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Sentinel EO-based Emission and Deposition Service

Funded by the European Union

Alternative approaches to derive emissions from satellite data

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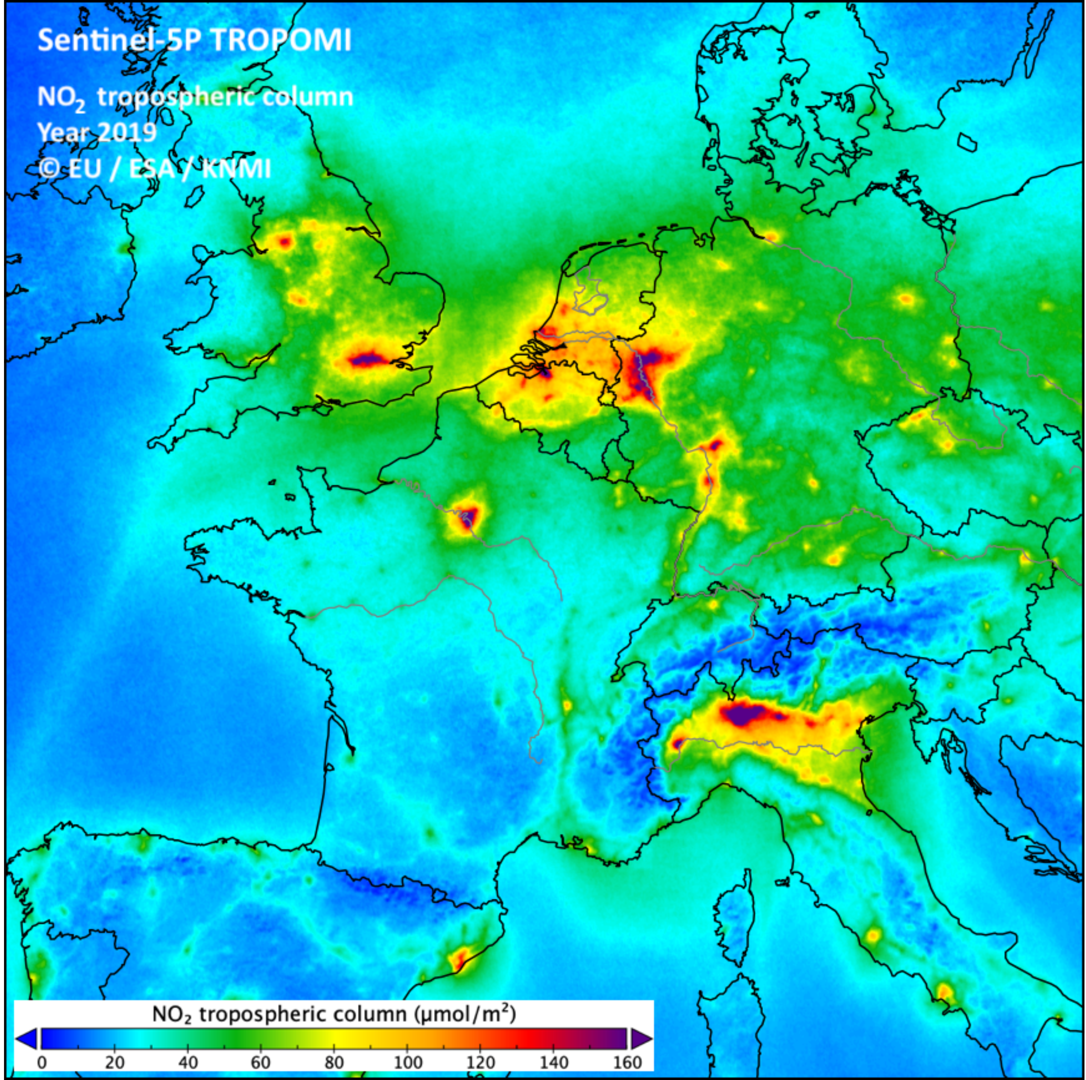
TROPOMI NO2 over Europe

From TROPOMI NO2 maps we can derive emission estimates for:

- cities
- highways
- ships (routes + individual cargo ships)
- airports
- various types of industries:
  power plants, vertiliser, (petro)chemical, cement …



Why use satellite data for knowledge on emissions?

