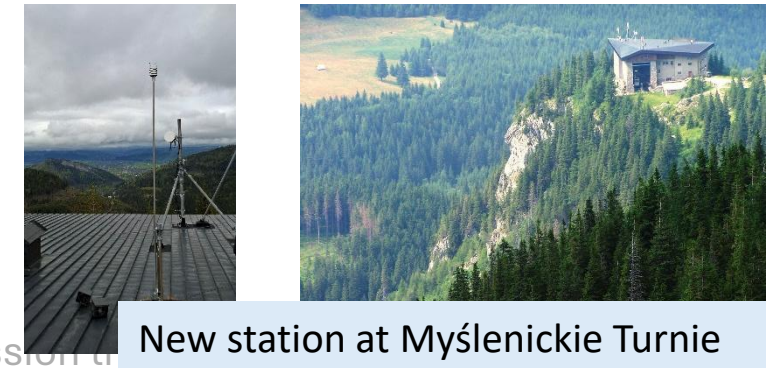
Objectives: Expansion of the ICOS network in Eastern Europe:

- **Poland:**
  1. New station: **Myślenickie Turnie** (49.2519°N, 19.9738°E, 1354 m a.s.l.)
     - Equipped with Picarro G-2201-i (CO_2, CH_4, $^{13}CO_2$ and $^{13}CH_4$) and Vaisala WXT530 meteo station
     - Operational since May/2025



  2. New ICOS flask sampler for CH_4 isotope monitoring: **Kasprowy Wierch (KASLAB)** (49°14'N 19°59'E 1989masl)
     - Equipped with Picarro G2401 (CO_2, CH_4 and CO) and ICOS sampler
     - Flask collection since July/2026

- **Romania:**
  1. 30m mobile tower: **MARS site** (south of Bucharest)
     - Continuous monitoring of CH_4, C_2H_6 and $d^{13}C\text{-}CH_4$
     - Operational since June/2026



New station at Myślenickie Turnie

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4.4 European inverse modelling

Objectives:

- **Long-term trends of CH_4** emissions obtained through 20-years inverse modelling using different transport models and inversion frameworks
- **Separate emissions into broad source sectors** through inversions using **isotope measurements**
- **Post-2020 inversions** with **satellite data**, using TROPOMI CH_4 observations and potentially new high-resolution satellite instruments

	UniVie	SP	EMPA	MPI-BGC	TNO
Transport model	FLEXPART-11	CHIMERE	ICON-ART	STILT	LOTOS-EUROS
Inversion Framework	FLEXINVERT	CIF	CIF	CSR	LEVar
Spatial resolution	0.25°x0.25°	0.25°x0.25°	~13 km	0.25°x0.25°	0.25°x0.25°
Meteorological data	ECMWF ERA5	ECMWF IFS	ECMWF ERA5	ECMWF IFS	ECMWF ERA5

Overview of all inverse modelling set-ups using stationary observations

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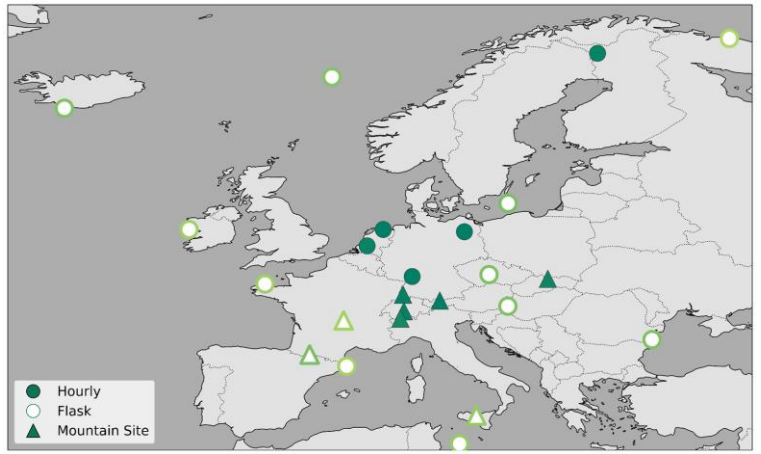
4.4 European inverse modelling

First steps:

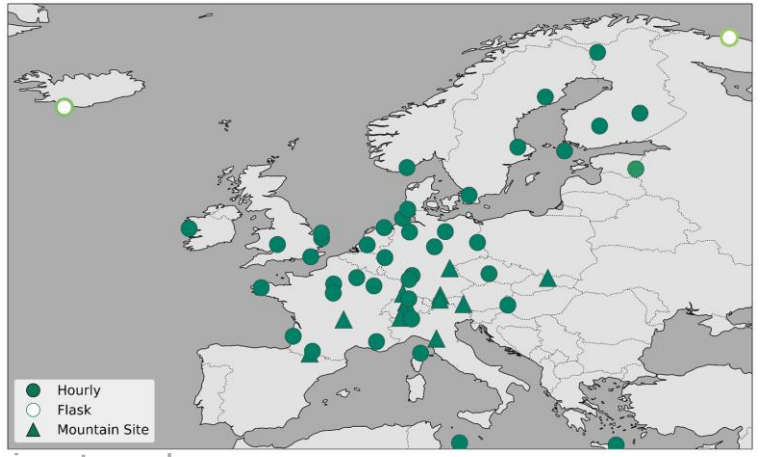
- First draft of **inversion protocol** for all inverse modelling set-ups
  - Inversion domain, time ranges for different tasks, background concentrations etc.
- Collection of **in-situ data**
  - Predominantly from ICOS network, but also various other sources
- Preparation of **prior flux estimates**
  - From tasks 4.1 and 4.1 and additional datasets of other natural CH_4 emissions

➔ **First results** from each contributing team planned to be finished by **end of 2026** to evaluate challenges and limitations

Observation sites 2005



Observation sites 2024



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Thank you!

