Prototyping an EO-enabled kit supporting greenhouse gas reporting – GHG-Kit

A priori flux estimates & GHG inversion on urban scales

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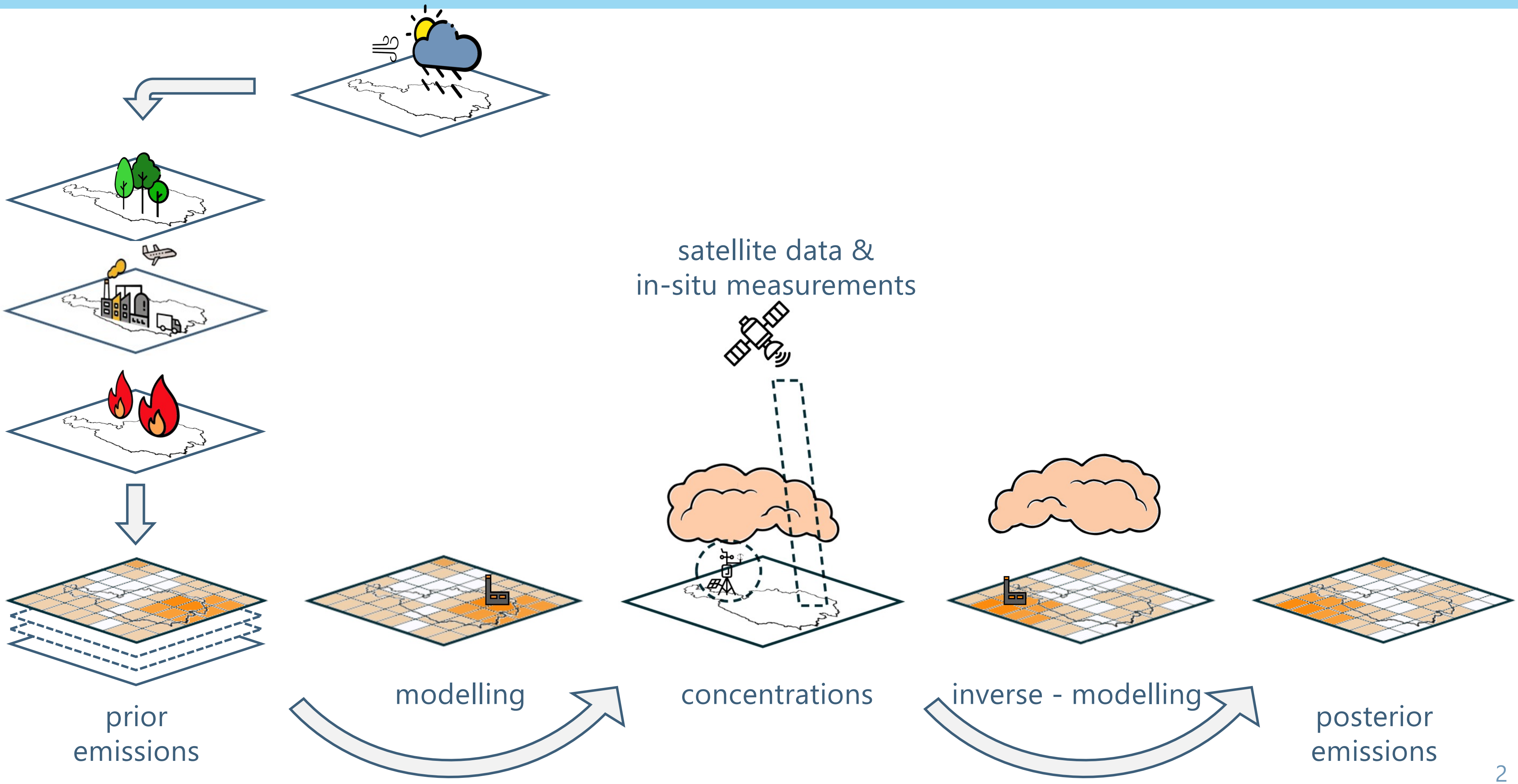
10. Österreichischer MeteorologInnentag 2025

5. & 6.6.2025

Keep it traceable!

FFG project || GHG-KIT
[contract #FO999893432]

GHG-KIT: INVERSION IN A NUTSHELL



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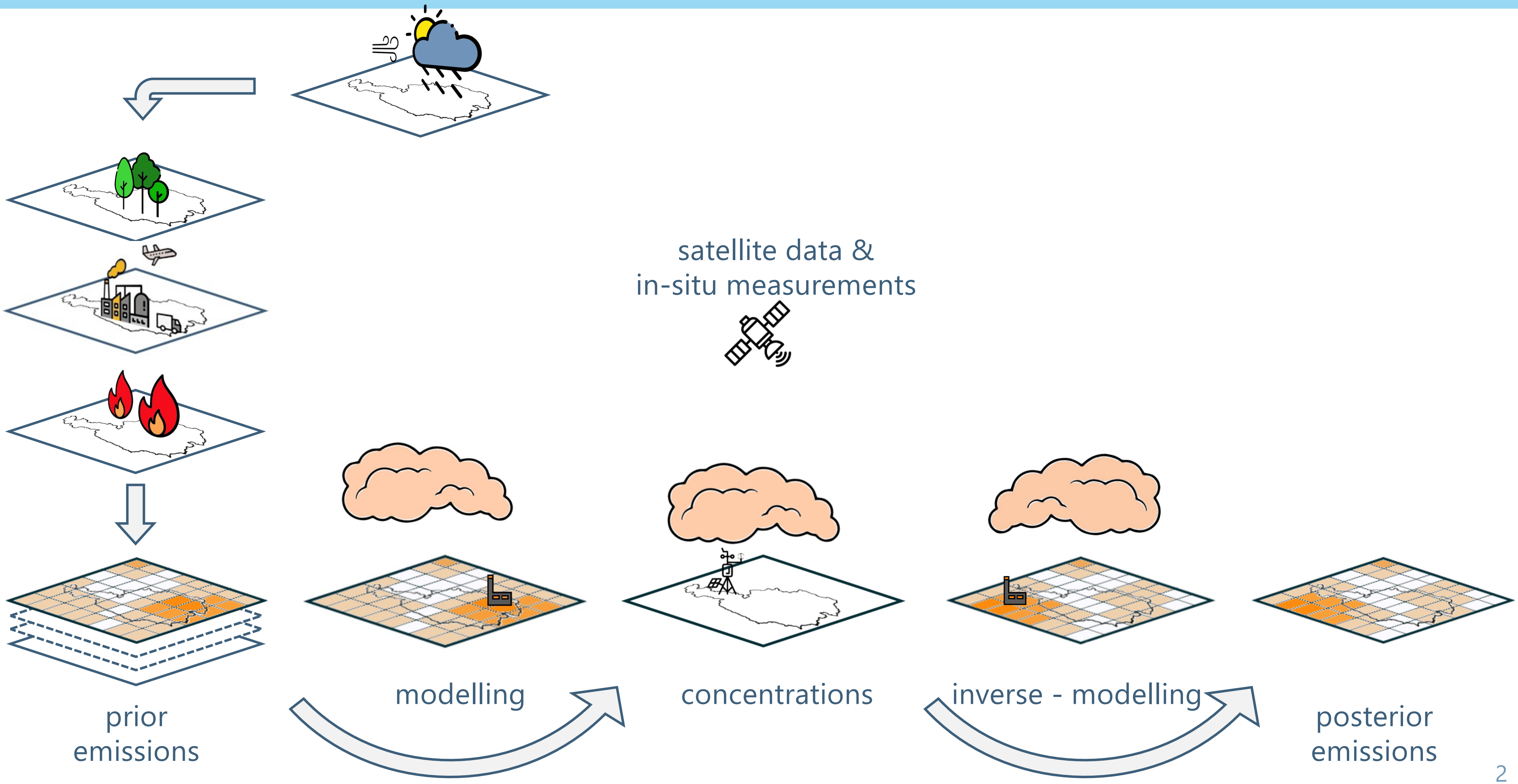
GHG-KIT: INVERSION IN A NUTSHELL



