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Inverse Modeling

FLEXPART Training 2026

M. Blaschek

25.09.2026 (updated)

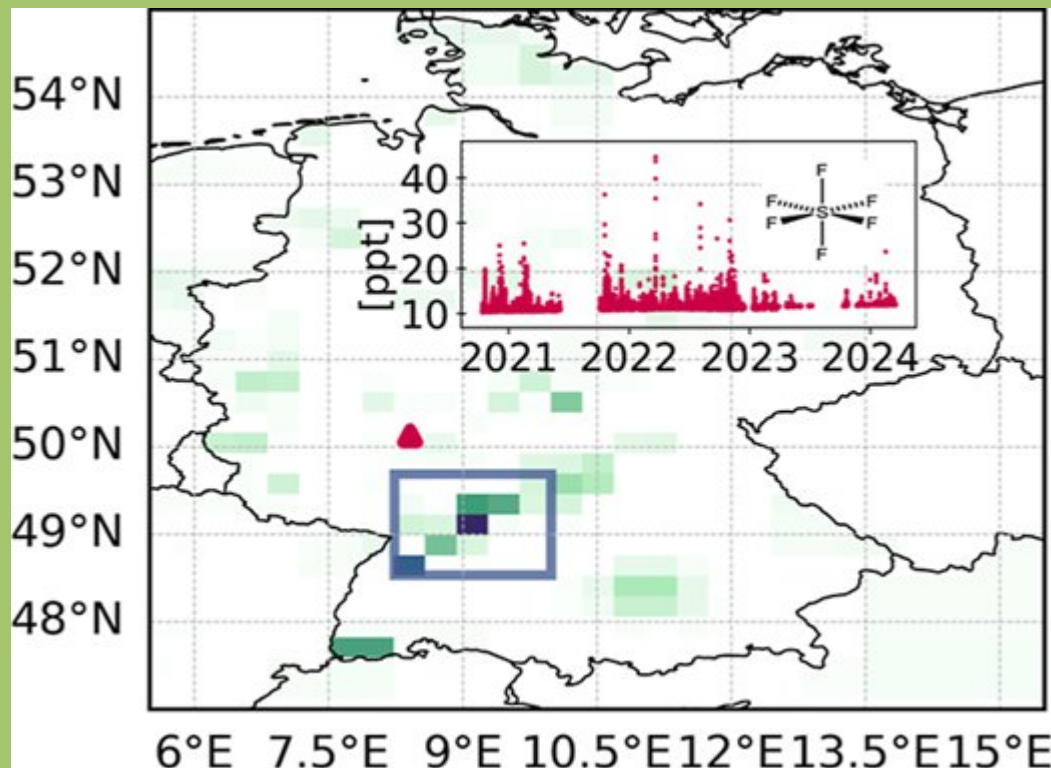


SPECIAL ISSUE:
The Inaugural Excellence
in Review Awards

SF₆

K. Meixner et al., 2025

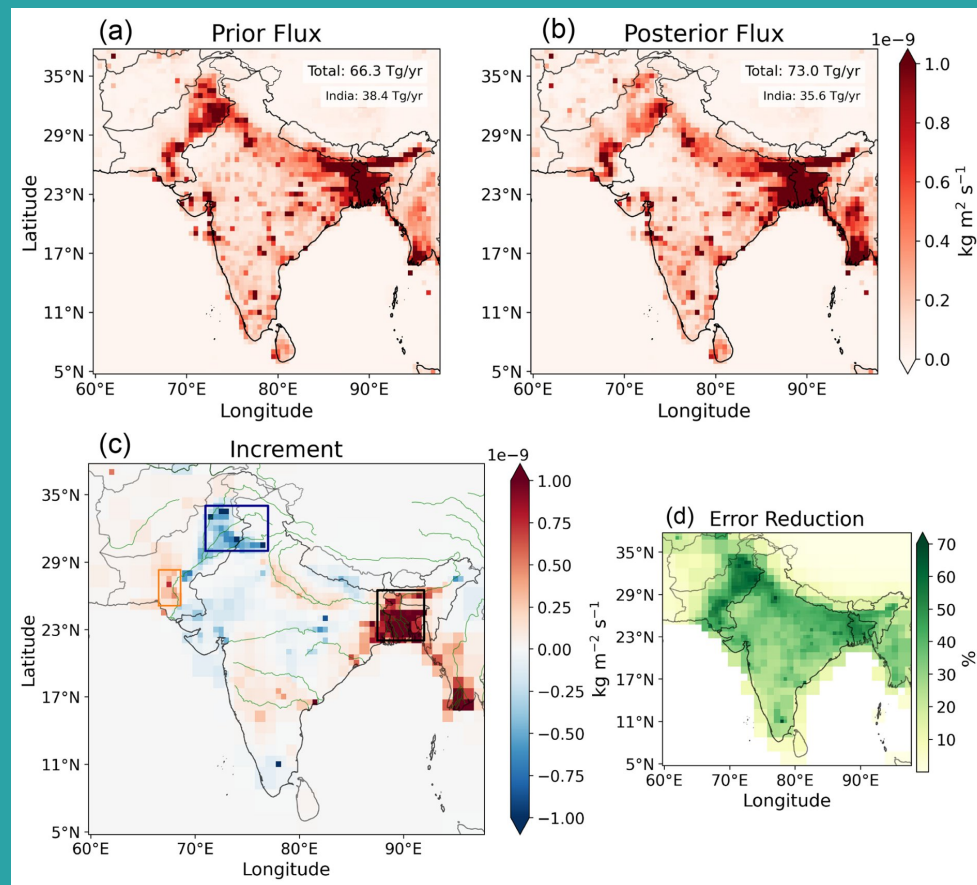
ACS EST Air 12 December 2025



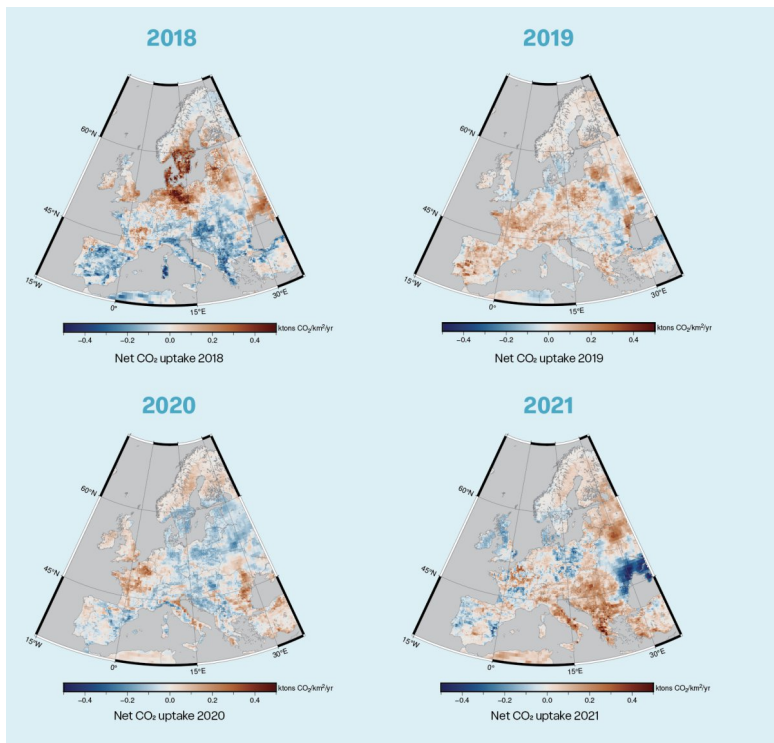
CH₄

Subramanian, R. et al. (2026)

TROPOMI



Why do inverse modeling?