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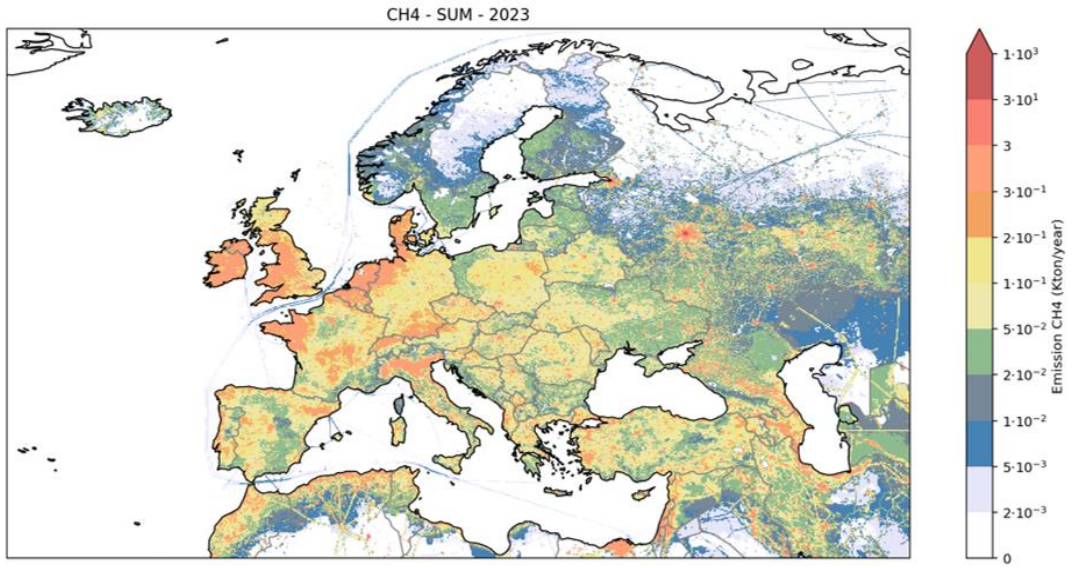
https://im4ca.eu

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Backup slides

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4.1 Milestone 4.1: First gridded emission dataset



Spatially distributed emission data

- Official reported emissions
- Spatially distributed, approach similar to CAMS-REG and HEU projects VERIFY, CoCO2 and AVENGERS

Updates for specific sectors:

- Updated national emissions and spatial distribution:
  - Waste water treatment
- Emission estimate and spatial distribution added to the inventory:
  - LNG terminals
  - Geothermal power plants
- Analysed, but not updated:
  - Agriculture
  - Coal mining

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4.1 Waste water treatment

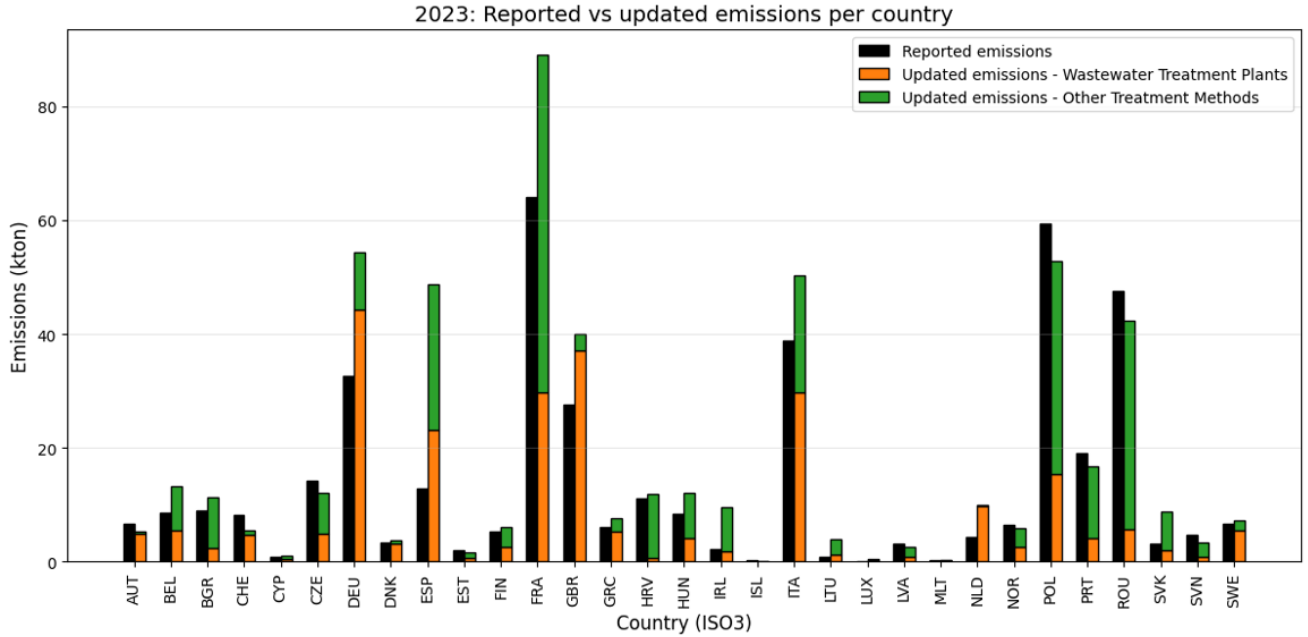
- Updated methodology in IPCC 2019 Refinement, but not taken up by all countries.
- Measurements suggest the updated methodology underestimates CH4 emissions from WWTP (Song et al. 2023; TNO 2025)

