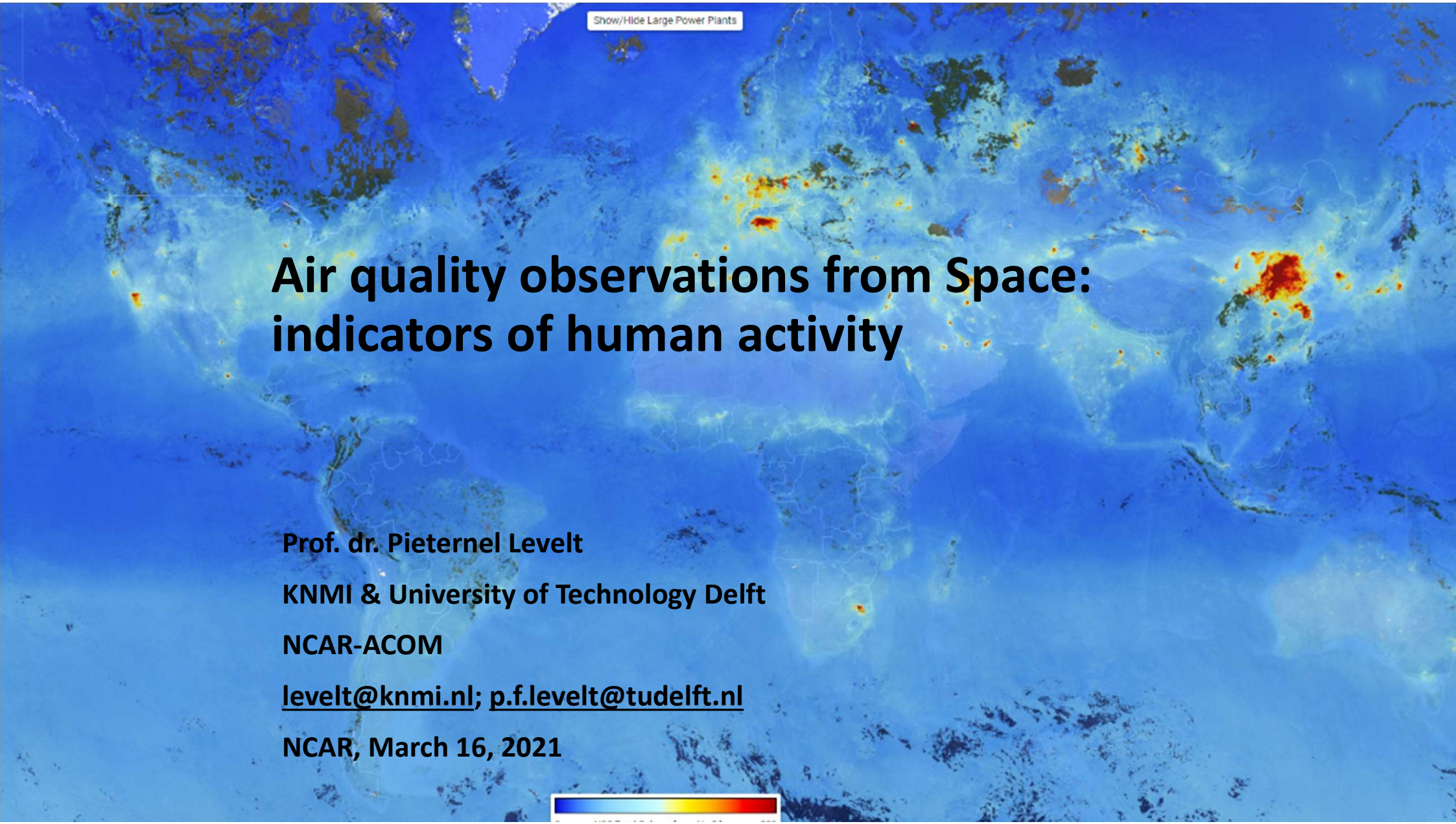


Air quality observations from Space: indicators of human activity

Prof. dr. Pieternel Levelt

KNMI & University of Technology Delft

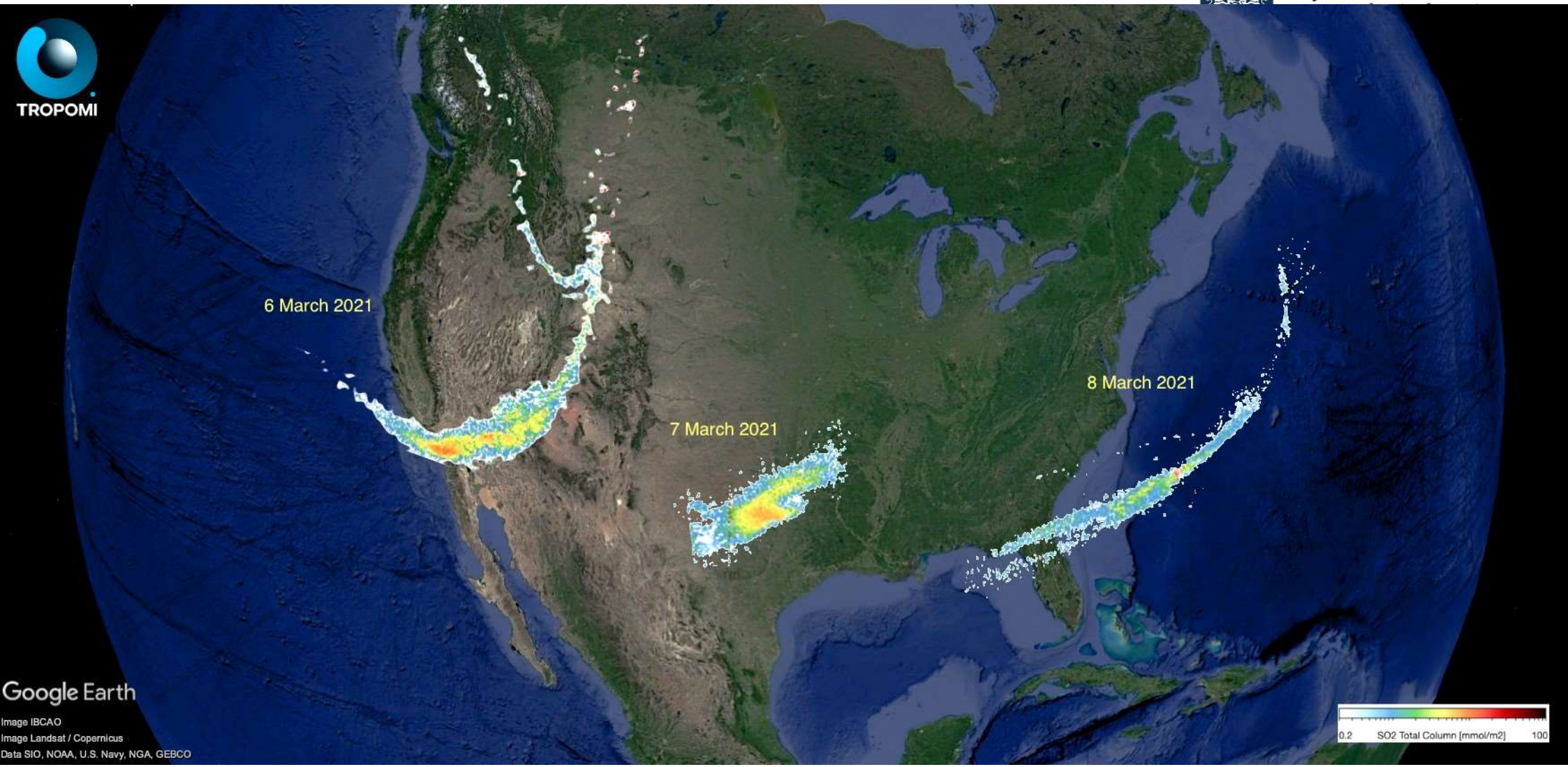
NCAR-ACOM

levelt@knmi.nl; p.f.levelt@tudelft.nl

NCAR, March 16, 2021

TROPOMI SO_2 from Etna volcano (Italy)

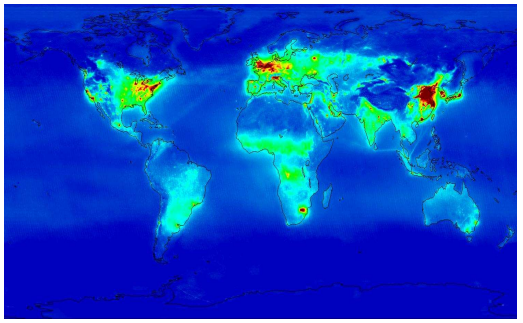
Royal Netherlands



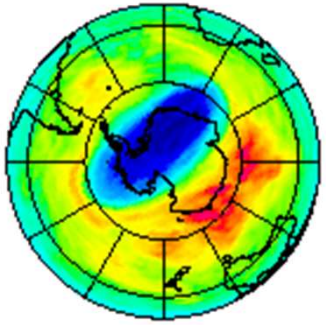
Department Head R&D Satellite Observations KNMI (60-70 scientists)

"World player in atmospheric composition and dynamics"
inclusive, transparant management and diversity

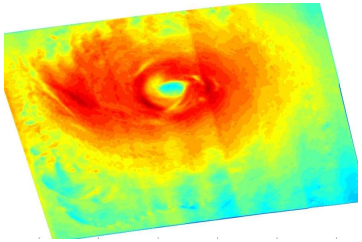
- Professor at University of Technology Delft
- Guest professor at NUIST, Nanjing, China
  KNMI-NUIST Co-operation Center on atmospheric composition



OMI and TROPOMI NO_2



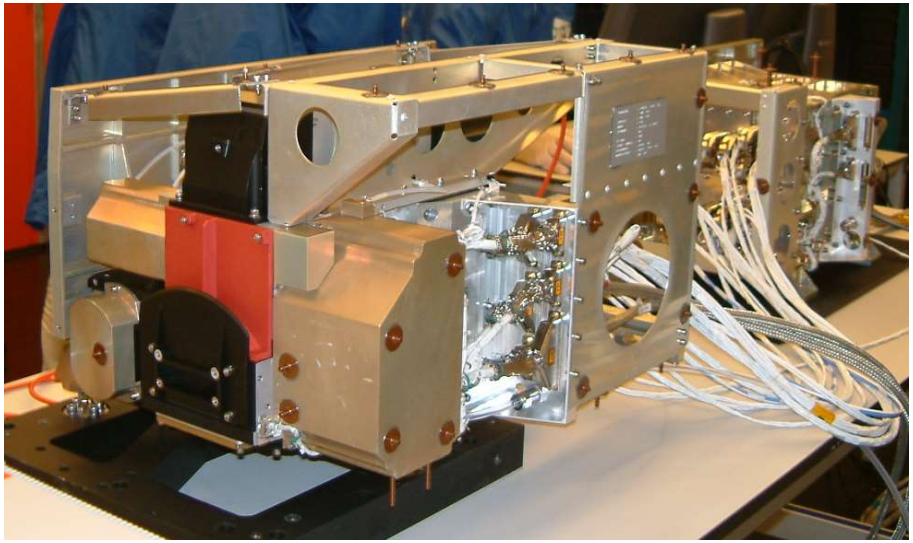
Ozone layer



Hurricane Earl (2010)

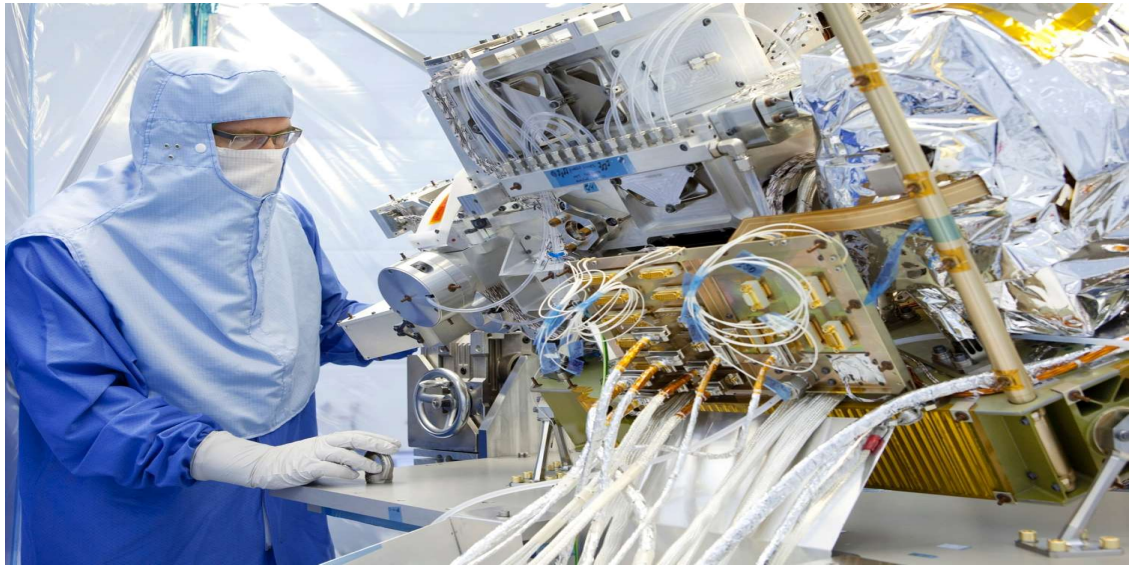
KNMI: PI institute OMI & TROPOMI

Royal Netherlands Meteorological Institute
Ministry of Infrastructure and the Environment



OMI launched on July 15, 2004 at NASA's EOS-Aura satellite

13 x 24 km^2 & daily global coverage



TROPOMI launched on October 13, 2017 at ESA's sentinel-5 precursor satellite

3.5 x 5.5 km^2 & daily global coverage

Personal role:
OMI: Principal Investigator
TROPOMI: Scientific Founder (PI 2003-2009)
End responsibility resides in R&D Satellite Observation Department KNMI

Aura Instrument PI's and project scientists
At the launch event

Outing with the International OMI Science Team in 2001 in The Netherlands

10th year Anniversary OMI instrument Meeting at KNMI in 2014

NASA/USGS Pecora Award 2018
AMS Special Award 2021

'For providing a stellar example of international collaboration to produce novel satellite observations that have transformed atmospheric chemistry research, especially air quality and health applications'

Agencies: NSO , NASA, Tekes

Principal Investigator
KNMI (PI), FMI (co-PI), NASA GSFC (US ST Leader)