Strong points:

- **Daily** measurements (for NO2 about 1 per 2 days due to clouds):
  detect **sudden changes in emissions** within a few days (e.g. COVID-19 lockdown related)
  Real-time emission estimates.
- **Full coverage**, not limited to station locations only: total emission budgets.
- Gradients in **total column** are a direct measure of **emissions**
  Daily pollution **plumes** can be analysed to provide emission estimates.
- Very little noise in NO2, TROPOMI: we can analyse daily data.
  (For HCHO / NH3 noise is larger - averaging in space / time)

Limitations:

- Only **one overpass** per day, close to noon time, **cloud-free**, resolution of about 5 km.
  TROPOMI observations need to be complemented with diurnal profiles.
- No direct emission **sector information**, but can be derived indirectly from spatial distribution

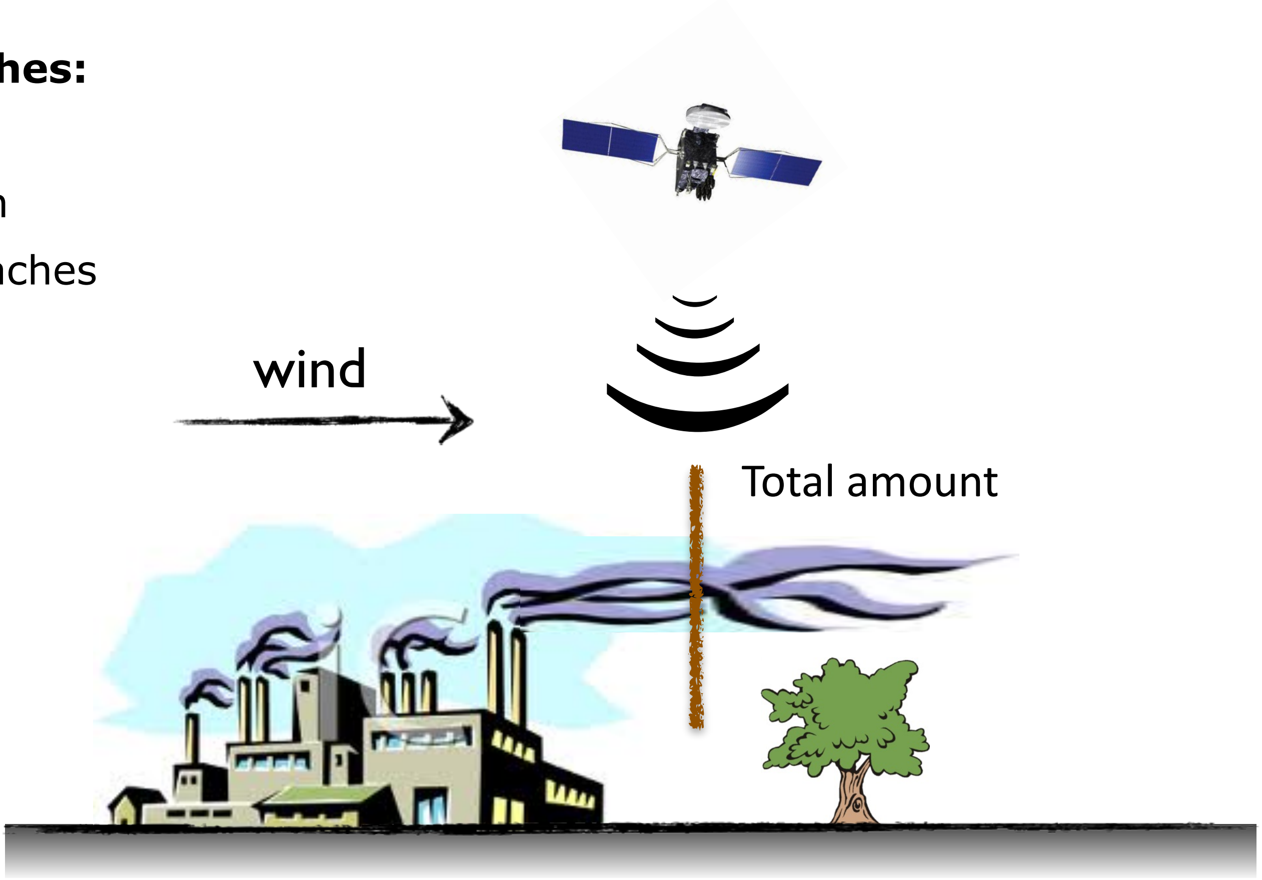
Future: Geostationary satellite observations over Europe with **Sentinel-4** (launce 2024)