Updated national emissions

- Measurement-based EF for WWTP
- Empirical implied EF for other waste water treatment based on reported values

Updated spatial distribution

- WWTP: Distributed based on WWTPs in EPRTR and EEA Waterbase UWWTP database
- Other waste water treatment: Distributed based on rural population

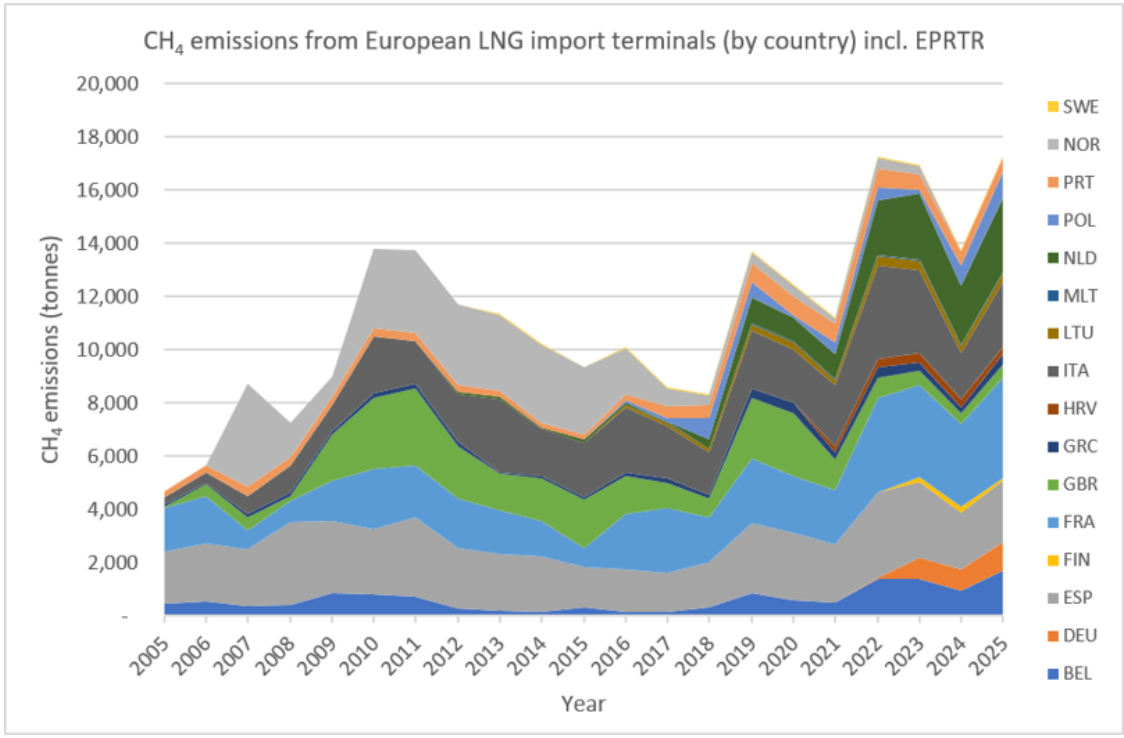


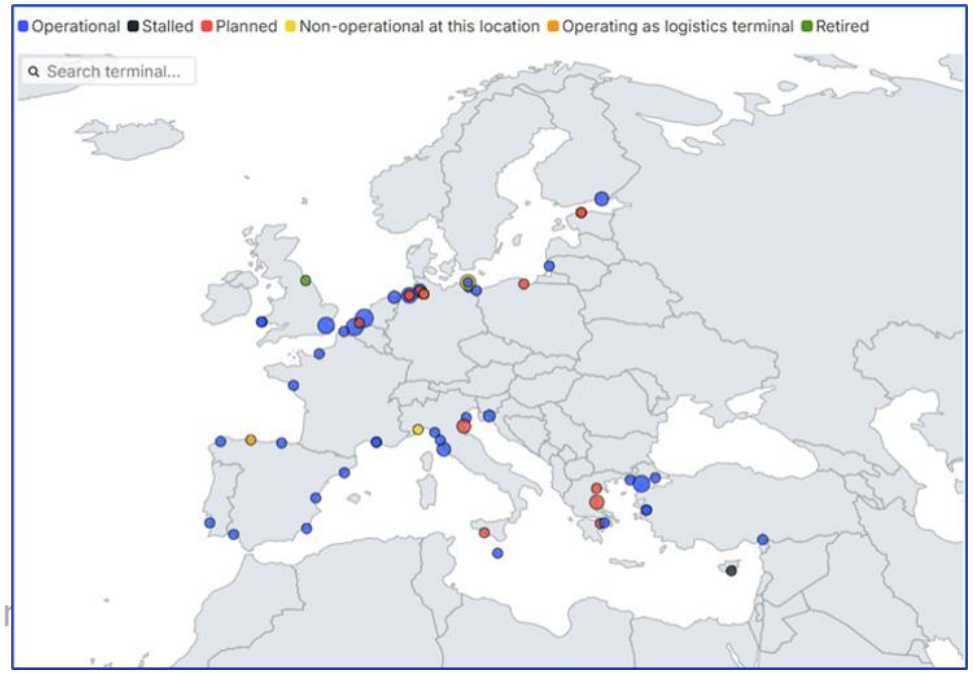
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4.1 LNG terminals