Science
KNMI, NASA, FMI, …

Validation
KNMI, NASA, FMI, …

Level 1-2
KNMI, NASA, FMI, …

Level 0-1B
DS, KNMI

Ground Segment
NASA, KNMI, FMI

Operations
KNMI, NASA

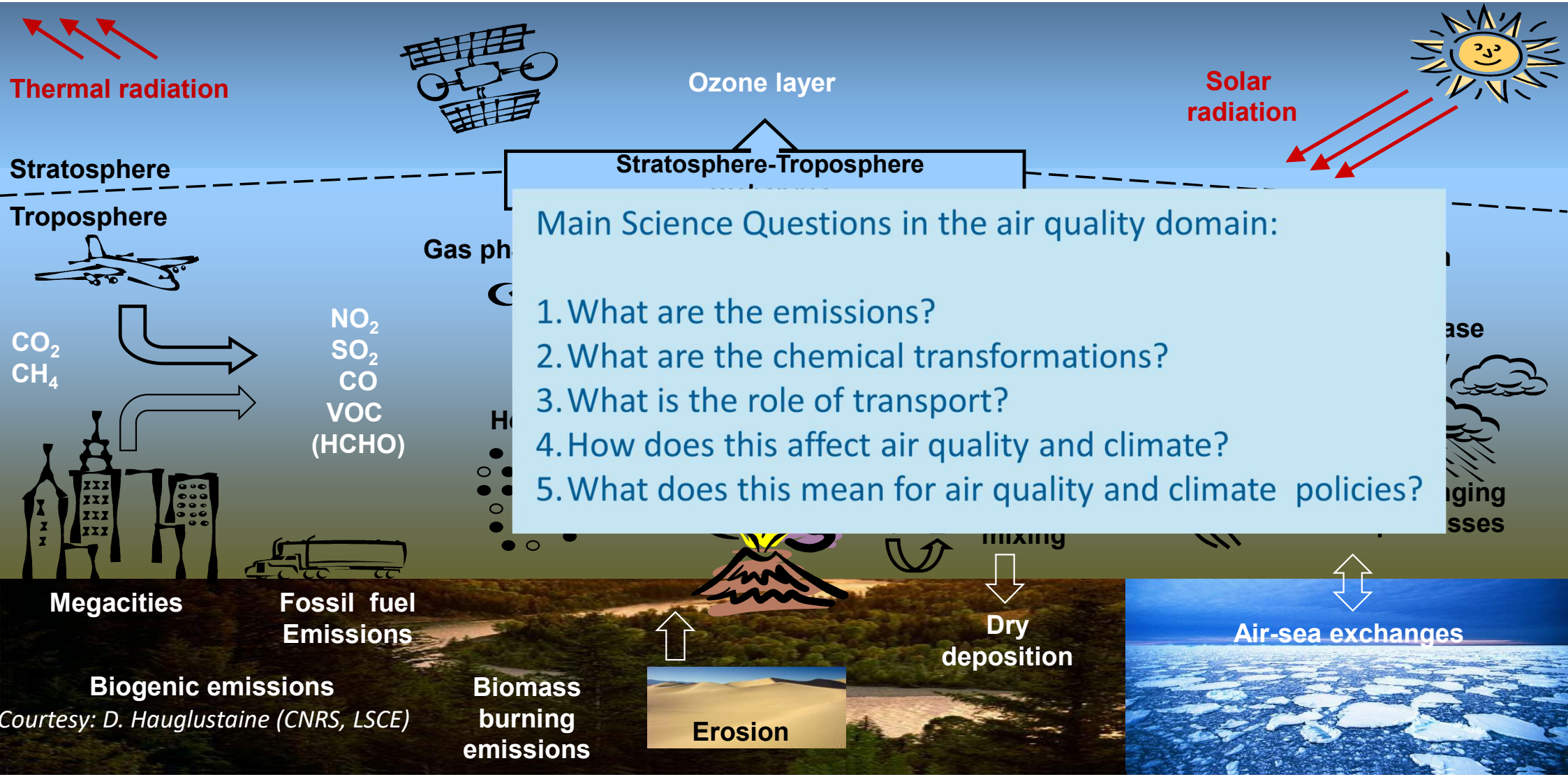
Calibration
KNMI , NASA
TNO

Instrument
prime Dutch Space&TNO, Finnish industry

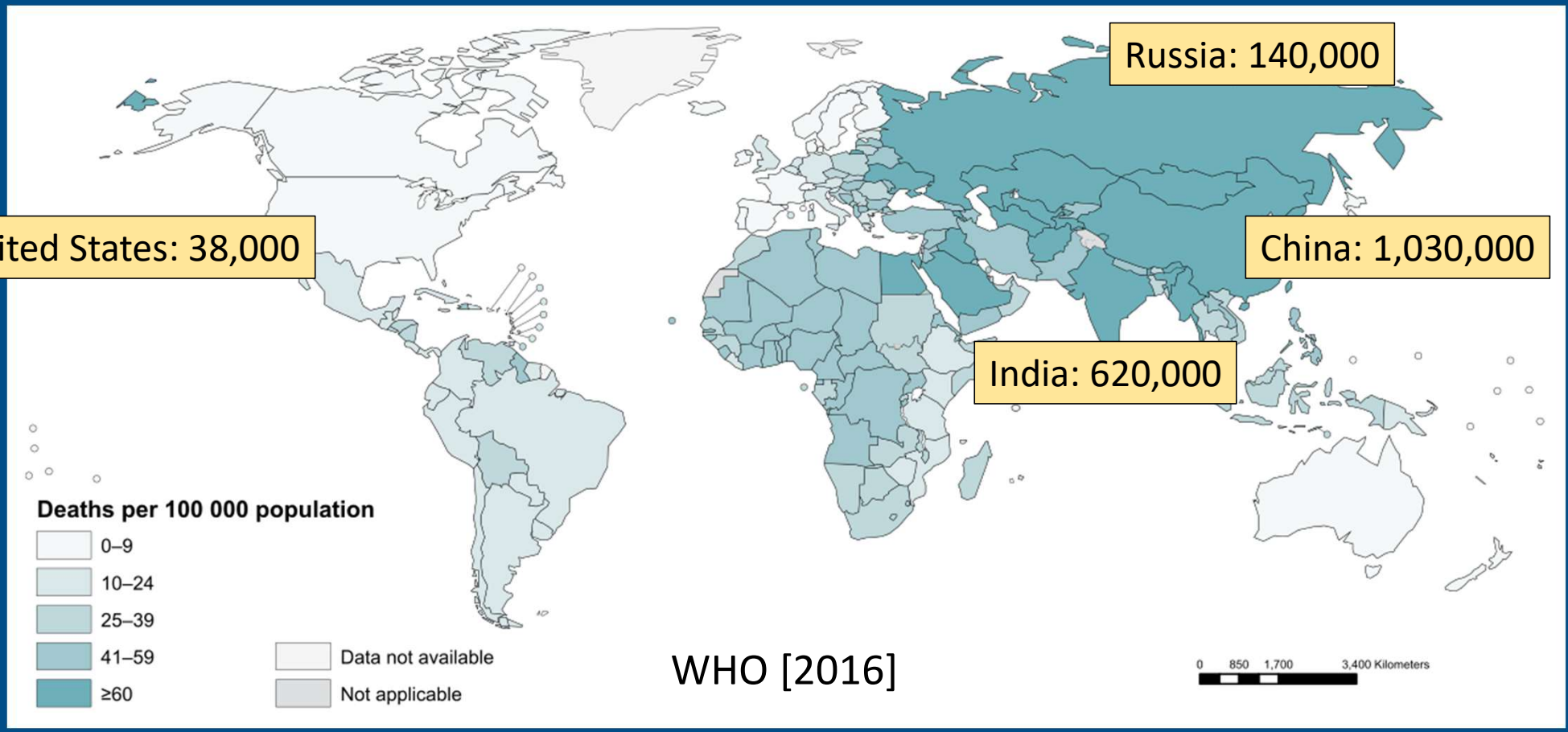
The “Anthropocene” Dutch Nobel Prize winner Paul Crutzen †

- Ozone Layer
- Air Quality
- Climate

Atmospheric Chemistry: fascinating and challenging



Air Pollution Accounts for 4.2 Million Premature Deaths per Year

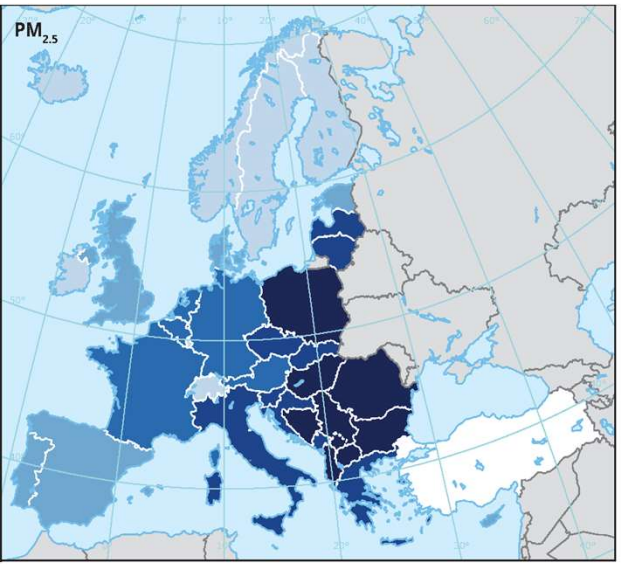


WHO [2016]

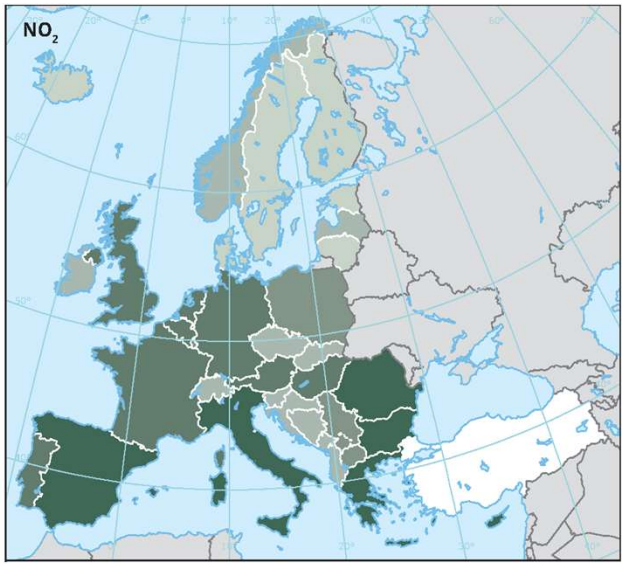
91% of World's population lives in places exceeding WHO air quality guidelines

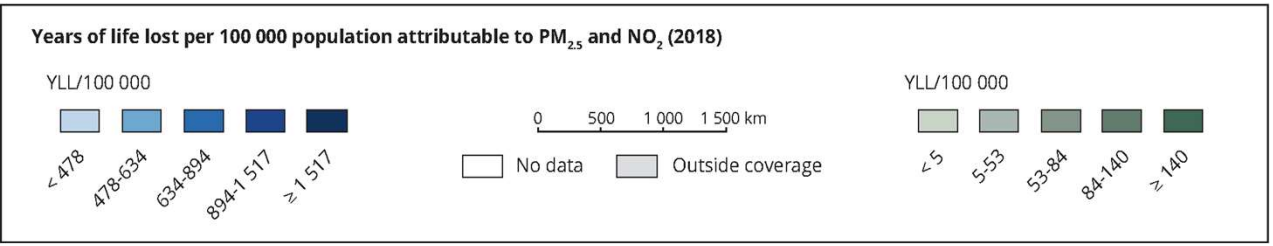
Air Quality and its effect on human health

PM 2.5



NO_2





European Environmental Agency 2018

- Europe is one of the most affected regions
- Global warming will lead to an increase in pollution episodes

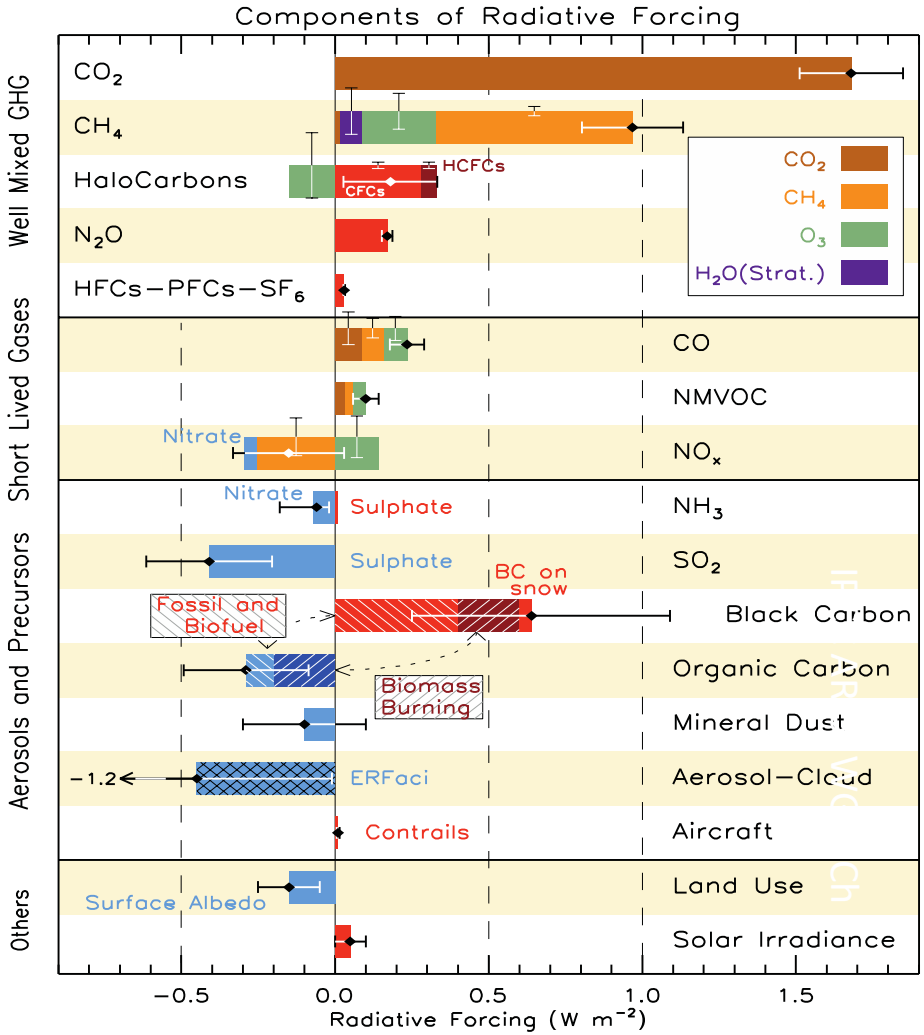
- 4000 death a year in The Netherlands
- Children are more vulnerable to air pollution
- NO_2 is more toxic than previously thought (Lancet paper 2019)

Years of life lost per 100 000 population attributable to PM2.5 and NO2 (2018)
The maps show the number of years of life lost per country attributable to air pollution (PM2.5 left and NO_2 right).
https://www.eea.europa.eu/data-and-maps/figures/years-of-life-lost-per-3 (Created 06 Feb 2020 Published 08 Sep 2020)

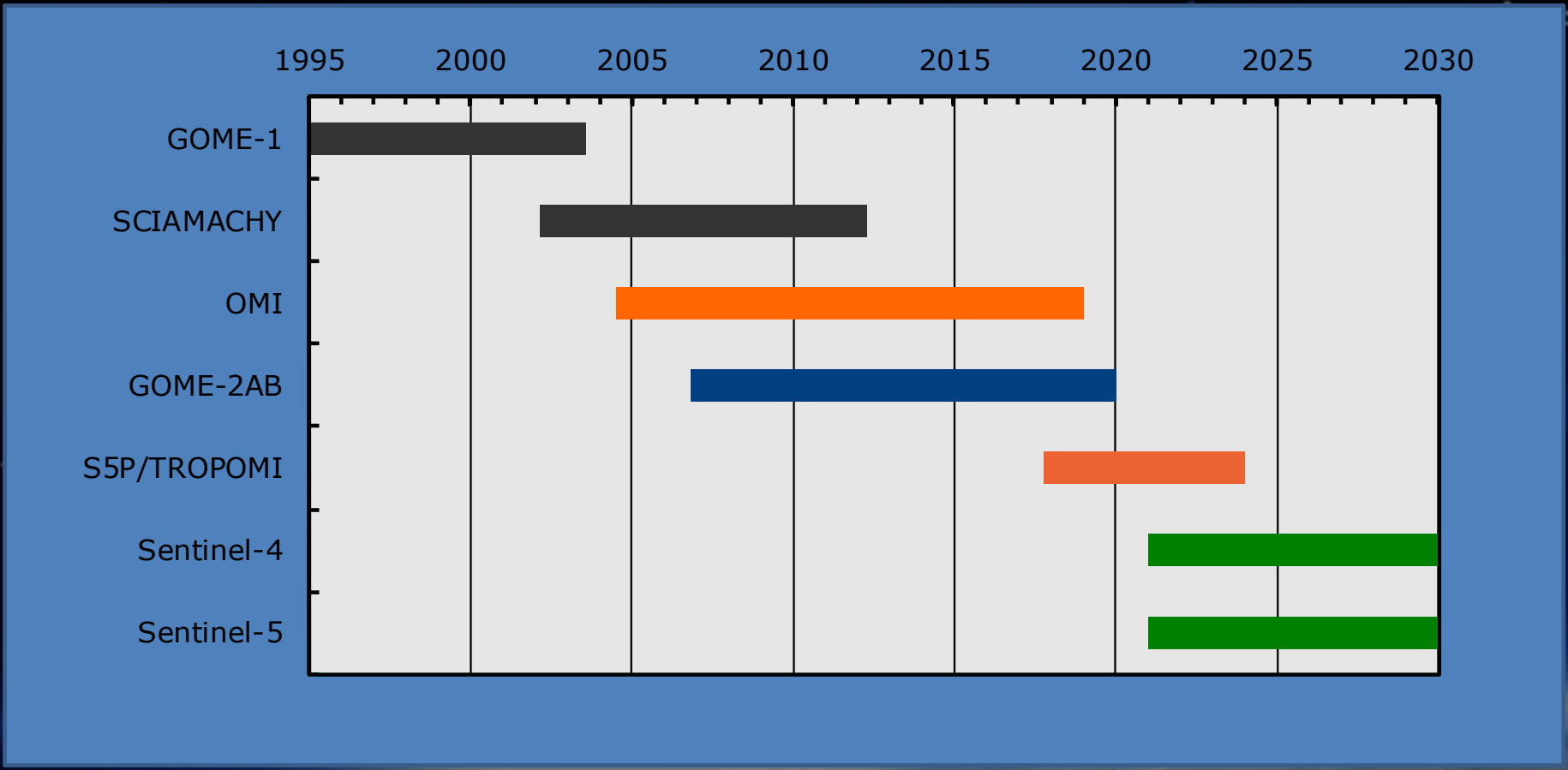
Emission based view of climate change

- Climate change is driven by changes in the atmospheric composition
- COP 21 addresses the emission control of long-lived greenhouse gases
- For the short and medium term, also the short-lived components - air pollutants - are important

Shindell,Science, 2009



European solar backscatter instruments **since** 1995



KNMI: PI OMI&TROPOMI
SRON: co-PI SCIAMACHY&TROPOMI
Dutch industry (TNO/Airbus Netherlands) designed and built GOME-1, SCIAMACHY, OMI and TROPOMI

Ozone Monitoring Instrument OMI

Royal Netherlands Meteorological Institute
Ministry of Infrastructure and the Environment

