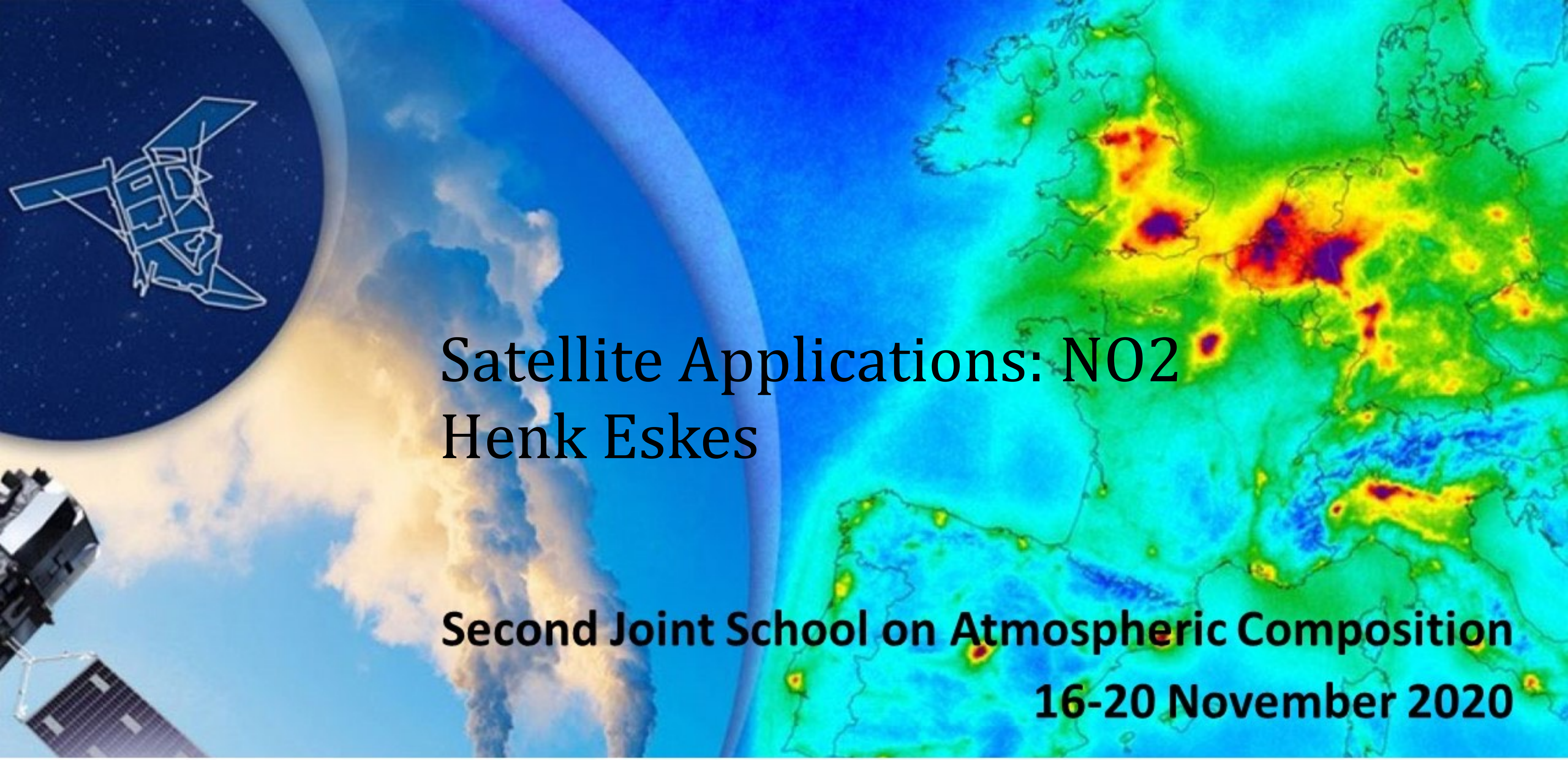
Satellite Applications: NO2

Henk Eskes



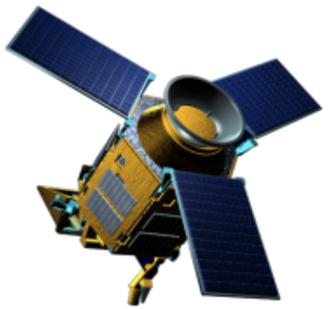
Satellite instruments measuring NO_2

- Past & present:
  25 years of NO_2 observations from space
  GOME, SCIAMACHY, GOME-2 A/B/C, OMI, OMPS, TROPOMI (Sentinel-5P)
  Increasing the spatial resolution from about 100 km to about 5 km
- Future:
  Geostationary: GEMS (launched 2020), TEMPO, Sentinel 4
  Sentinel 5
  CO2M (2 km resolution), with NO_2 for plume identification
  …

Copernicus Sentinel-5P TROPOMI instrument

Dutch instrument   Pepijn Veefkind PI (KNMI)   Airbus DS, TNO, SRON, KNMI, NSO, ESA, EU

Mission objectives: **Air Quality, Climate Change, Ozone layer**

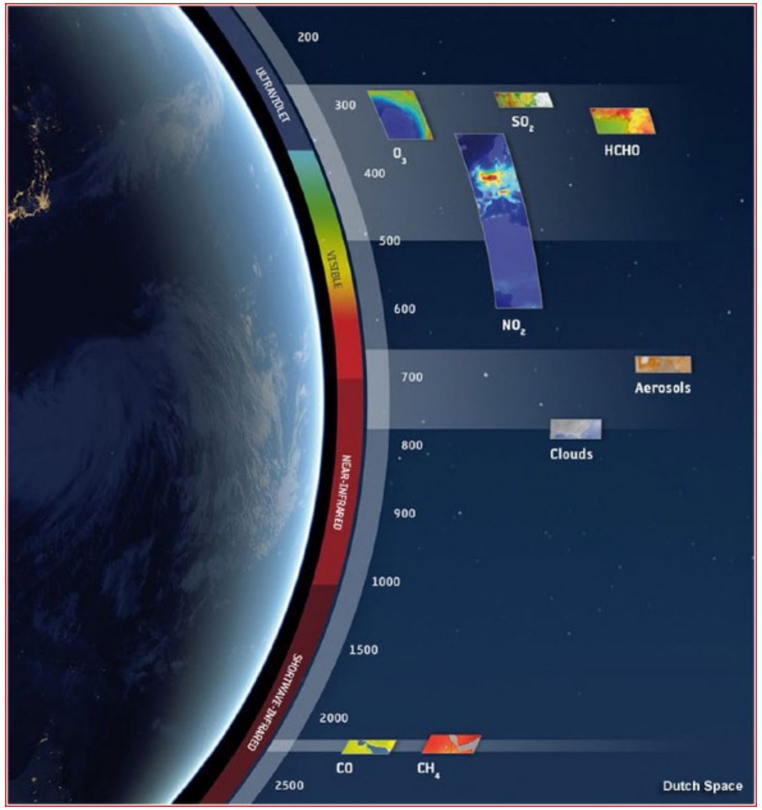


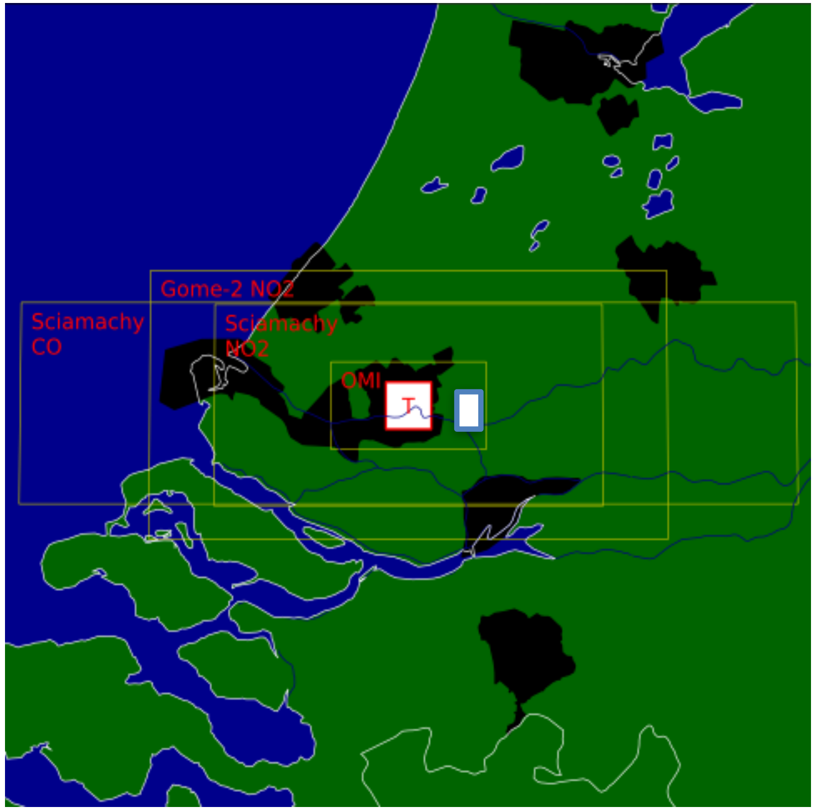
TROPOMI combines:

High signal-to-noise
Large spectra range
(large number of trace gas species)

High spatial resolution (3.5 x 5.5 km)