Annual mean net ecosystem exchange of central Europe from 2018 to 2022, ICOS

- Observations are all we need, right?
- “... *better quantification of the net fluxes helps improving our understanding of the emitting/absorbing processes ...*”
- Which are essential for future climate change projections.
- Land carbon sink is one of the larger uncertainties.

Bottom up ↑

- **Incomplete** or uncertain activity **data** in certain sectors.
- Complex processes, such as land-use change or fugitive emissions, that are **difficult to quantify precisely**.
- Methodological **differences across countries** and time periods, which can make direct comparisons less straightforward.
- Used for **UNFCCC**

Top down ↓

- It provides **spatially integrated estimates** across large regions.
- It can help **identify sources** that may be underestimated or missing in bottom-up inventories.
- It relies **directly on atmospheric measurements**, making it less dependent on national activity data or emission factors.
- **Adds** to bottom-up

Background + FLEXPART

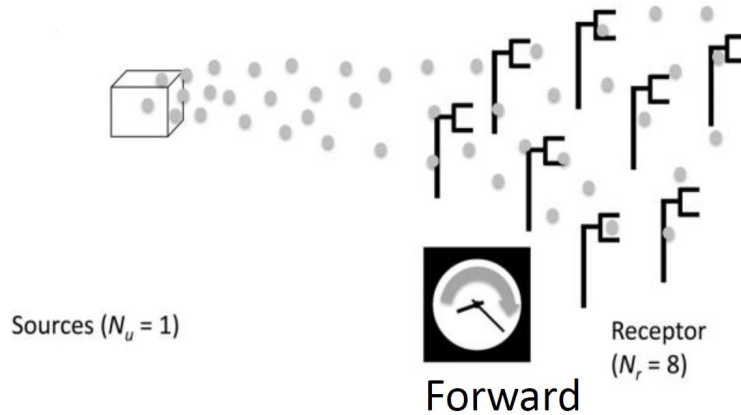
Lecture + Exercise

Big **Thank You** to M. Vojta and R. Thompson

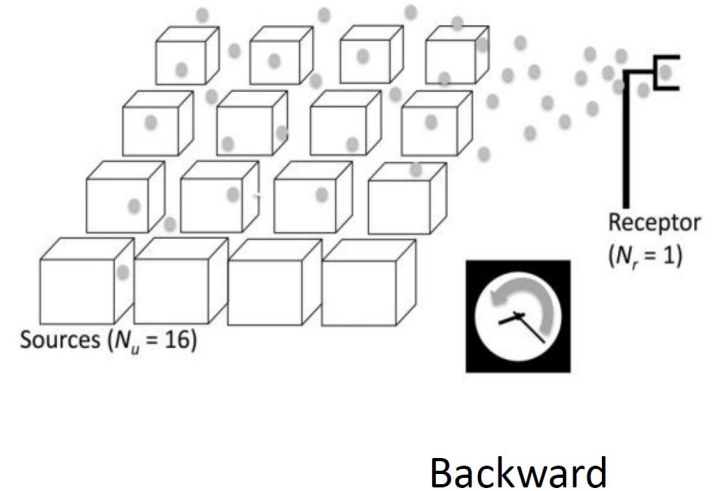
Lagrangian Model

Forward ————<>————Backward

More receptors than sources



More sources than receptors



Greenhouse Gases (GHG)

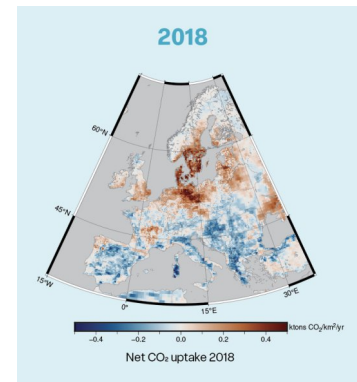
Inverse Problem?

- Observations of GHGs (CO₂, CH₄, N₂O, etc.) are used to:
 - Determine radiative forcing and thus warming effect
 - Guide for realistic forcing of climate models
 - Verification of GHG emissions / adaptation plans / controlling
- Model simulations can help to understand:
 - Sparse observations
 - Prior emissions (e.g. bottom up estimates)
 - Satellite retrievals of GHGs
 - Observed variability

Inverse Modeling of Greenhouse Gases (GHG)