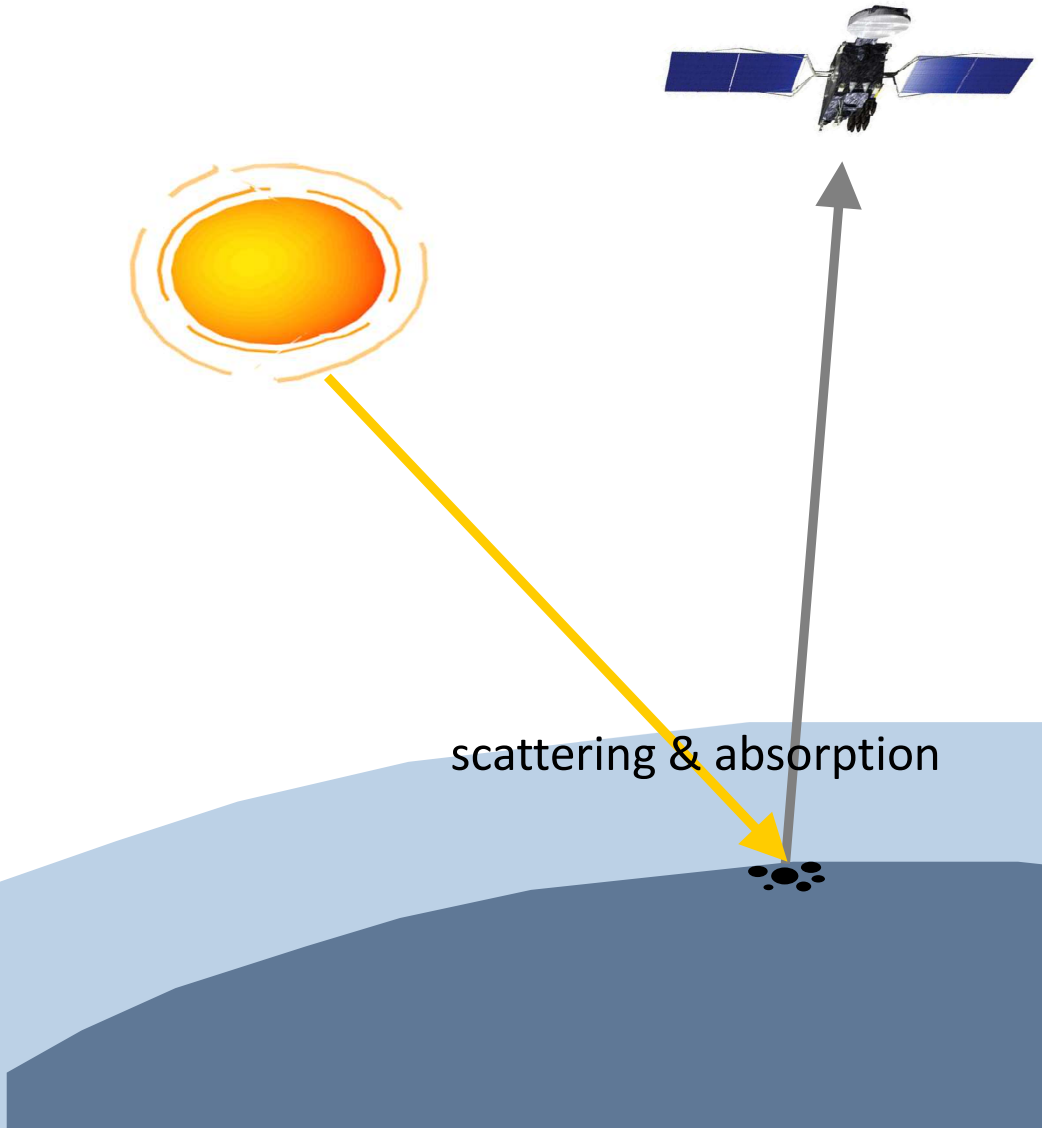
- UV and VIS backscatter instrument (270 - 500 nm)
- Wide swath telescope yields daily global maps (2600 km)
- First instrument with urban scale resolution of air quality measurements from space (13 x 24 km^2)
- Dutch-Finnish instrument launched at NASA's EOS-Aura in July 2004
- Heritage: GOME, SCIAMACHY, GOMOS and TOMS

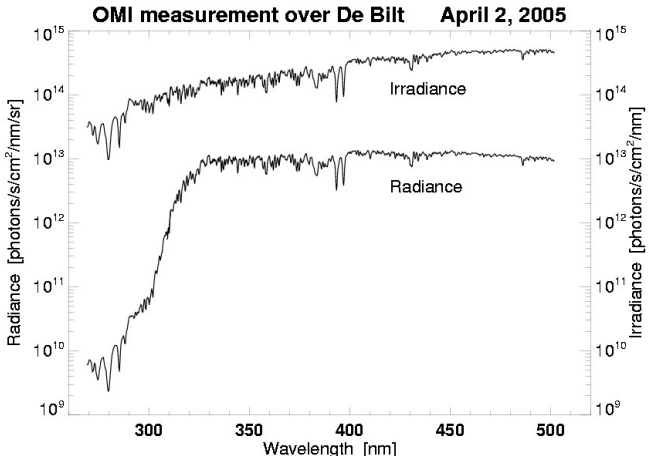
- *Levelt et al., OMI Overview Paper accepted for publication in AMT/ACP OMI Special Issue, March 2018.*

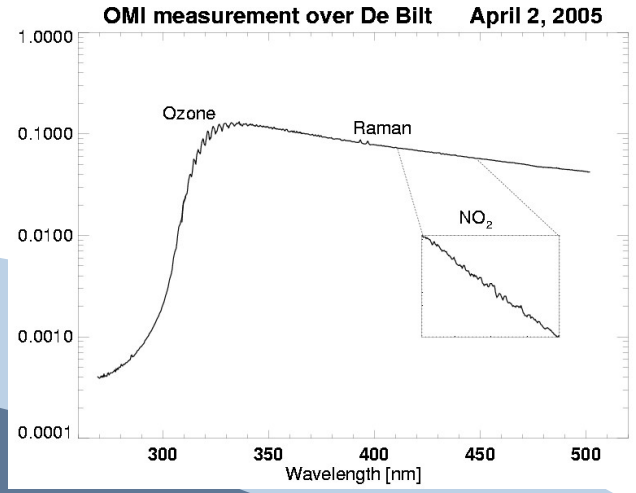

Pieternel Levelt and Bert van den Oord
OMI PI and deputy PI (2003)

Measurement Technique

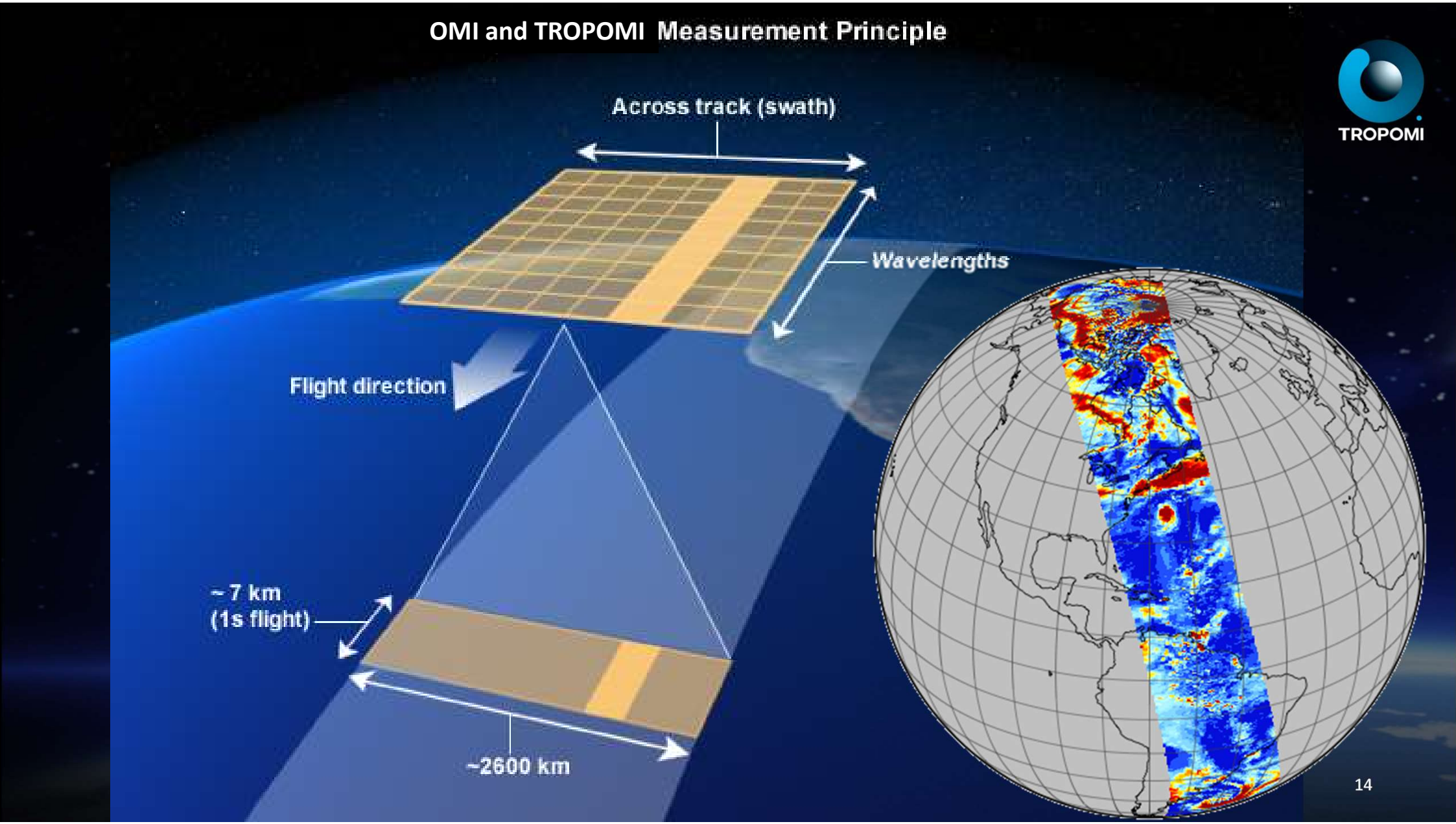
Royal Netherlands Meteorological Institute
Ministry of Infrastructure and the Environment







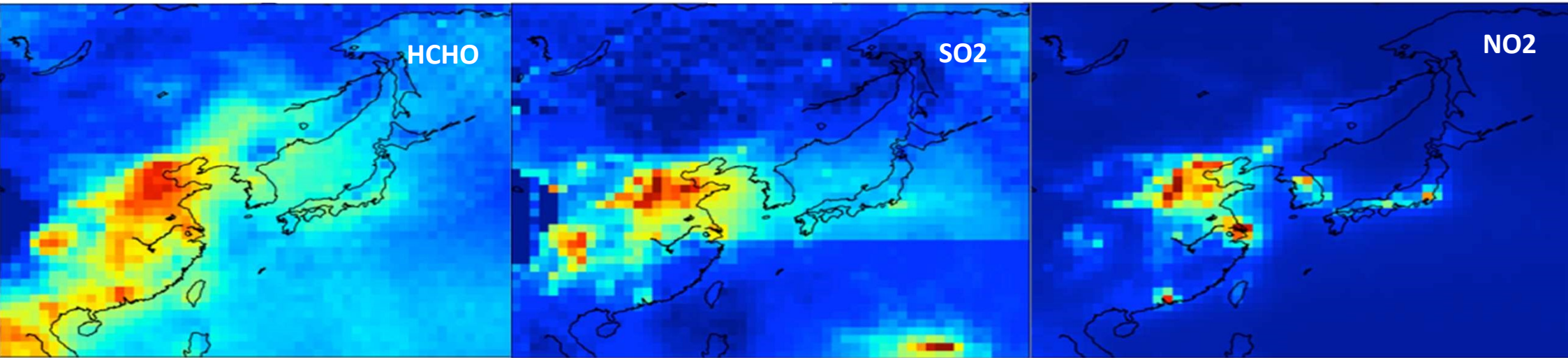
OMI and TROPOMI Measurement Principle



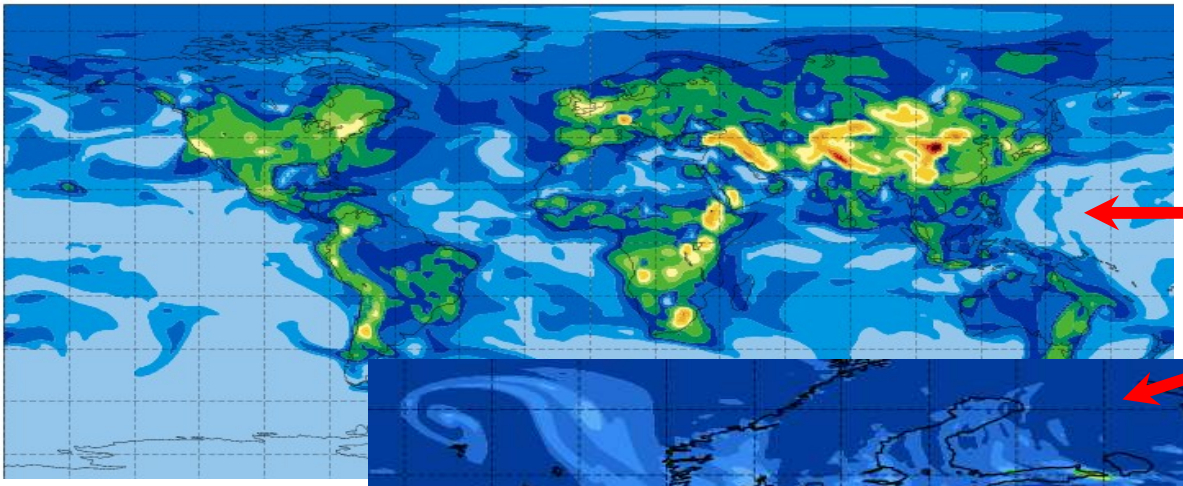
OMI lead to new findings in Air Quality Domain

- Air Quality forecast
- Environmental Trend Monitoring
- Calculation of Emissions

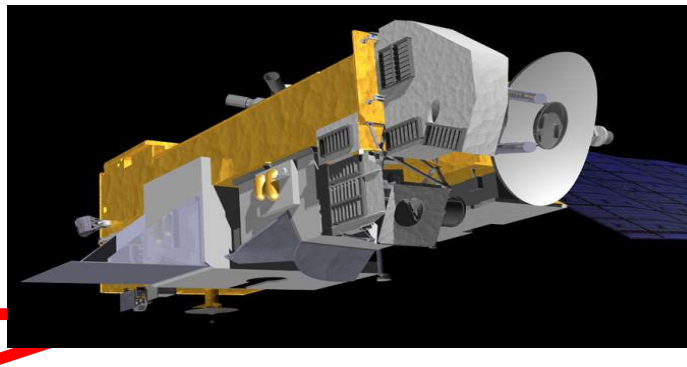
Product	Application
Ozone column	*Ozone layer monitoring / NWP*
Ozone profile	*Ozone layer monitoring / Tropospheric ozone*
NO_2	*Air quality / Emission monitoring*
SO_2	*Volcanic eruptions / Air quality / Emission monitoring*
Formaldehyde	*Air quality / Emission monitoring*
BrO	*Polar chemistry / stratospheric chemistry*
Aerosol	*Absorbing aerosol plumes / Volcanic ash*
Cloud	*Cloud fraction and height variability*
UV index	*Health / Biosphere*
Surface reflectivity	*Climatology*
Solar irradiance	*Solar variability*