SEEDS has performed a case study for Sentinel-4 potential using TROPOMI data at high latitudes

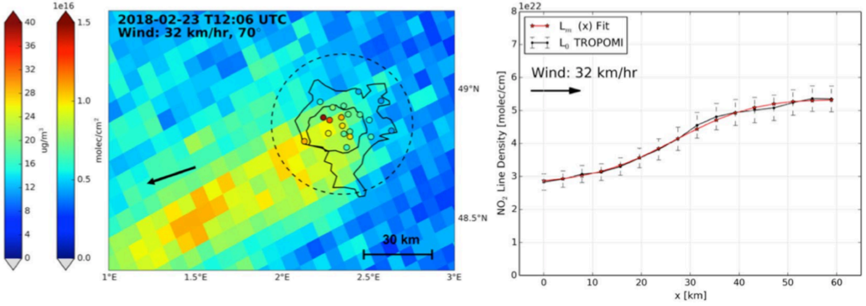
Emission estimates from satellites: different approaches

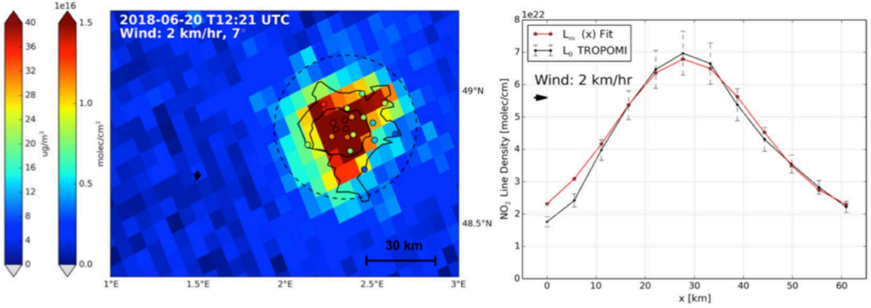
Three groups of approaches:

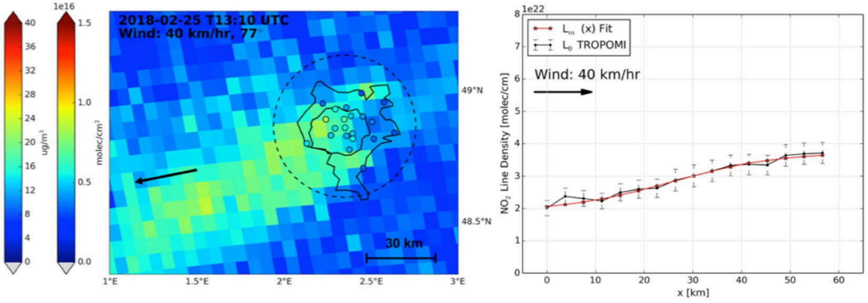
- Plume analysis methods
- Flux divergence approach
- Inverse modelling approaches



