



# Monitoring anthropogenic emissions from space

**Gerrit Kuhlmann ([gerrit.kuhlmann@empa.ch](mailto:gerrit.kuhlmann@empa.ch))**

Remote Sensing of Air Pollutants and Greenhouse Gases  
Empa, Laboratory for Air Pollution / Environmental Technology

## JAXA GOSAT-GW

29 June 2025



## MTG-S1 Sentinel-4

1 July 2025



## CNES MicroCarb

26 July 2025

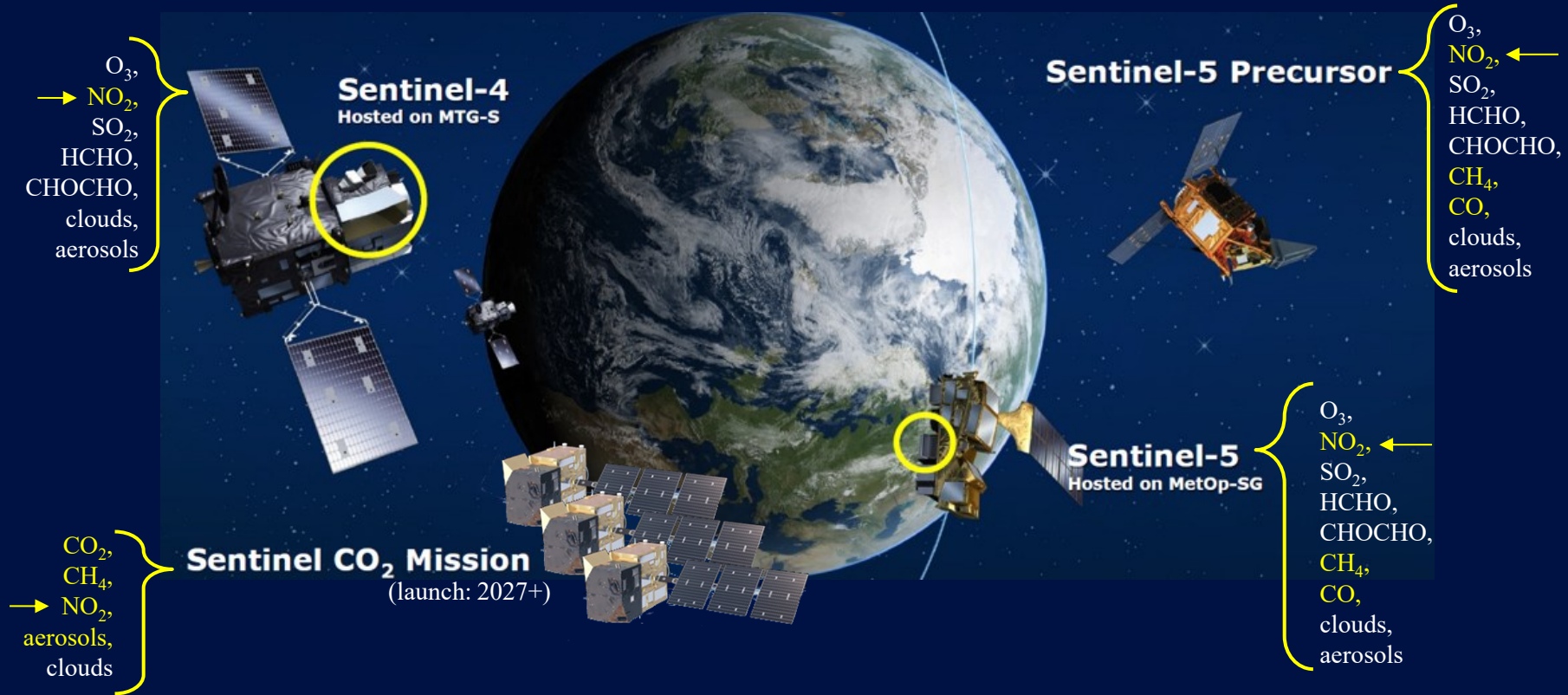


## MetOp-SG Sentinel-5

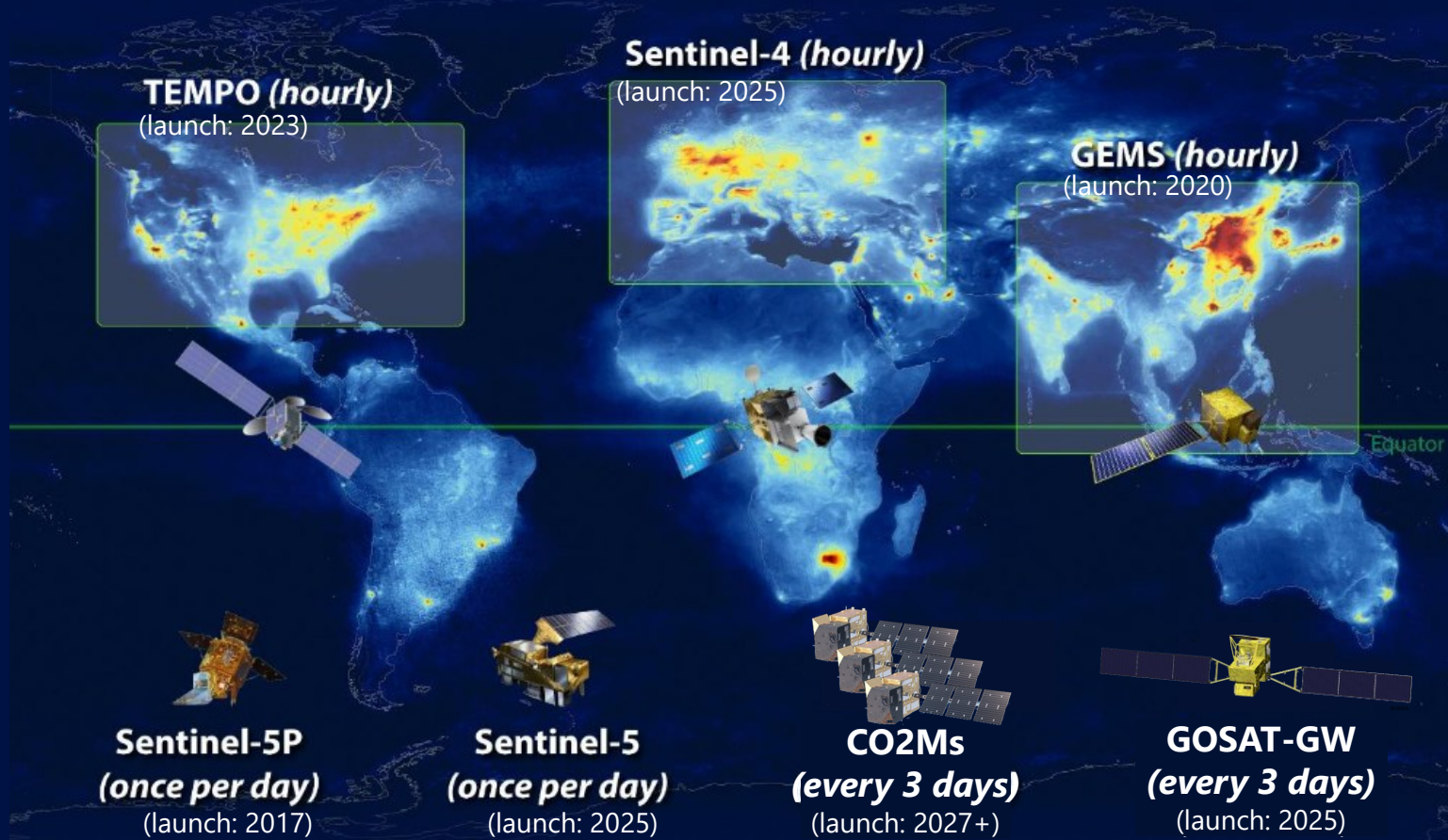
13 August 2025



# European Sentinels for Atmospheric Monitoring



# Atmospheric Composition Virtual Constellation

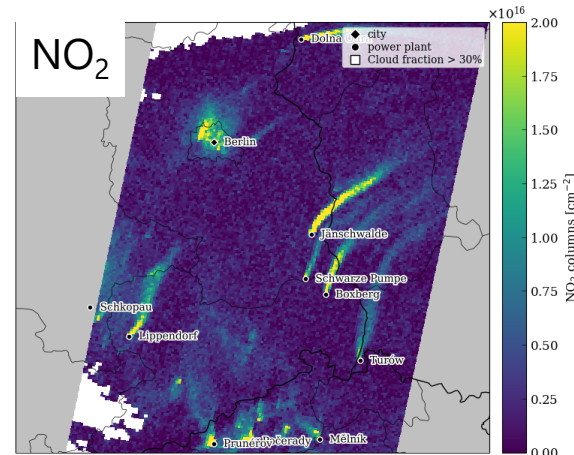
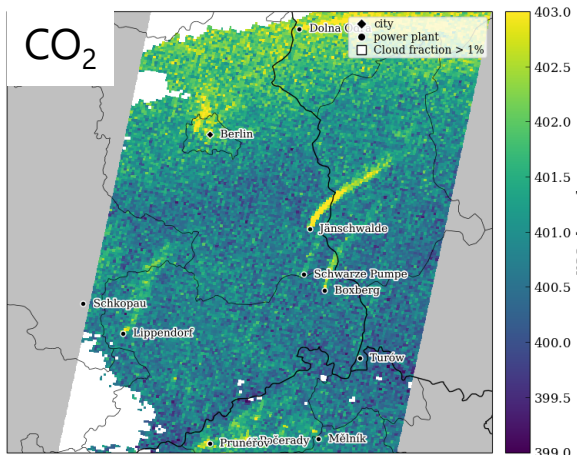
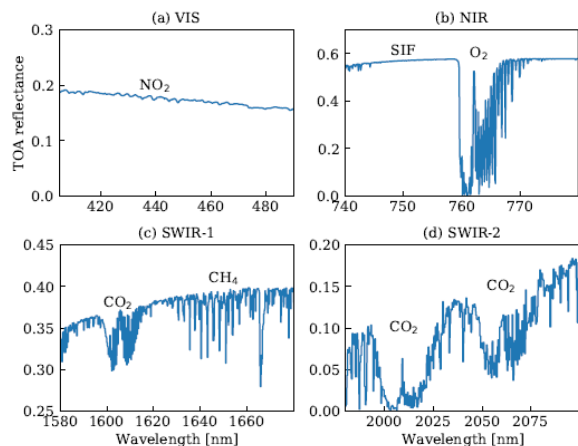
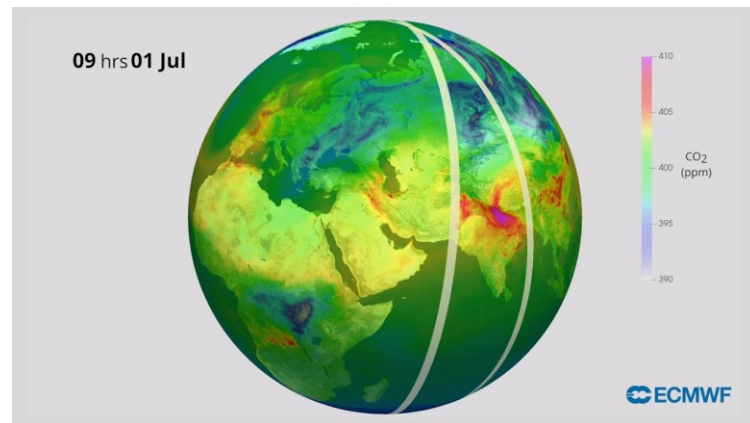