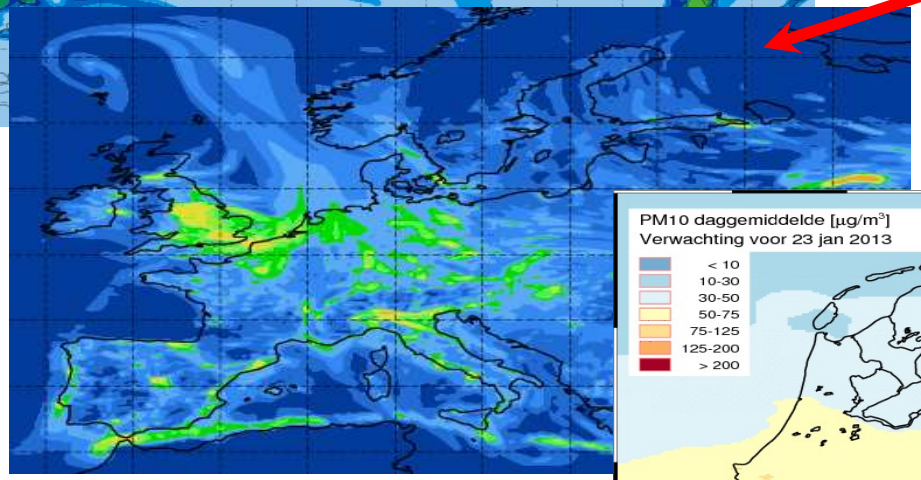


EU Copernicus Atmosphere: Air Quality product chain

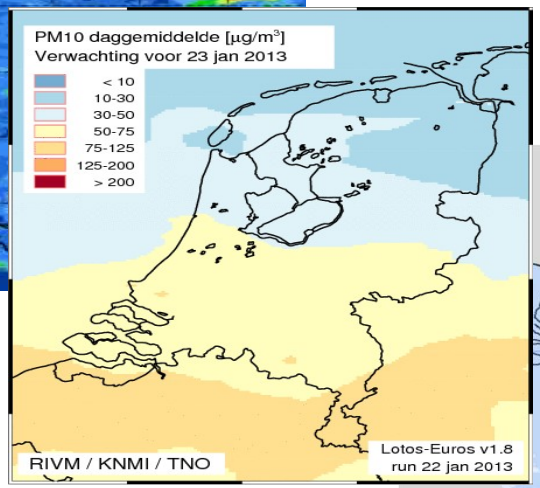


OMI NRT contributions

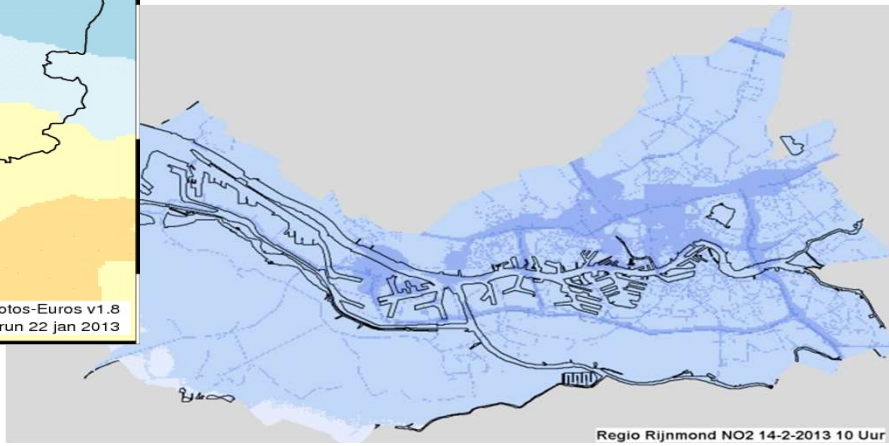




National forecasts:
Nesting in MACC regional

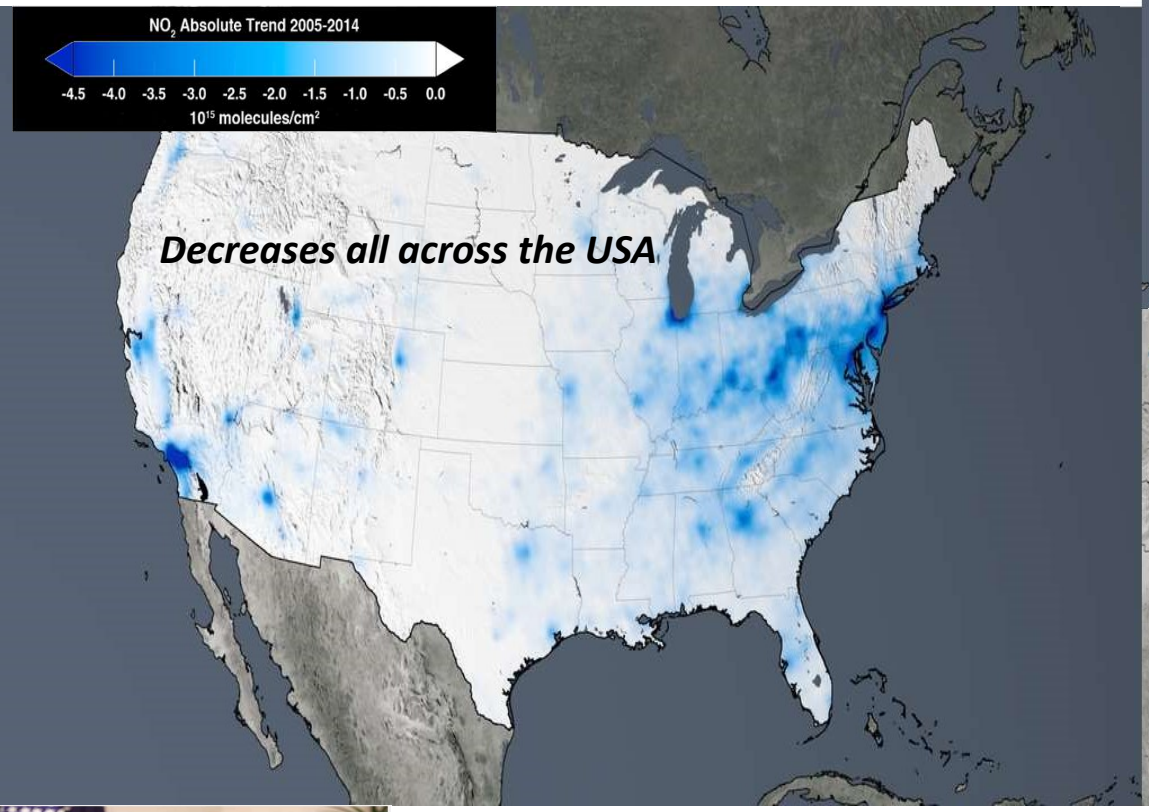


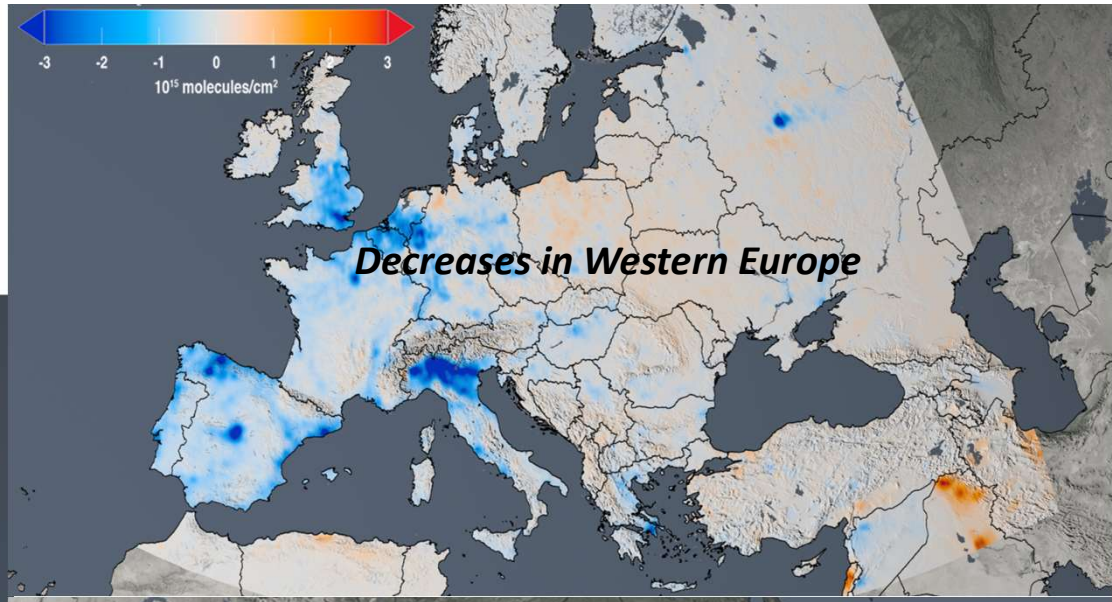
Couple to
city-scale models

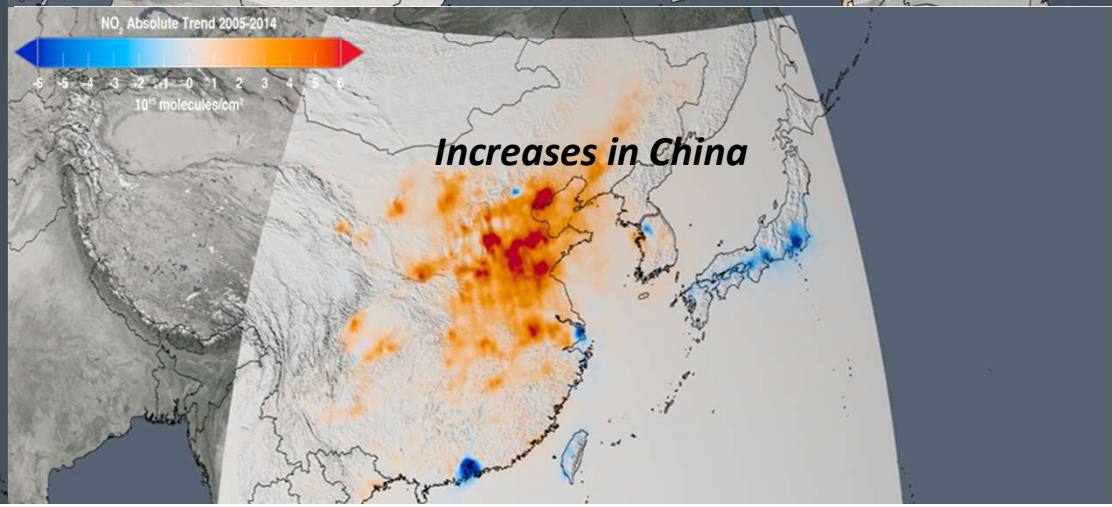


Use of
CAMS-global analyses as
boundary conditions for
CAMS-Europe

OMI: 2005 compared to 2014 (NASA/KNMI)





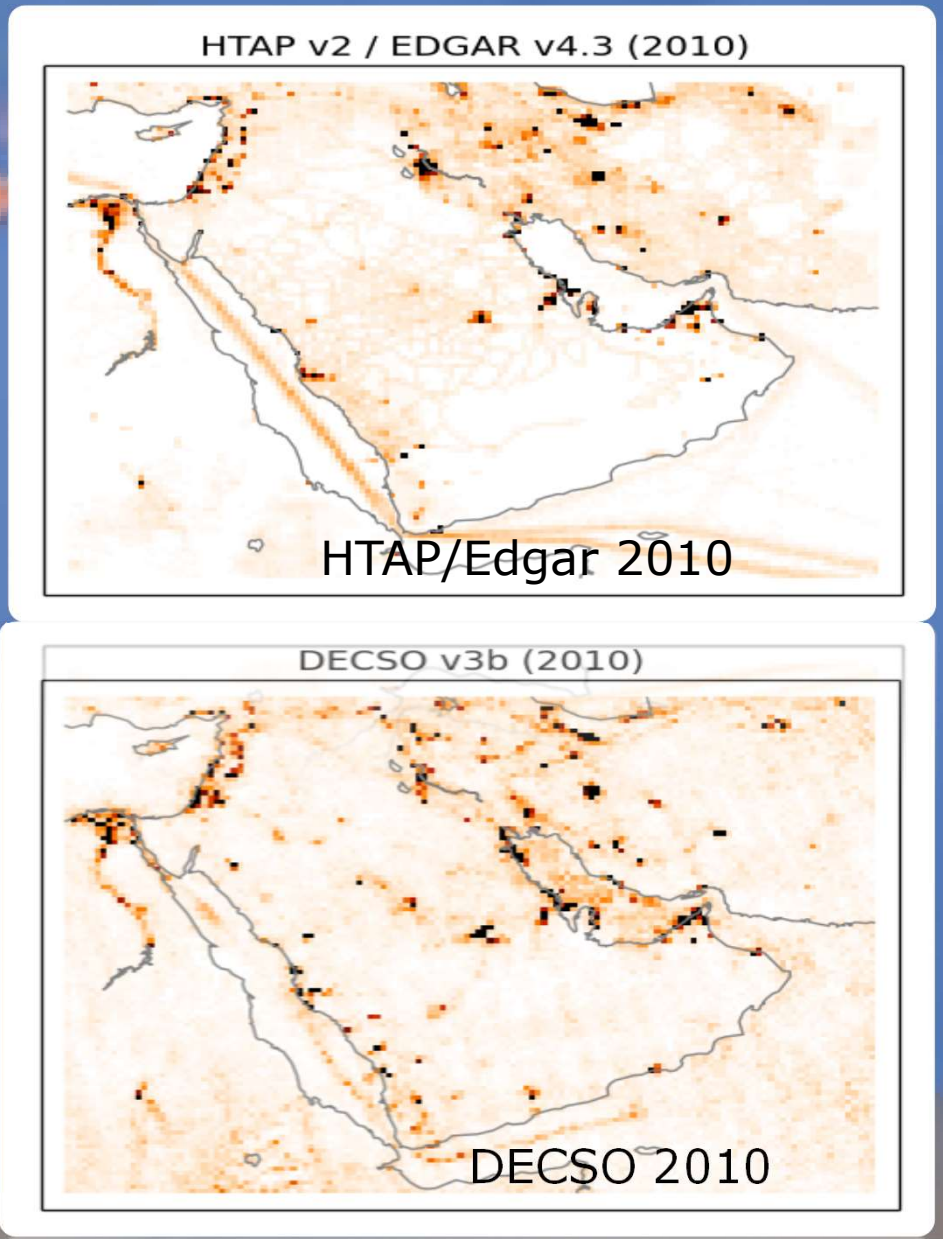


President Obama Explains How Pollution Affects Our Planet

President Barack Obama
about OMI NO_2 and emission control
Science Channel, April 12, 2016

https://www.youtube.com/watch?v=LKe5FdKInJs

Top-down emission estimates based on satellite data



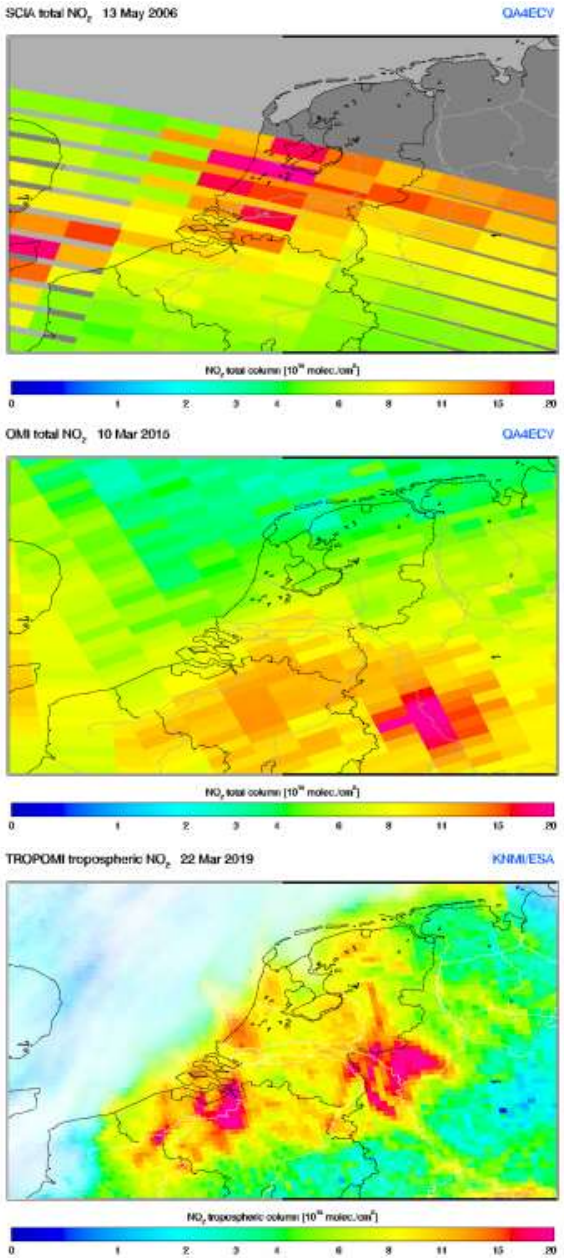
Daily emission estimates constrained by satellites: DECSO algorithm from KNMI

Bas Mijling , Ronald van der A
KNMI

From OMI to TROPOMI

- **16 x higher spatial resolution**
  3,5 x 5,5 km^2 vs. 13 x 24 km^2
- **1-5x higher sensitivity** per ground pixel
- **CO and Methane (7 x 5,5 km^2)**
  SWIR band added
- **Better cloud information**
  oxygen A band added

- *TROPOMI was launched on the ESA/EU sentinel-5 precursor satellite on October 13, 2017*