Emission estimates #1: plume analysis







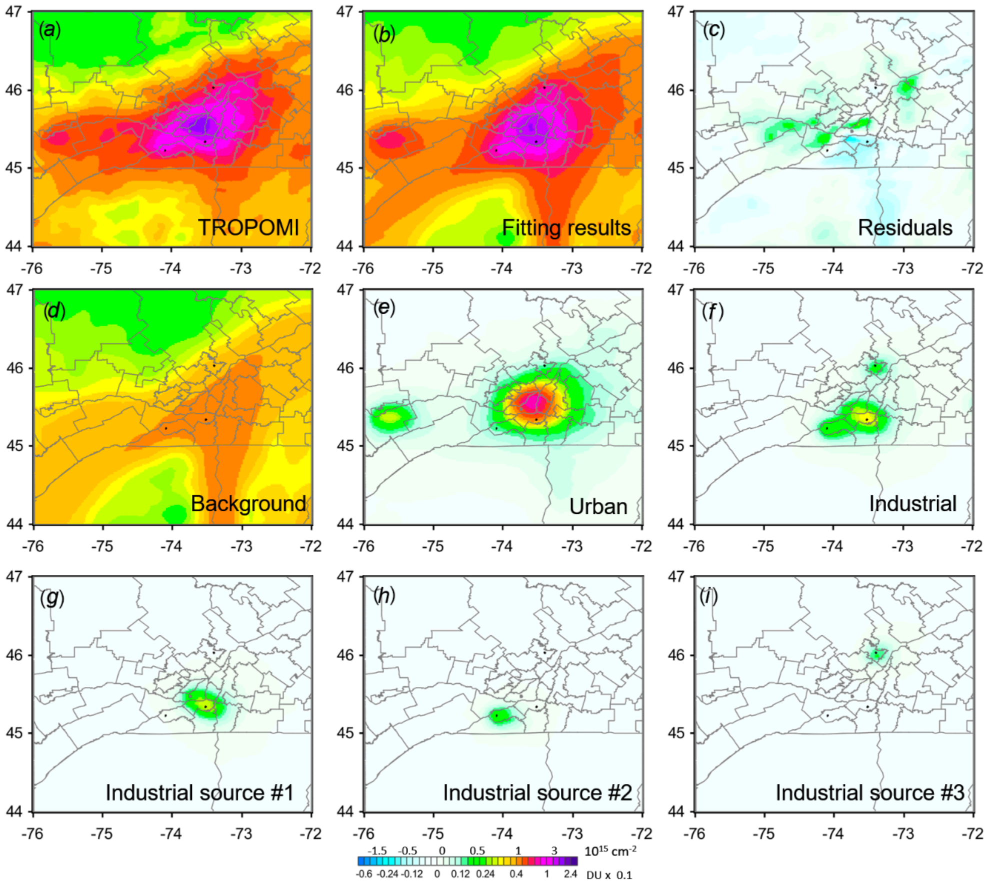
Plume fit depending on
- emission strength,
- plume width,
- NO2 lifetime

Emission distribution within megacity

Estimating NOx emissions of Paris
Lorente et al., Nature Sci. Rep. 2019

Emission estimates #1: plume analysis

Montreal, Canada



Fitting TROPOMI NO2 data with a statistical model with empirical plume dispersion functions driven by a meteorological reanalysis.