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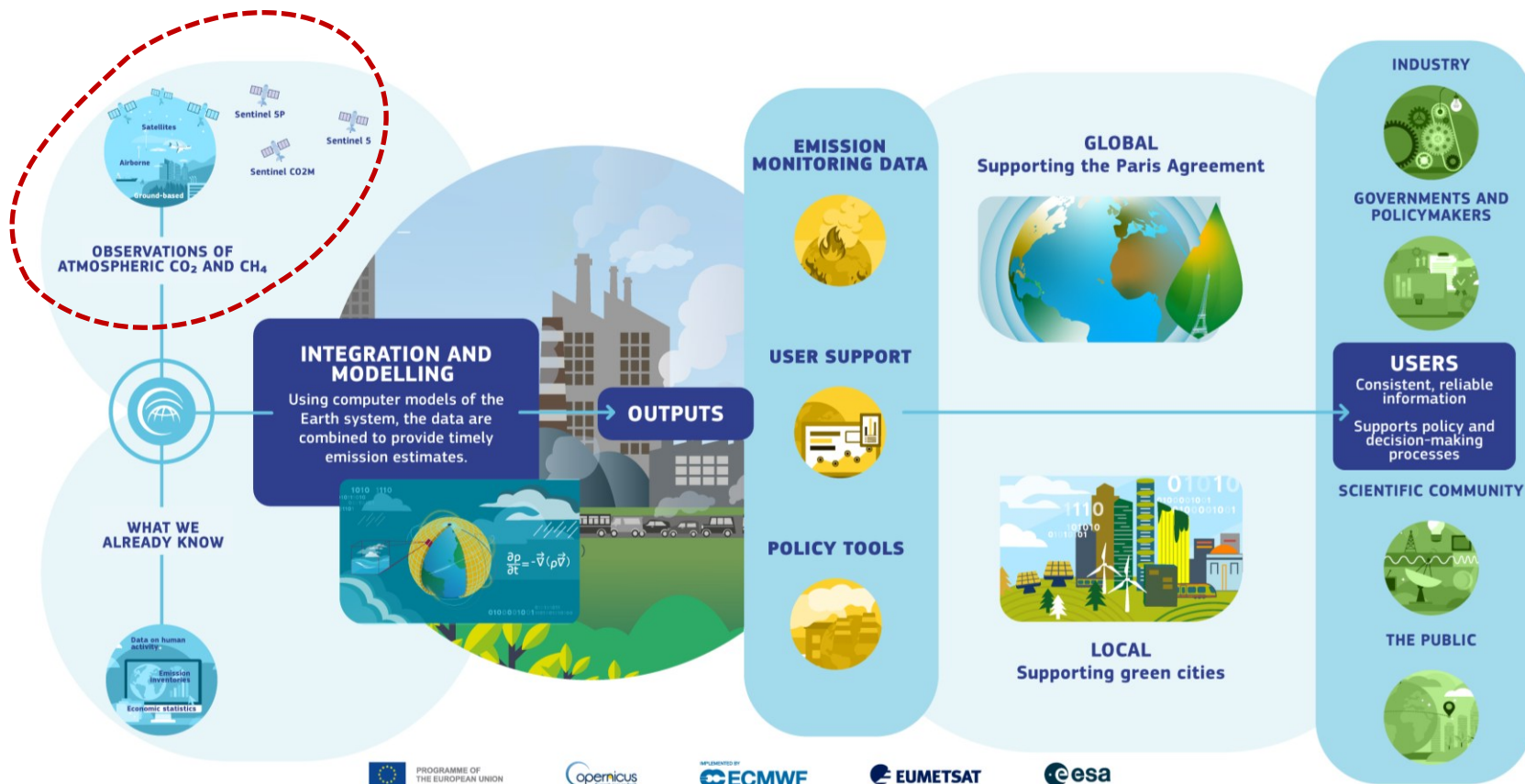
## Copernicus CO<sub>2</sub> Monitoring (CO2M) constellation



- 3 satellites launch from 2027 (>250-km swath)
- 4-channel imaging spectrometer for CO<sub>2</sub>, CH<sub>4</sub>, NO<sub>2</sub> and SIF (4 km<sup>2</sup> resolution)
- Multi-Angle Polarimeter (MAP) and cloud imager (CLIM) for aerosol and cloud corrections