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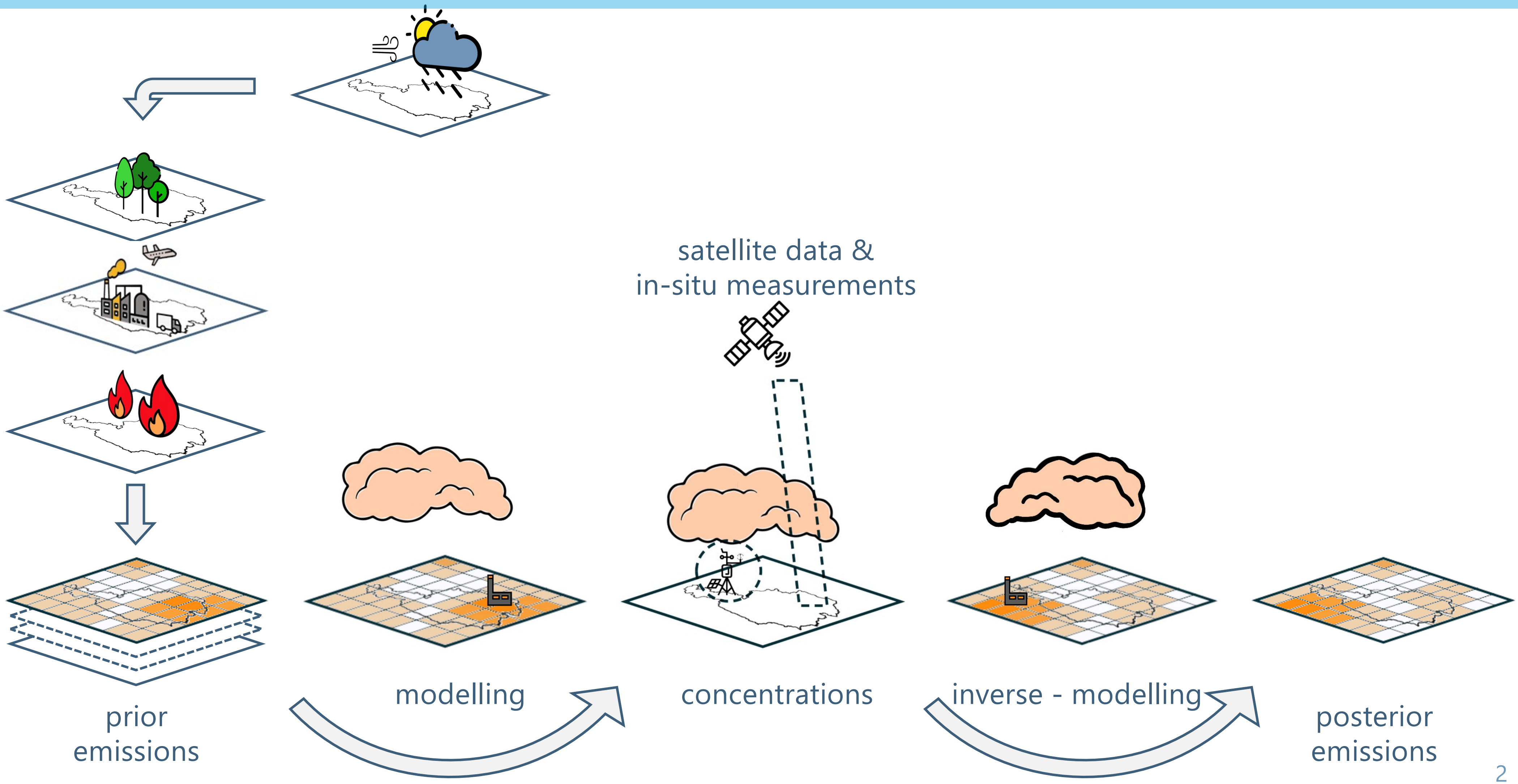
GHG-KIT: INVERSION IN A NUTSHELL