- multiple point sources
- area sources

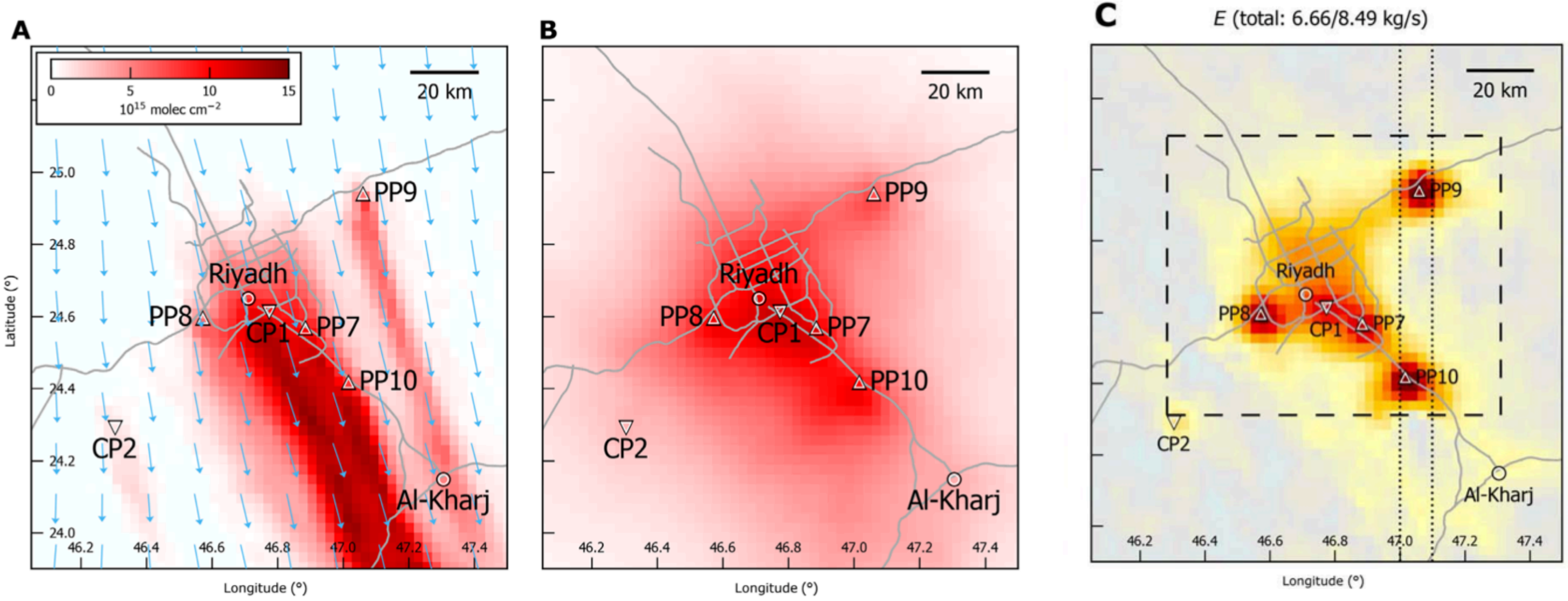
Make use of:

- point source locations
- population density
- elevation

Fioletov et al., https://doi.org/10.5194/acp-22-4201-2022

Can be used to create point source emission catalogue

Emission estimates #2: flux divergence approach



One overpass over Riyadh | Yearly mean concentration | Yearly mean emission

Flux divergence method, Beirle et al., Science Adv. 2019

Emission estimates #2: flux divergence approach

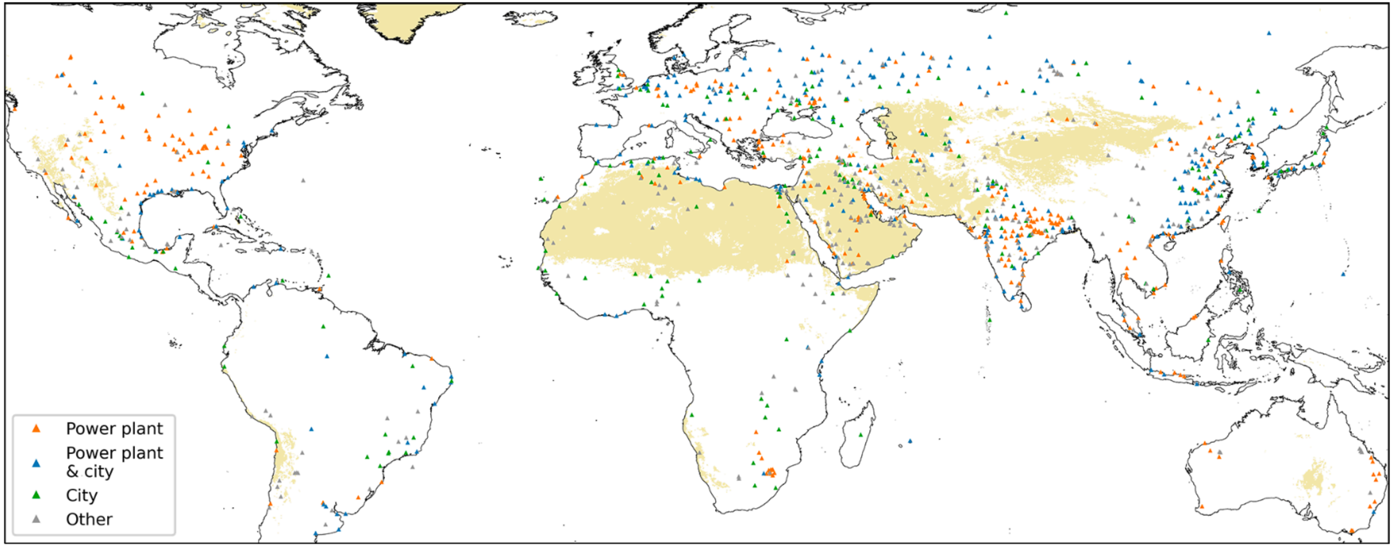


Figure 8. Location of point sources listed in v2 of the catalog. Matches in GPPD and/or WCD are indicated by colors as in Fig. 7. The background map highlights regions with high LER, where a detection limit of 0.03 kg s^{-1} is assumed.