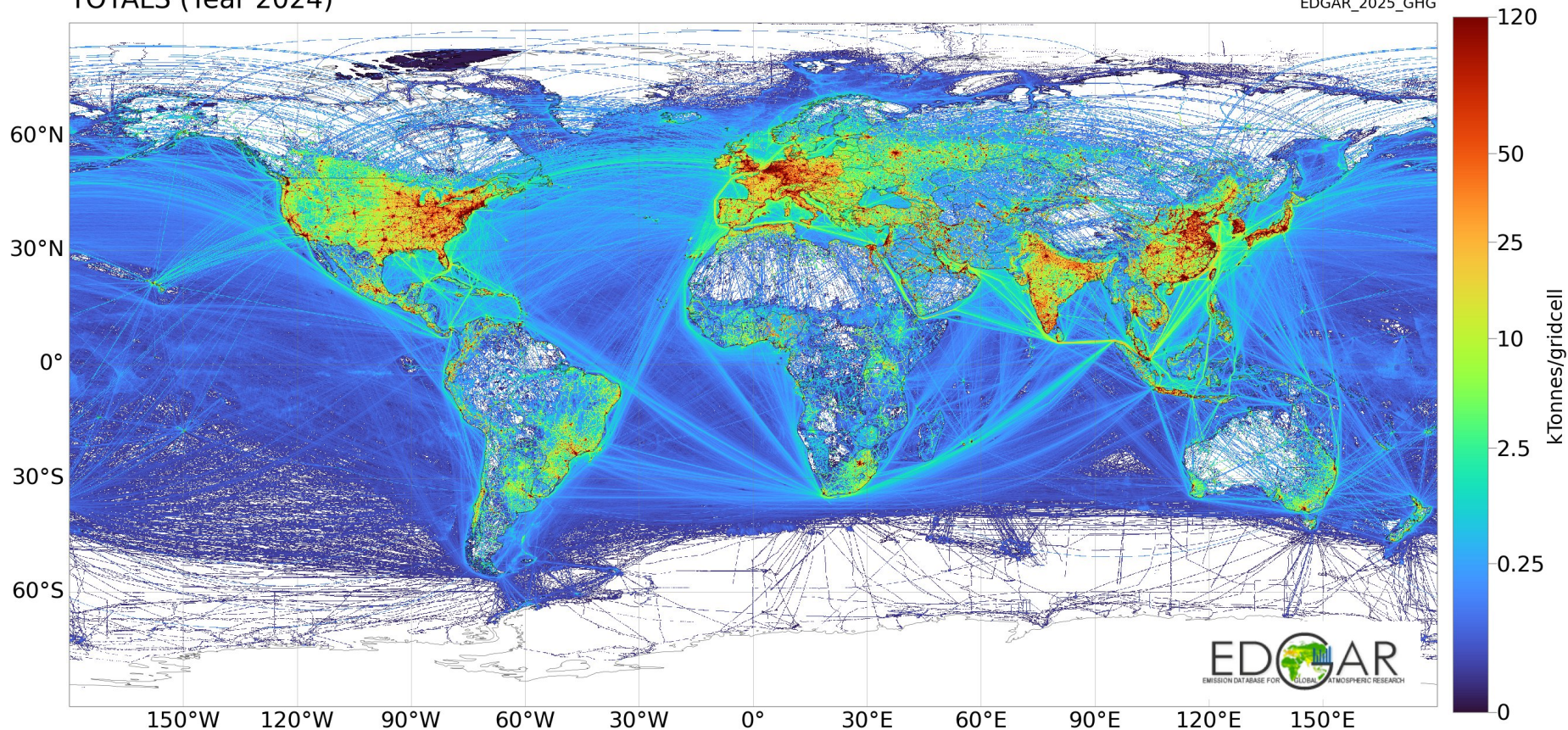
Considerations

- Most GHGs are long-lived species:
 - Need to have a history of the atmosphere before that simulation starts (initial conditions)
- GHG sources:
 - Point sources or diffuse sources
 - Emission estimates are broken down to grid-cells
 - Temporal aggregation (measurement averages, ...)
- Ill-Posed nature of Inversions (under determination)
 - Using different priors (species dependent) or increasing observation/model errors
 - Ensemble

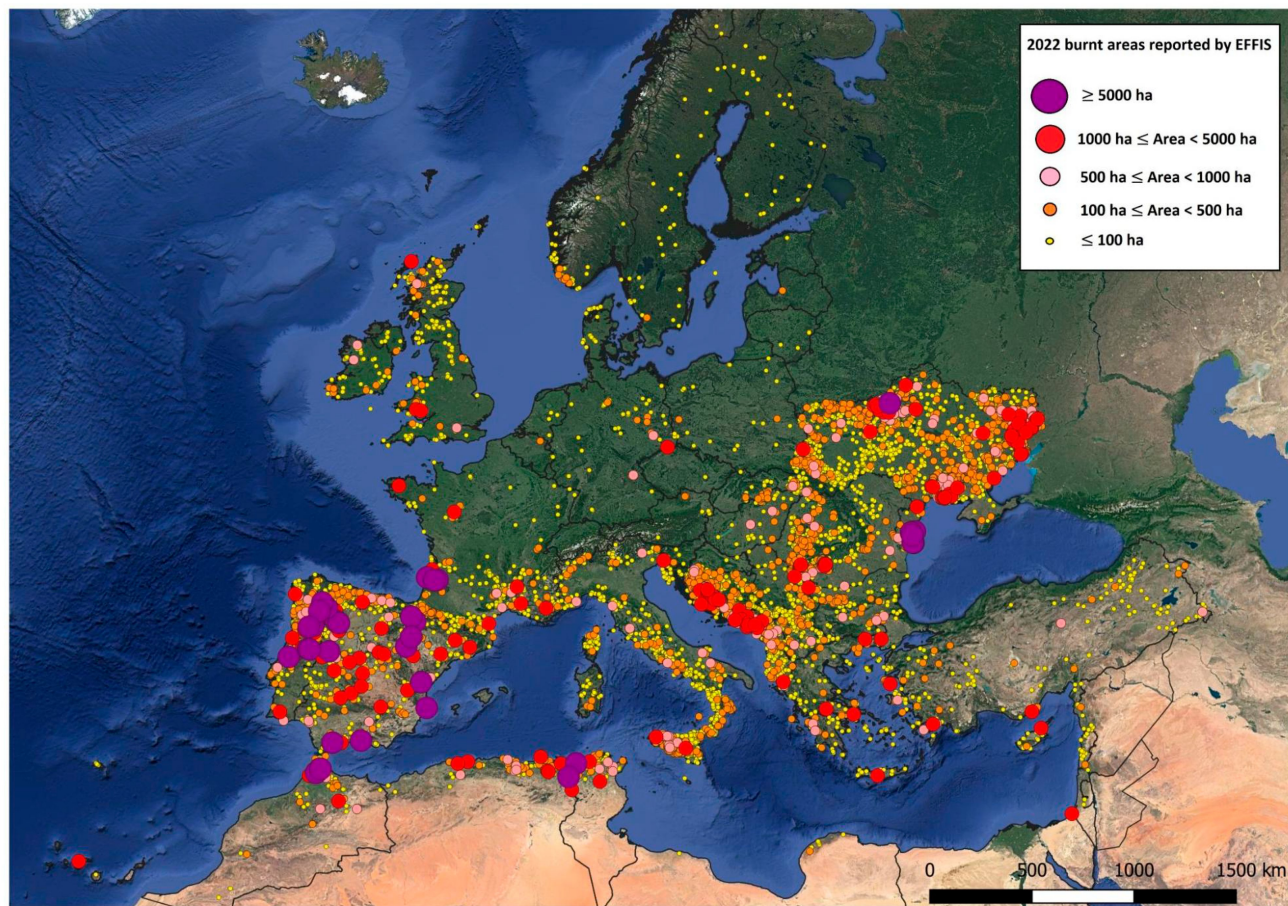


CO2 emissions: TOTALS (Year 2024)

Global total:39.63Gt
EDGAR_2025_GHG



Burn



GHG – species

CO₂

- Lifetime: ∞
- GWP: 1
- Implications:
 - Sensitivity < weeks
 - Biosphere
 - Fossil fuels
 - Agriculture / forests
 - Different timescales

CH₄

- Lifetime: 9-10y (OH)
- GWP: 30
- Implications:
 - Sensitivity < weeks
 - Chemical loss OH
 - Agriculture
 - Wetlands
 - Pipeline leakage
 - Ground based