# CAMS emissions monitoring system in support of Paris Agreement



PROGRAMME OF THE EUROPEAN UNION



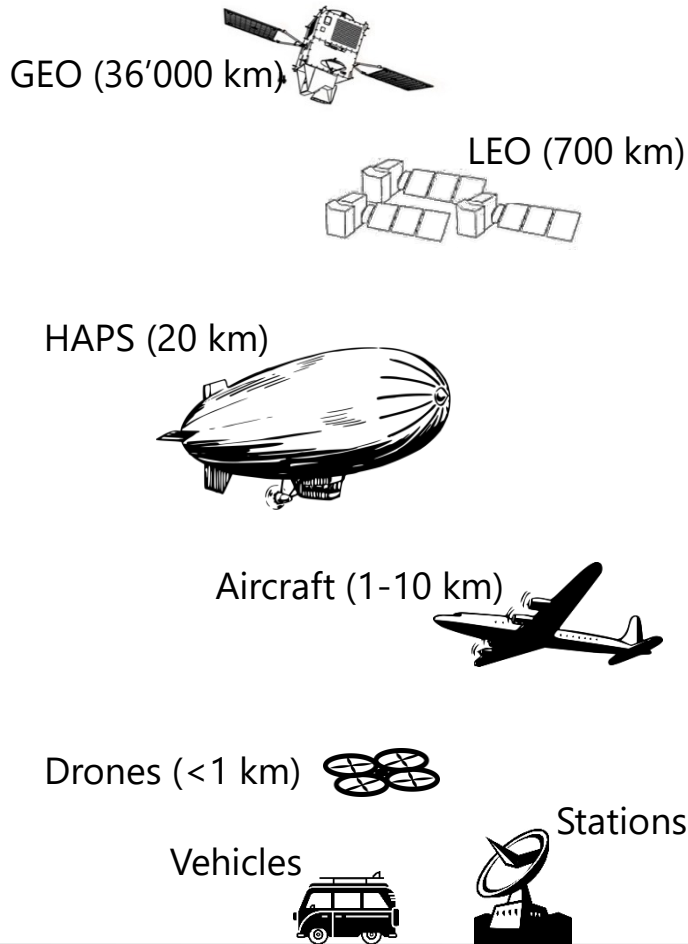
ECMWF



## Remote sensing of air pollutants and greenhouse gases

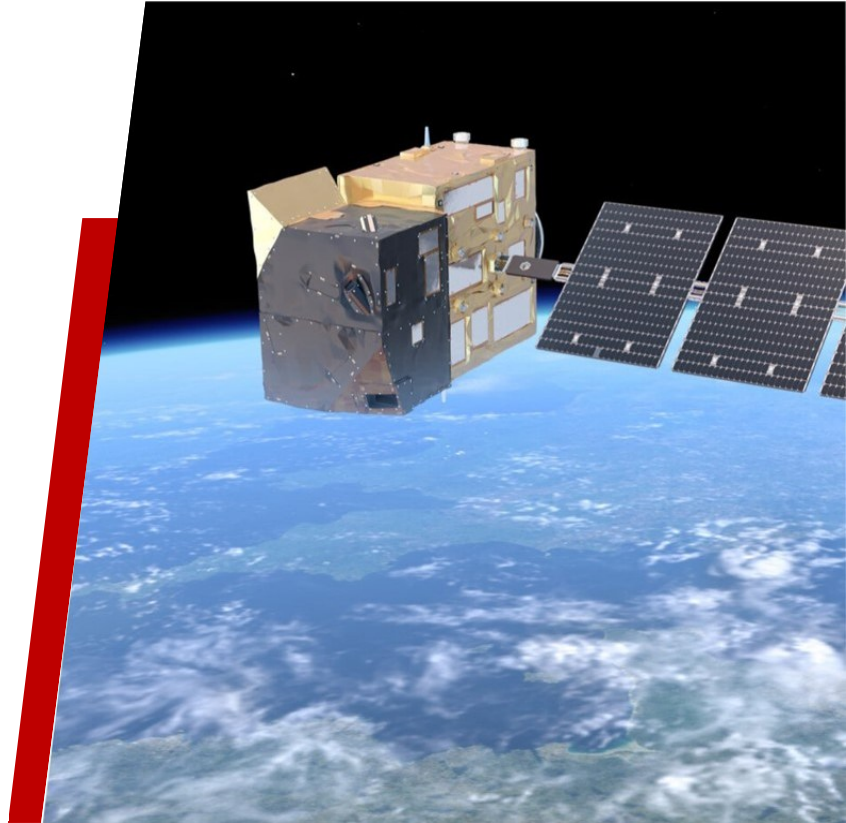


- How to use of **remote sensing** for atmospheric monitoring to provide meaningful information?
- How can we take full advantage of the **improved resolution and coverage** of the new satellite generation?
- How to develop methods that provide **accurate, reliable** and **timely** information on air pollution and emissions?
- Where are the **uncertainties** of these methods, how can we reduce them, and how do we communicate them to stakeholders?

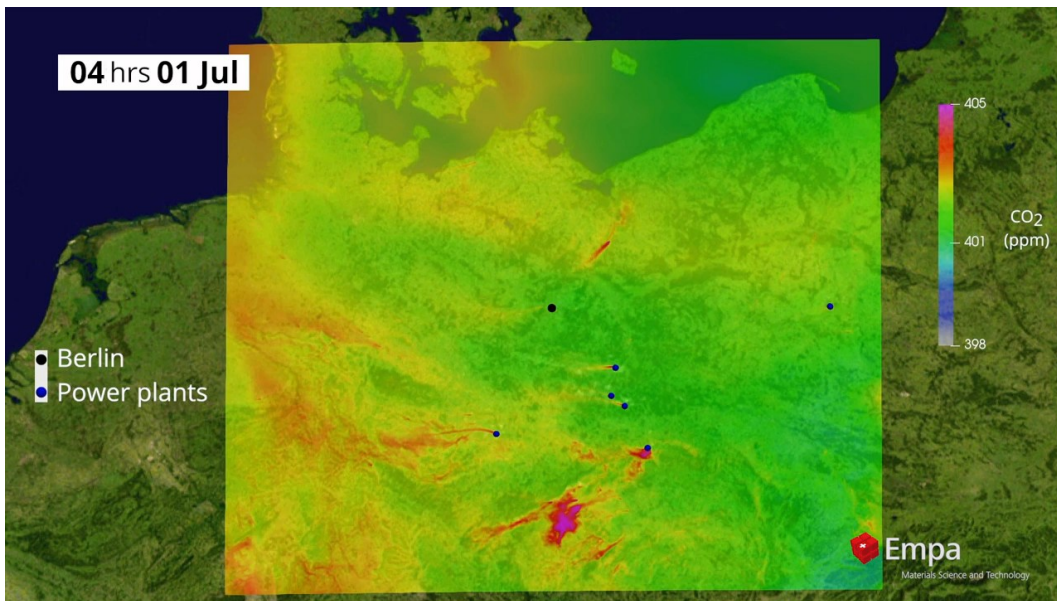




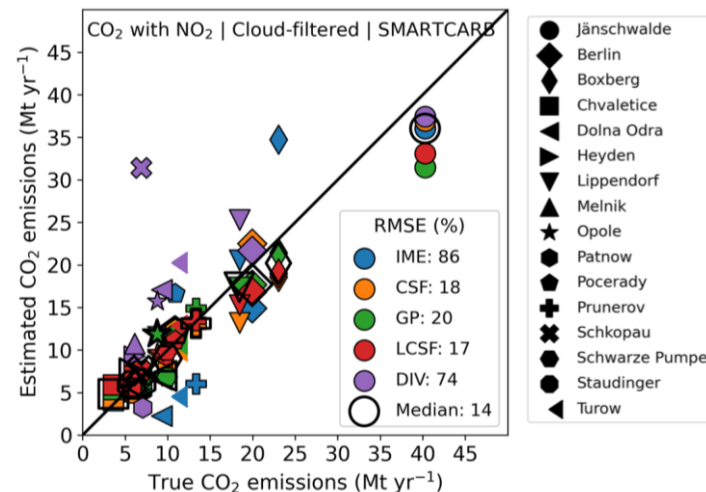
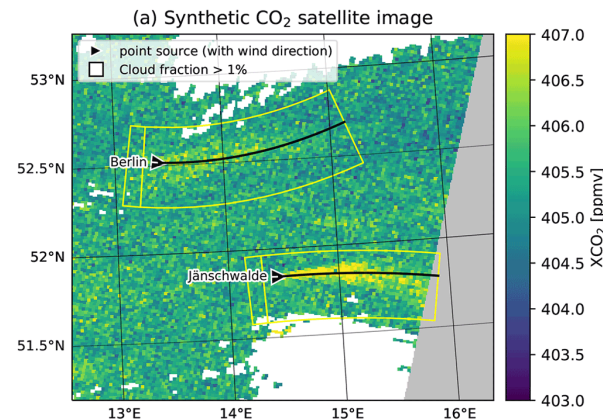
# Highlights in recent years



- Synthetic satellite images from realistic atmospheric transport simulations.
- CO2M will be able to quantify CO<sub>2</sub> annual emissions of point sources with an accuracy of 20% or better.

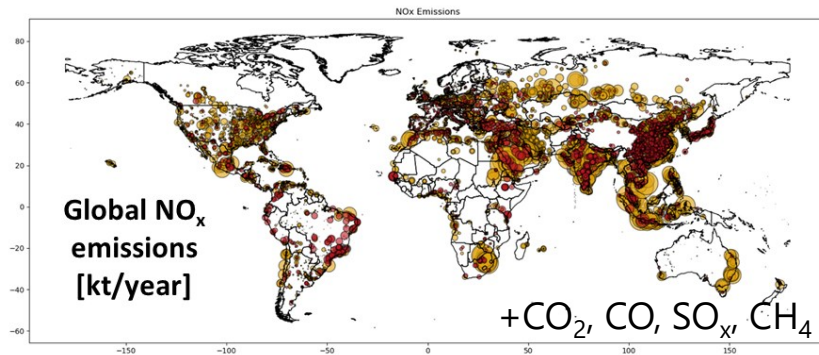


(Brunner et al. 2019, 2023; Dumont Le Brazidec et al. 2024; Hakkarinen et al. 2022, 2025; Koene et al. 2024, 2025; Kuhlmann et al. 2019, 2020, 2021, 2024; Santaren et al. 2025.)