Method improvements
- Profile shape (plume height)
- Lifetime
- NO2/NOx ratio

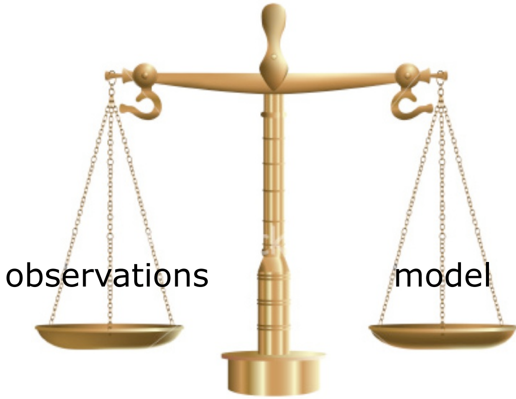
Improved catalogue of NO2 point source emissions
Beirle et al., ESSD, 2023

Global point source catalogue identifying power plants, cities and other sources

Emission estimate #3: Inverse modelling and data assimilation

Match of **satellite observations** and **chemical-transport model** simulations via **data assimilation**:

- *Kalman Filter* (**DECSO** algorithm of KNMI) — **SEEDS**
  - Based on French CHIMERE model
  - Fast, only one model run needed
  - No a-priori needed, unknown sources
  - Error estimates
- *4D-Var or Ensemble Kalman Filter approaches*
  More computer-intense to run. Development of 4D-Var adjoint.
  - Ex: EnKF global tropospheric multi-species reanalyses
    Optimising concentrations + emissions;
    TCR-2, Miyazaki et al., ESSD, 2020.
  - Ex: Magritte inversion of HCHO for Isoprene emissions — **SEEDS**
  - Ex: Development of the 4DEnVar system, Emanuele Emili — **SEEDS**
  - CAMS is now developing emission inversion capabilities in IFS-COMPO.
    -> Building on SEEDS products and developments.



Three approaches for emission estimates: Pros and Cons

Plume analysis:

- Pro: Analyse individual plumes on daily basis
- Pro: Derive lifetime from plume shape
- Con: Overlapping plumes more messy.
- Con: Atmospheric transport does not always lead to well-defined single plumes: turbulence, wind sheer, orography
- Con: Emissions are retrieval a-priori dependent

Emission estimates: Pros and Cons

Flux divergence method:

- Pro: Easy to implement, fast to run
- Pro: No identification of plumes needed
- Pro: High spatial resolution, good for creating point-source catalogues
- Cons:
  - Emissions depend on the retrieval a-priori, typically (low) biased in simplest approach
    Good quantitative results requires additional complexity and corrections.
  - Lifetime most difficult part:
    Use of OH from model often very uncertain / model dependent
    Spurious background emissions
  - Noisy: can not be used for individual days.
    Typically results averaged, producing monthly-to-yearly emission maps