- LNG import is of increasing importance for Europe

- Emissions calculated for all countries:
  - Activity data on major LNG import terminals:
  - Gas Infrastructure Europe (GIE) transparency platform
  - Containing 36 major LNG import terminals, from 2012 onwards
  - Emission factors and leakage rates for LNG import:
  - 3 studies with similar estimates
  - Innocenti et al 2023 loss rate is used: Most transparent, measurement-based and peer-reviewed



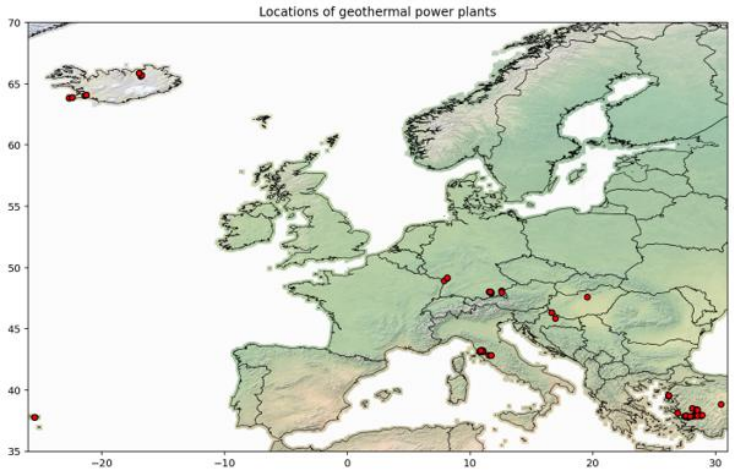


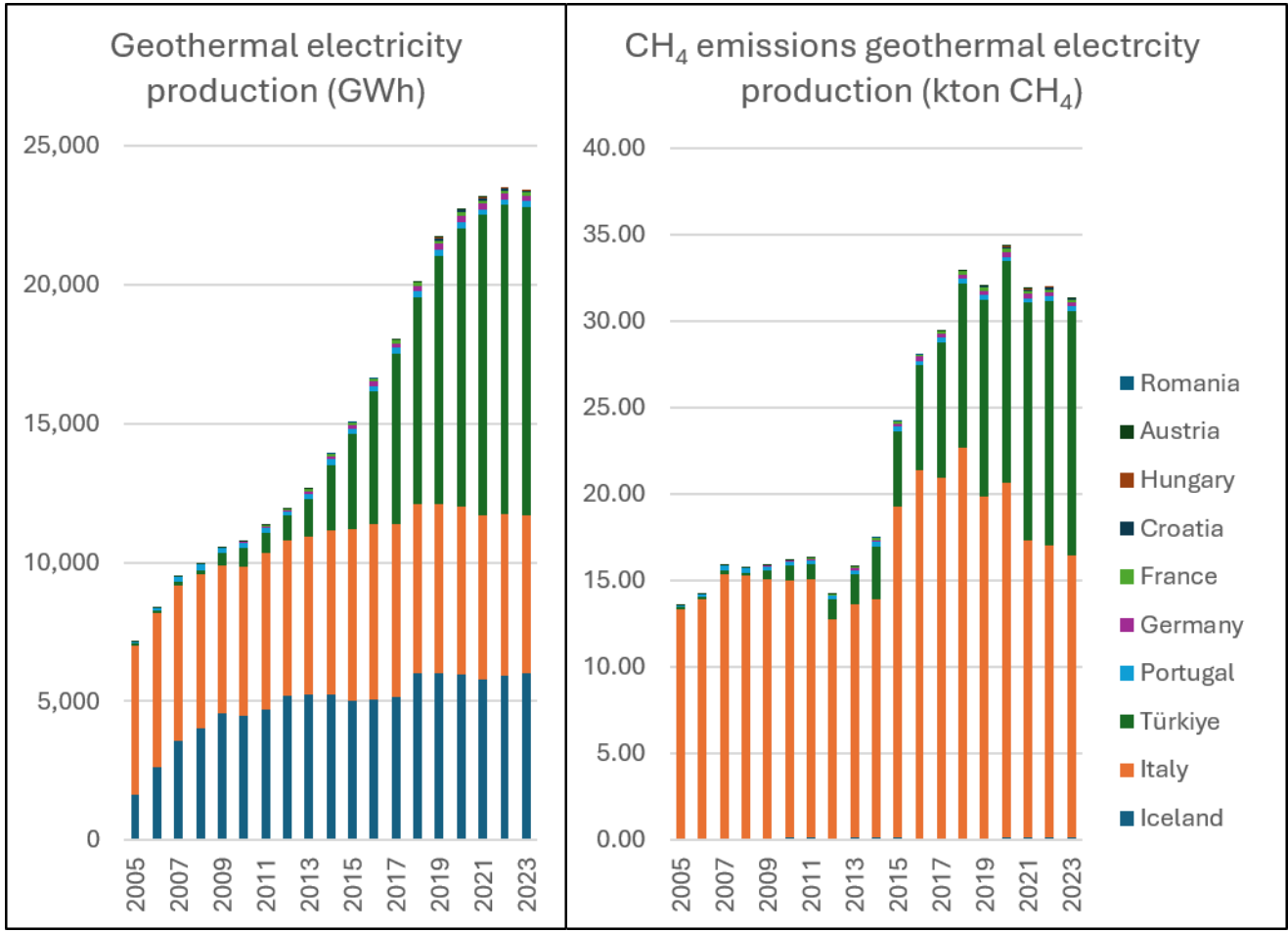
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4.1 Geothermal Power Plants