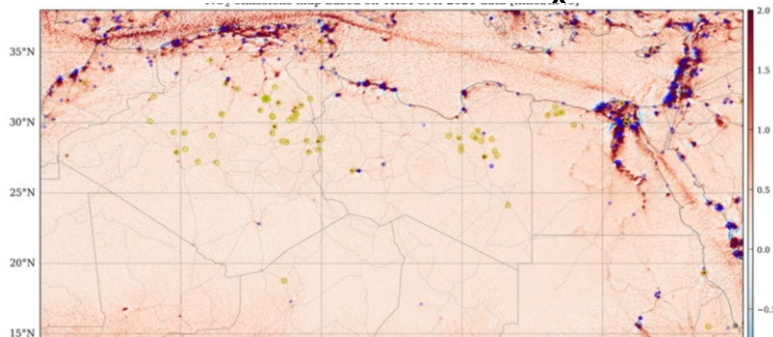




## 17257 power, iron/steel and cement plants



## Global Sentinel-5P/TROPOMI NO<sub>x</sub> emission map



## Point source locations:

- Corrected the location of 41 plants and added 8 unlisted power plants
- Identified additional large emitters (refineries and mines)

## Annual NO<sub>x</sub> emissions (TOP 173 emitters):

- Wrong characterization of dual fuel power plants in Saudi Arabia.
- NO<sub>x</sub>:CO<sub>2</sub> emission ratios do not reflect national technology in Indonesia.
- Bug associated to the filtering of “operating” units.

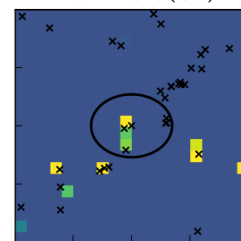
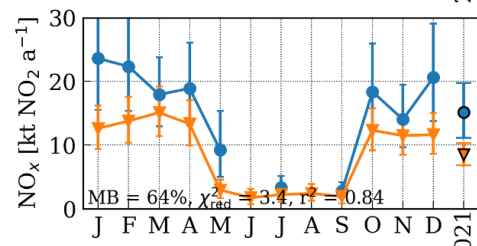
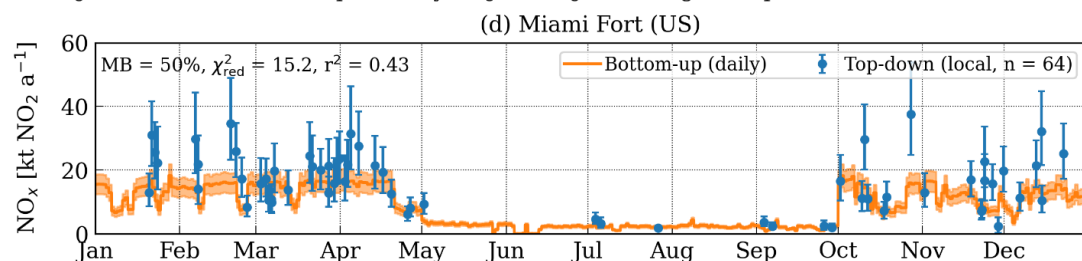
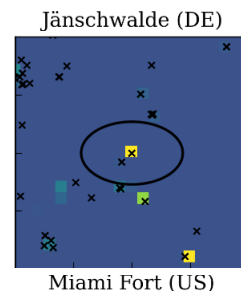
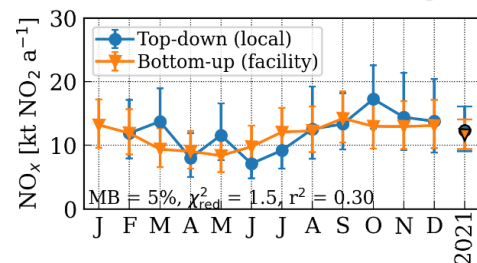
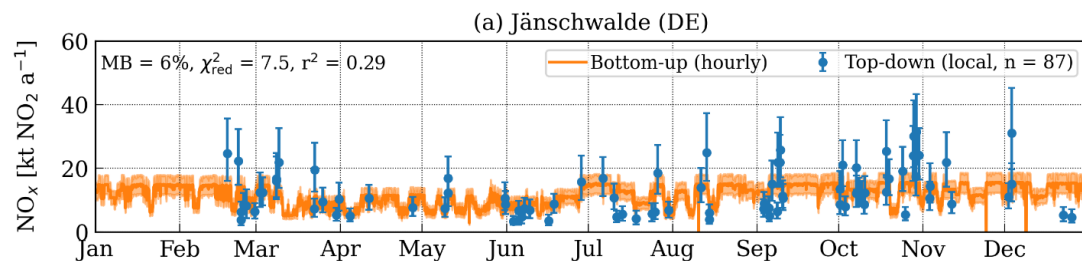
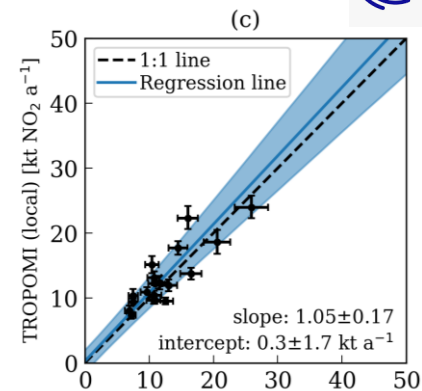
→ Adjustment of bottom-up database with 19% decrease in total NO<sub>x</sub> emissions.