N₂O

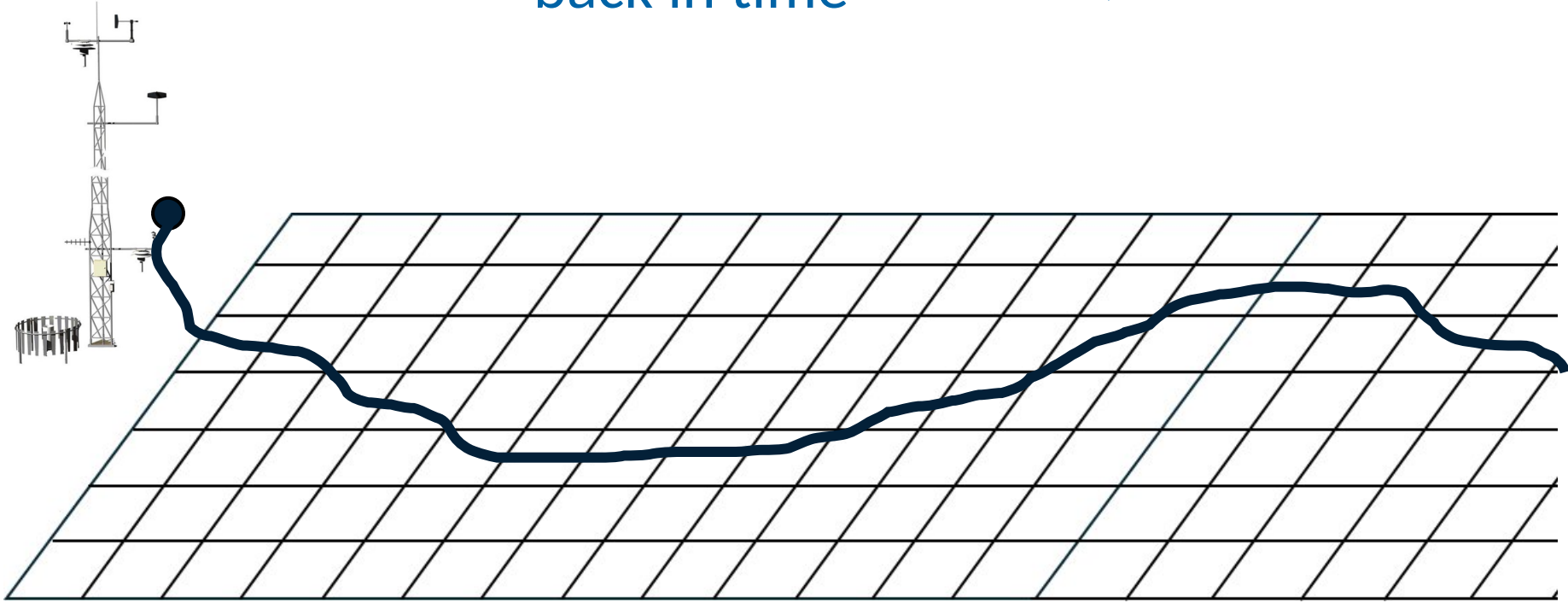
- Lifetime: 100y
- GWP: 273
- Implications:
 - Sensitivity very long
 - Agriculture
 - Biosphere
 - Oceans

SF₆

- Lifetime: <3200y
- GWP: 24k
- Implications:
 - Sensitivity back forever
 - Point sources
 - Electrical insulator
 - Only anthropogenic

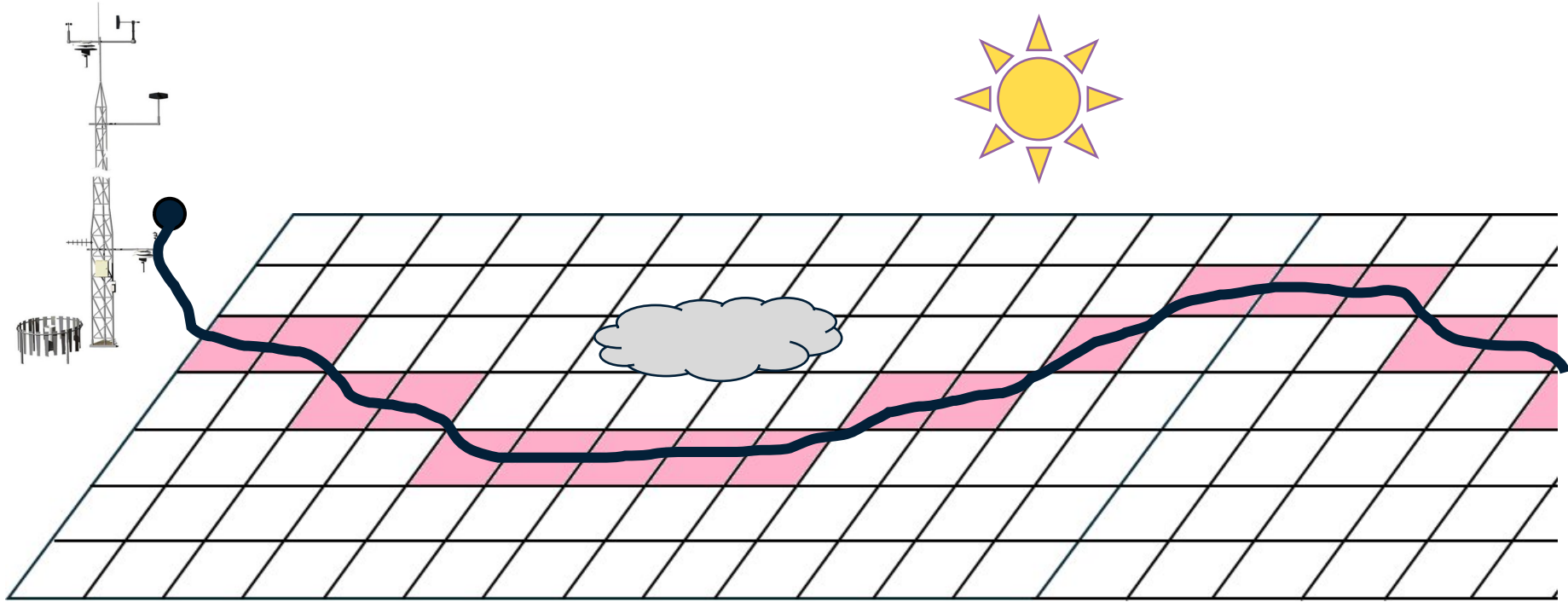
What is a source-receptor relationship (SRR)?