- Release of gases from geothermal fluid during energy extraction process

- Emissions reported by Italy and Iceland
- Additional emission estimate for the other countries
- Emission factor for additional estimate:
  - Based on literature on geothermal power plants in Turkey
  - Approximately in the middle between the IEF of Iceland and Italy





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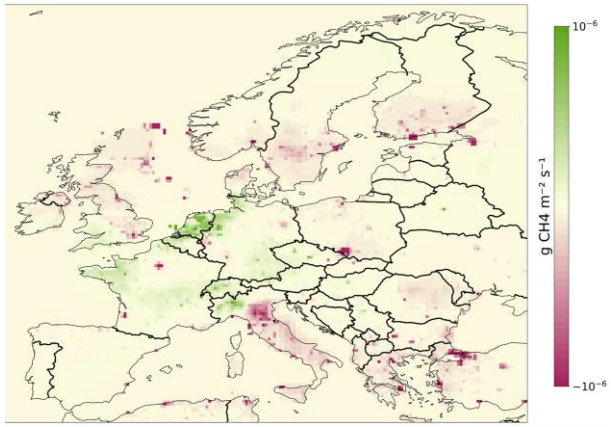
4.4 European inverse modelling: 4.4.1 and 4.4.2

4.4.1 Long-term top-down flux trends for CH4

	UniVie	SP	EMPA	MPI-BGC	TNO
Transport model	FLEXPART-11	CHIMERE	ICON-ART	STILT	LOTOS-EUROS
Inversion Framework	FLEXINVERT	CIF	CIF	CSR	LEVar
Spatial resolution	0.25°x0.25°	0.25°x0.25°	~13 km	0.25°x0.25°	0.25°x0.25°
Meteorological data	ECMWF ERA5	ECMWF IFS	ECMWF ERA5	ECMWF IFS	ECMWF ERA5

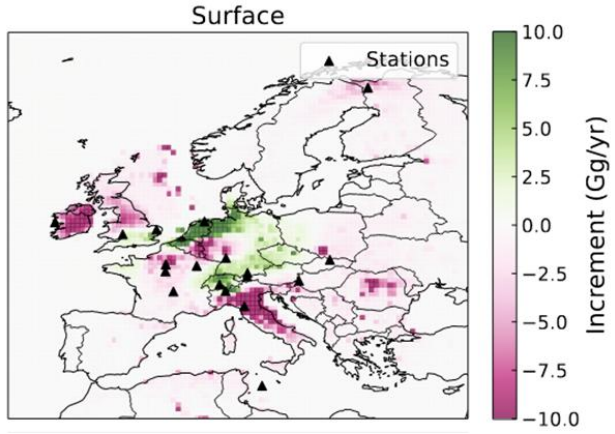
- Multi-decadal inversion for Europe (2005 to 2024)
- Domain: 13.75°W to 35°E and latitudes from 35°N to 72°N
- Background : CAMS global inversion-optimised greenhouse gas fluxes and concentrations Version v24r2
- Prior fluxes from T4.1 and T4.2 and WP5

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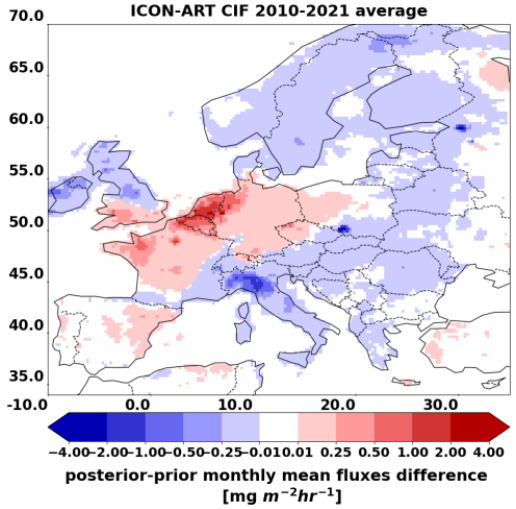
FLEXINVERT

Increment 2022, figure from GHG-KIT project



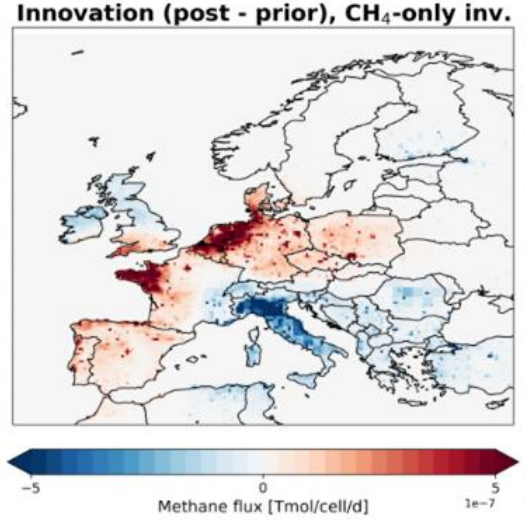
CIF-Chimere

Increment 2019, figure from Sicsik-Paré et al. (2025)