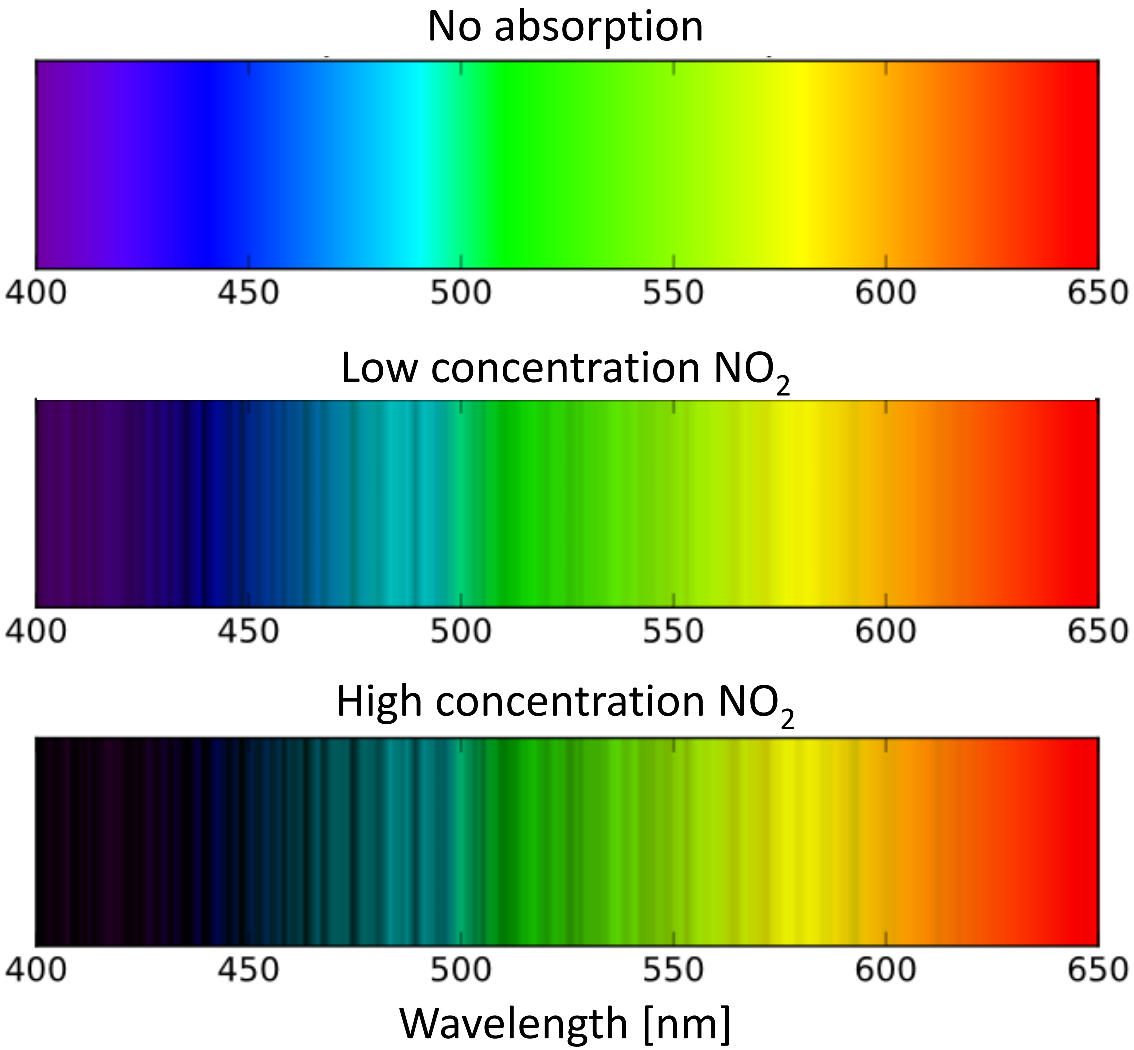
Daily global coverage





Retrieval of NO_2

From spectra to concentrations



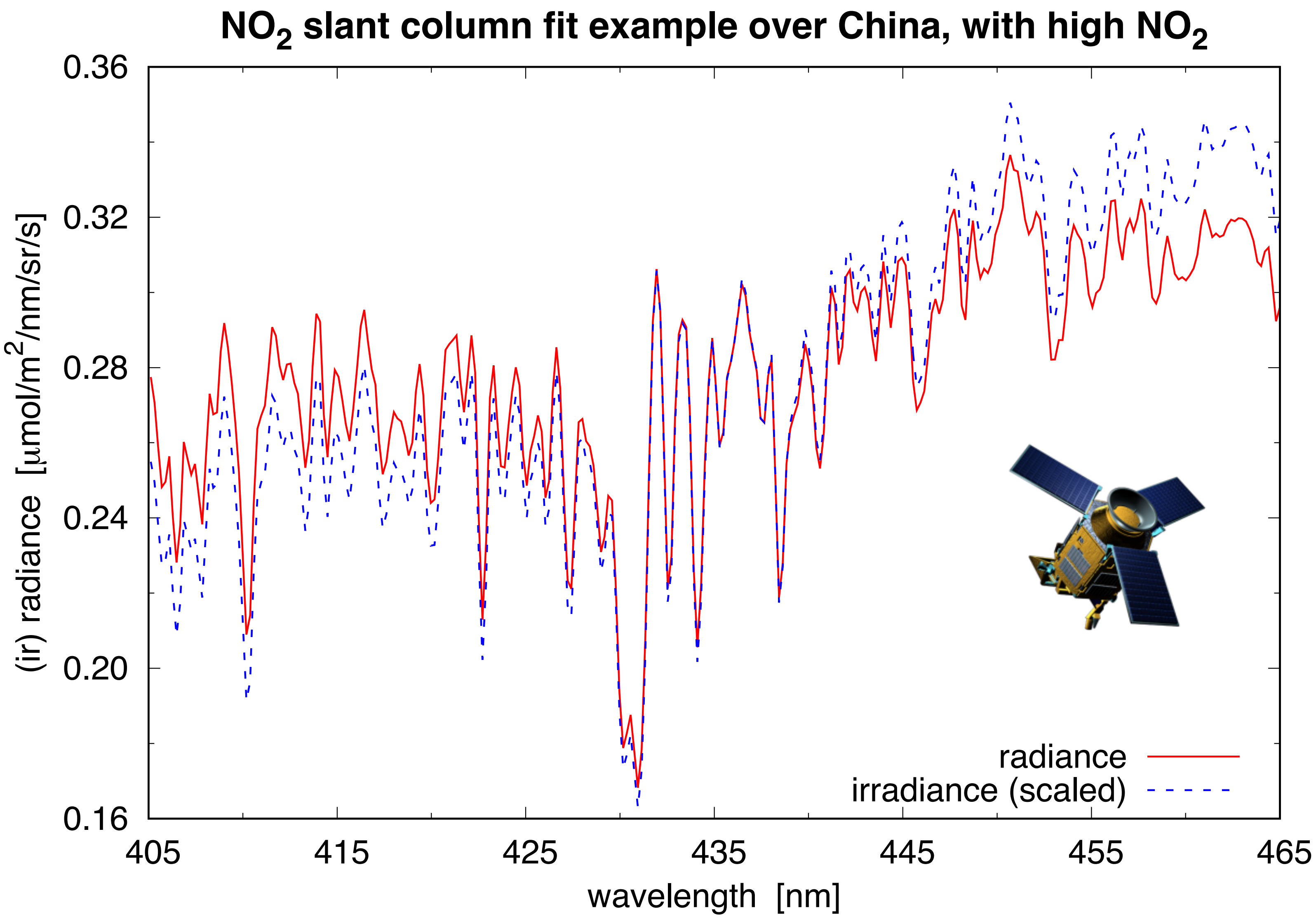
NO_2 typical concentration is 1 molecule per 10^9 air molecules: how can we measure this ??

TROPOMI observations

405-465 spectral range

When looking at the Earth the main spectral features observed are coming from the Sun (solar spectrum)