=====back in time=====>



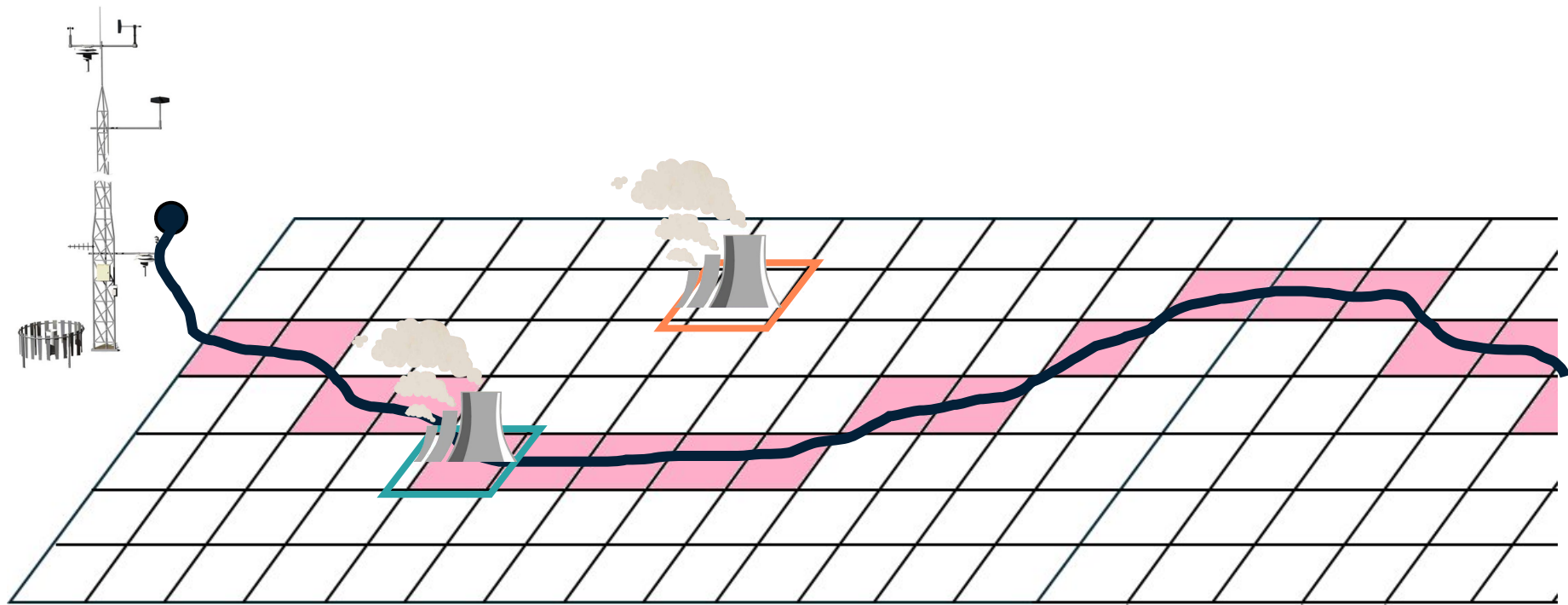
@M. Vojta

SRR - footprint



@M. Vojta

Sensitivity == residence time



@M. Vojta

relate measurements with emissions

$$\left[\frac{kg}{m^3} \right]$$

$$[s]$$

$$\left[\frac{kg}{s m^3} \right]$$

measurement = sensitivities × emissions

$$[ppt]$$

$$\left[\frac{s m^3}{kg} \right]$$

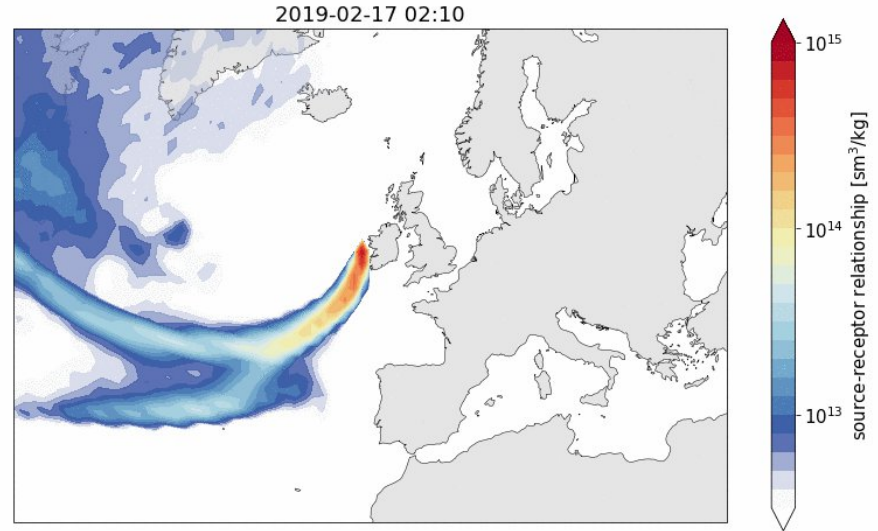
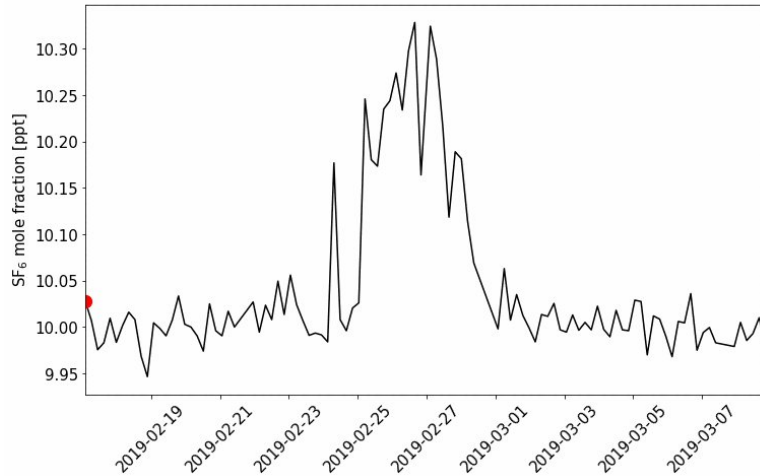
$$\left[\frac{kg}{s m^3} \right]$$

Direction	IND_SOURCE	IND_RECEPTOR	INPUT	OUTPUT
backward	1	1	1	s
backward	1	2	1	s m ³ kg ⁻¹
backward	2	1	1	s m ³ kg ⁻¹
backward	2	2	1	s