CIF-ICON-ART

Avg. increment 2010-2021, figure from AVENGERS Project

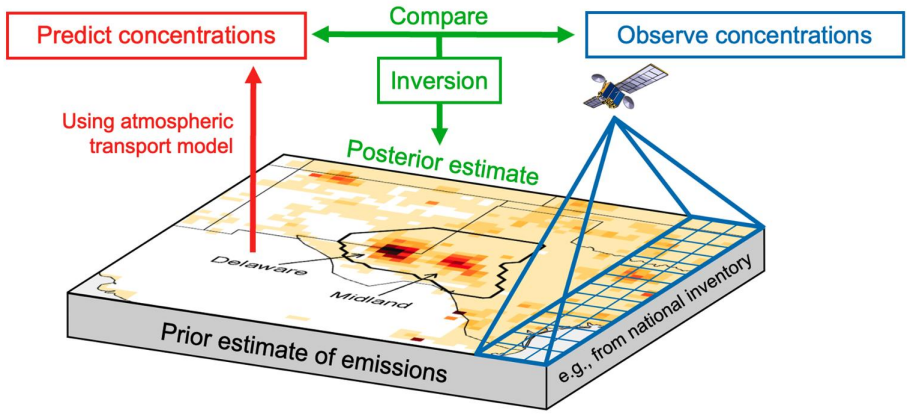


CarboScope-Regional

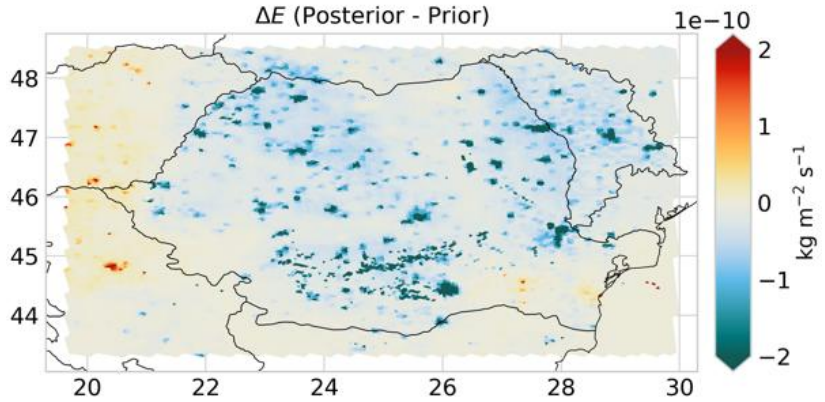
Increment 2021, figure from Fabian Maier (MPI-BGC)

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4.4.3 CH4 fluxes, including from point sources, based on satellite observations



IMI inversion scheme from IMI website, carboninversion.com



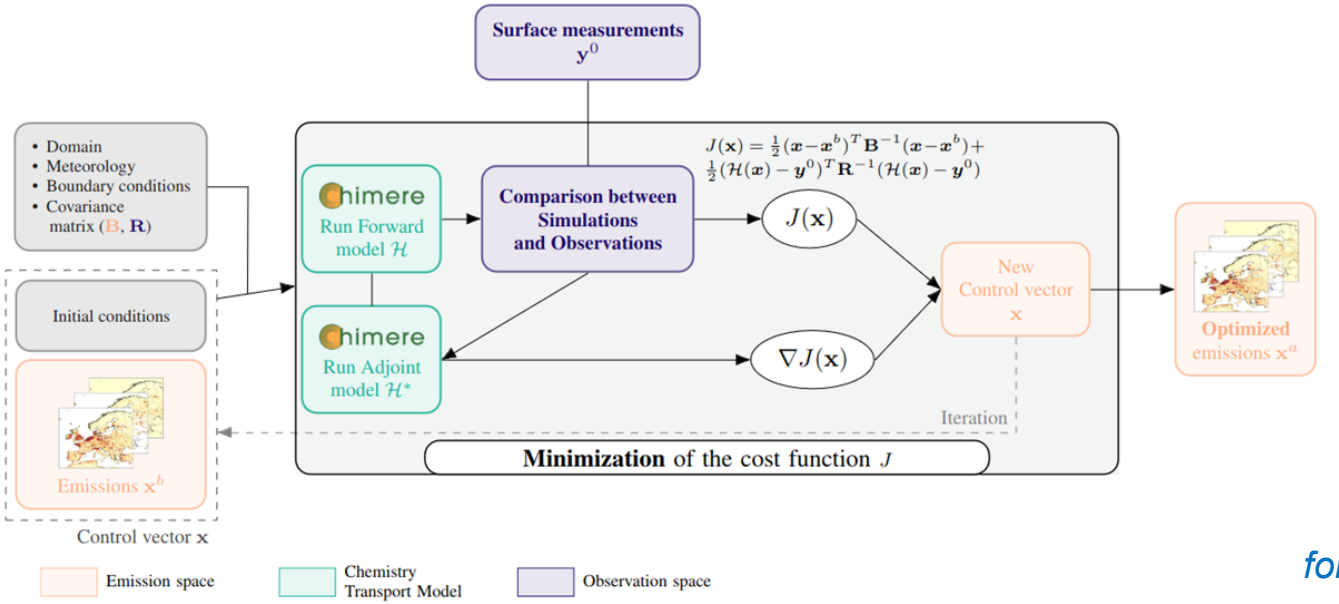
CH4 flux adjustment, 1 year inversion in CIF-ICON-ART using TROPOMI observations as part of the SMART-CH4 project

- **SRON**:
  - Analytical inversions using the Integrated Methane Inversion (IMI) tool with GEOS-Chem
  - 12 km or 25 km resolution
  - Will incorporate high-resolution satellite observations where available. Will explore using various TROPOMI data products and priors.
- **EMPA**:
  - Inversions using CIF-ICON-ART with an Ensemble Square Root Filter (EnSRF) (Thanwerdas et al, 2025)
  - Simulations at higher resolution planned, integration of high-resolution satellites (possibly developed as part of SMART-CH4)