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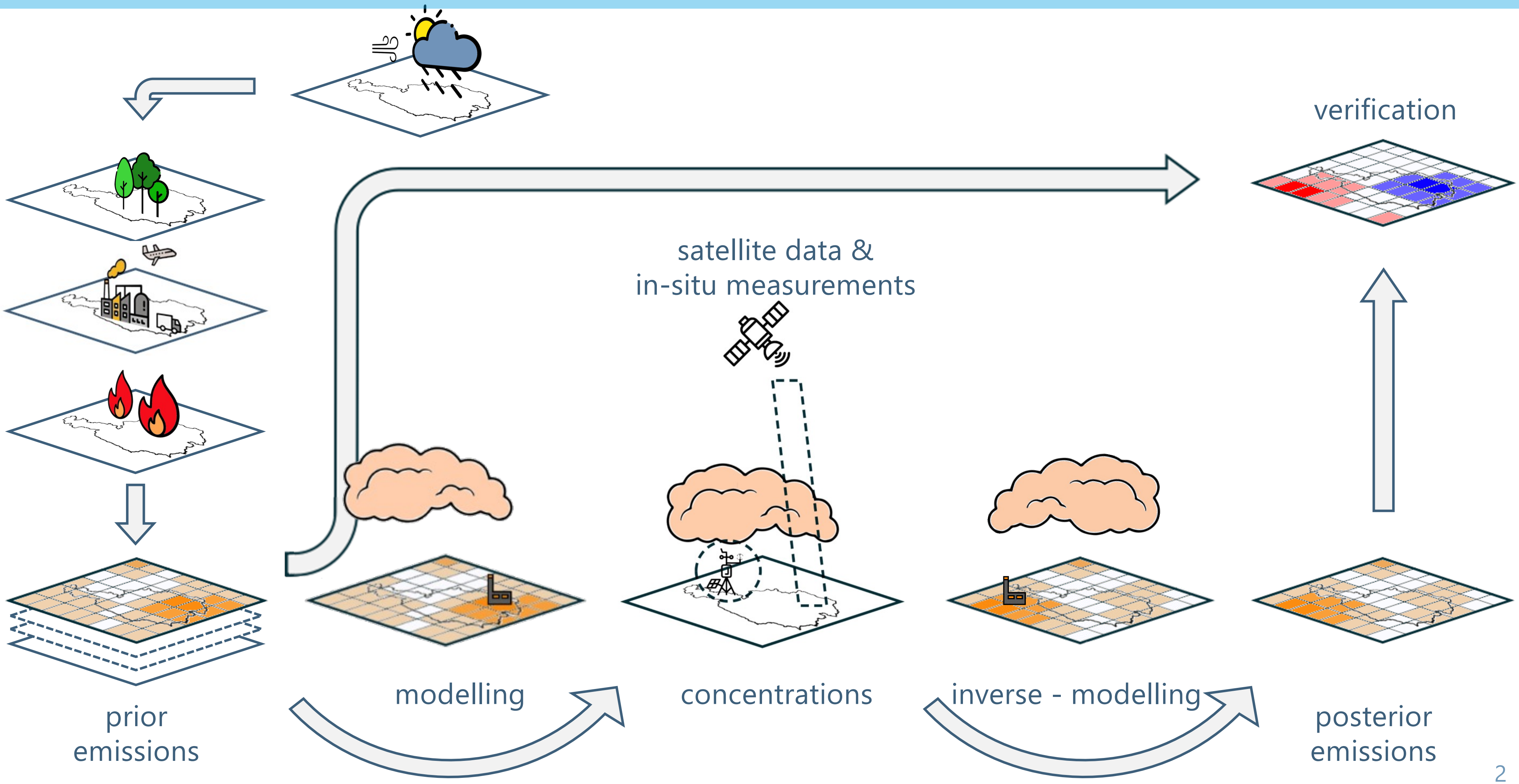
GHG-KIT: INVERSION IN A NUTSHELL



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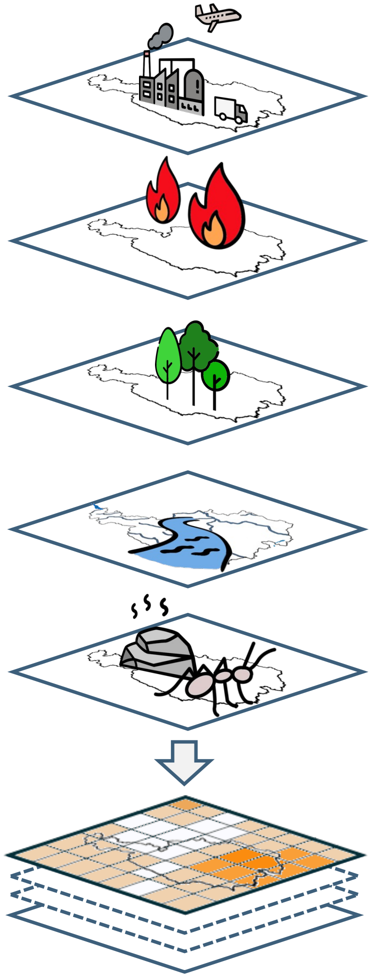
CO_2 & CH_4 emission estimates



anthropogenic (CO_2 & CH_4) → CAMS-REG, CAMS-GLOB CAMS-TEMPO

\+

wildfires (CO_2 & CH_4) → GFAS

\+

net ecosystem exchange (nee, CO_2) / wetlands & soils (CH_4) → **VPRM model with Sentinel-2 Data** / JSBACH-HIMMELI Model

\+

rivers & lakes (CH_4) → R. Lauerwald & P. Regnier (pers. comm. 2024)

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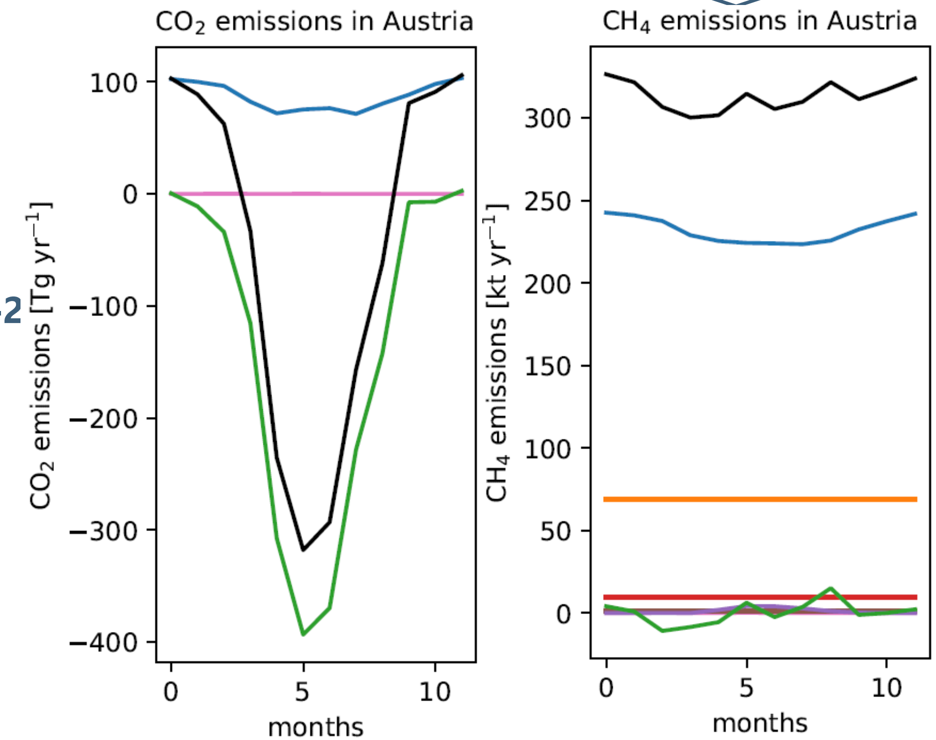
geological & termite (CH_4) → Etiope et al. (2019) & Sanoise et al. (2020)

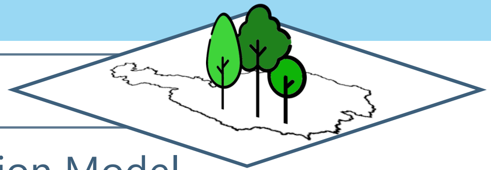
=

prior emission fluxes



2022

Biogenic CO_2 emission estimates – VPRM[1]