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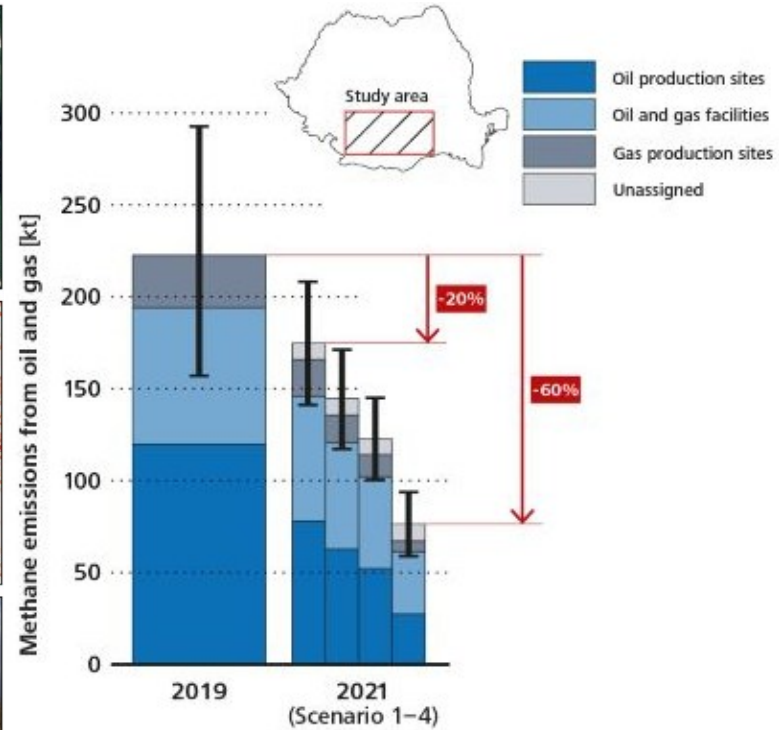
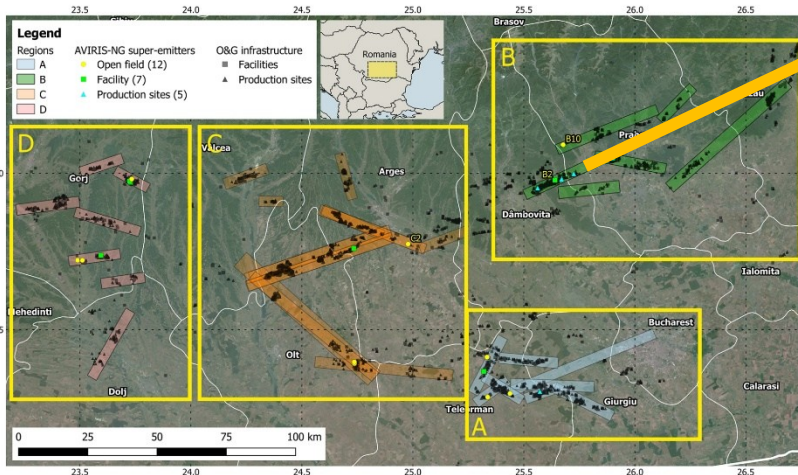
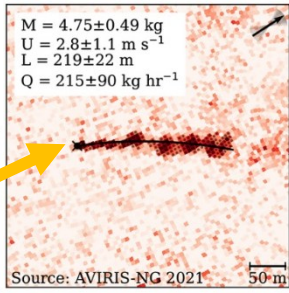
## Temporal variability of power plants from space



- Comparing TROPOMI NO<sub>x</sub> emissions with electricity generation statistics in Europe and Continuous Emission Monitoring Systems (CEMS) in the USA.
- Besides challenging NO<sub>x</sub> chemistry inside emission plumes, bottom-up and top-down agree very well.



Gerrit Kuhlmann (gerrit.kuhlmann@empa.ch)  
**Methane emissions with AVIRIS-NG and AVIRIS-4**



(Stavropoulou et al. 2023, Kuhlmann et al. 2025, Meier et al. 2026)



## Future research



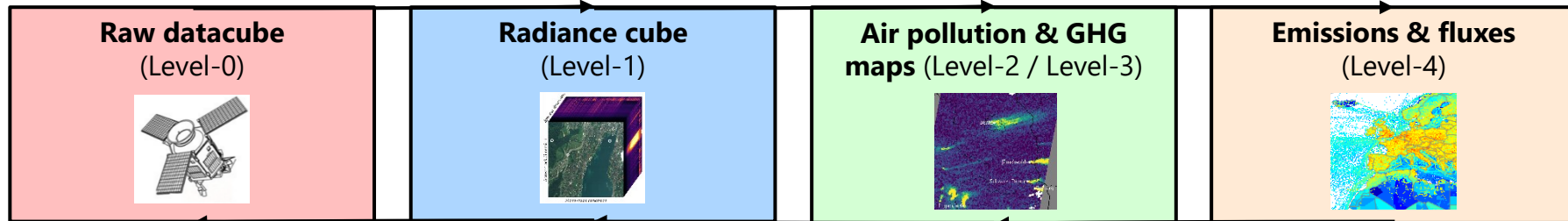
# Remote sensing of air pollutants and greenhouse gas emissions