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T4.4.1 Long-term top-down flux trends for CH4

Regional inversions using CIF-CHIMERE from in-situ measurements from 2005 to 2025 using CH4 fluxes from T4.1 and T4.2



Principle of the CIF-CHIMERE variational inversions

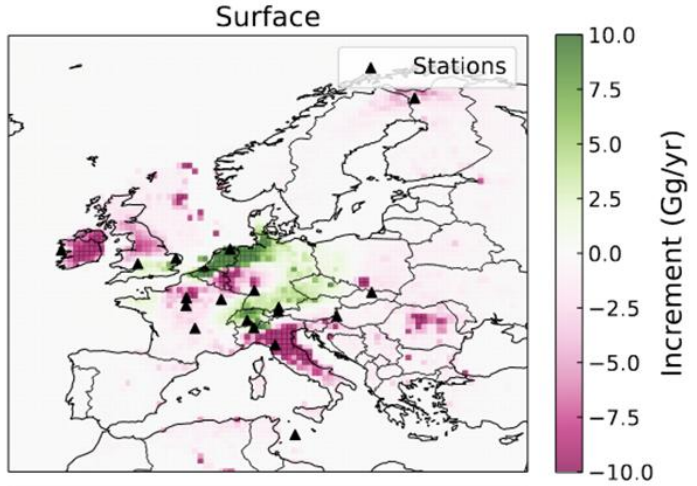
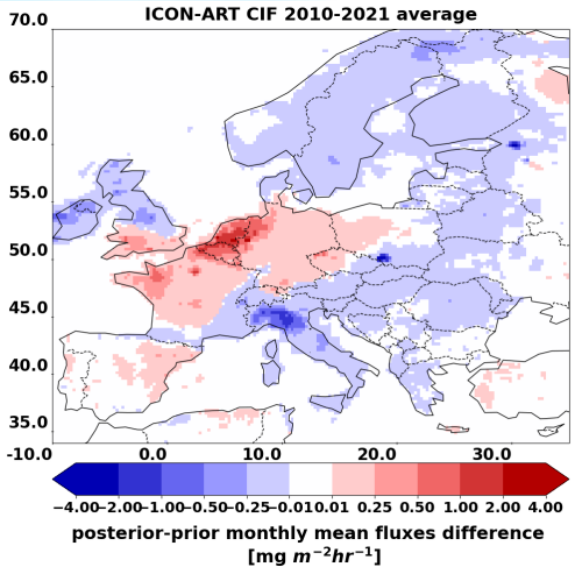


Illustration of the corrections to prior CH_4 emissions from the inversion for the year 2019 using surface measurements at a 0.5° resolution over Europe
Figure : Sicsik-Paré et al. (2025)

Funded by the European Union

Inversions using CIF-ICON-ART with an Ensemble Square Root Filter (EnSRF)

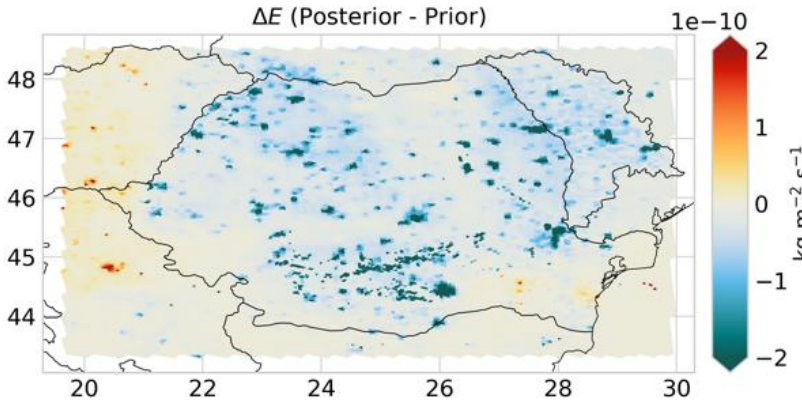
[Thanwerdas et al, 2025]



CH4 flux adjustment for 12 year inversion in CIF-ICON-ART using ICOS observations as part of the AVENGERS project

Tasks 4.4.1 & 4.4.2: Simulations at ~13 km resolution for in-situ and TROPOMI-based inversions planned