Jos van Geffen, KNMI

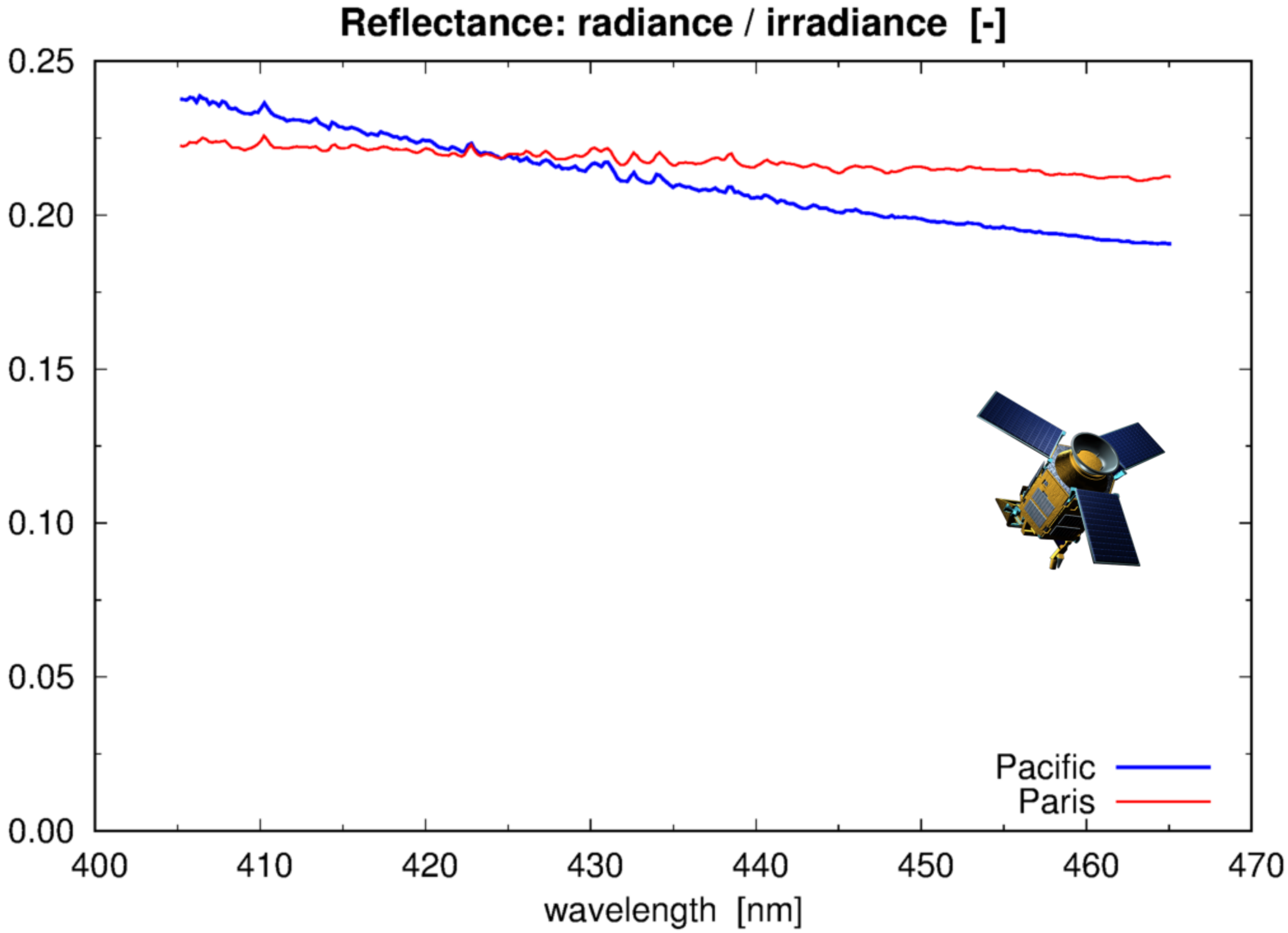


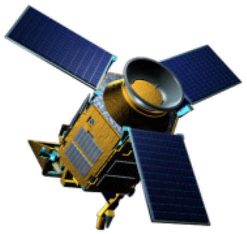
TROPOMI observations

405-465 spectral range

Reflectance is a

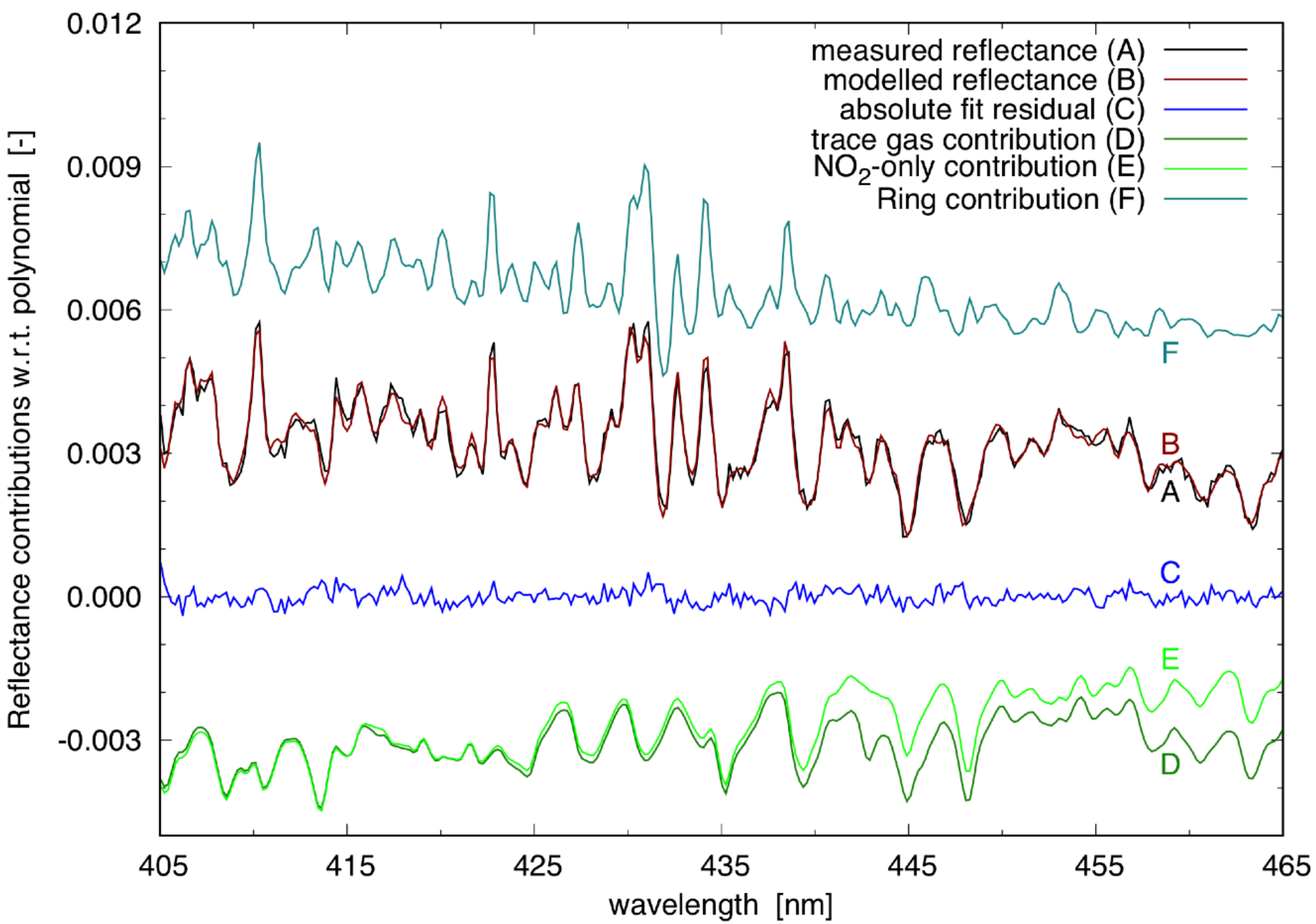
“nearly” straight line





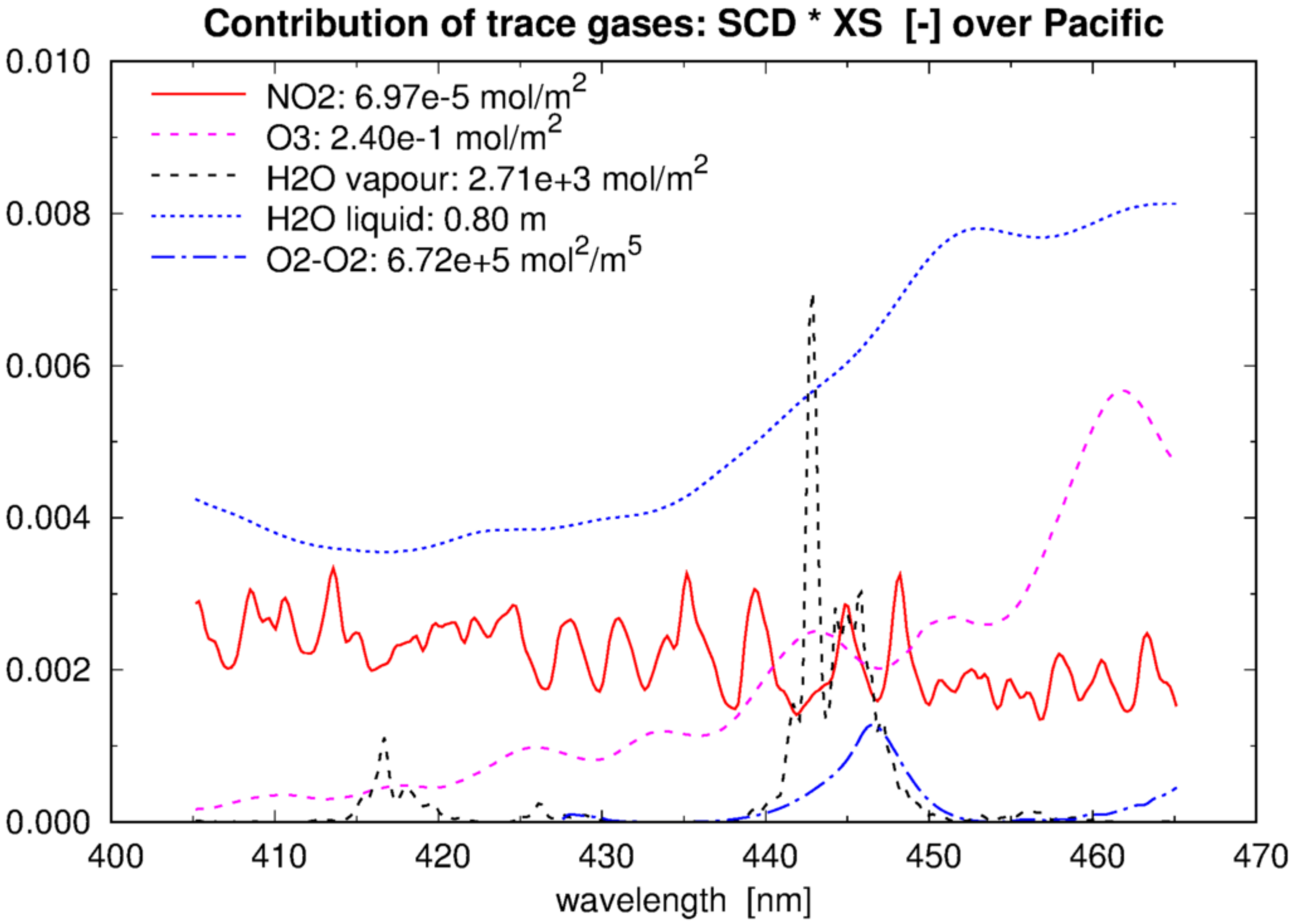
Also in the reflectance the solar spectral features are still dominant

Ring effect = inelastic Raman scattering of sunlight in the atmosphere



Absorbers accounted for:

- NO_2
- Ozone
- Water vapour
- Liquid water
- O_2-O_2



NO2 spectral fitting: summary

Instrument:

- Need high signal to noise, typically 1000.
- Need accurate calibration of Earth and solar spectra.

Conclusions related to the fits in NO2 window:

- We understand the Earth radiance in great detail, residuals ~1e-4
- NO2 has a very distinct spectral fingerprint and the slant column can be quantified accurately with current instruments.

What did we determine so far?

The amount of NO_2 along the path of the light through the atmosphere:

The “slant column”

What we do not yet know:

How far did the light pentrate into the atmosphere ?

Where is the NO_2 ? (At what altitude?)

Translate “slant column” into vertical column amount

How did the light travel through the atmosphere?

Aspects that influence the light path:

Surface properties (reflection)

Aerosols

Clouds

Air-mass factor

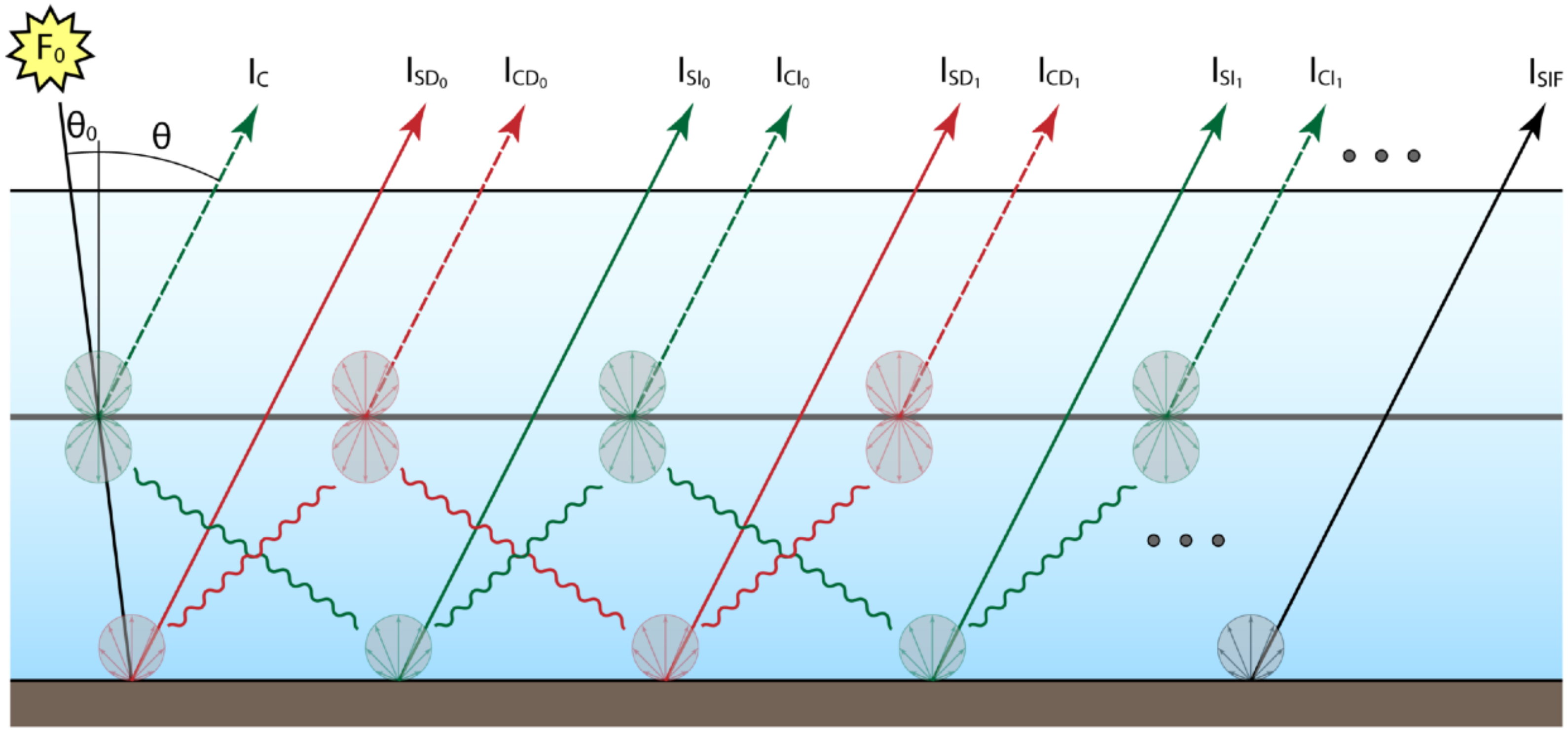
There are substantial uncertainties linked to this (20-60%)!

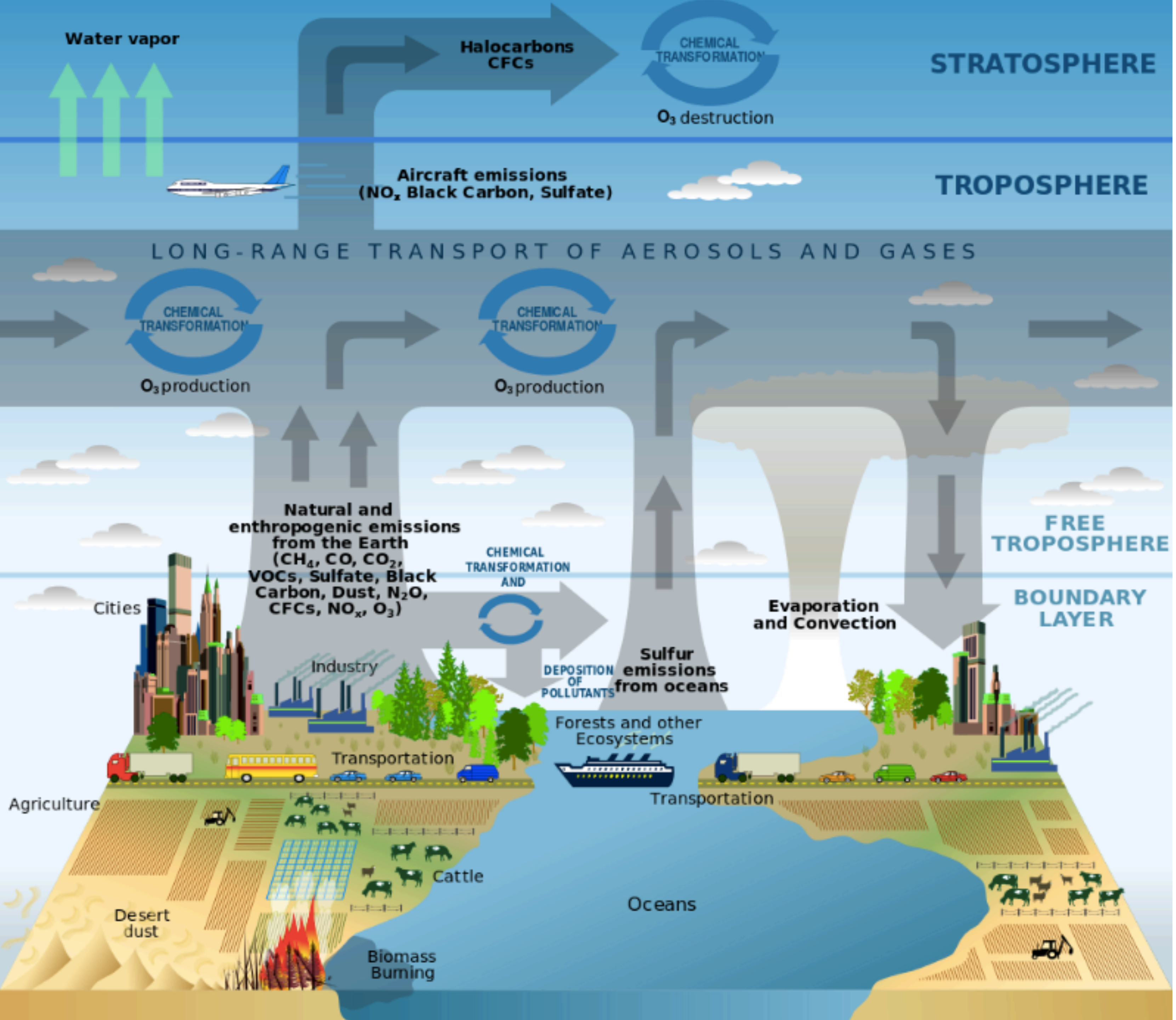
Where did the light travel ?