SCIAMACHY
13 May 2006

30 x 60 km^2
6 day global coverage

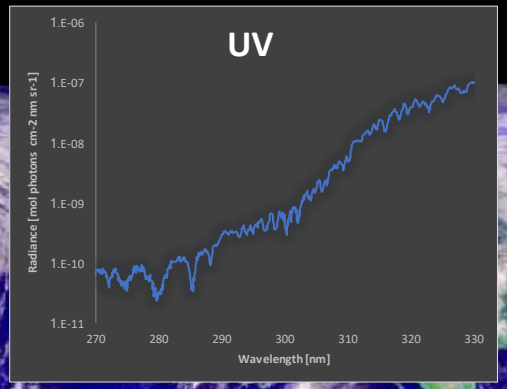
OMI
10 March 2016

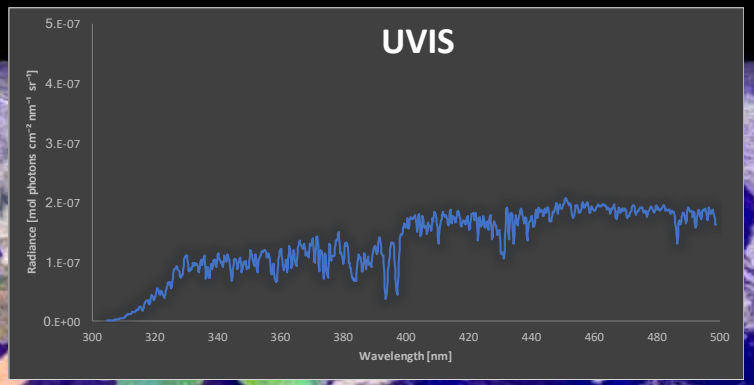
13 x 24 km^2
Daily global coverage

TROPOMI
22 March 2019

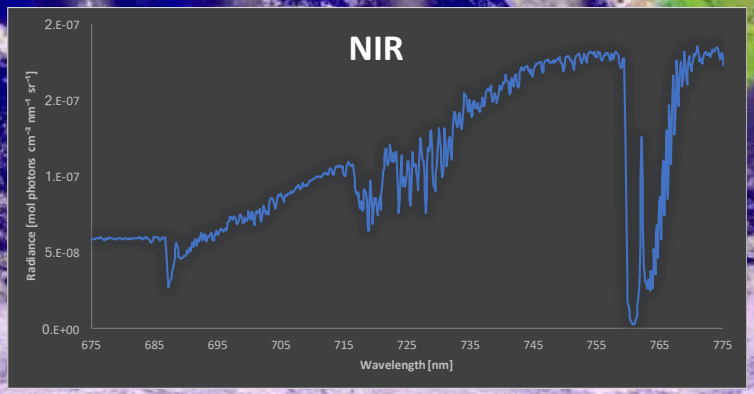
3,5 x 5,5 km^2
Daily global coverage

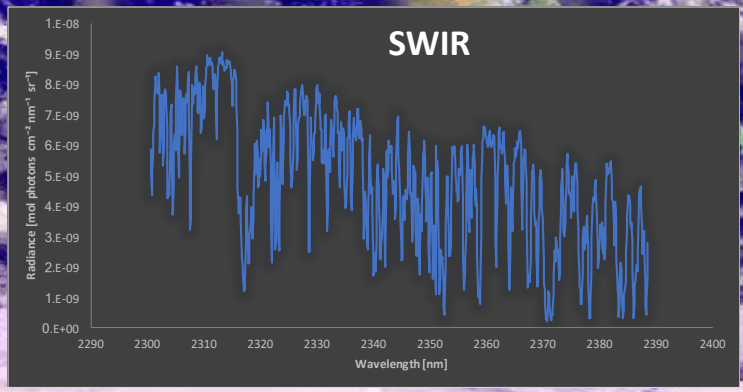

sentinel-5p
→ GLOBAL AIR MONITORING FOR COPERNICUS
TROPOMI Launch Successful!
See further updates at
www.esa.int/sentinel5p
#sentinel5p
Friday October 13, 2017





- 1 scanline per second
- 440 spectra per scanline
- 3000 scanlines per orbit
- 15 orbits per day
- 20 million groundpixels per day
- 225 Gbyte raw data per day
- 1 Tbyte L1b data per day



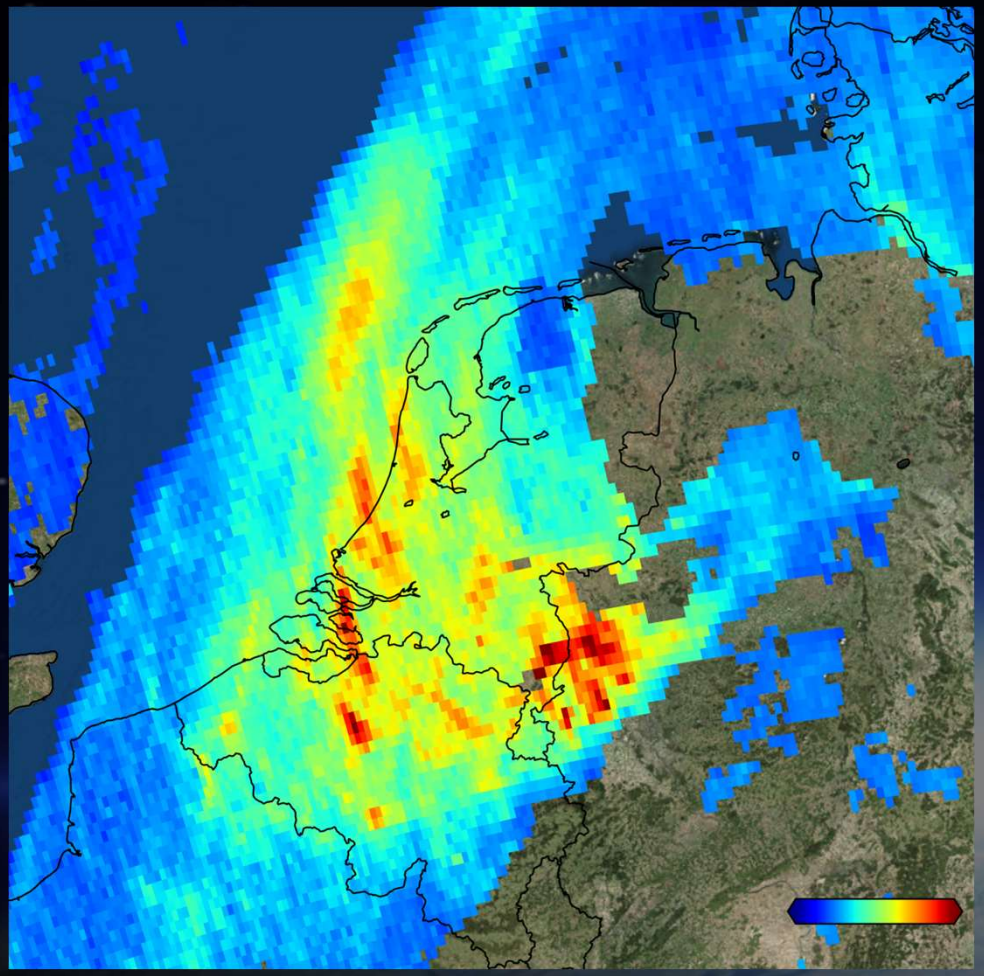


First NO_2 measurements after launch from S5p/TROPOMI

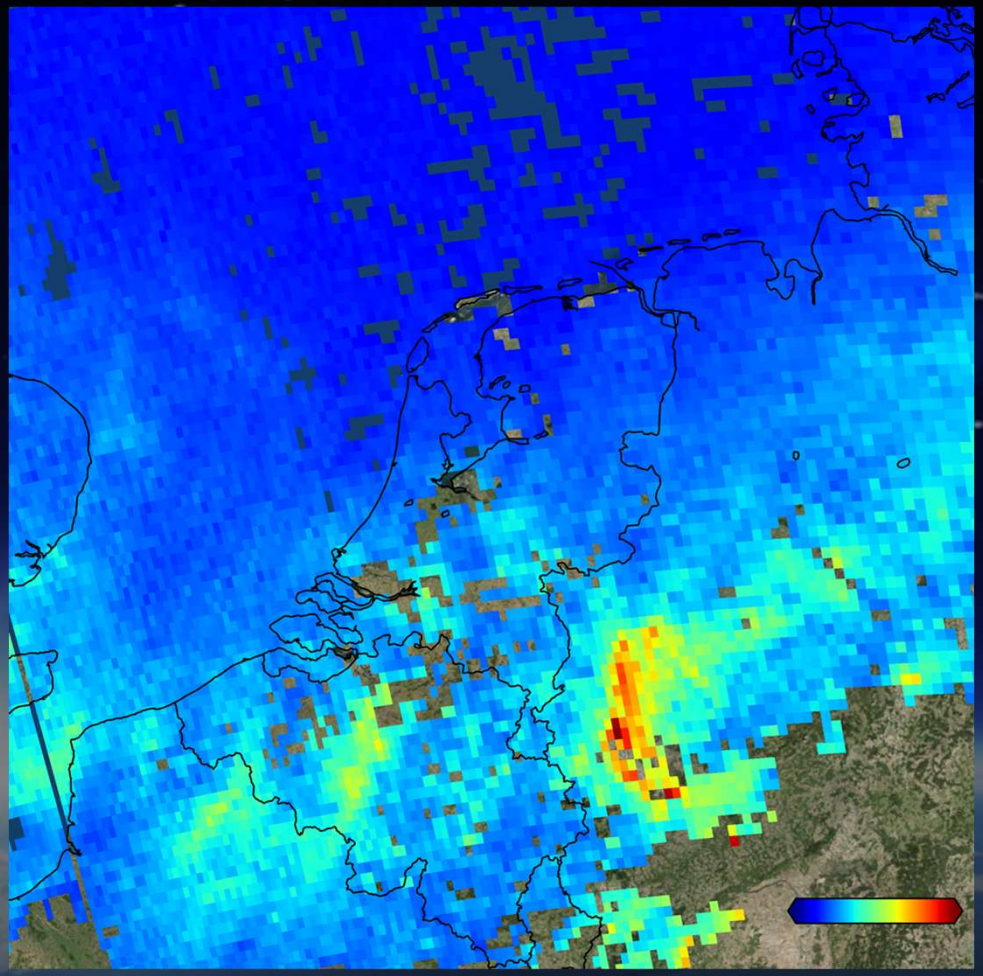
KNMI/NSO/ESA

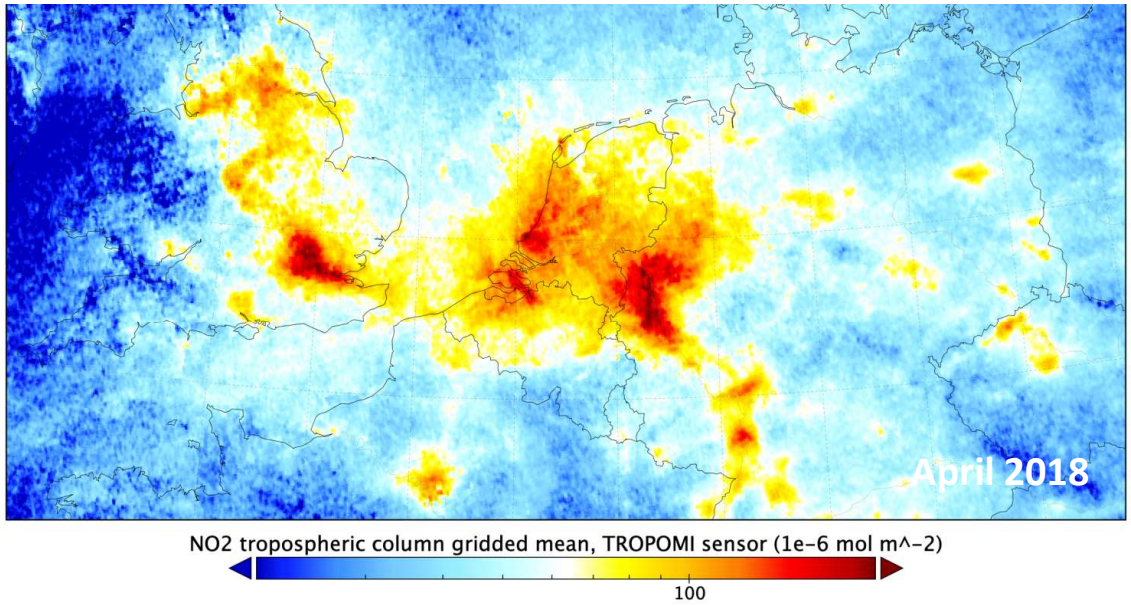
TROPOMI

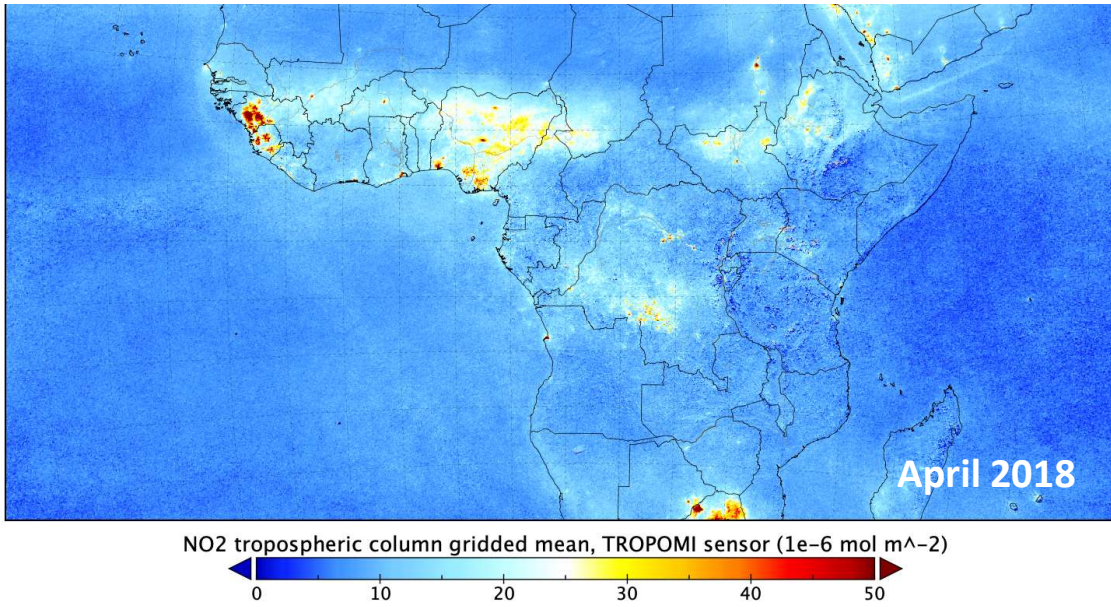
NO_2 07-11-2017

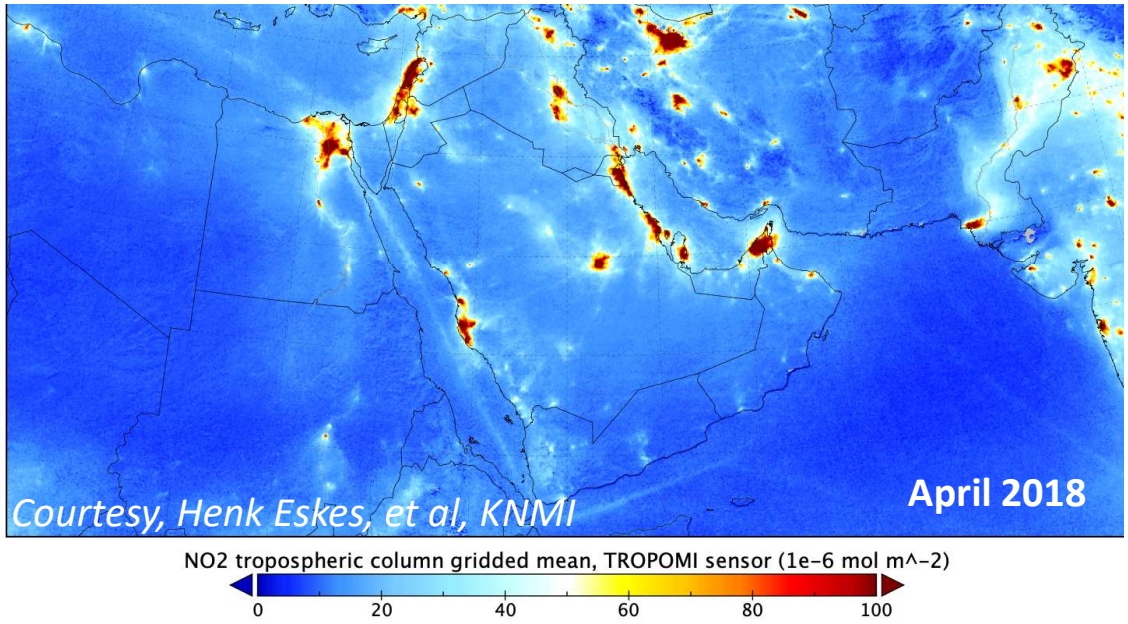


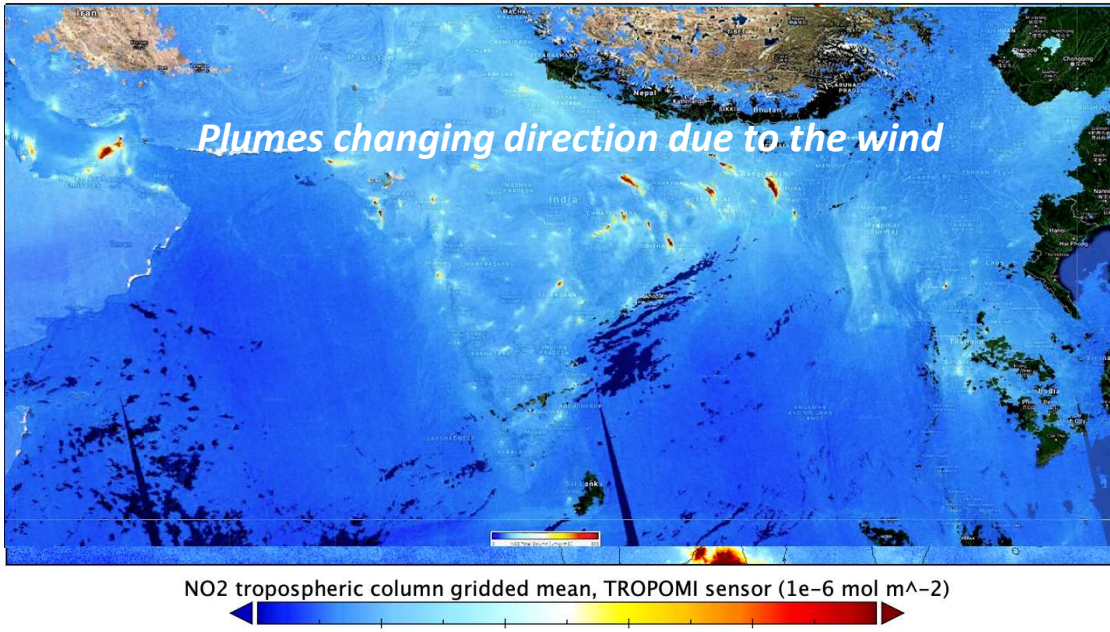
NO_2 17-11-2017

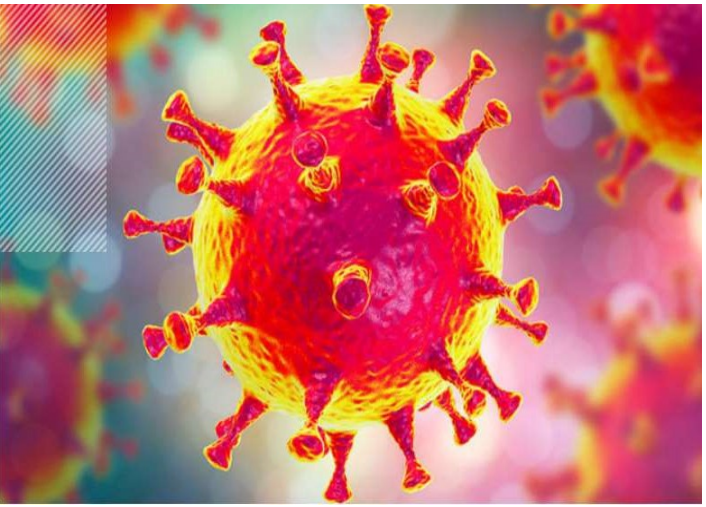



April 2018
NO2 tropospheric column gridded mean, TROPOMI sensor (1e-6 mol m^-2)
100