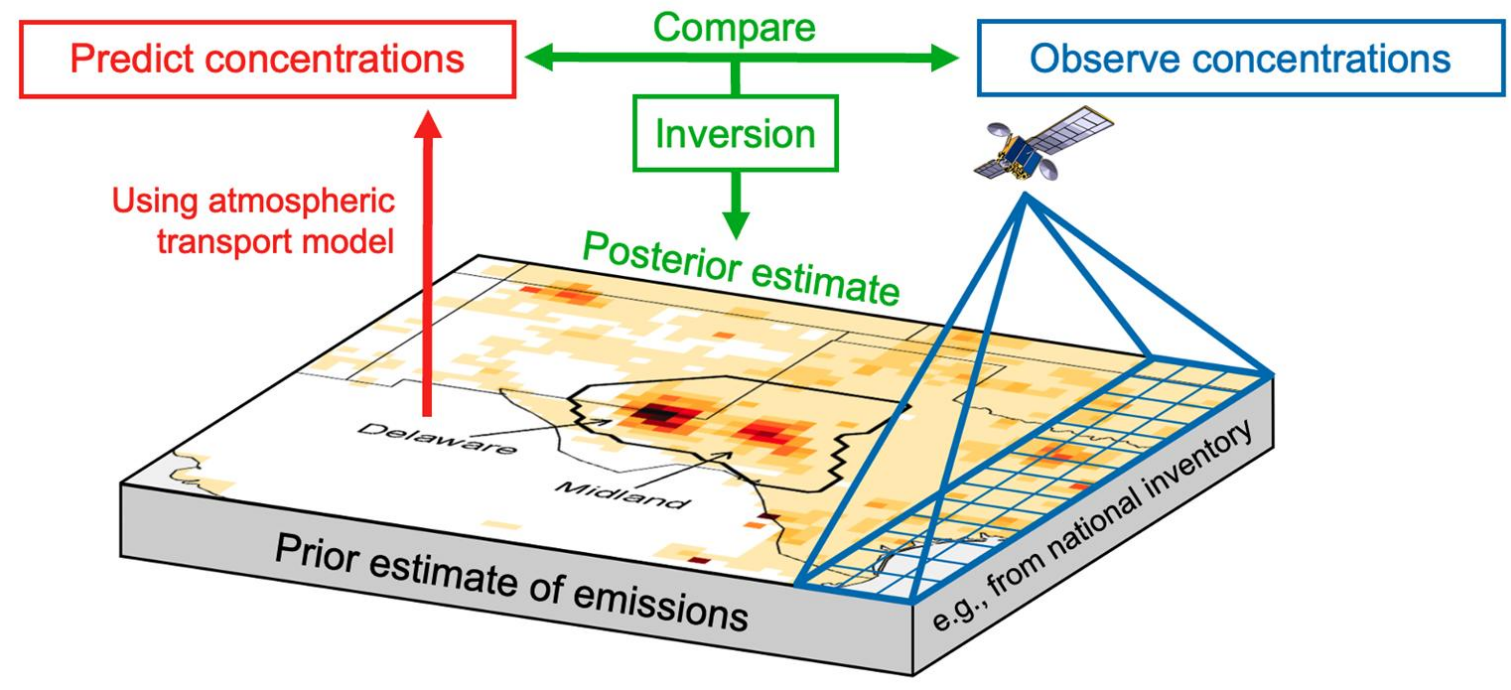
Task 4.4.3: Simulations at higher resolution planned. Integration of high-resolution satellites (possibly developed as part of smart-CH4)



CH4 flux adjustment for 1 year inversion in CIF-ICON-ART using TROPOMI observations as part of the SMARTCH4 project

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Analytical inversions using the Integrated Methane Inversion (IMI) tool with GEOS-Chem



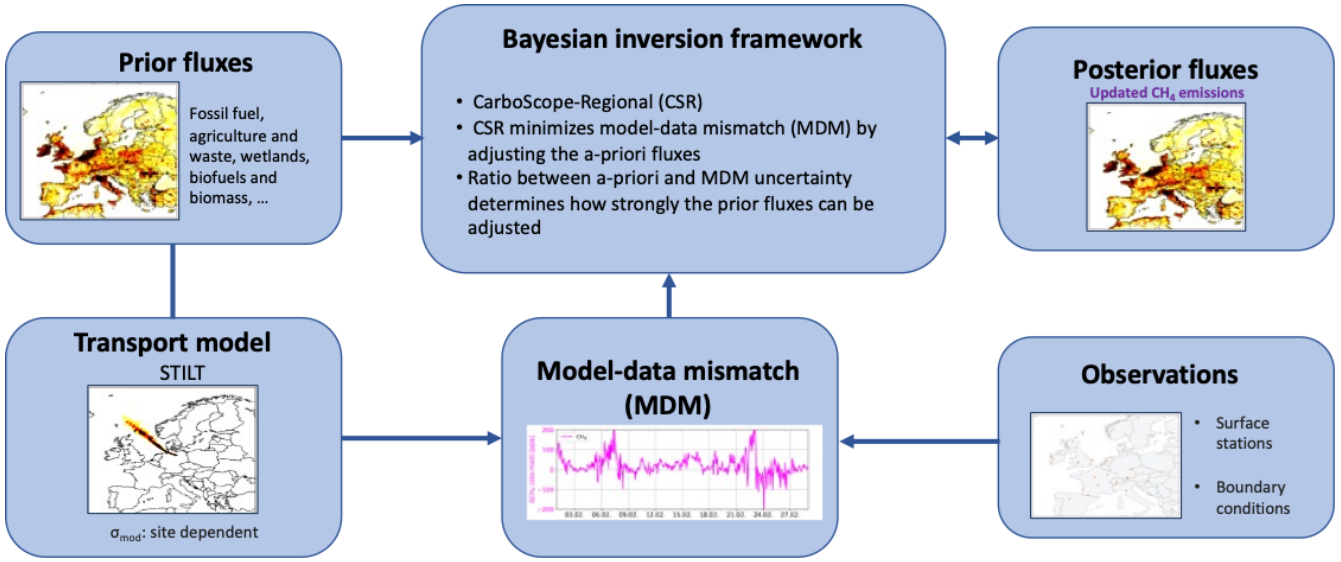
IMI inversion scheme from IMI website, carboninversion.com

- Aim is to provide multi-year, post-2020 analytical inversions for Europe, using TROPOMI methane observations
- IMI run at 12km or 25km resolution
- May explore using various TROPOMI data products and incorporate high-resolution satellite observations where available.

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Inversions using the CarboScope-Regional (CSR) model

- Multi-decadal inversion for Europe, using in-situ measurements from surface stations;
- A-priori fluxes from T4.1
- Spatial resolution of 0.25° x 0.25°
- ECMWF IFS met. data
- Optimized MDM (leave one out)



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