@M. Vojta

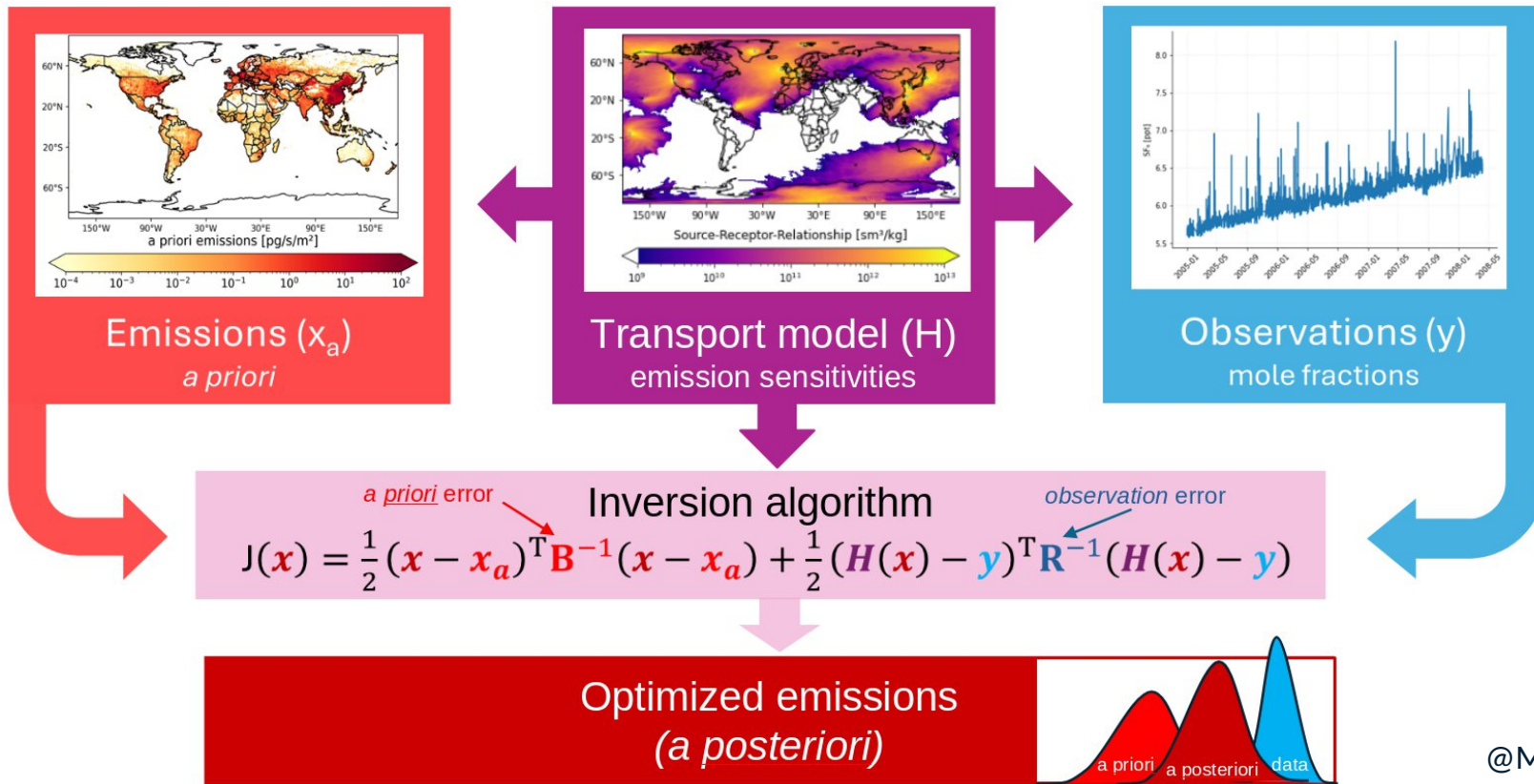
relate measurements with emissions

$$\text{measurement} = \text{sensitivites} \times \text{emissions}$$



@M. Vojta

What makes inverse modeling so much fun?

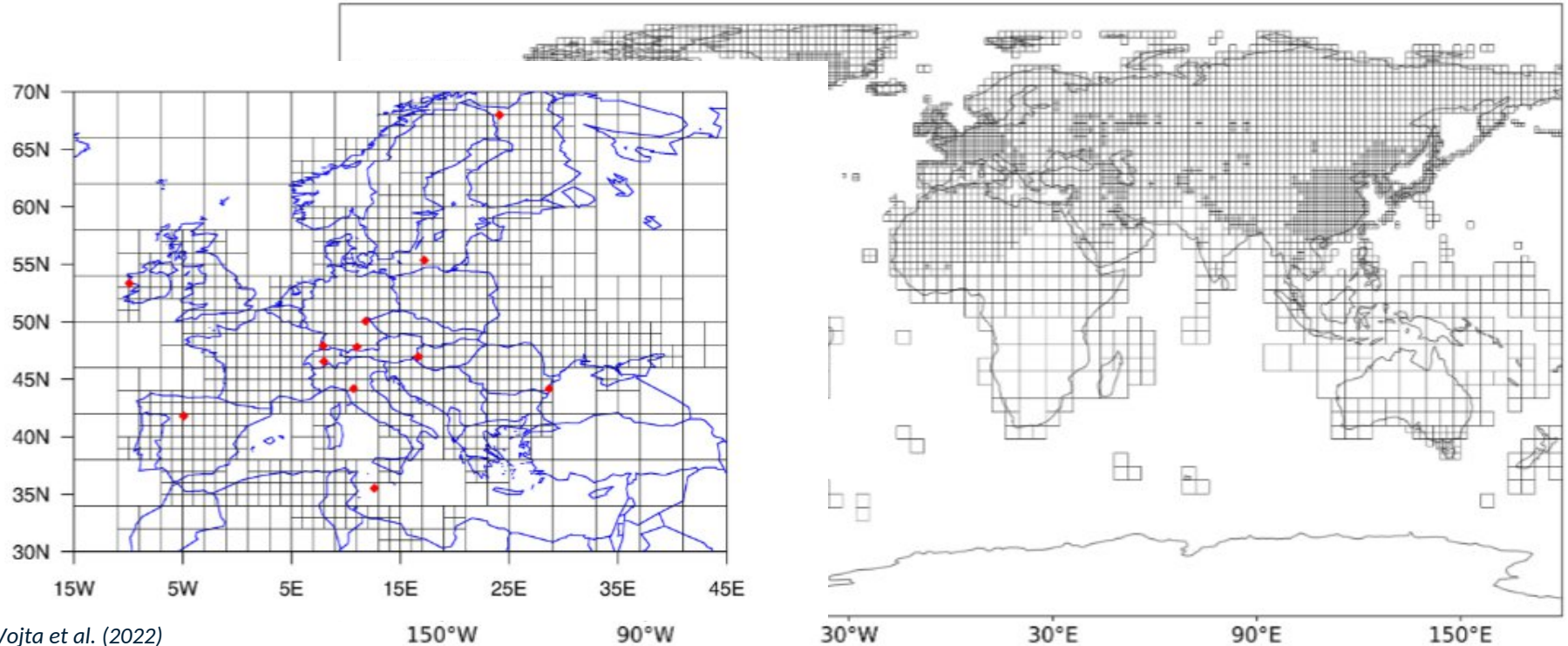


Key Challenges in inverse modeling

Observations (sampling time, **sparse**, satellites)

Σ Errors (obs, models, **background** concentrations)

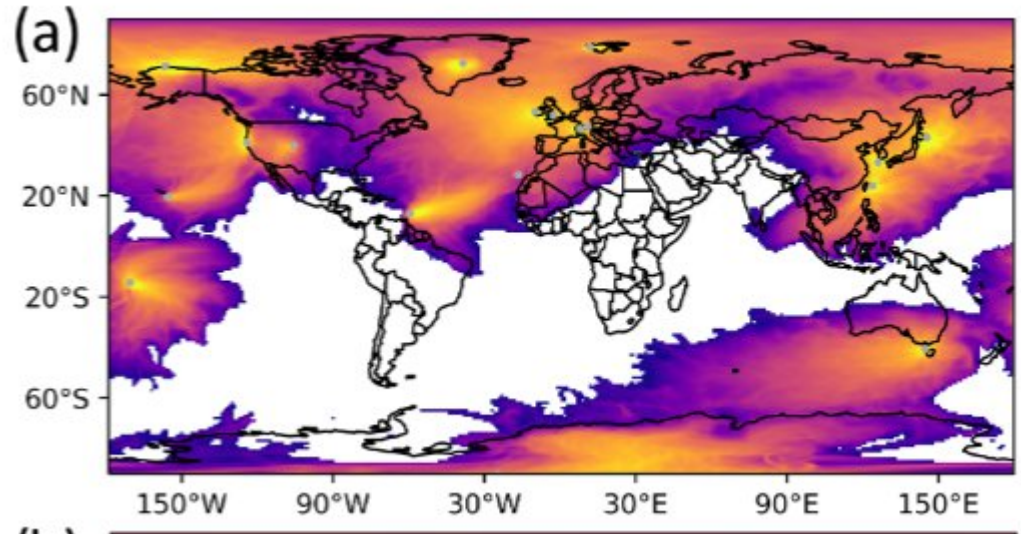
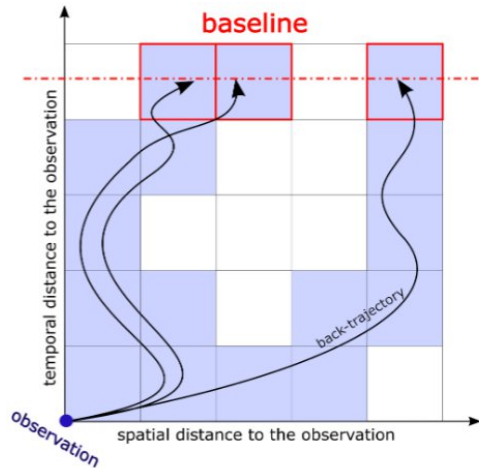
Sparseness - Variable resolution grid for inversions



Vojta et al. (2022)

Need a Background

- in order to reproduce background signals, such as seasonal variability, simulations of months to years would be necessary
- Global distribution-based (GDB)



Exercise ☀

Introduction first!