Calibration algorithms

Retrieval algorithms

Atmospheric inverse models

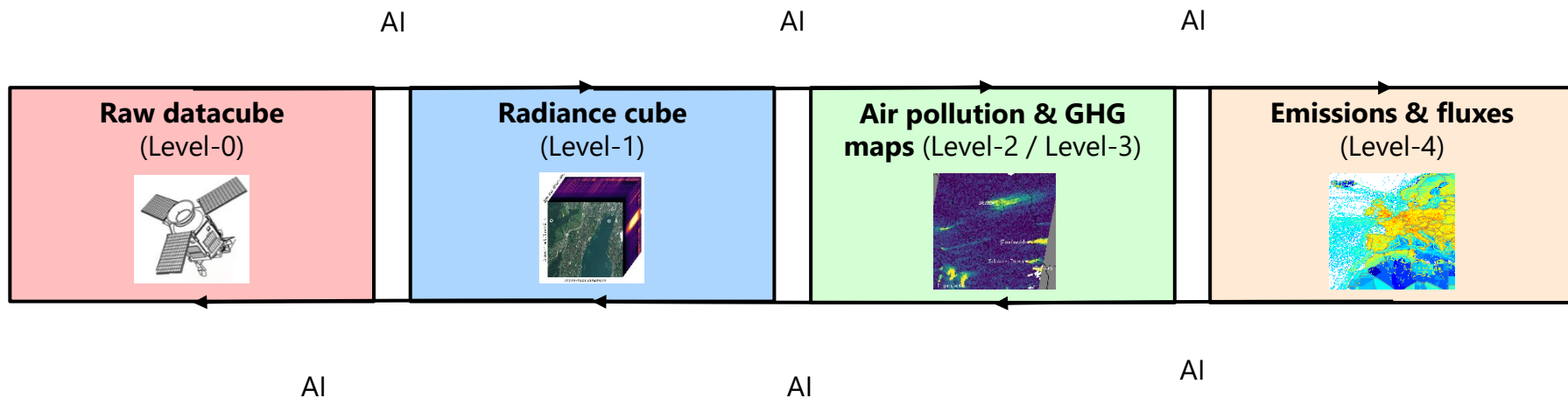


Sensor models

Radiative transfer models

Atmospheric transport models

# Remote sensing of air pollutants and greenhouse gas emissions



# Remote sensing of air pollutants and greenhouse gas emissions



AI



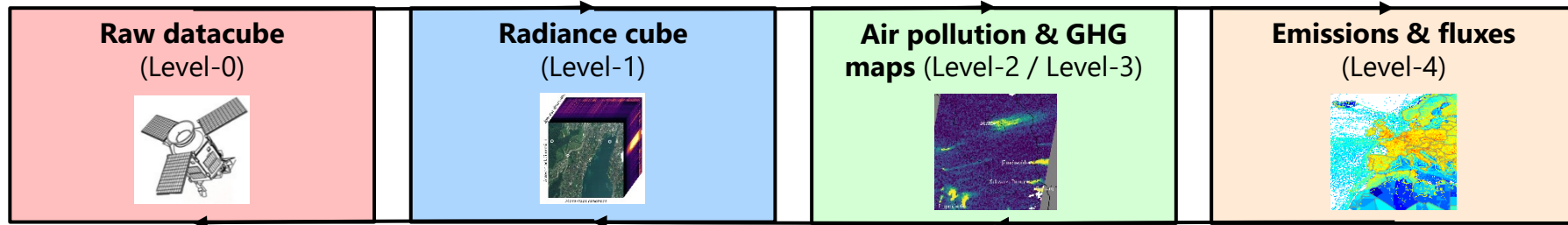
# Remote sensing of air pollutants and greenhouse gas emissions



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## Training data

- CEMS for facilities (yes, but not everywhere)
- CH<sub>4</sub> emission leaks (release experiments)
- Cities and countries (complex)

→ **Synthetic data from models**

## Domain gap

- Realistic model simulations to generate training data (incl. systematic errors).
- Computational expensive!
- Validation with measurements.
- Mismatch between simulations and reality will be an issue.

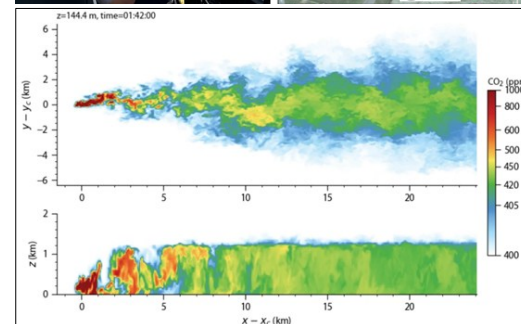
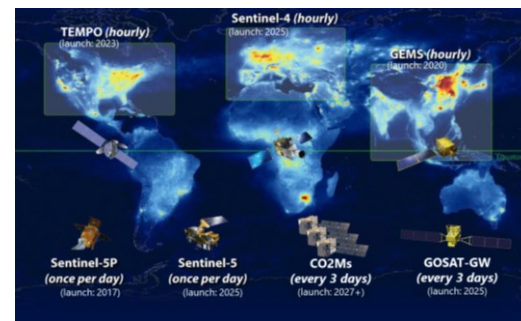
## Information bias

- Ill-posed problem!
- Auxiliary information from other measurements and models.
- Machine learning models with insufficient information will hallucinate.

## Concluding remarks



- New generation of satellite and airborne remote sensing instruments:
  - Copernicus programme
  - Swiss ARES observatory
- Moving towards operational emissions monitoring systems based on remote sensing data.
- Machine learning will be important but needs to be backed by physics-based (or processed-based) models that are validated with measurements.
- Combination of in situ and remote sensing measurements (incl. campaigns) with models will be essential for understanding methods and their uncertainties.
- Knowledge transfer to society (international, national, municipality level).



# Acknowledgements

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AGH, BSC, SNRS, CICERO,  
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TNO, Cyprus Institute, Uni Edinburgh, VU, WUR



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Uni Edinburgh, Uni Groningen



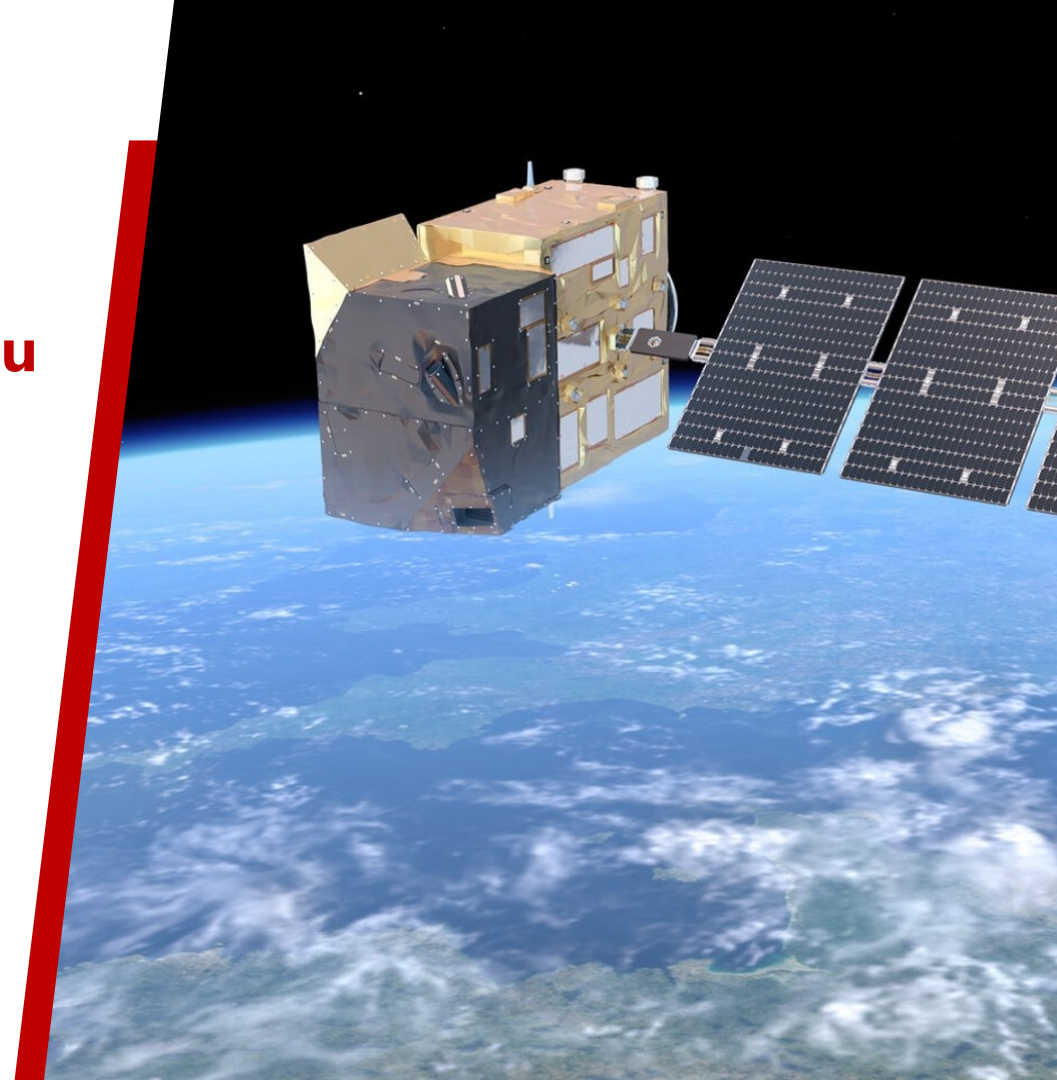
**SMARTCARB consortium:** Empa, ETHZ, MPI BGC,  
MeteoSwiss, LSCE