[1]Vegetation Photosynthesis and Respiration Model

NEE: Next Ecosystem Exchange; *GPP*: Gross Primary Production; R_{eco}: Ecosystem Respiration

PAR: total Photosynthetically Active Radiation; ϵ: light-use efficiency; *EVI:* Enhanced Vegetation Index representing the „greenness“ of vegetation; *LSWI:* Land Surface Water Index

$$\mathbf{NEE = -GPP + R_{eco}}$$

$$\mathrm{GPP} = \epsilon \times \underbrace{\frac{1}{1+\mathrm{PAR}/\mathrm{PAR_0}}}_{\text{saturation effect}} \times \mathrm{PAR} \times \mathrm{EVI}$$

$$\mathbf{R_{eco}} = \alpha \times \max(\mathrm{T}, \mathrm{T_{low}}) + \beta$$

$$\mathrm{PAR} \approx 0.505 \text{ x } \mathrm{SW}$$

$$\epsilon = \lambda \times T_{scale} \times W_{scale} \times P_{scale}$$

$$\mathrm{T_{scale}} = \frac{(\mathrm{T}-\mathrm{T_{min}})(\mathrm{T}-\mathrm{T_{max}})}{(\mathrm{T}-\mathrm{T_{min}})(\mathrm{T}-\mathrm{T_{max}}) - (\mathrm{T}-\mathrm{T_{opt}})^2}$$

$$\mathrm{W_{scale}} = \begin{cases} \dfrac{\mathrm{LSWI} - \mathrm{LSWI_{min}}}{\mathrm{LSWI_{max}} - \mathrm{LSWI_{min}}}, & \text{grassland} \\ \dfrac{1+\mathrm{LSWI}}{1+\mathrm{LSWI_{max}}}, & \text{other classes} \end{cases}$$

$$\mathrm{P_{scale}} = \begin{cases} 1, & \text{evergreen; leaf full expansion to senescence} \\ (1+\mathrm{LSWI})/2, & \text{grassland; bud burst to leaf full expansion and during senescence} \end{cases}$$

satellite measured | modelled variable | fitted parameters (based on flux tower measurements over different vegetation classes)

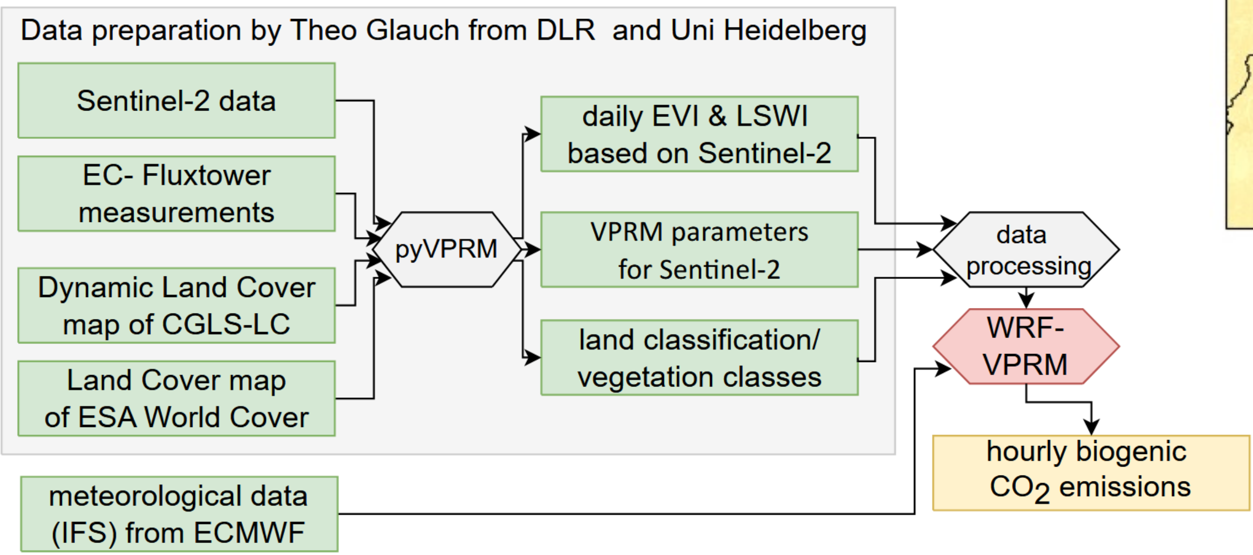
Equations modified after Glauch et al.,2025

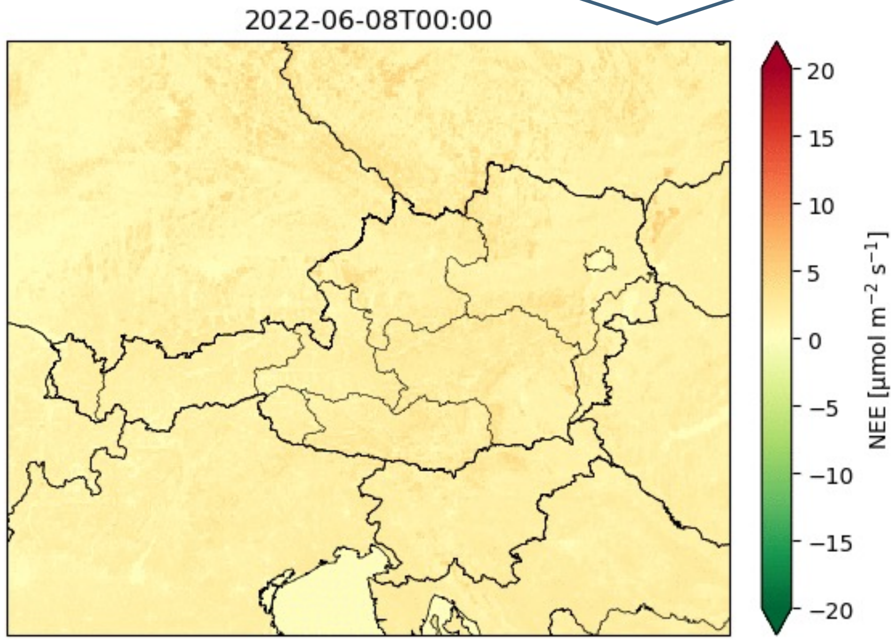
Biogenic CO_2 emission estimates – WRF-VPRM

Three approaches:

a) Original method by Mahadevan et al. (2008) based on **MODIS**
b) Input for VPRM based on **Sentinel-2** products
c) Modelled input for VPRM created with **SURFEX** and **soil moisture** (TU Wien) assimilation

Data preparation Sentinel-2 approach:

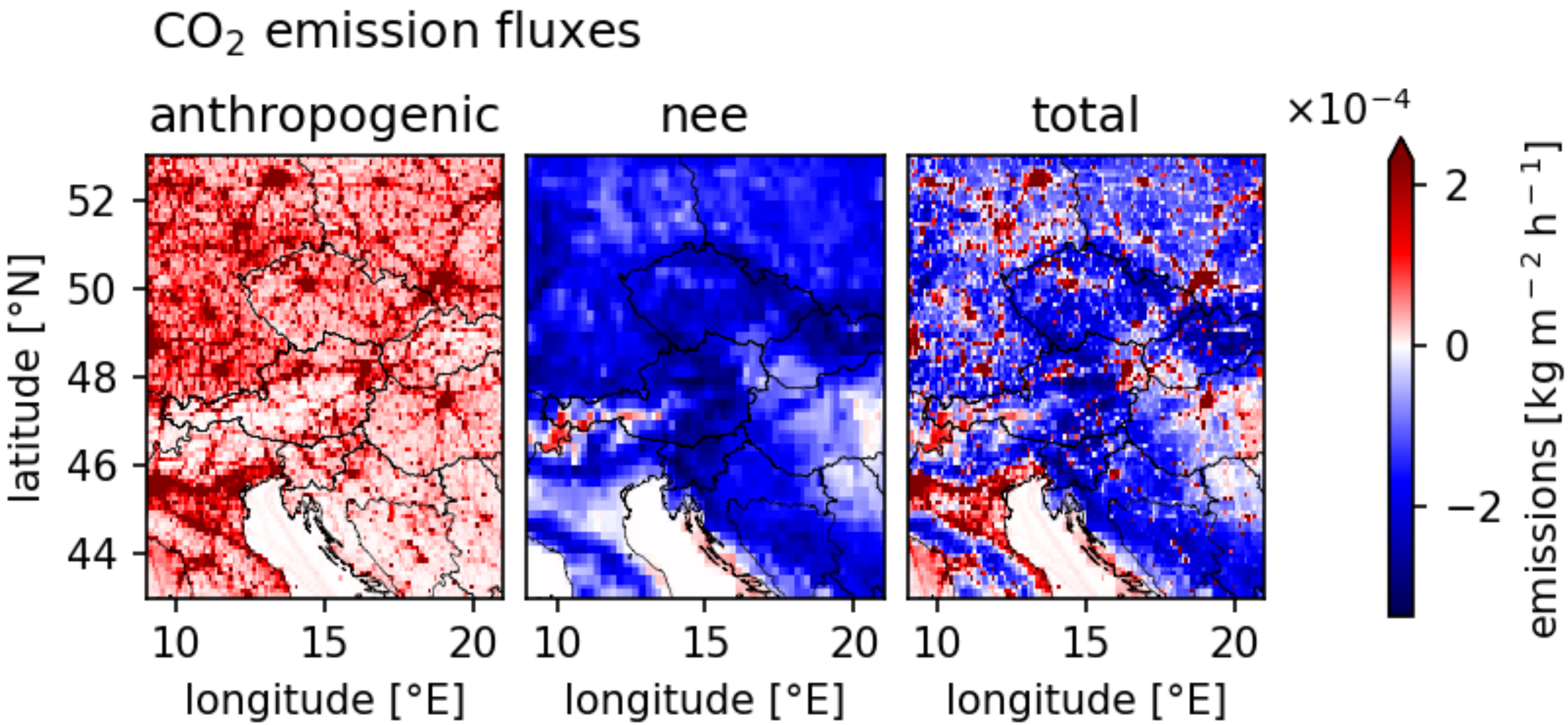


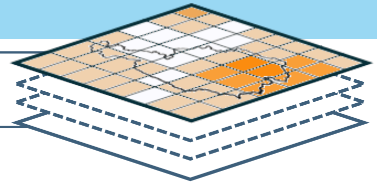


WRF-VPRM CO_2 emission/uptake, hourly resolution, based on Sentinel input for Austrian (and European) domain

Glauch, T., Marshall, J., Gerbig, C., Botía, S., Gałkowski, M., Vardag, S. N., and Butz, A.: *pyVPRM*: A next-generation Vegetation Photosynthesis and Respiration Model for the post-MODIS era, EGUsphere [preprint], https://doi.org/10.5194/egusphere-2024-3692, 2025.

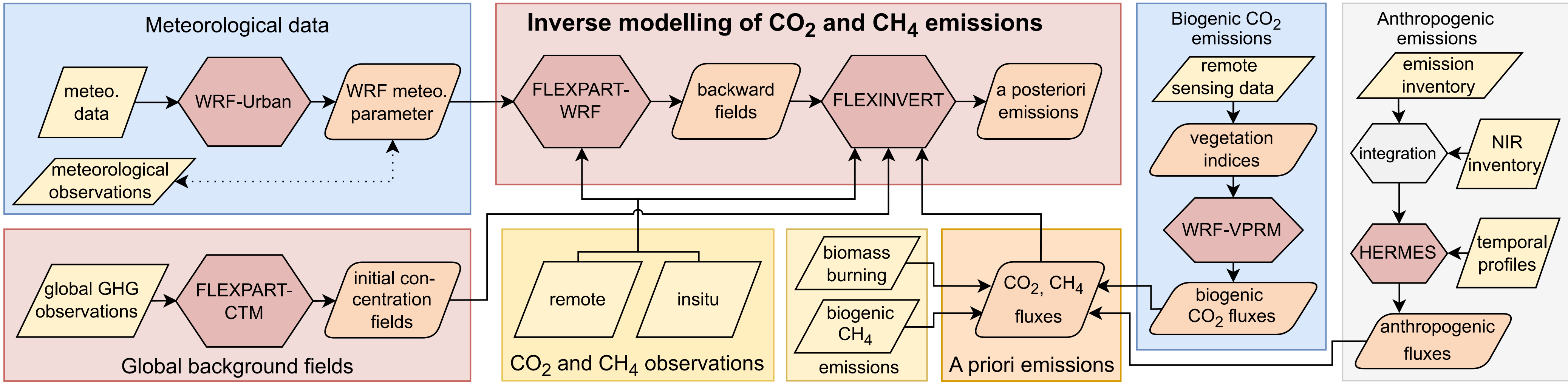
CO_2 emission estimates – annual average





Inverse modelling set up

- CO_2 and CH_4 a posteriori emissions of Vienna are estimated with **FLEXINVERT**.
- A priori emissions are prepared using **WRF-VPRM** (biogenic CO_2, see before) and **HERMES** (anthropogenic GHGs).
- GHG measurements from the Vienna Urban Carbon Laboratory (**VUCL**) are used.
- Meteorological input is modelled with **WRF-Urban**.
- Atmospheric back trajectories for the GHG observations are calculated using **FLEXPART-WRF**.