Radiative transfer models

Depending on geometry, clouds, surface albedo, aerosols

Air-mass factor





Where is the NO2 ?

Atmospheric model describing chemistry, emissions, transport, deposition.

Most of the NO_2 is in the stratosphere!

The NO_2 data product

Averaging kernels

Atmos. Chem. Phys., 3, 1285–1291, 2003
www.atmos-chem-phys.org/acp/3/1285/

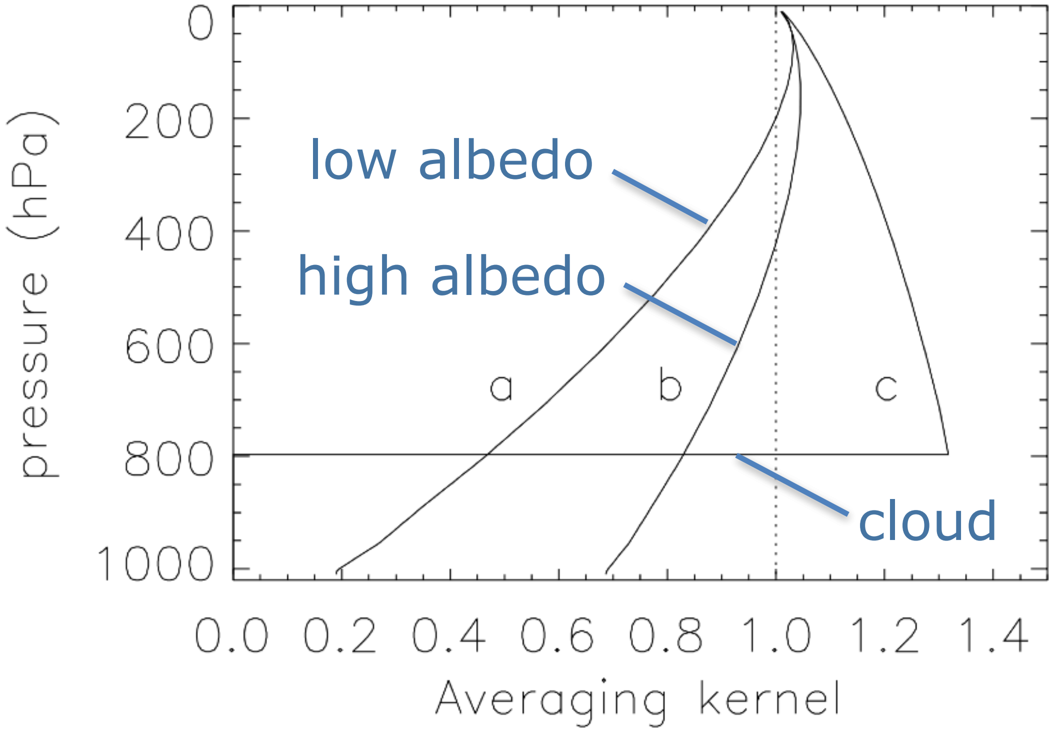
Atmospheric Chemistry and Physics

Averaging kernels for DOAS total-column satellite retrievals

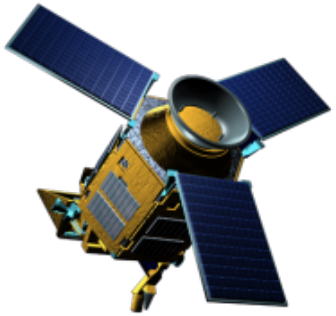
H. J. Eskes and K. F. Boersma

The DOAS retrieval approach
may be re-formulated
using Rodgers Optimal Estimation
formalism.

DOAS averaging kernel profiles:
sensitivity of the measurement to
NO_2 at a given altitude



Filtering: the *qa_value*



- `qa_value > 0.75`

  This is the recommended pixel filter. It removes cloud-covered scenes (cloud radiance fraction > 0.5), partially snow/ice covered scenes, errors, and problematic retrievals.

- `qa_value > 0.50`

  Compared to the stricter filter, this adds the good quality retrievals over clouds and over scenes covered by snow/ice. Errors and problematic retrievals are still filtered out. In particular, this filter may be useful for assimilation and model comparison studies.

Use of the NO_2 product

Depending on the application different datasets should be extracted from the L2_NO2 file

	user application	*data sets needed*
# 1	Tropospheric chemistry / air quality model evaluation and data assimilation Validation with tropospheric NO_2 profile measurements (aircraft, balloon, MAX-DOAS)	N_v^{trop}, $\Delta N_v^{trop,kernel}$ M^{trop}, M, $\mathbf{A}$ † A_l^{TM5}, B_l^{TM5}, l_{tp}^{TM5}, p_s
# 2	Tropospheric column comparisons, e.g. with other NO_2 column retrievals	N_v^{trop}, ΔN_v^{trop}
# 3	Stratospheric chemistry model evaluation and data assimilation Validation with stratospheric NO_2 profile measurements (limb/occultation satellite observations)	N_v^{strat}, ΔN_v^{strat} M^{strat}, M, $\mathbf{A}$ ‡ A_l^{TM5}, B_l^{TM5}, l_{tp}^{TM5}, p_s
# 4	Stratospheric column comparisons, e.g. with ground-based remote sensors	N_v^{strat}, ΔN_v^{strat}
# 5	Whole atmosphere (troposphere + stratosphere) data assimilation systems	N_v, ΔN_v^{kernel} § $\mathbf{A}$ A_l^{TM5}, B_l^{TM5}, l_{tp}^{TM5}, p_s
# 6	Whole atmosphere (troposphere + stratosphere) comparisons with ground-based remote sensing (e.g. Pandora)	N_v^{sum}, ΔN_v^{sum} §
# 7	Visualisation of the NO_2 product	N_v^{trop}, N_v^{strat}, N_v^{sum} §

† The tropospheric kernel $\mathbf{A}^{trop}$ is derived from the total kernel $\mathbf{A}$ and the air-mass factors M and M^{trop}.
‡ The stratospheric kernel $\mathbf{A}^{strat}$ is derived from the total kernel $\mathbf{A}$ and the air-mass factors M and M^{strat}.
§ Note that the total NO_2 vertical column $N_v \equiv N_s/M$ is *not* the same as the sum $N_v^{sum} \equiv N_v^{trop} + N_v^{strat}$

Replacing the a-priori using the averaging kernels

The TROPOMI NO_2 tropospheric column may be re-computed using the profile $x_{m,l}$ from an alternative model (high-resolution regional air-quality model). Needed are the tropospheric averaging kernel and AMF, and the following equations:

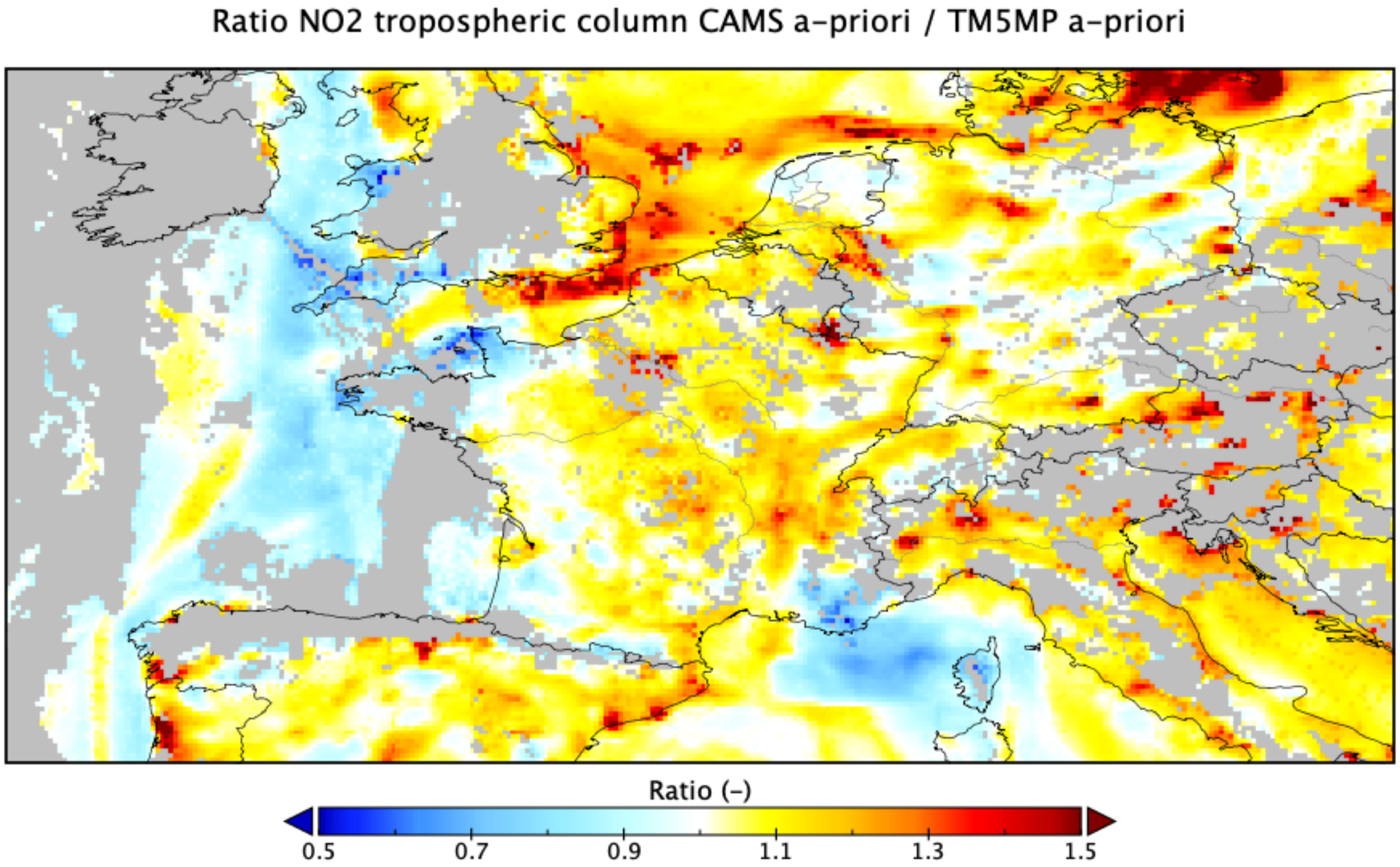
$$N_{\mathrm{v}}^{\mathrm{trop}'} = \frac{M^{\mathrm{trop}}}{M^{\mathrm{trop}'}} N_{\mathrm{v}}^{\mathrm{trop}}$$

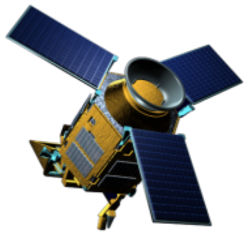
$$\mathbf{A}^{\mathrm{trop}'} = \frac{M^{\mathrm{trop}}}{M^{\mathrm{trop}'}} \mathbf{A}^{\mathrm{trop}}$$

$$M^{\mathrm{trop}'} = M^{\mathrm{trop}} \sum_l A_l^{\mathrm{trop}} x'_{m,l} \Big/ \sum_l x'_{m,l}$$

All quantities on the left with a prime ′ are recomputed using the model NO_2 partial-column profiles $x'_{m,l}$. Other quantities are taken from the S5P_L2_NO2 file.