You: Lab 35 min + 10 min Group discussion with ALL

Getting Started

- What you need to do:
 1. Go to [MyBinder](#), Go into the Inversion Folder
 2. **Optional:** Open "Introduction.ipynb"
 1. **Shutdown all kernels**
 3. Open "Emissions.ipynb" + Complete all Tasks
 1. run FLEXPART (**SAVE OUTPUT + Download: tar cf inversion.tar output/**)
 2. Answer questions
 3. **Shutdown all kernels**
 4. Open "Inversion.ipynb" + Test different scenarios.

Reminder: Save your output directory, by downloading it. You will run out of memory!!!

Server Connection Error

A connection to the Jupyter server could not be established. JupyterLab will continue trying to reconnect. Check your network connection or Jupyter server configuration.

☐ Do not show this message again in this session.

Close

Reminder: Shutdown all other kernels. Use just one notebook at a time.

Introduction + Emissions

- *I assume you did some of the other exercises before*
 - *E.g. compile the model, modify files, ...*
- **Introduction** is optional, Look at the input data (met. files)
- **Emissions:**
 - Define your simulation (COMMAND, OUTGRID, AGECLASS)
 - Run FLEXPART & create tar and download
 - Plot your results / adjust parameters

Inversion

- Look at the emission sensitivities
- Define your sources and prior estimates. run inversion
- Experiment with
 - source location
 - errors
 - number of sources

go to
BREAKOUT
ROOMS

Results + Exercise

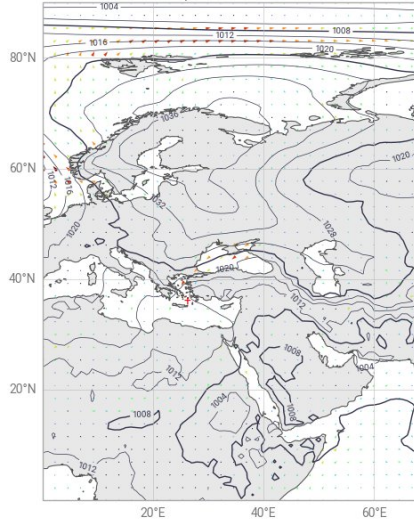
What you should get



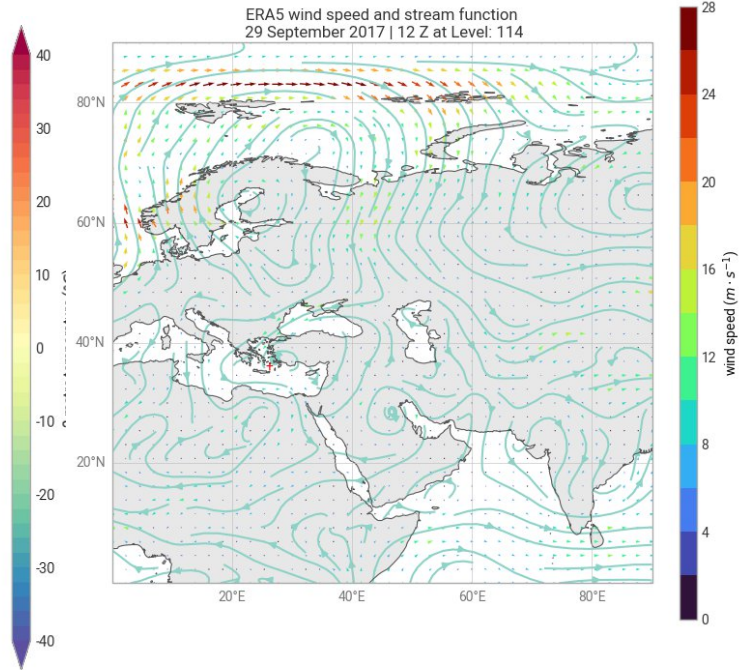
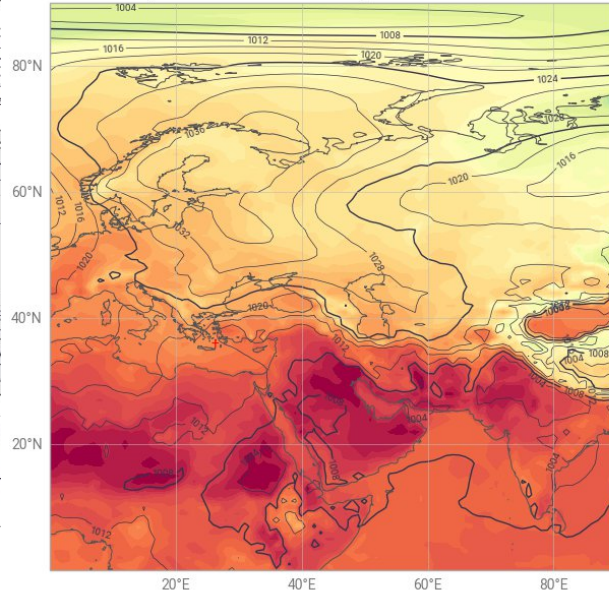
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Input data

10 metre U wind component and 10 metre V wind component pressure at 12:00 on 2017-09-29