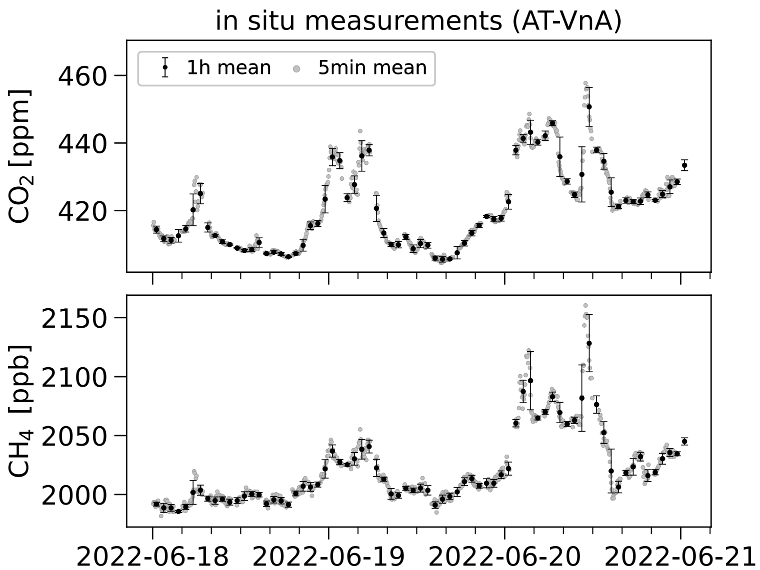
Ground-based observations of CH_4 and CO_2 mole fractions in Vienna

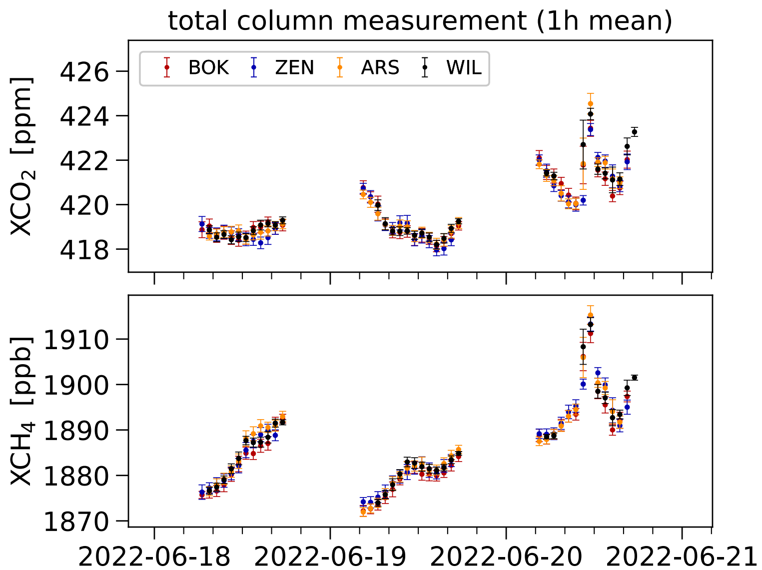
In situ observations:
- at the Arsenal Tower
- by BOKU
- with CRDS

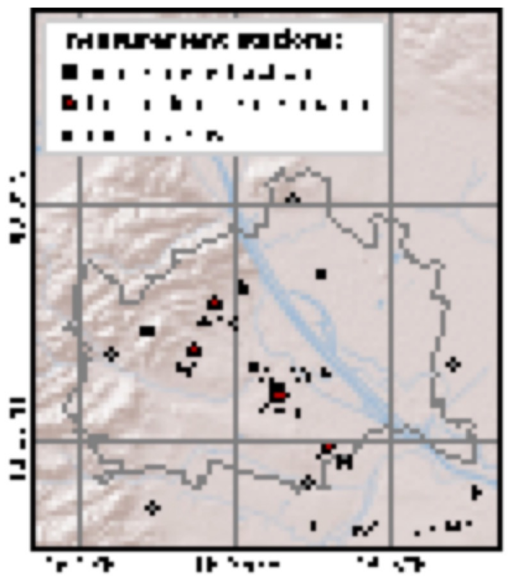
Total column measurements:
- at four locations in Vienna
- by TU Munich
- with FTIR spectrometers

For inversion:
- June and July 2022
- 15 min averages
- 5 locations

In-situ obs. contain more information on local sources & sinks compared to total column obs.!





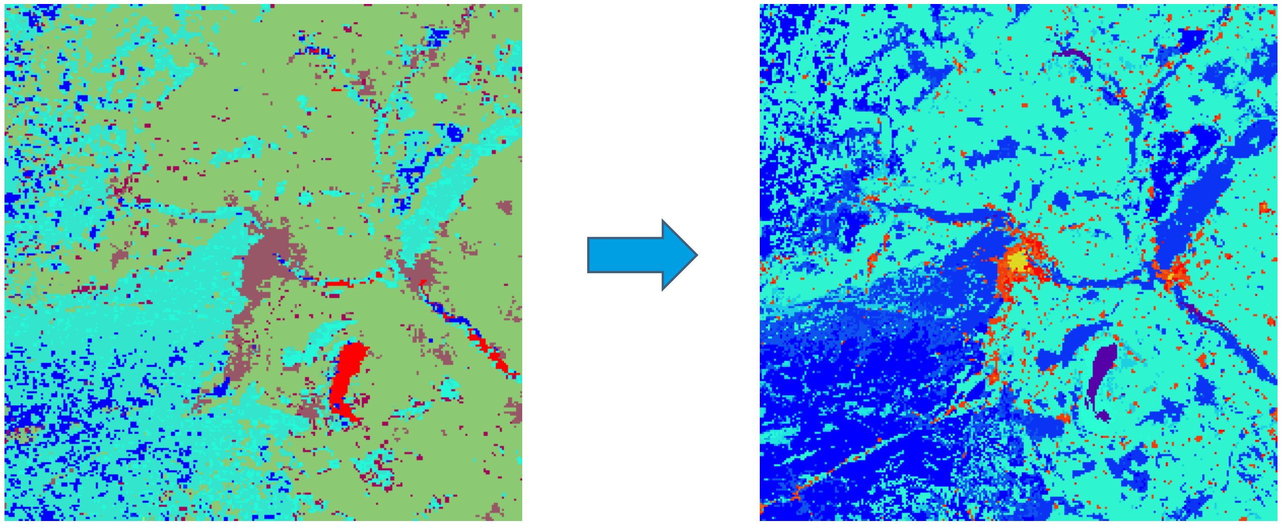


CRDS: Cavity Ring Down Spectroscopy
FTIR: Fourier-Transform Infrared Spectroscopy