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**Thank you**



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Materials Science and Technology

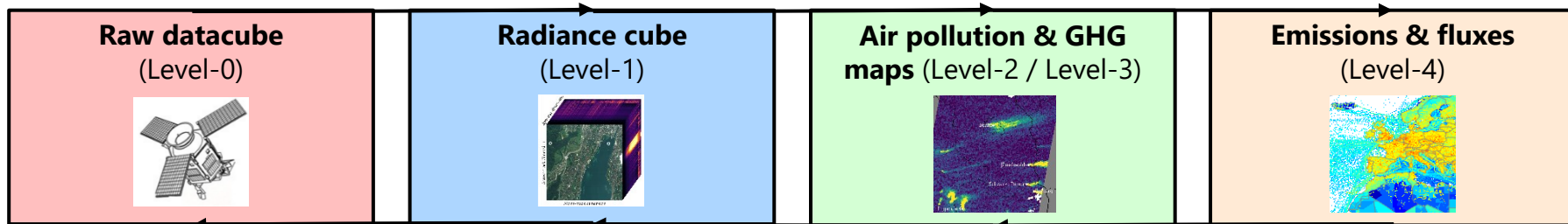
# Remote sensing of air pollutants and greenhouse gases



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# Switzerland's greenhouse gas emissions



SWI swissinfo.ch

The Swiss voice in the world since 1935

GEOPOLITICS DEMOCRACY SCIENCE SWISS IDENTITY ECONOMY SWISS ABROAD

Emissions reduction >

## Why Switzerland's carbon footprint is bigger than you think

January 23, 2025

Switzerland's CO<sub>2</sub> emissions are much higher if one takes into account its consumption

Evolution of Switzerland's CO<sub>2</sub> and consumption-related emissions (carbon footprint). In tonnes.

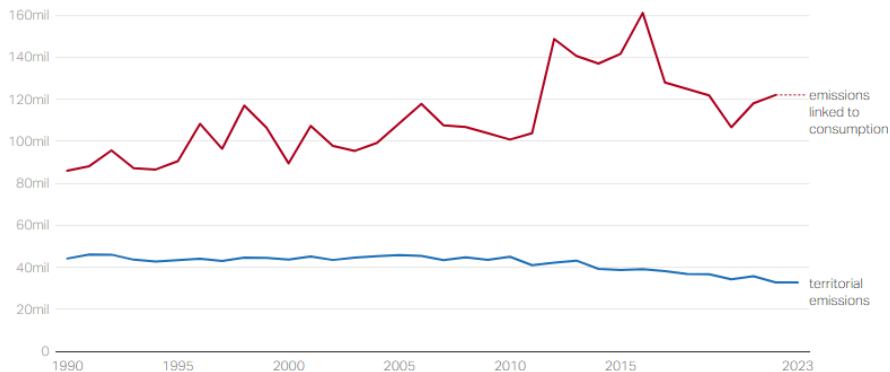


Grafico: ptur • Fonte: [Global Carbon Budget via Our World in Data](#) • [Scaricare i dati](#)

SWI swissinfo.ch

<https://www.swissinfo.ch/eng/emissions-reduction/why-switzerlands-carbon-footprint-is-bigger-than-you-think/88761356>

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Imported emissions account for almost 80% of Switzerland's carbon footprint

Share of imported emissions and territorial emissions (excluding exports) in the carbon footprint of a selection of countries, in 2022.

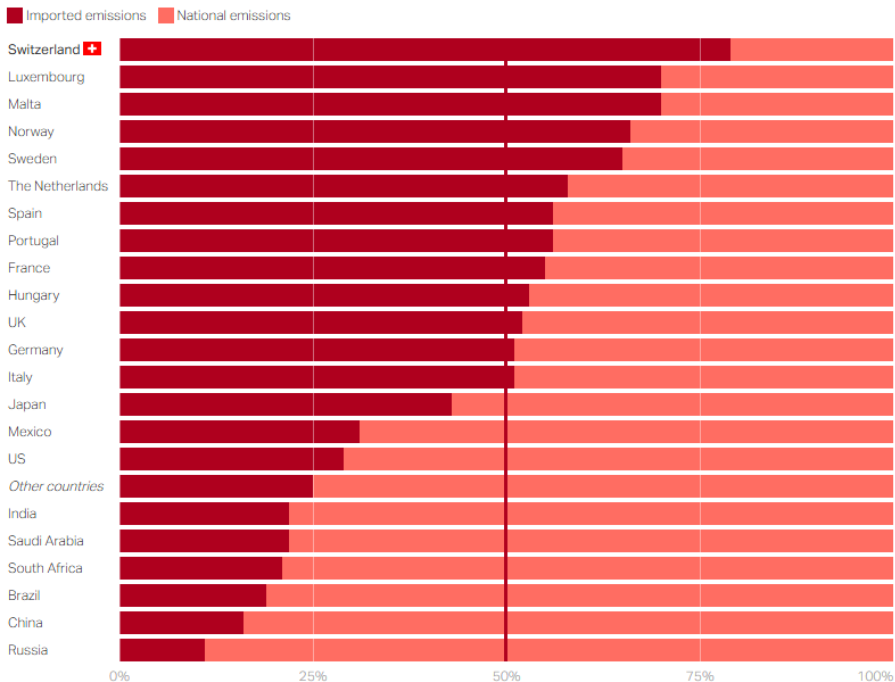


Chart: ptur • Source: [Eurostat \(environmental footprint based on FIGARO, 2024\)](#); [Carbone 4 & European Climate Foundation; calculations by SWI swissinfo.ch](#) • [Get the data](#)

SWI swissinfo.ch