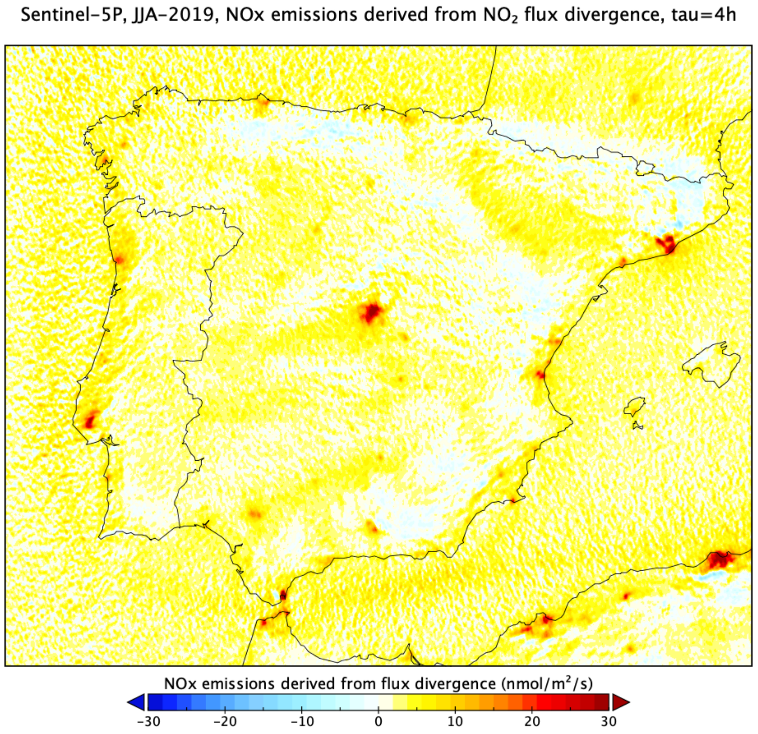
Emission estimates: Pros and Cons

Inverse modelling methods:

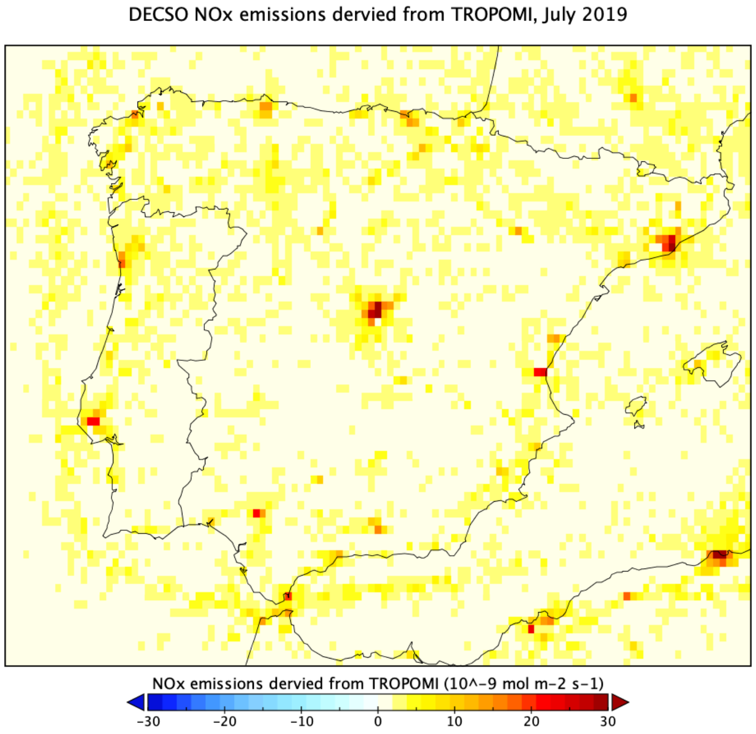
- Pro: Using state-of-the-art chemistry modelling to relate concentrations to emissions,
  based on NWP weather analyses.
- Pro: Full 3D approach, modelling of vertical mixing and 3D transport of profiles
- Pro: Averaging kernels can be used, making emission estimates independent
  of the retrieval a-priori
- Con: Model uncertainties and error covariances, and final emission uncertainty
  in practice difficult to quantify
- Con: Often inversion systems dependent on a-priori emissions (by design)
  (optimise scaling factors of existing bottom-up emission inventory)
  -> DECSO approach is exception.
- Con: Large-scale computing, big codes, more specialised

Verification of NOx emissions: DECSO versus Flux-divergence

Flux-divergence



DECSO



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Using satellites to derive emissions

Three groups of approaches:

- Plume fitting methods
- Flux divergence approach
- Inverse modelling approaches

There are strengths and weaknesses in each of these approaches.

They are based on very different inputs, tools and assumptions, highly complementary.

Conclusion:

We can learn about the top-down emission uncertainties by comparing the results of different emission estimation approaches

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