April 2018
NO2 tropospheric column gridded mean, TROPOMI sensor (1e-6 mol m^-2)
0
10
20
30
40
50


Courtesy, Henk Eskes, et al, KNMI
April 2018
NO2 tropospheric column gridded mean, TROPOMI sensor (1e-6 mol m^-2)
0
20
40
60
80
100


Plumes changing direction due to the wind
NO2 tropospheric column gridded mean, TROPOMI sensor (1e-6 mol m^-2)



NEWS · 09 APRIL 2020

Why pollution is plummeting in some cities — but not others

Tantalizing signs that coronavirus lockdowns are making air cleaner aren't as straightforward as they seem.

Quirin Schiermeier

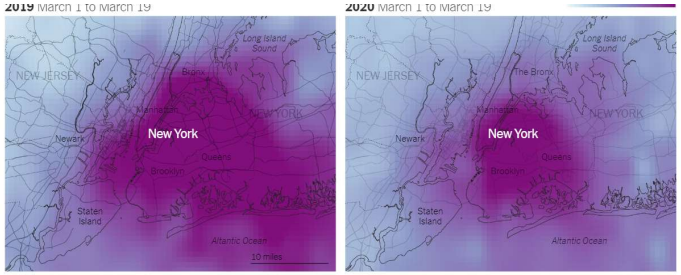
Nature Physics news item

ENGLISH ESPAÑOL 中文

The New York Times

Traffic and Pollution Plummet as U.S. Cities Shut Down for Coronavirus

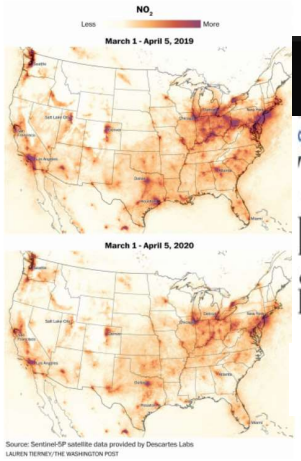
By Brad Plumer and Nadja Popovich March 22, 2020



Source: Sentinel-5P satellite data processed by Descartes Labs

New York

In New York City, residents are less dependent on car travel than in other metro areas, but vehicle traffic has still seen a steep drop-off in recent days as office buildings, schools and restaurants have shut down. On Wednesday afternoon, rush-hour traffic moved 36 percent faster than normal as the roads cleared out, according to data from INRIX.



The Washington Post
Democracy Dies in Darkness

Capital Weather Gang

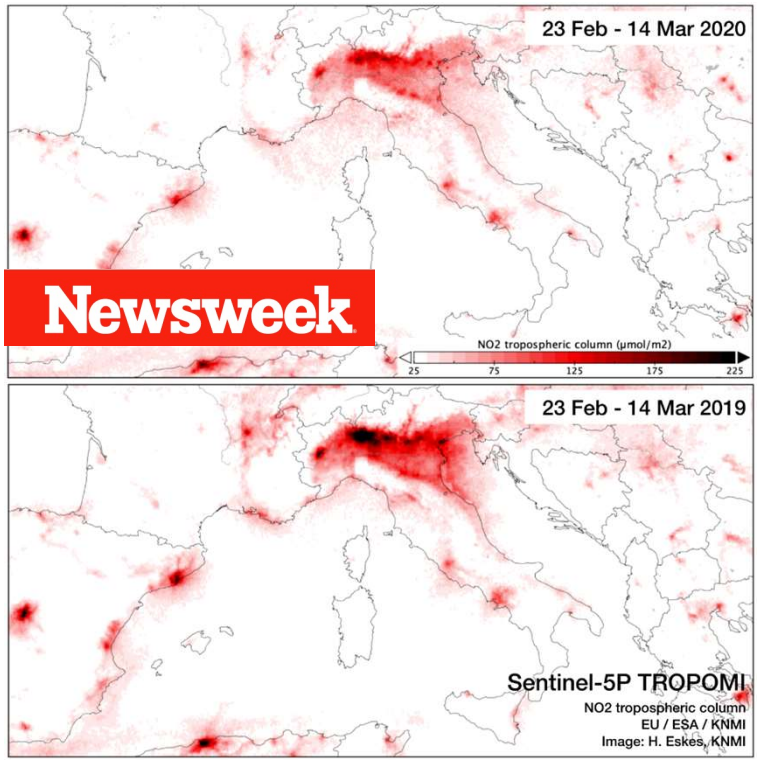
The silver lining to coronavirus lockdowns: Air quality is improving

By Andrew Freedman and Lauren Tierney
April 9

TECH & SCIENCE

Coronavirus Is Having a Major Impact on the Environment, With Reduced CO2, Better Air Quality and Animals Roaming City Streets

BY ARISTOS GEORGIOU ON 3/24/20 AT 5:43 AM EDT



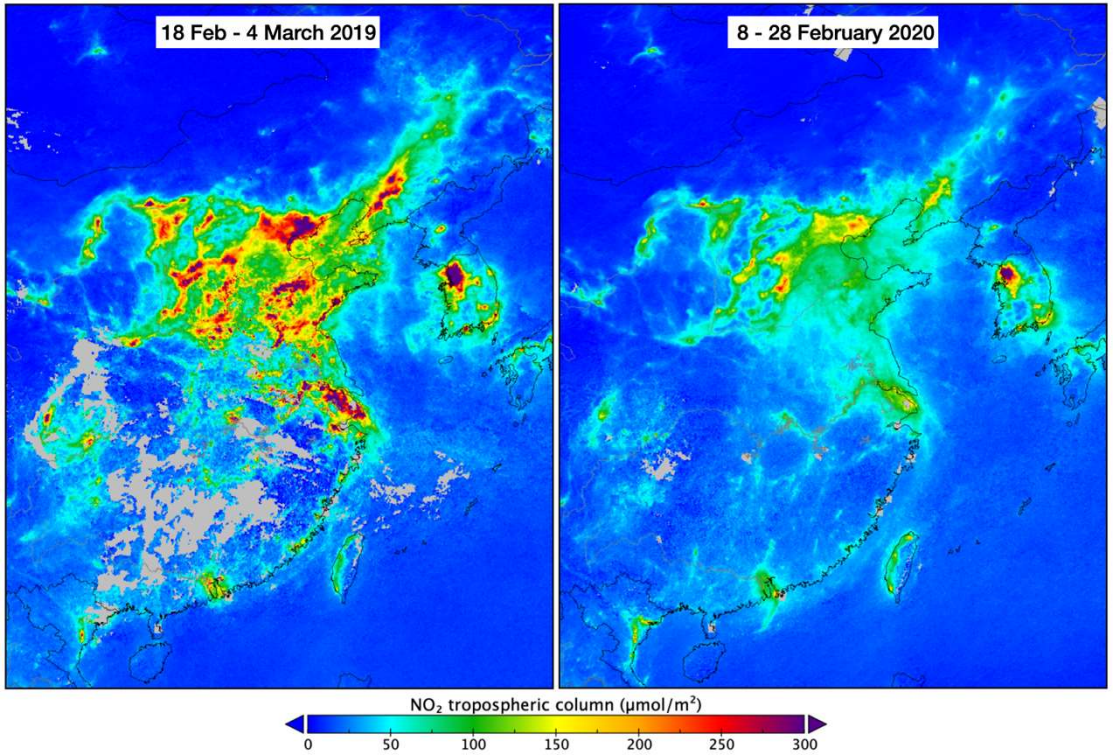
Newsweek

Pieternel Levelt from the Dutch Met office KNMI and Delft University of Technology in the Netherlands, echoed DeCarlo's comments telling Newsweek that there have been significant reductions in nitrogen dioxide over China and northern Italy in particular.

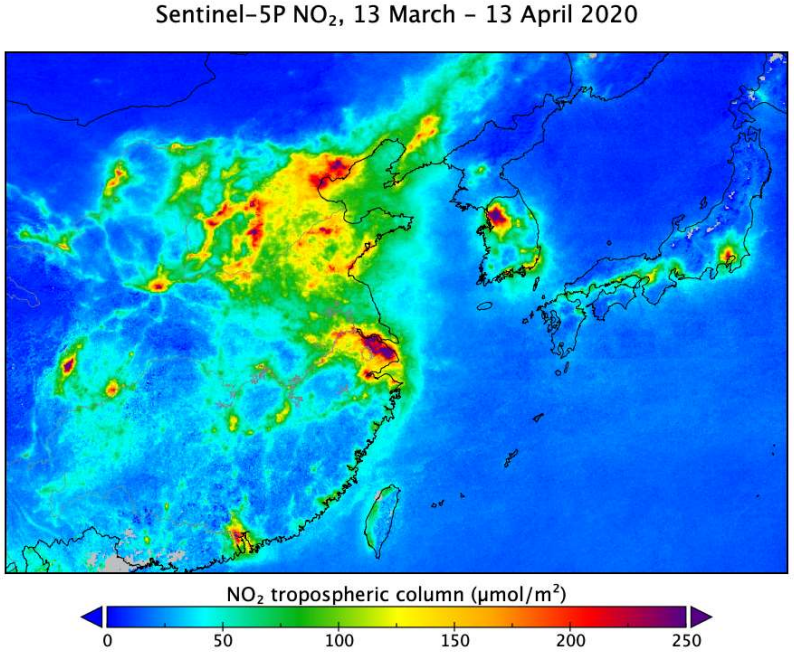
NO2 pollution reductions related to COVID-19 lockdown in China

Royal Netherlands Meteorological Institute
Ministry of Infrastructure and the Environment

Normal situation February 2019 **Lockdown in February 2020**



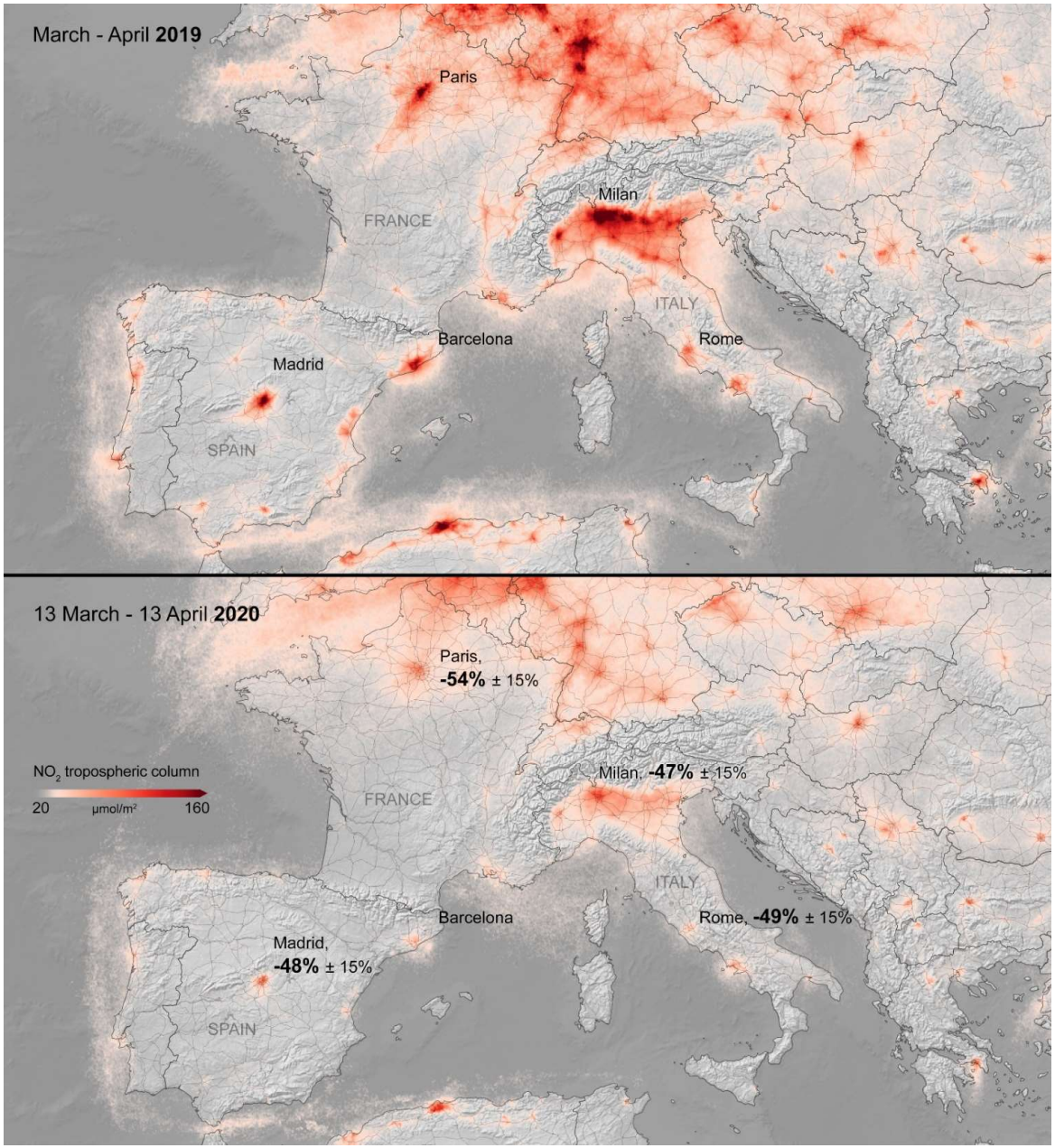
China back to work in March 2020



Courtesy Henk Eskes et al, KNMI

Sentinel 5p/TROPOMI

Update of the situation in South Europe confirms the reduction of NO2 in several cities up to 50 % with an uncertainty bar of 15 %