Using a-priori profiles from CAMS-regional AQ forecasts for Europe





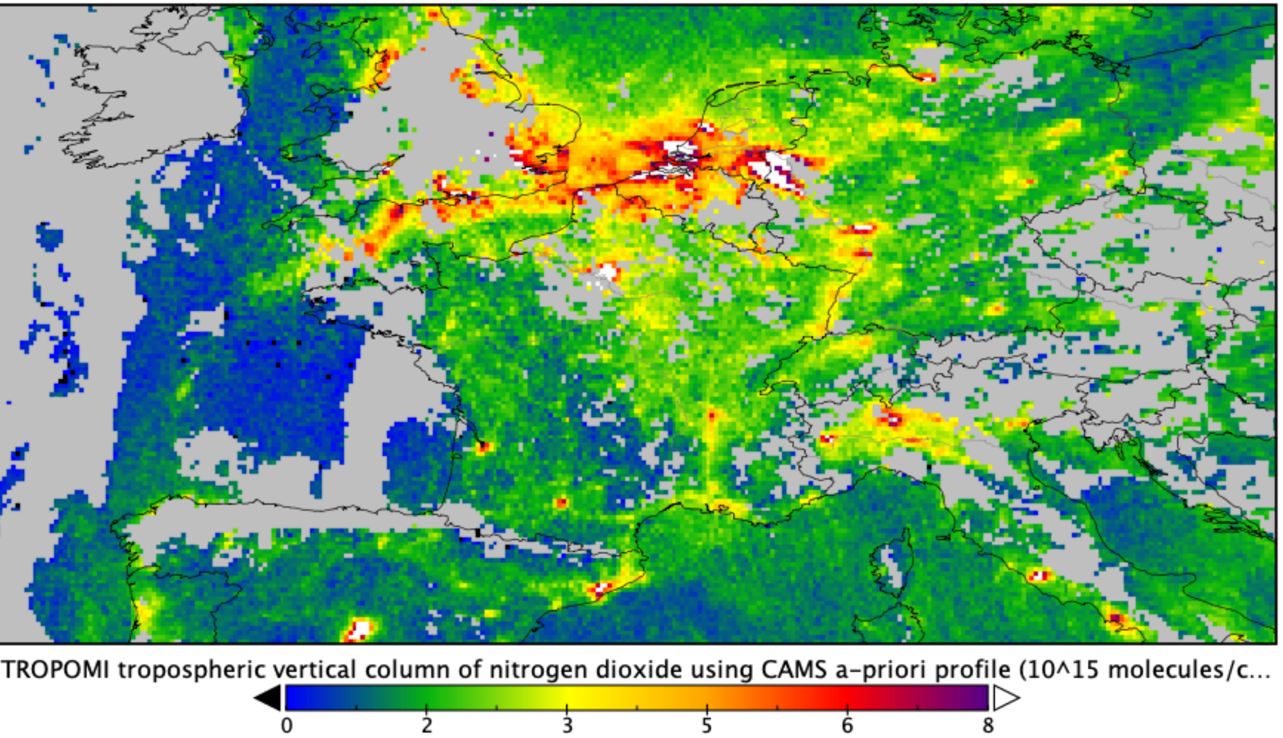
Tropospheric column increases by 10-50% over hotspots when using high-resolution regional model a-priori profiles
1x1 degree ->
0.1x0.1 degree

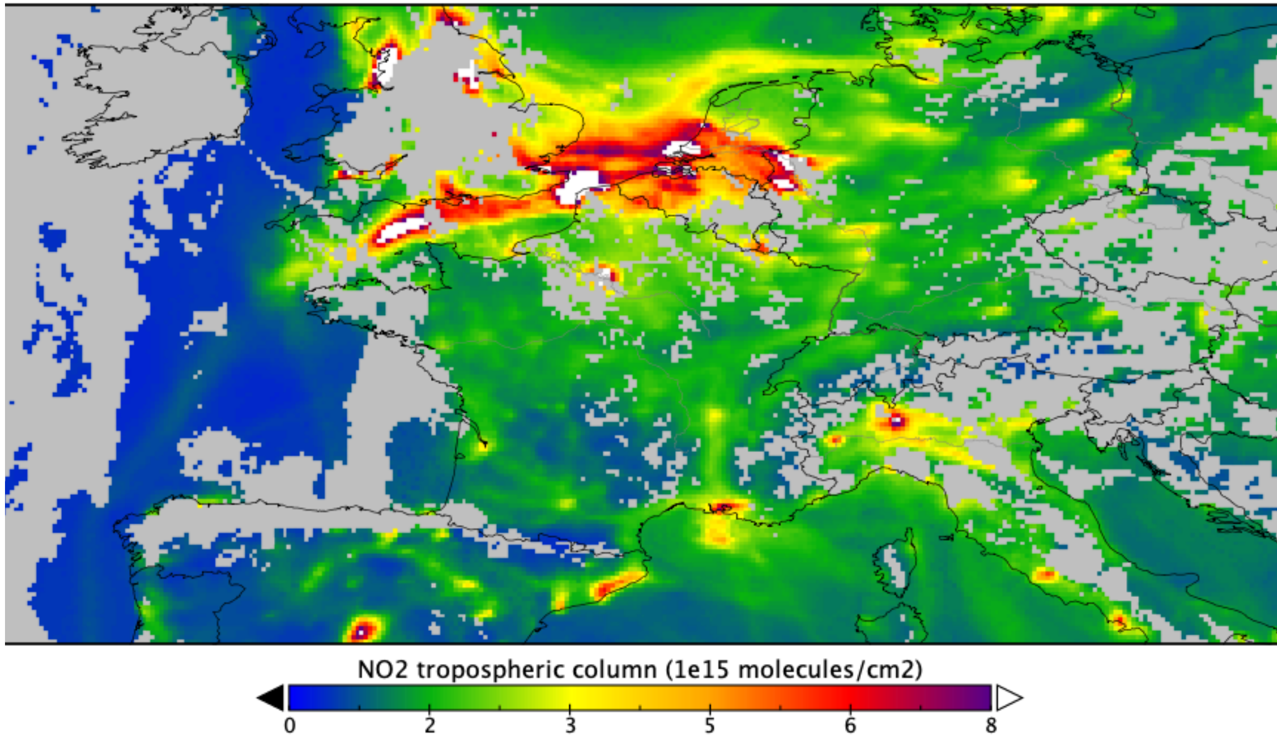
John Douros, KNMI

Using a-priori profiles from CAMS-regional AQ forecasts for Europe

TROPOMI NO2 based on CAMS-regional a-priori

CAMS-regional vertical column NO2





Single overpass, 26 July 2018

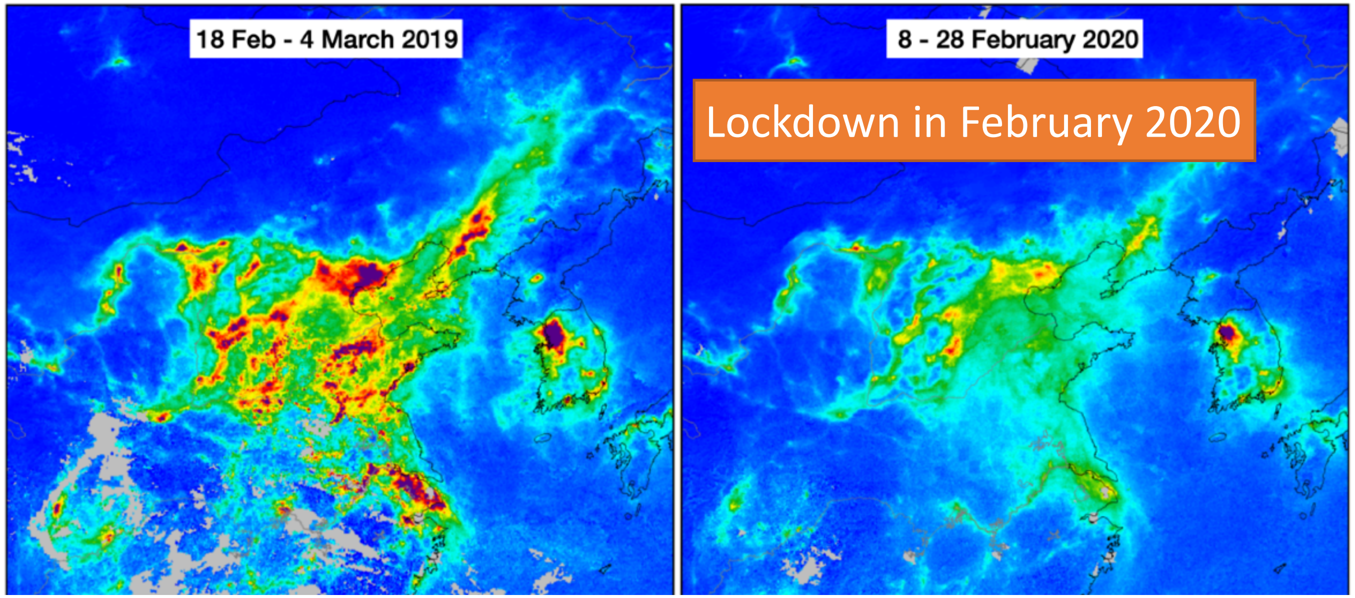
John Douros, KNMI

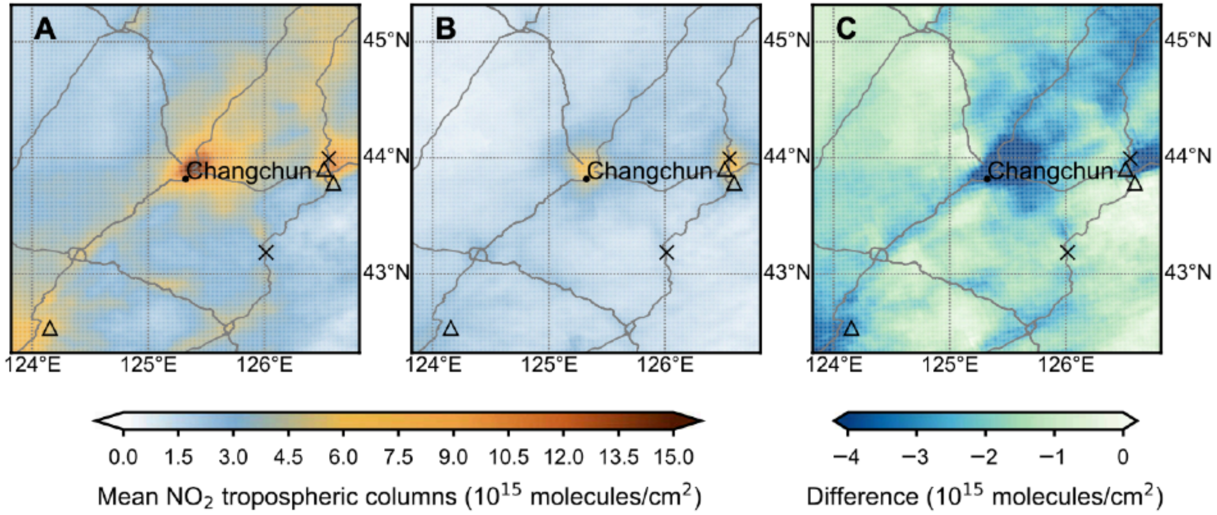
Applications

The NO_2 measurements may be used for:

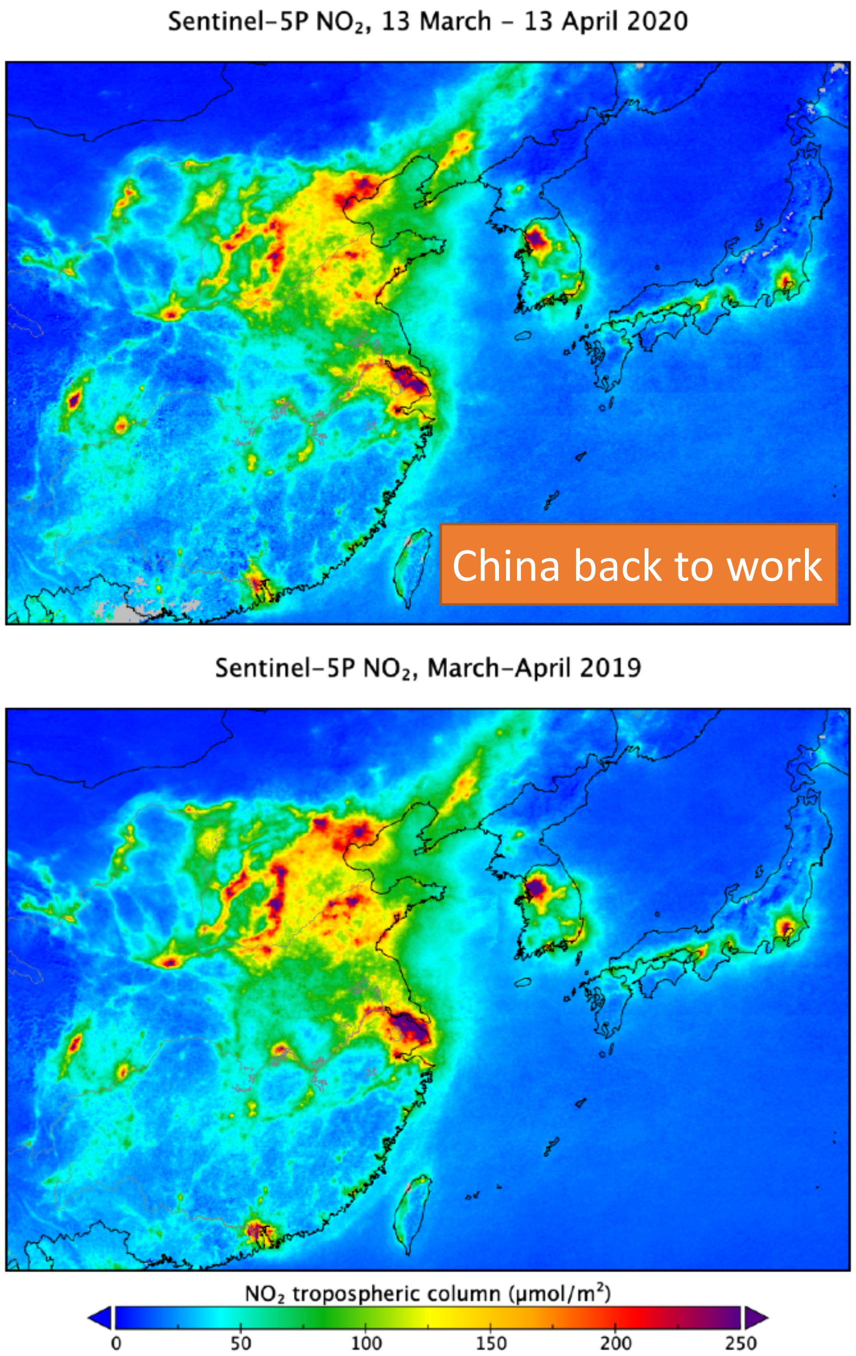
- Emission estimates
  - Inverse modelling
  - Plume analysis using wind information
  - Flux divergence (Steffen Beirle et al., 2019)
- Source identification
- Data assimilation
  - Primary user is CAMS (Copernicus Atmospheric Monitoring Service)
- Model validation
- Reactive nitrogen mapping (improving knowledge N-deposition)
- Trend studies / emission change monitoring
- Visualisation

NO2 pollution reductions related to COVID-19 lockdown in China, measured with Sentinel-5P TROPOMI