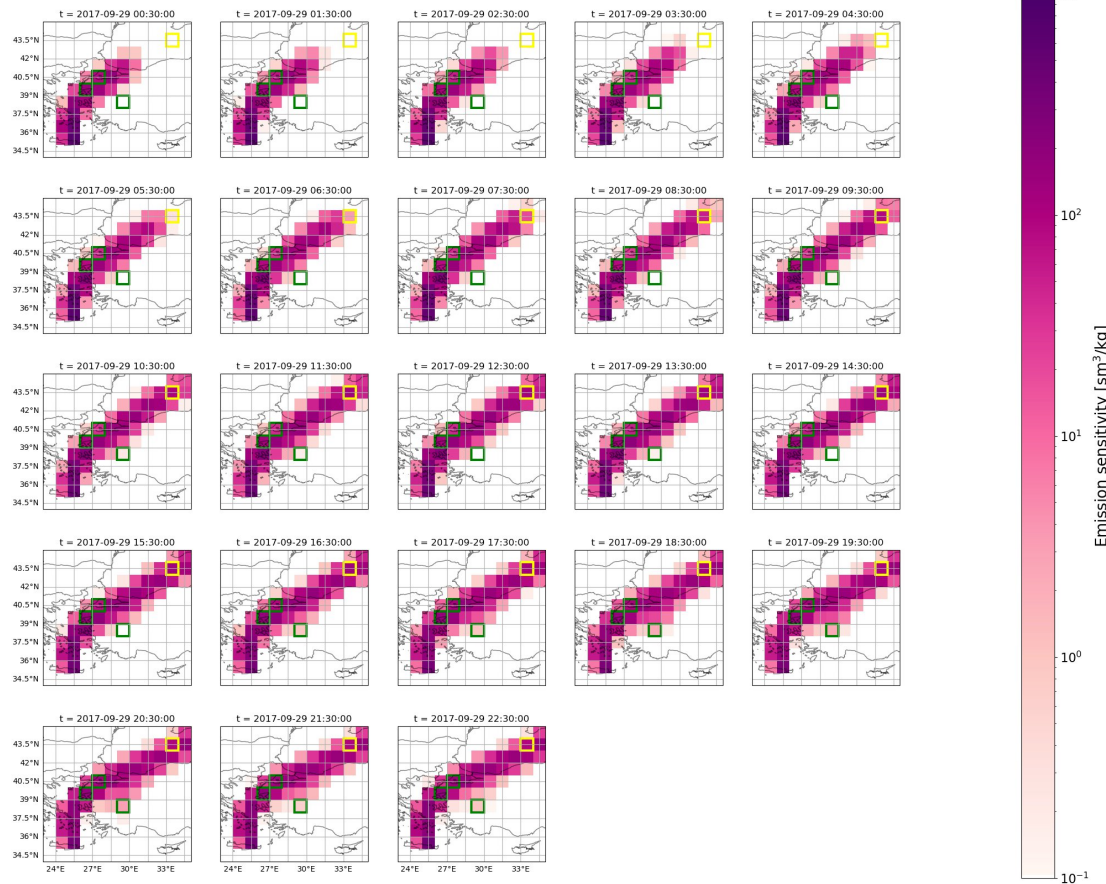
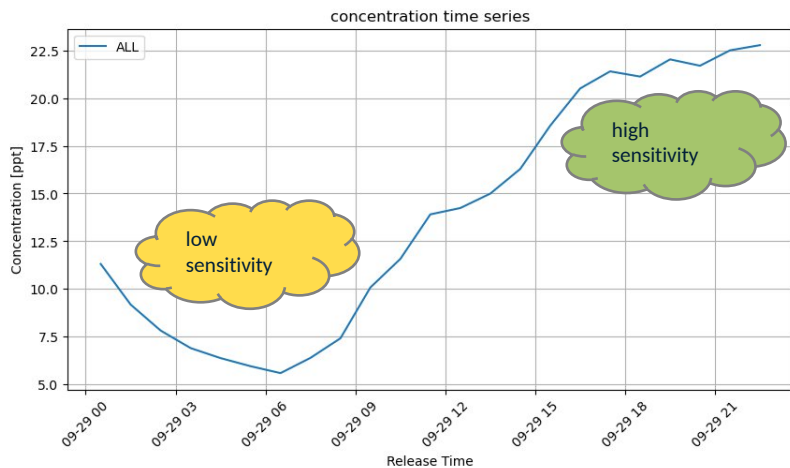


2 metre temperature and Mean sea level pressure at 12:00 on 2017-09-29



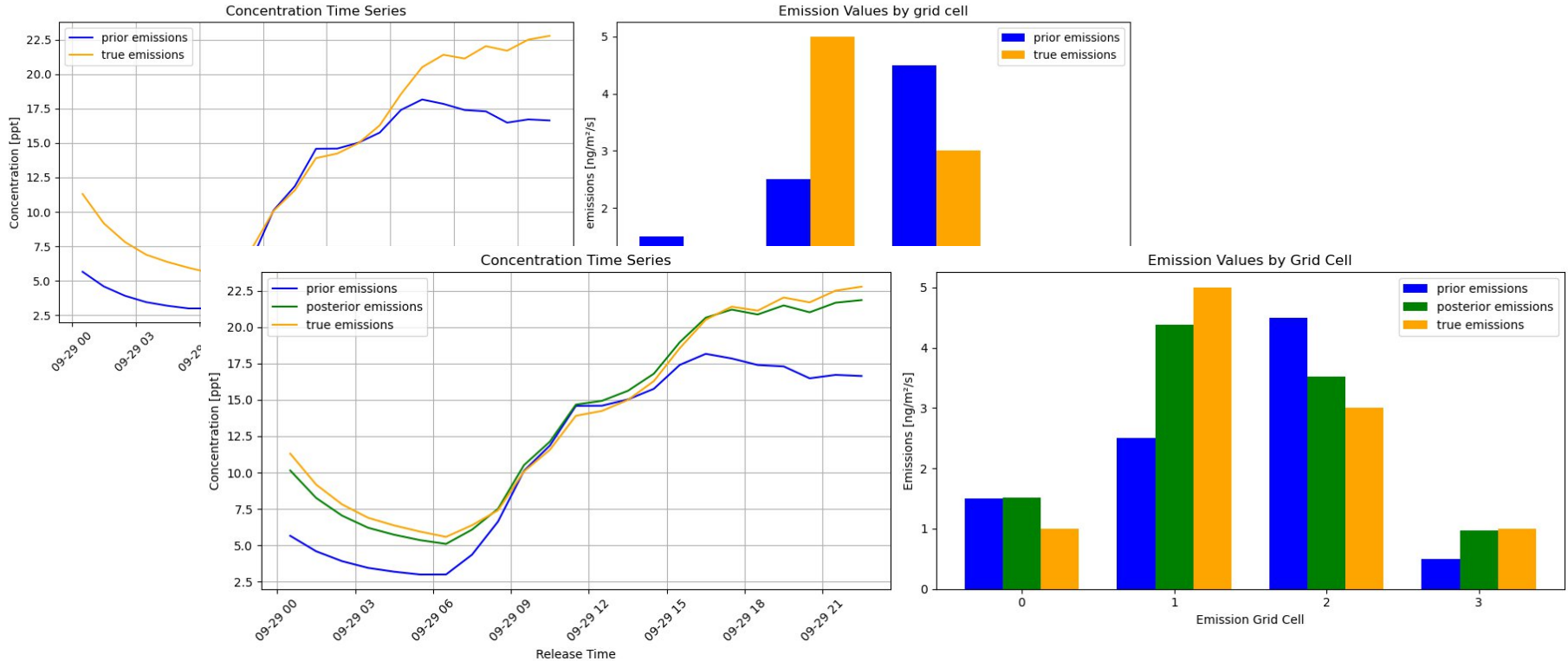
ERA5 FLEXPART input files. Reading GRIB. Plotting GRIB using earthkit

Emission sensitivities to emission sources?



Emission sensitivities for different source areas

Inversion + sources + errors



Before and after running the inversion. Using 4 different sources.

ENDE