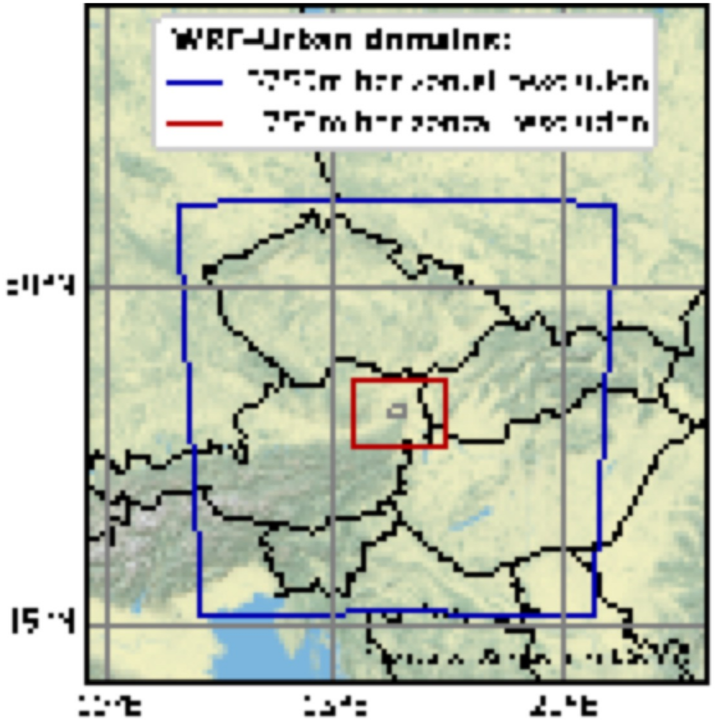
Meteorological input – Weather Research & Forecasting Model

Meteorology improvements based on **WRF-Urban**:

- spatial resolution: up to 750 m
- newer land use dataset: United States Geological Survey (USGS) → Copernicus Global Land Cover maps (CGLC, 100 m res.)
- additional land use classes for Building Effect Parameterization (BEP) + Building Energy Model Model (BEM) in urban areas
- updated WRF version 4.6



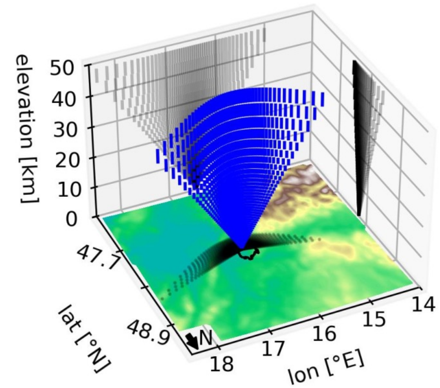
Updated WRF land use classes for Vienna domain



Atmospheric transport: FLEXPART-WRF for FTIR measurements

Source-receptor relationship (SRR) for ground based total column measurements

- FLEXPART-WRF was prepared to handle slant column (FTR) measurements. Each slant column is approximated by 50 vertical lines up to ~50 km.
- For each vertical line source, a backward field is calculated with FLEXPART-WRF.
- FLEXPART-WRF internally calculates one single result (= footprint) for every retrieval (15 minutes mean), i.e., every slanted column taking into account the pressure weighting factor and the averaging kernel.



Approximation of slant columns

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Prior vertical profiles

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FLEXPART-WRF + FLEXINVERT – general updates

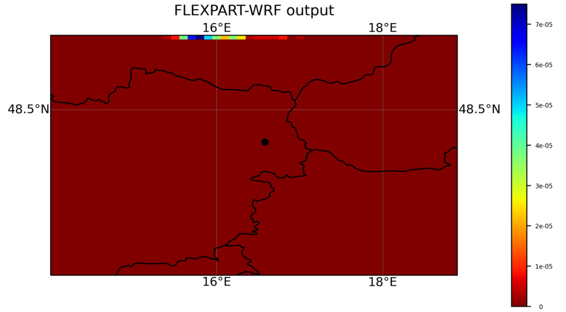
Adaption of sensitivity to initial conditions calculation for FLEXPART-WRF accounting for a limited area domain

- Current approach as used in FLEXPART is only applicable to a global domain where a computational particle is just terminated based on user specification, i.e. the AGECLASS parameter. Particles reach the mother output grid boundaries at different instances of time for a limited area domain and likely before the defined life time.
- Termination of particles NOT at the computational domain boundary or when ageclass time is reached, but at / within the mother outgrid boundary according to a switch – not desirable in general.

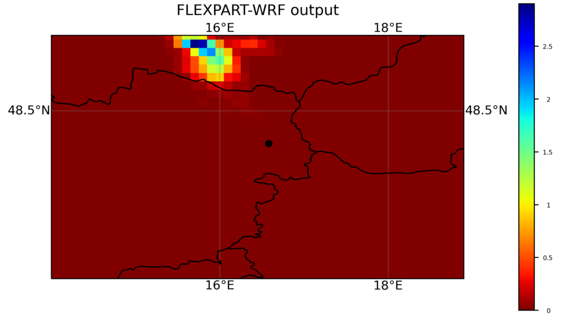
Adaption of FLEXINVERT

- Enabling simultaneous use of in-situ and FTIR observations
- Code adaptions to high resolution FLEXPART-WRF input

Initial conditions written at the edge of the mother OUTGRID domain as function of time!