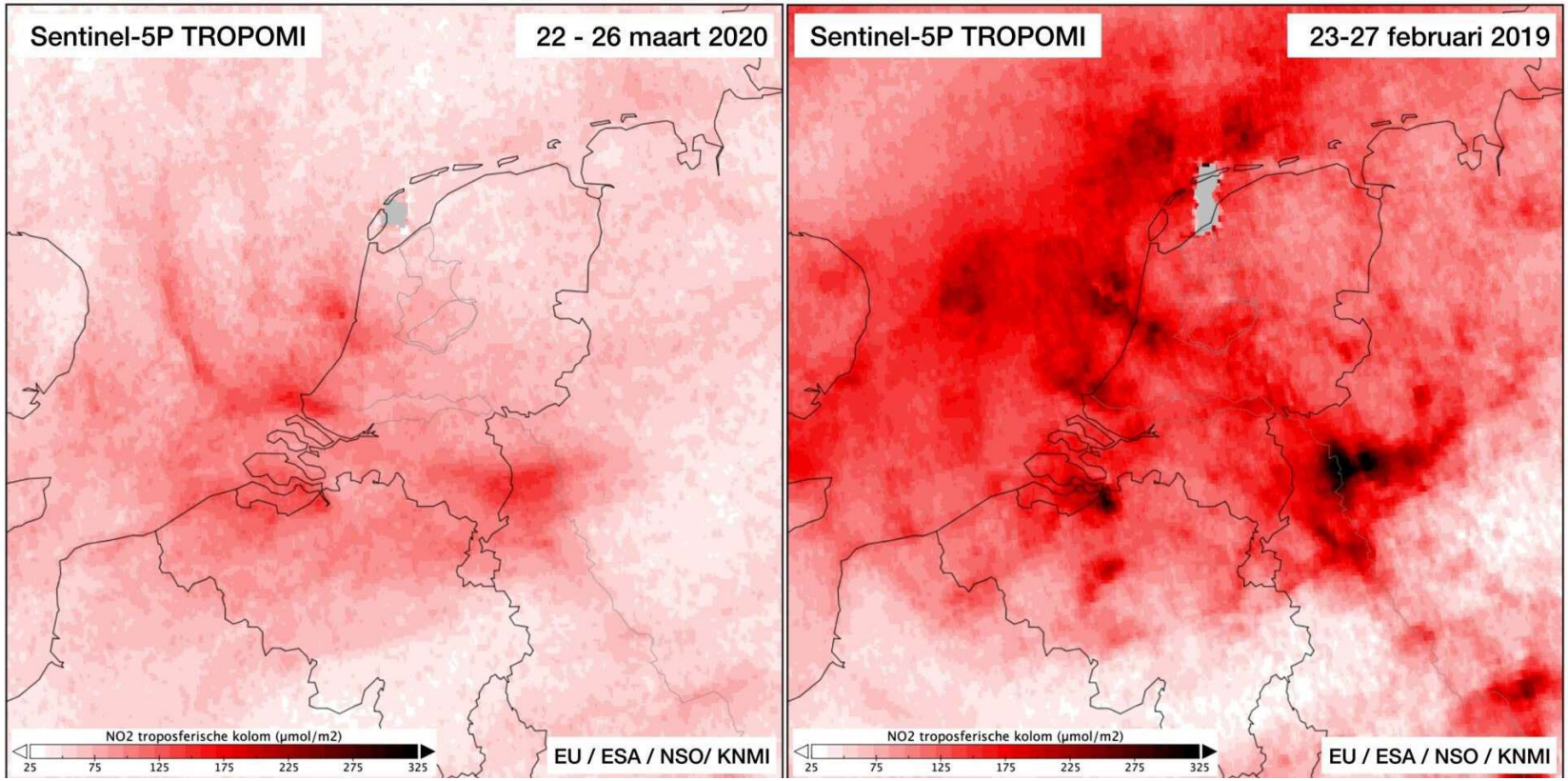


The Netherlands/Western Europe

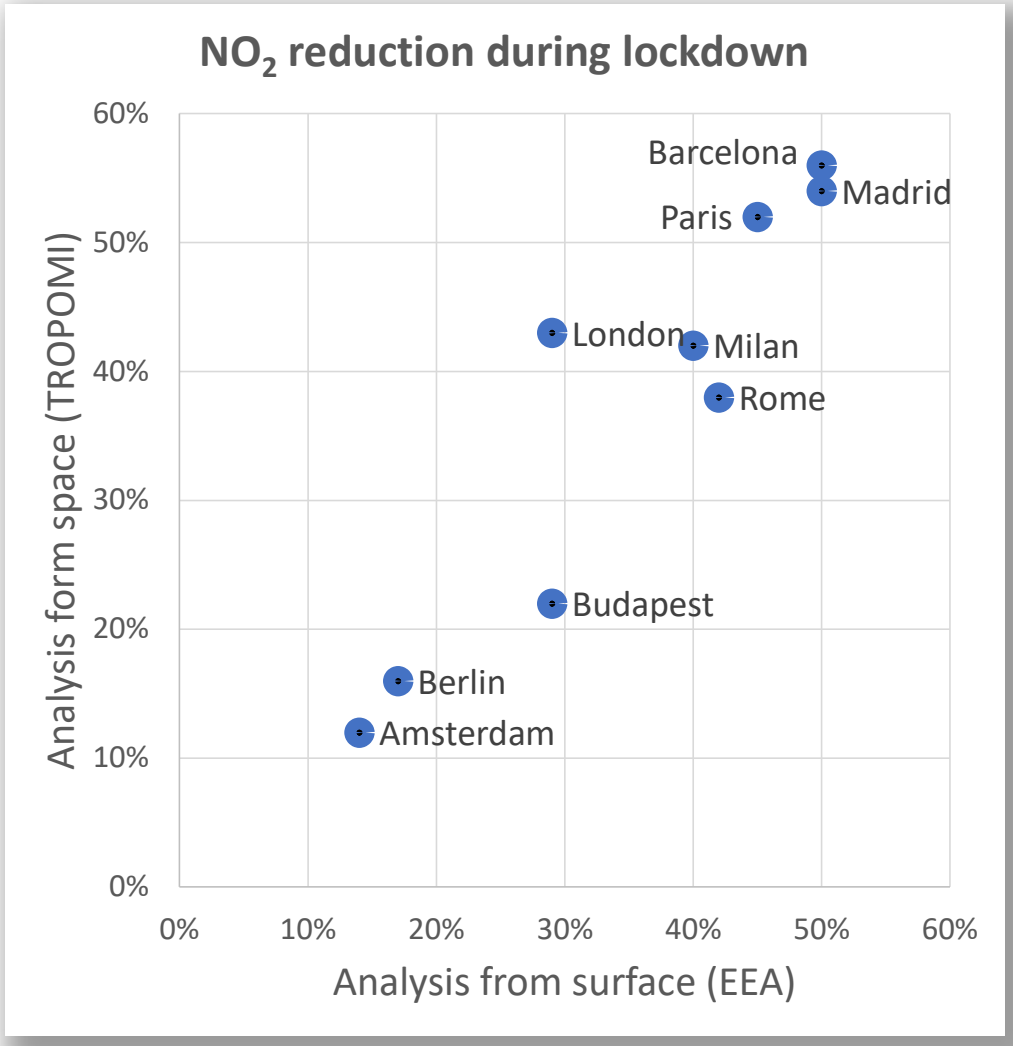
Always more difficult due to changeable weather
And now extra due to uncommon weather situation with constant wind from the East and a lot of sun
Therefore comparison to limit impact weather and season is done with similar weather conditions last year
(which is not automatically the same week last year!).

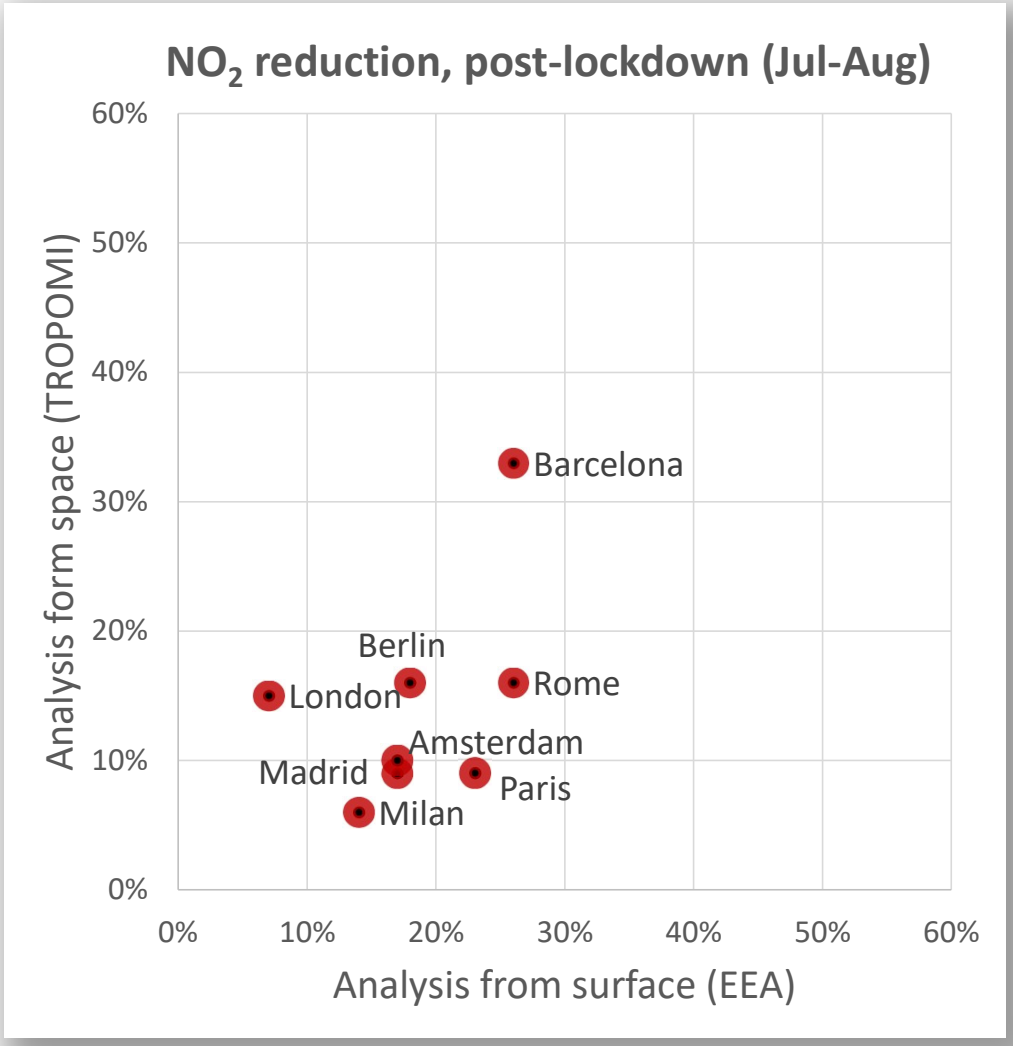
https://www.knmi.nl/over-het-knmi/nieuws/afname-luchtvervuiling-boven-nederland

20-60% reduction in NO2



NO_2 columns compared to in-situ measurements

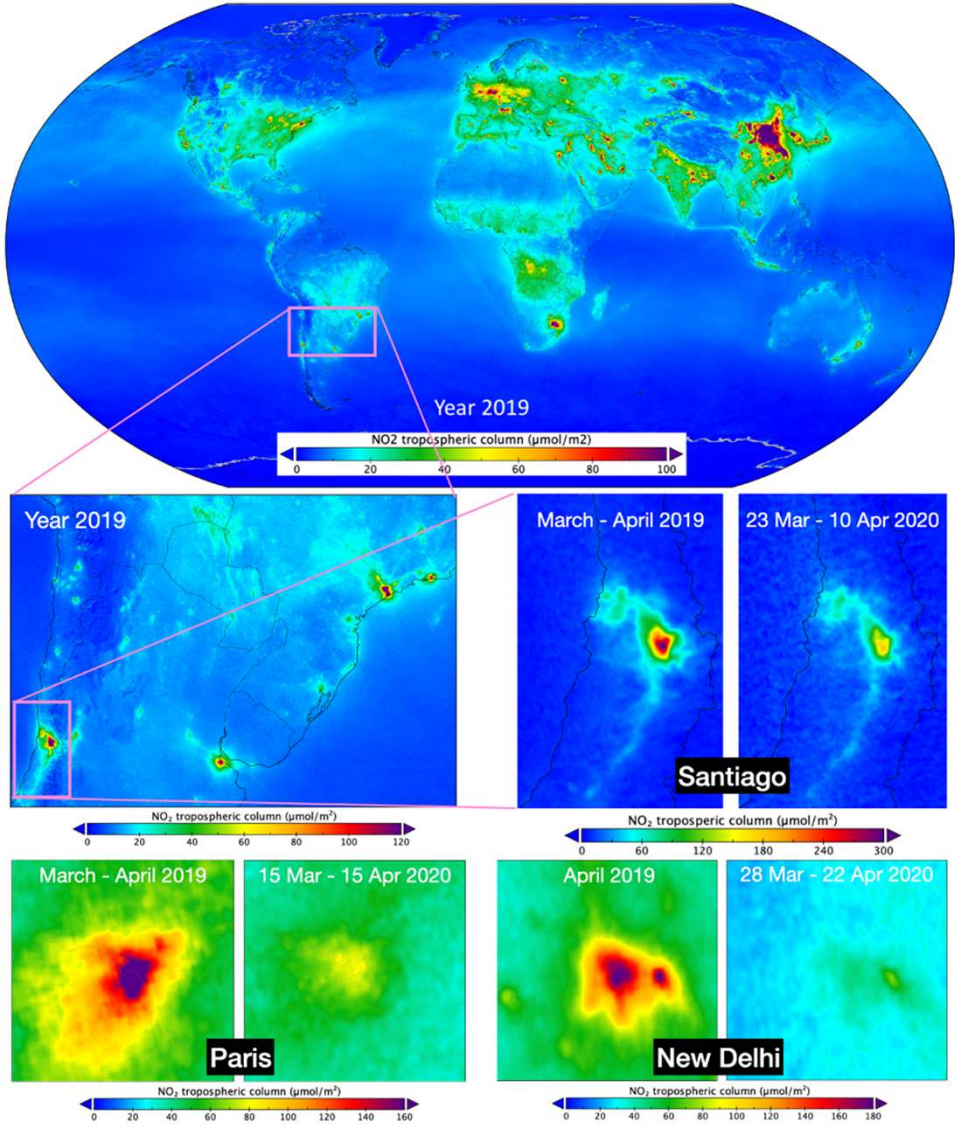




Mijling, Eskes et al., KNMI, 2021

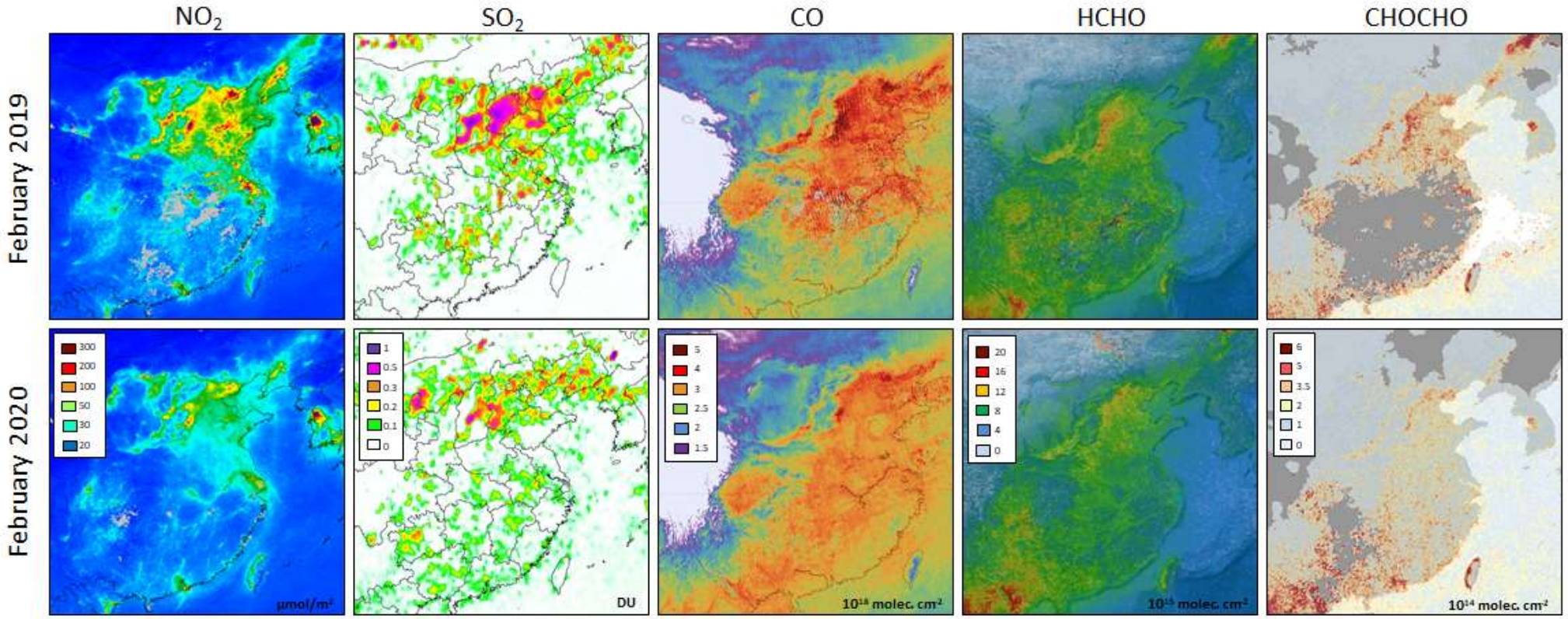
Global Distributions of TROPOMI NO2
Comparison between 2019 and 2020
to show impact COVID lock down
measures