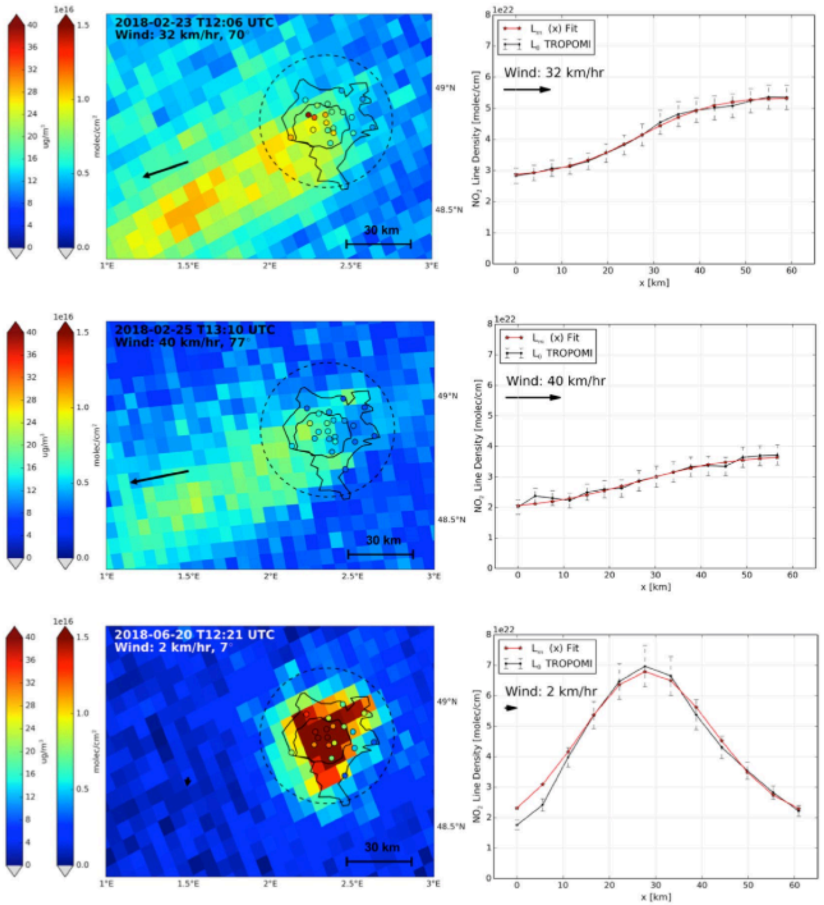




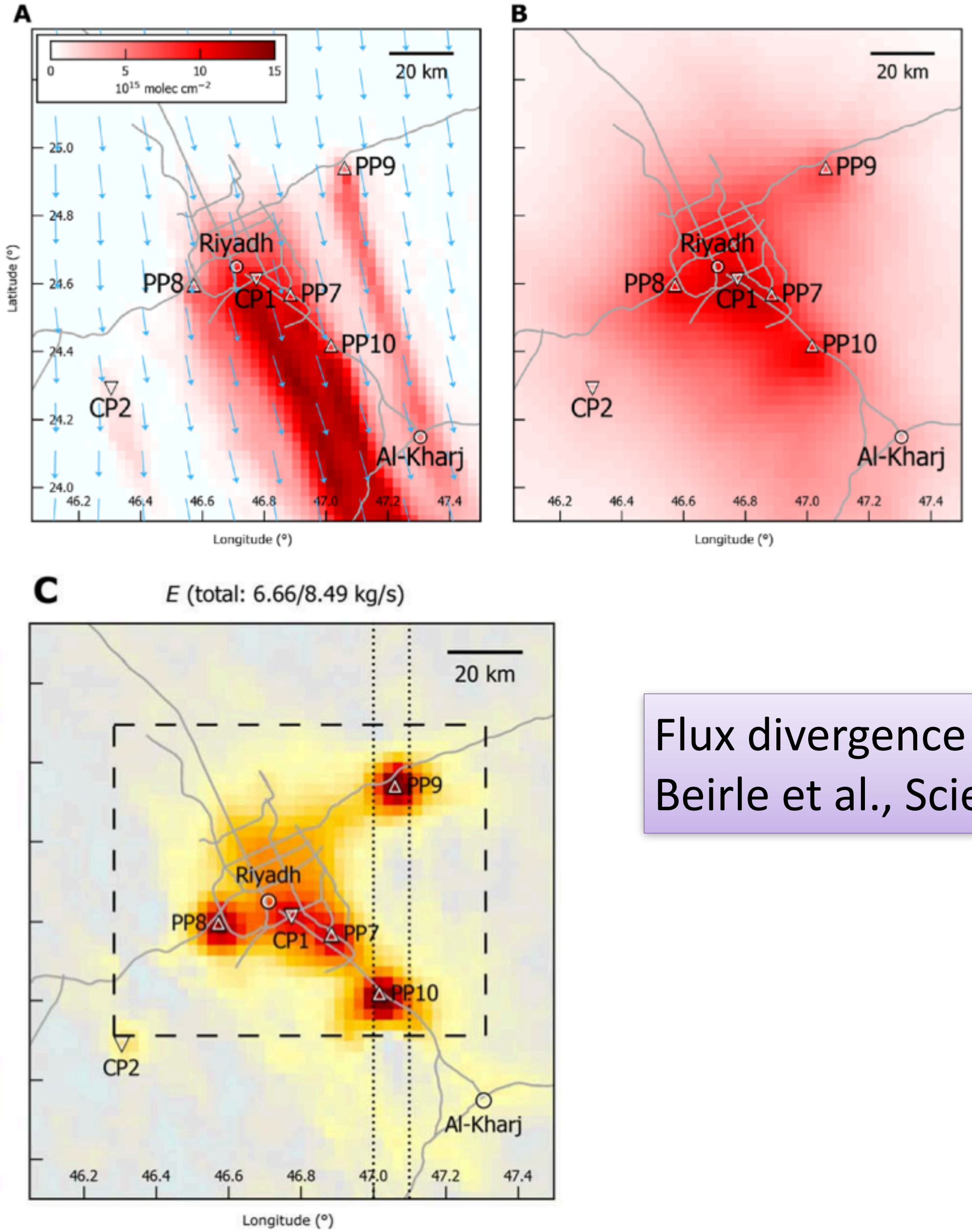
F. Liu et al., Science Advances 2020



Emission estimates: plume analysis

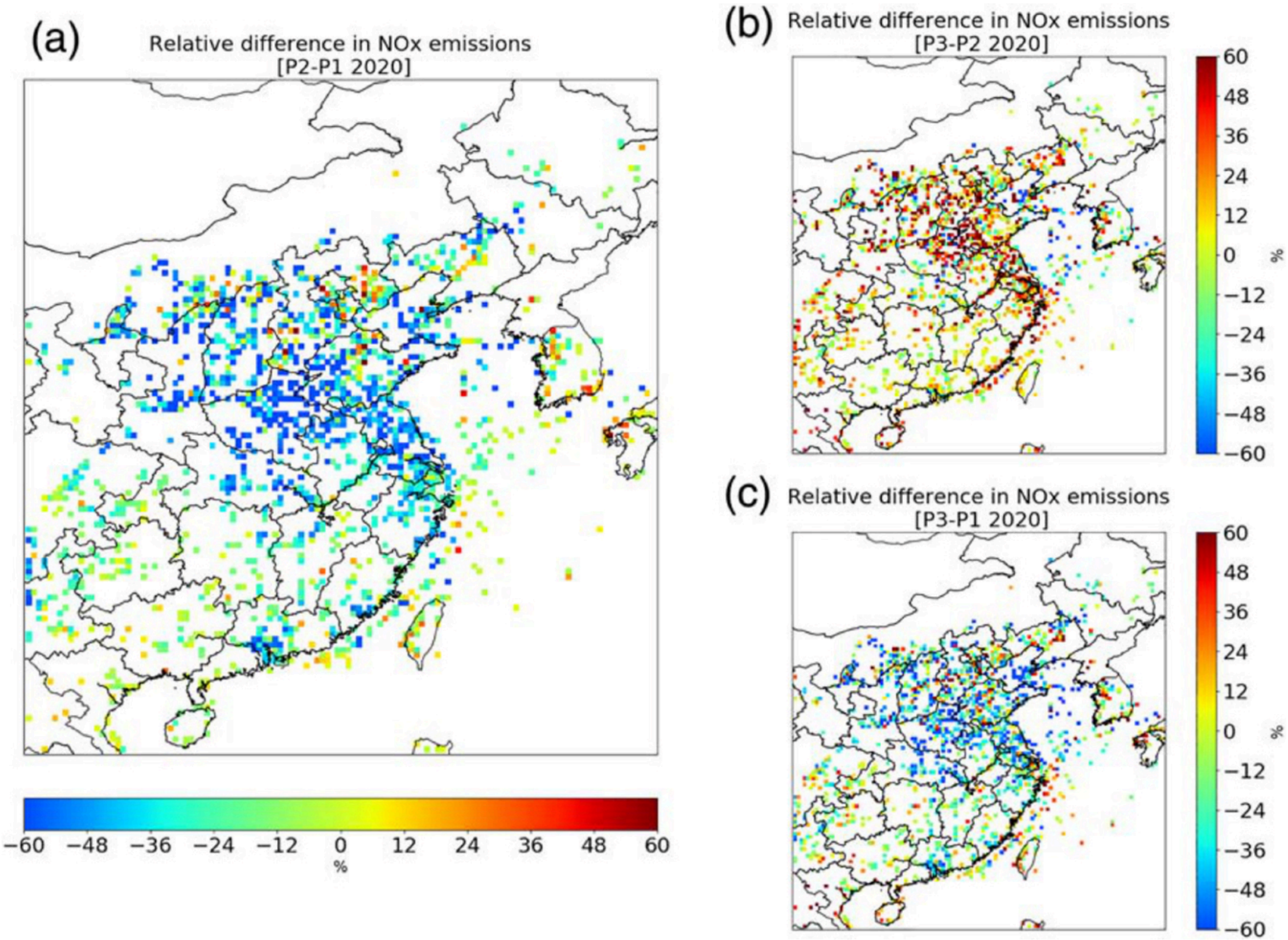


Estimating emissions of Parijs
Combining daily plume observations
with wind information
Lorente et al., Nature Sci. Rep. 2019



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

Emissions, using inverse modelling



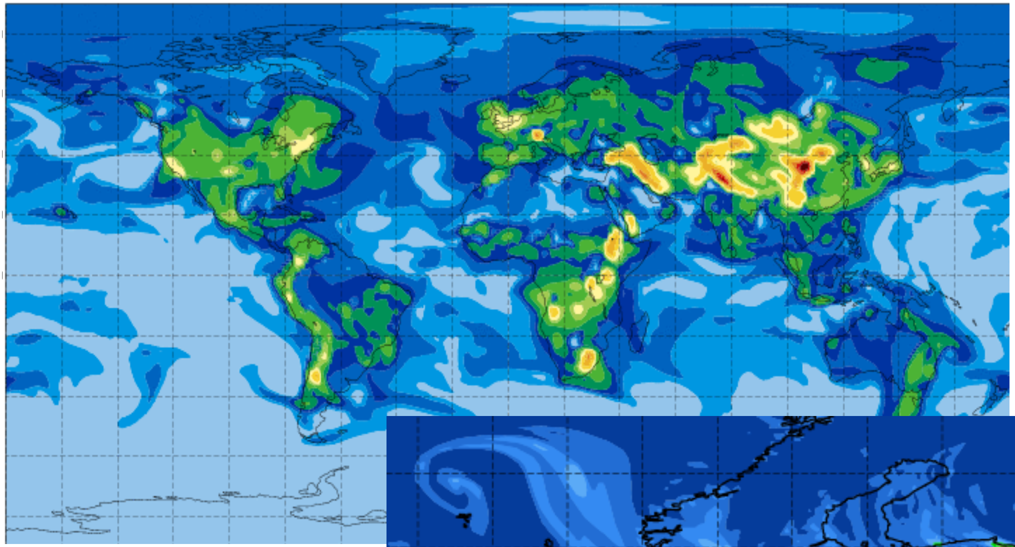
Emissions in China
Ding et al., GRL 2020