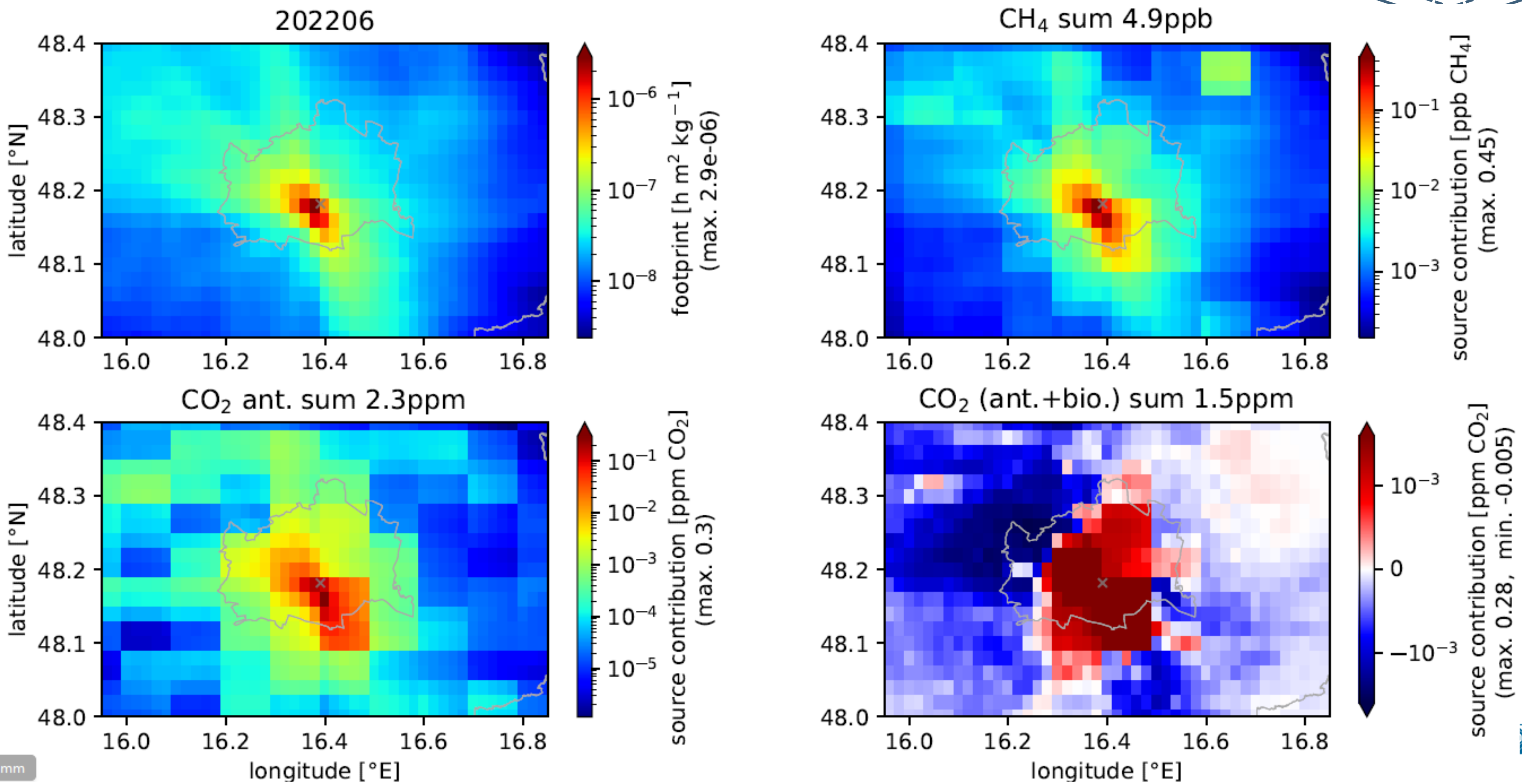


Example: Sensitivity to initial conditions (3-hourly)



Example: Residence times (hourly)

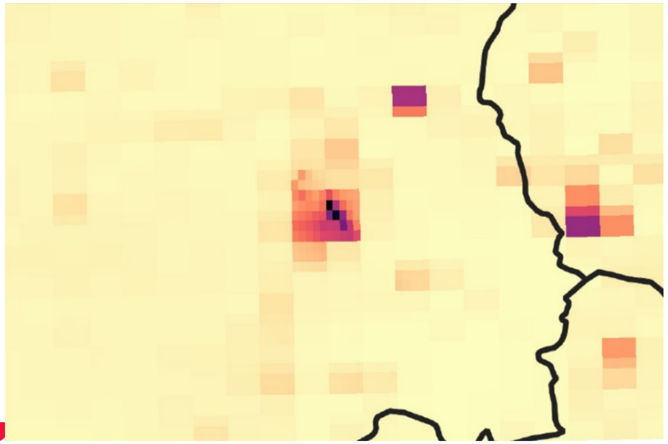
Footprint and source contribution



Inversion – preliminary outcome

Prior

Posterior

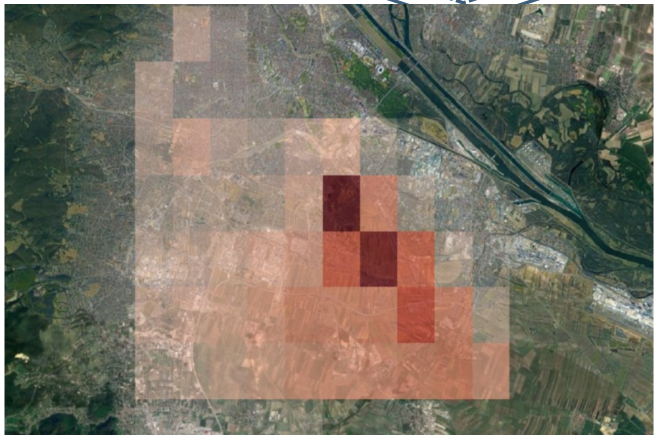


Excellent starting point for a follow-up project („*ClimateLENSE*“, proposal submitted in April) **focusing on urban scales.** Possible topics:

- Exploitation of the full data period (June to midst of July 2022)
- Extension to CO_2 (diurnal cycle, different emission sources) – CH_4 easier to handle
- Verification: E.g., bootstrapping, error reduction of a posteriori, judging a possible (FTIR) observation bias

0 40 80 km — scale top

0 7,5 15 km — scale bottom



Increment

CH_4 mol/(km²*h)

0,0
0,4
0,8

SUMMARY

- **<u>GHG inversions:</u> Observation** (*in situ*, *satellite* and *ground-based FTIR*) **based inversions (top-down approach)** are gaining increasing importance **for verifying bottom-up GHG inventories, even on urban scales.**
- **<u>Prior emissions:</u> A new Sentinel-2 based approach** was employed **to calculate biogenic fluxes on high spatial resolution** based on the Vegetation Photosynthesis and Respiration Model for Vienna, Austria and the whole of Europe.
- **<u>Observations:</u> FTIR measurements** could be used to **amend the data from** the only one **in-situ measurement** station in Vienna **for local GHG inversion**. **In-situ GHG measurements in Austria are unfortunately very scarce (just 3)!**
- **<u>FLEXPART-WRF:</u> FLEXPART-WRF got equipped for FLEXINVERT purposes,** including the **calculation of proper sensitivity to initial conditions for a limited area mother domain.**
- **<u>FLEXINVERT:</u> CH_4 preliminary results**, CO_2 code modifications still ongoing. **Current results are qualitative**, not yet evaluated. Alignment of the stations along the main wind axis (NW-SE in Vienna, originally taken with different intent) will reduce the areal sensitivity of the inversion.

CBRN Incident Modelling
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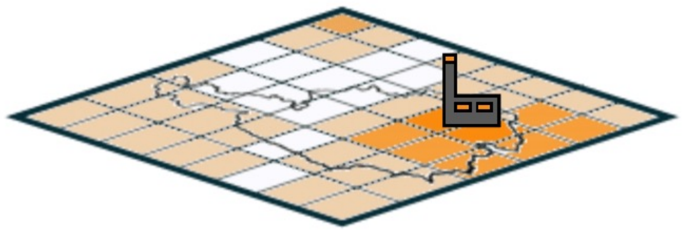

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