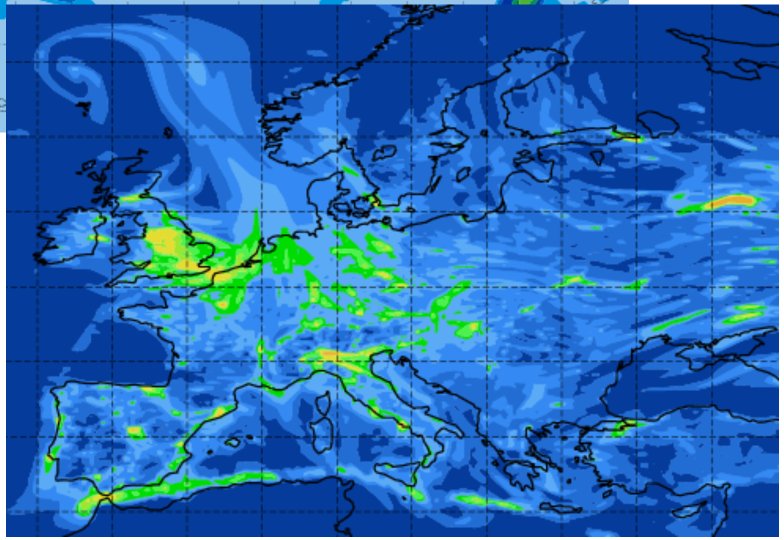
P1: Before lockdown

P2: during lockdown

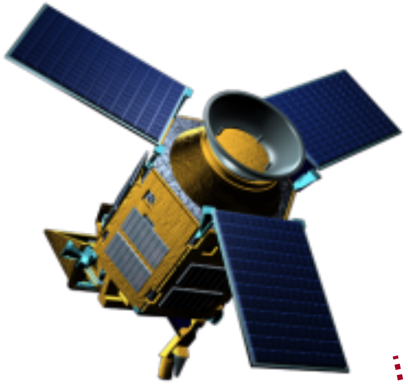
P3: after lockdown

CAMS as main user of the Copernicus Sentinel 5P, 4, 5 composition observations



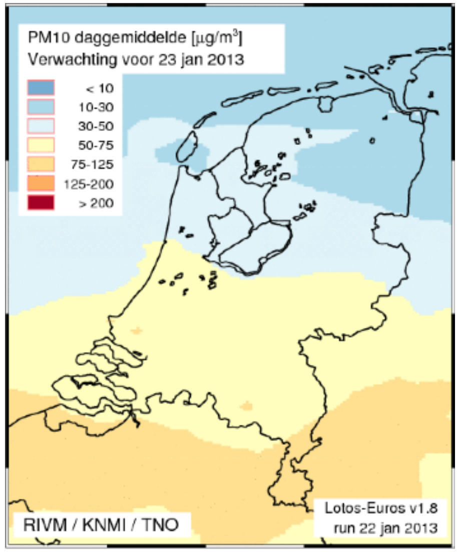


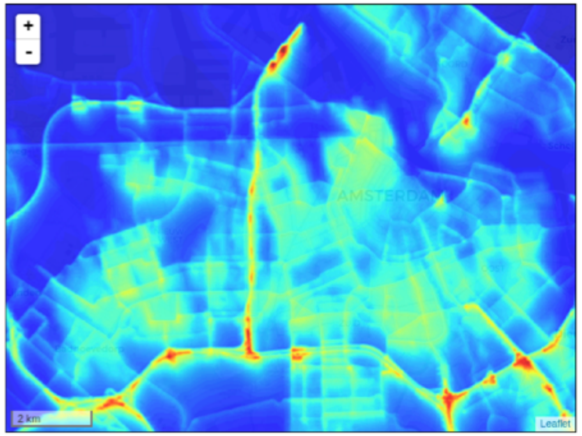
Assimilation
TROPOMI
observations



CAMS-Europe as boundary condition for countries and city regions

Amsterdam



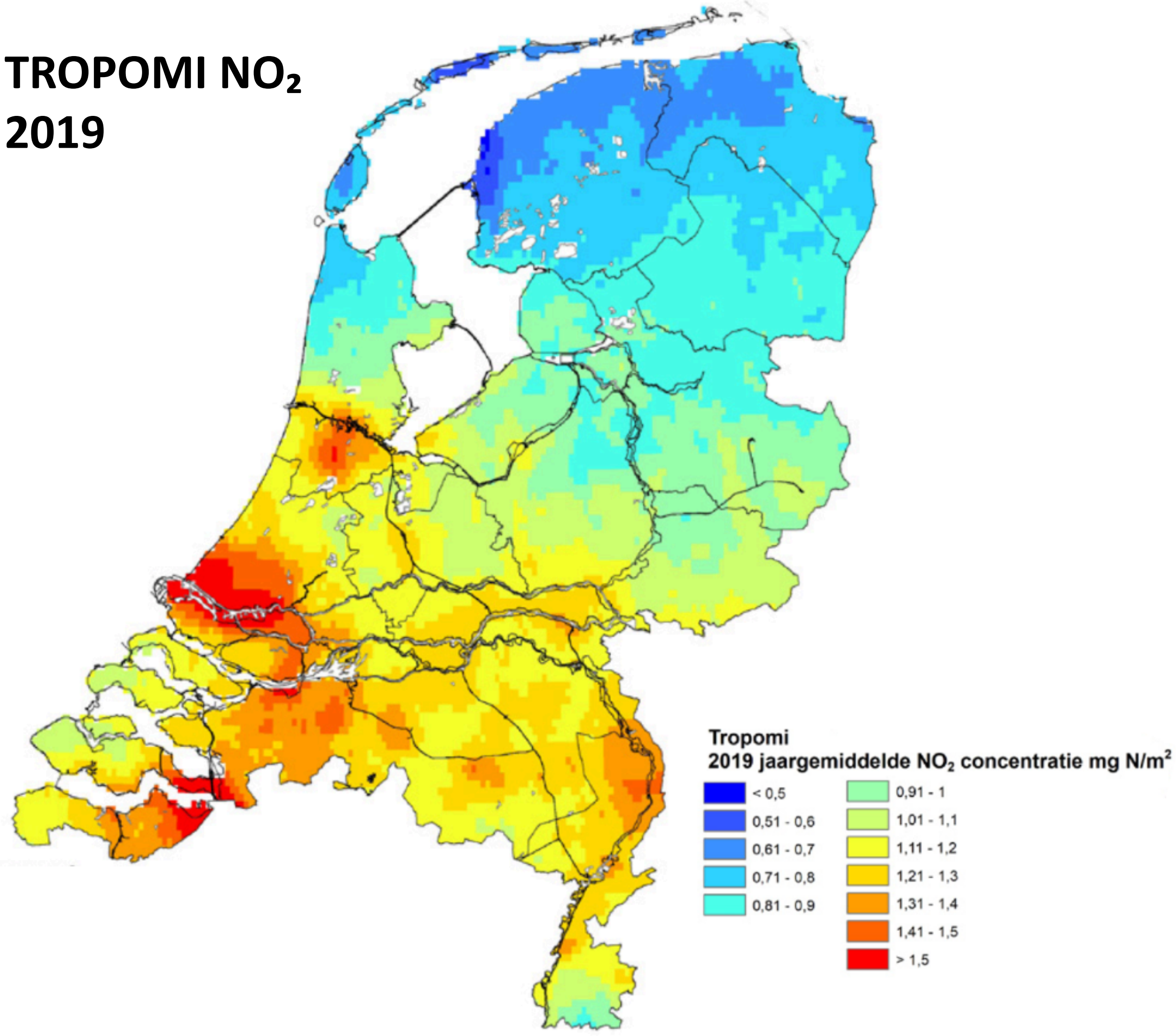


Analyses of CAMS-global as boundary condition for CAMS-Europe

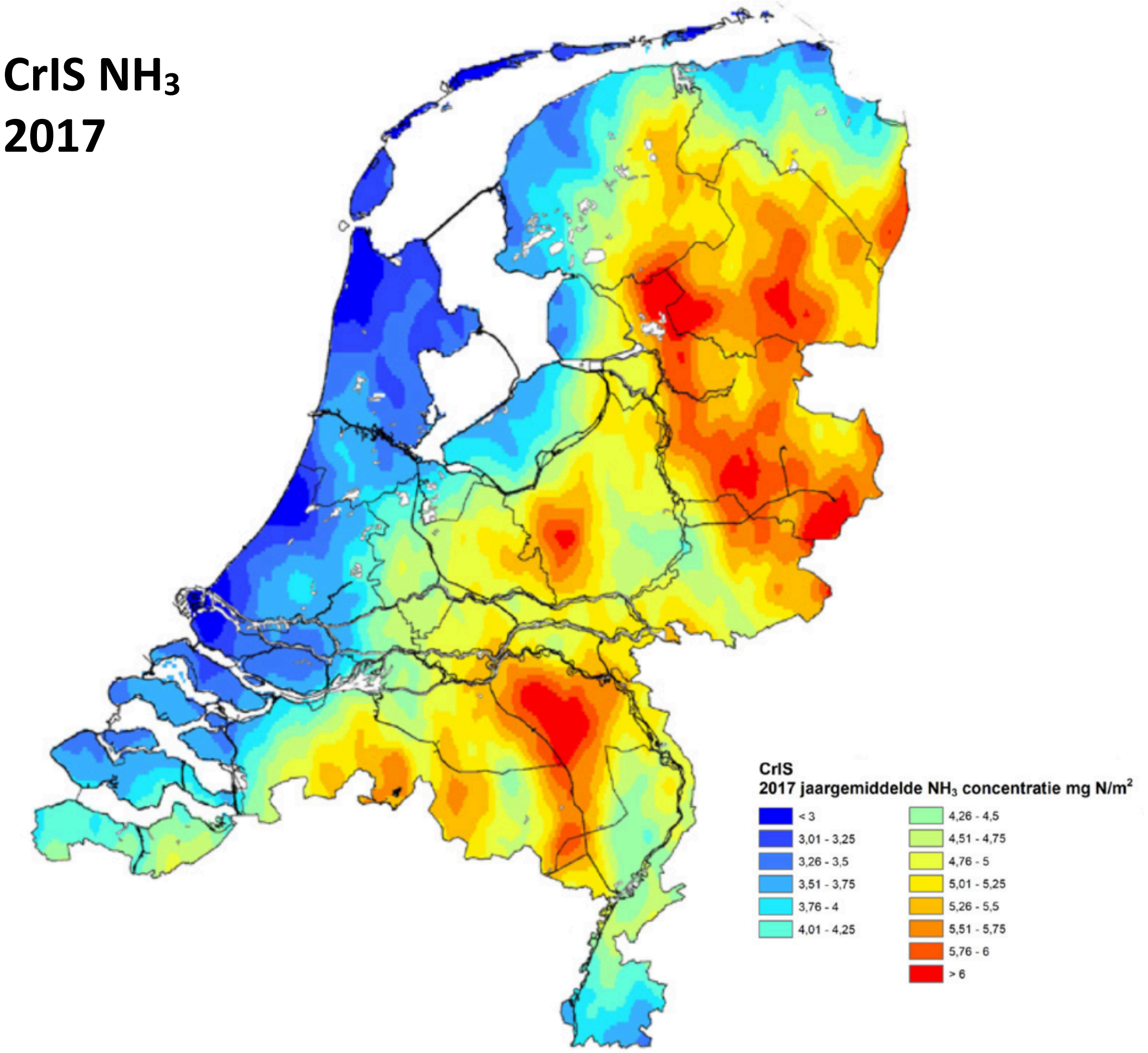
atmosphere.copernicus.eu

The nitrogen (deposition) problem: loss of biodiversity

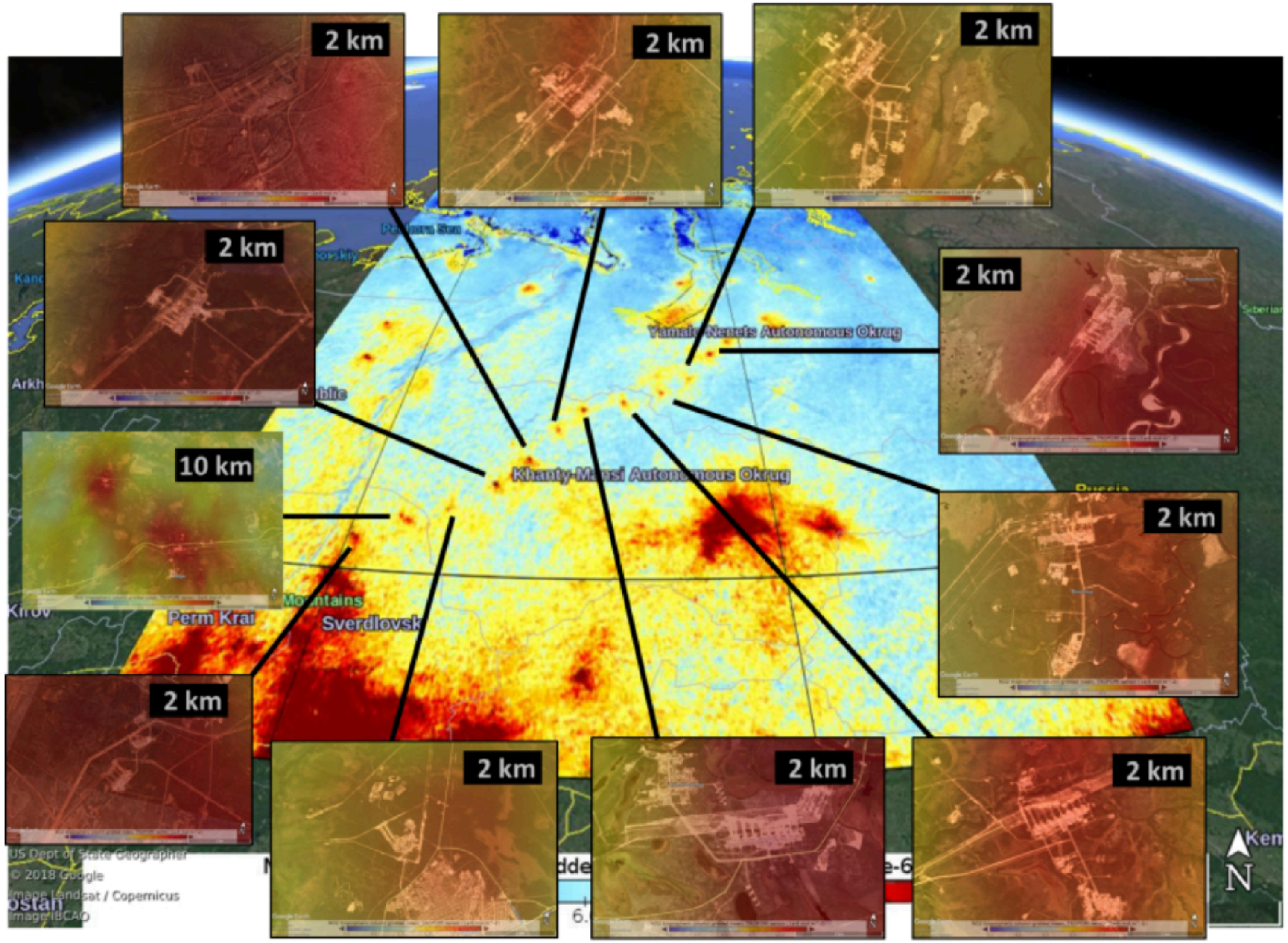
TROPOMI NO_2
2019



CrIS NH_3
2017

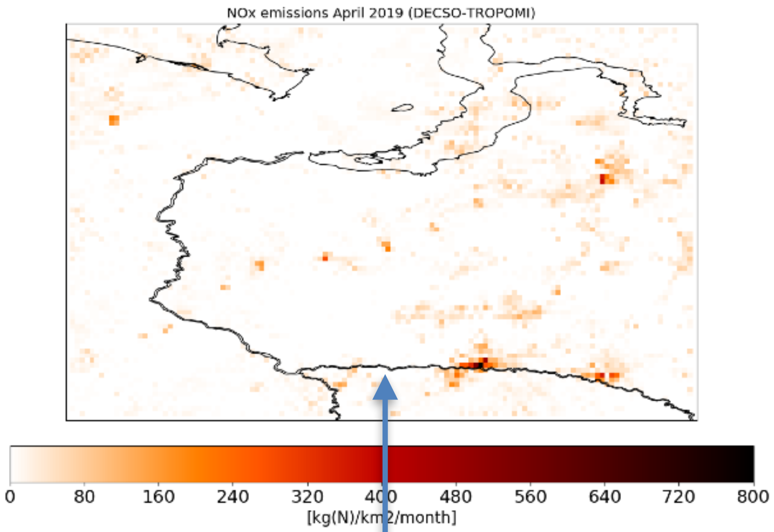


Identification of emision sources

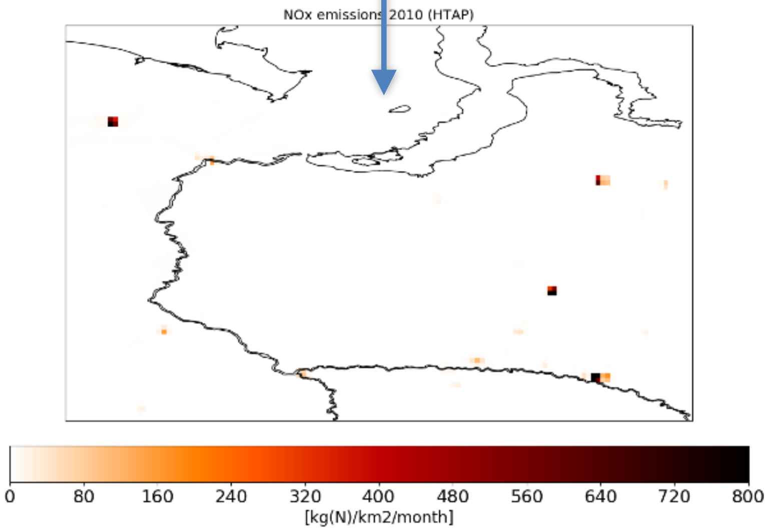


string of gas compressor stations along natural gas pipeline every ≈ 100 km

R. v.d. A et al., NPJ Clim. Atmos. 2020



TROPOMI NO_2 emission inversion (DECSO) for April 2019 *compared with* bottom up emission inventory (HTAP/EDGAR)



Summary NO_2

- The NO_2 (tropospheric slant) column can be accurately determined from space with UV-Vis spectrometers, covering a two order of magnitude range of column values, but require high signal-to-noise spectrometers.
- The air-mass factor, depending on clouds, surface albedo, aerosol, is a major source of uncertainty.
- The data products are extended, contain intermediate and input products and offer full traceability. Averaging kernels can be used to remove dependence on a-priori, or replace a-priori with high-resolution (regional) model NO2 profiles.
- A large range of applications: Emission estimates and source identification, data assimilation and model validation, reactive nitrogen mapping, emission change monitoring (trends, COVID-19 lockdown impacts), visualisation