‘City tour’ around the world



Levelt, et al, almost submitted to ACP

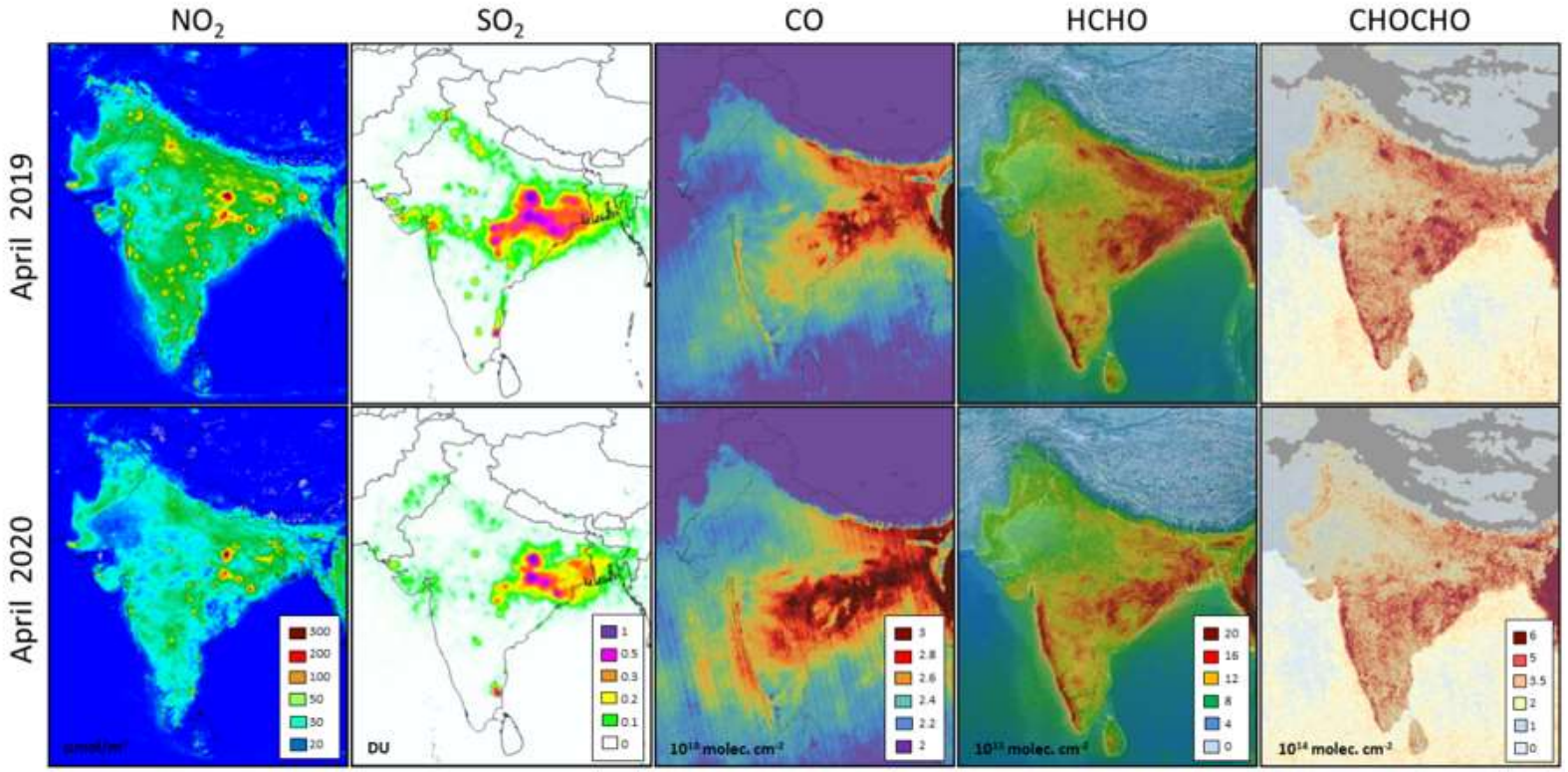
TROPOMI NO_2, SO_2, CO, HCHO, CHOCHO COVID lockdown impact (comparison February 2019 with 2020) over China



Tropospheric and total columns for various trace gases over China as observed by TROPOMI over China in February 2019 (upper panels) and 2020 (lower panels)

Levelt, et al, almost submitted to ACP

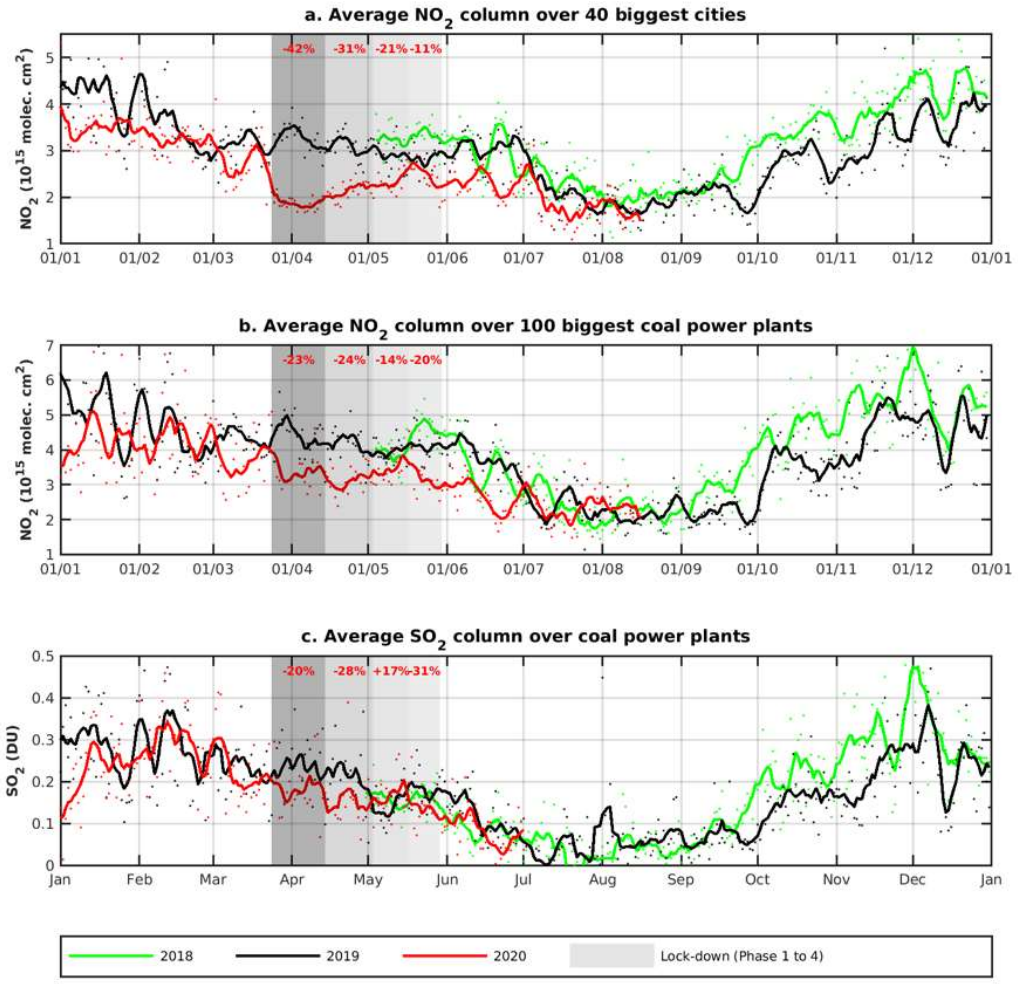
TROPOMI NO_2, SO_2, CO, HCHO, CHOCHO COVID lockdown impact (comparison February 2019 with 2020) over India



Concentrations maps for April 2019 and April 2020 for the various species measured by TROPOMI: NO2, SO2, CO, HCHO and CHOCHO.

Levelt, et al, almost submitted to ACP

TROPOMI NO_2, and SO_2 over Indian cities and powerplants



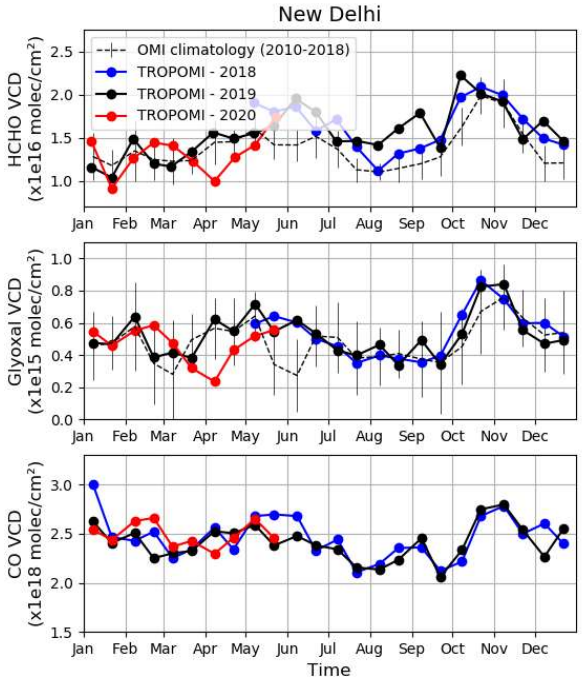
Levelt, et al, almost submitted to ACP

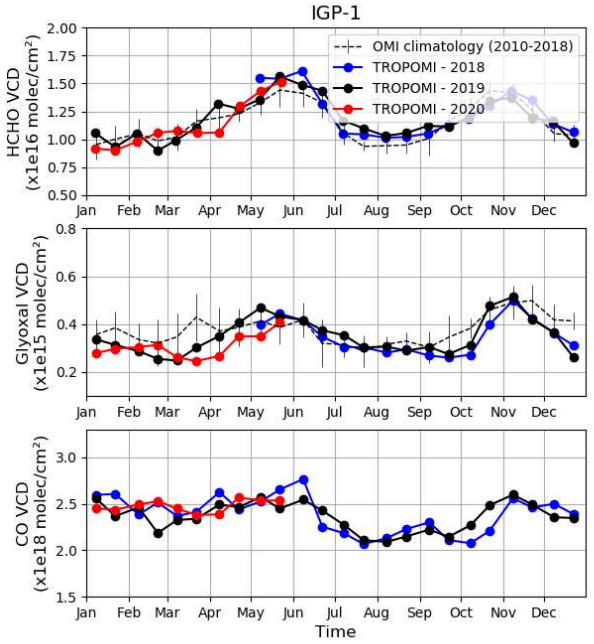
Average tropospheric NO2 concentrations for 2018 (green), 2019 (black) and 2020 (red) :

- over the 40 largest Indian cities (top);
- over the 100 largest power plants in India (middle);
- average SO2 concentrations over the 59 largest SO2-emitting power plants in India (bottom).

The reductions in NO2 (or SO2) concentrations are given relative to the same period in 2019.
The dots are the daily means, and the solid lines represent the 7-day running means.

New Delhi and Indo-Gangetic plane as observed by TROPOMI





Time evolution of HCHO, CHOCHO, and CO over Indo-Gangetic plain and New Delhi (2020 in red, 2019 in black, 2018 in blue).

HCHO and CHOCHO : OMI climatology is shown in dashed black line, 2010-2018.
Error bars : interannual variability of the bi-weekly averaged columns.

Levelt, et al, almost submitted to ACP

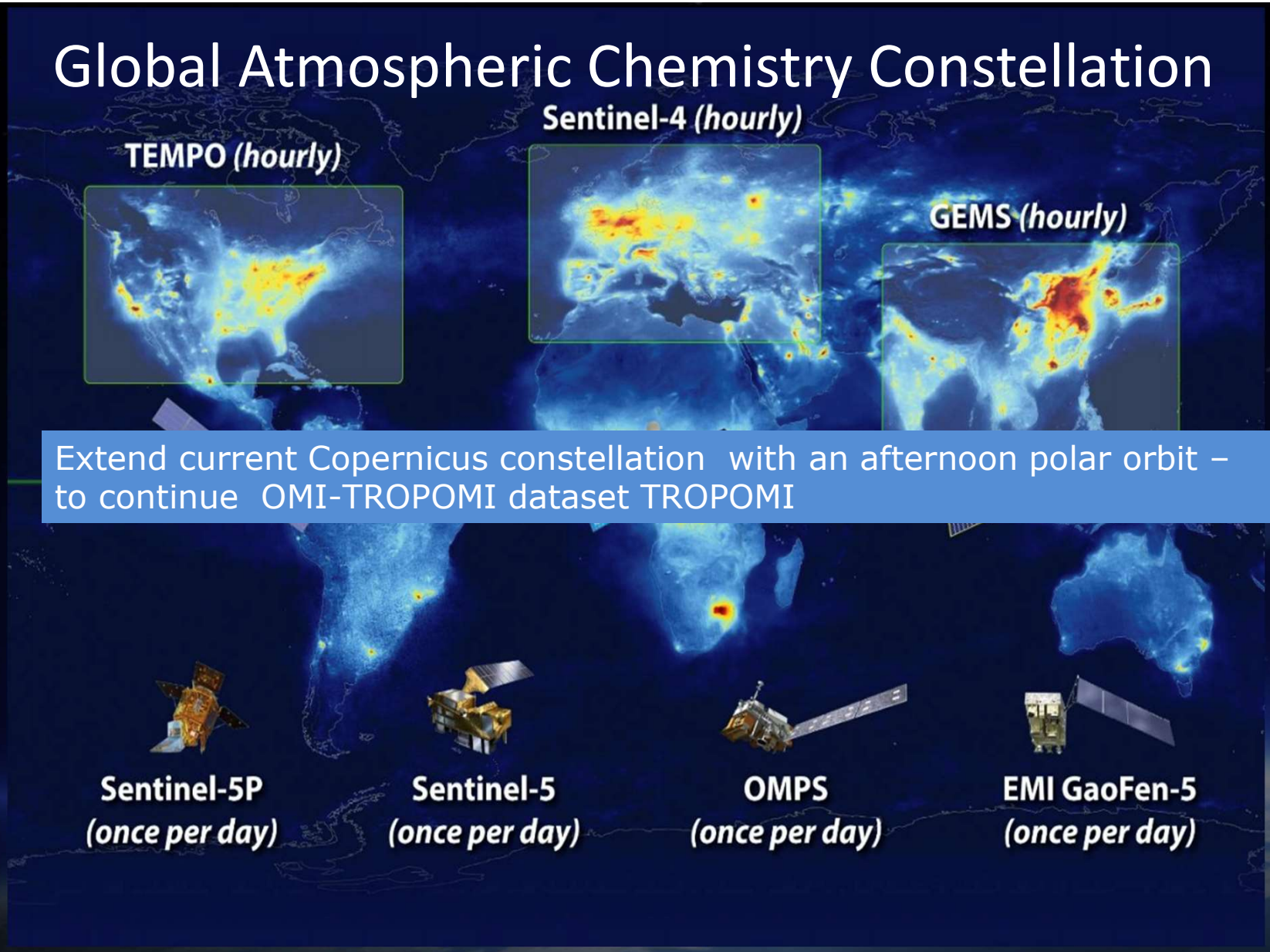
Future research

Royal Netherlands Meteorological Institute
Ministry of Infrastructure and the Environment

What are the emissions and what are the sources?

- New satellite observations
  - Global atmospheric chemistry constellation
  - Towards 500 x 500 m^2 spatial resolution from space
- New approaches to improve the bottom-up emission data bases
  - Update bottom-up data bases with satellite measurements
  - Use new satellite observations like methane and ammonia
  - Derive CO_2 emissions from NO_2 emissions for the same source
- Explore satellite measurements for quantifying new and unknown sources
  - Africa

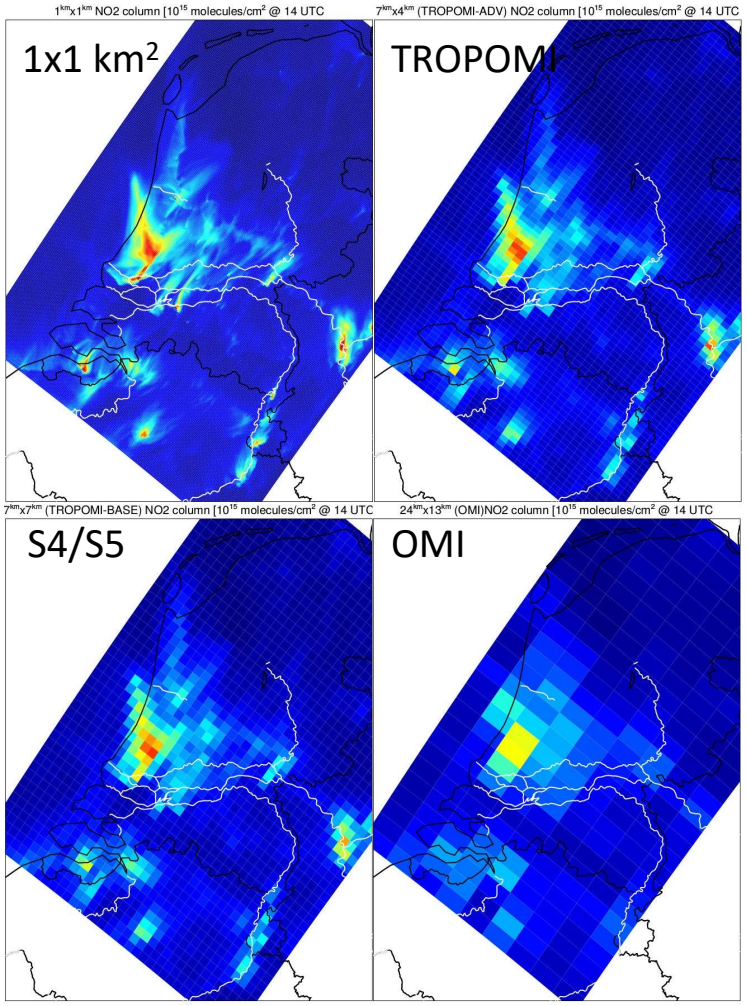
Global Atmospheric Chemistry Constellation



Extend current Copernicus constellation with an afternoon polar orbit – to continue OMI-TROPOMI dataset TROPOMI

TROPOMI

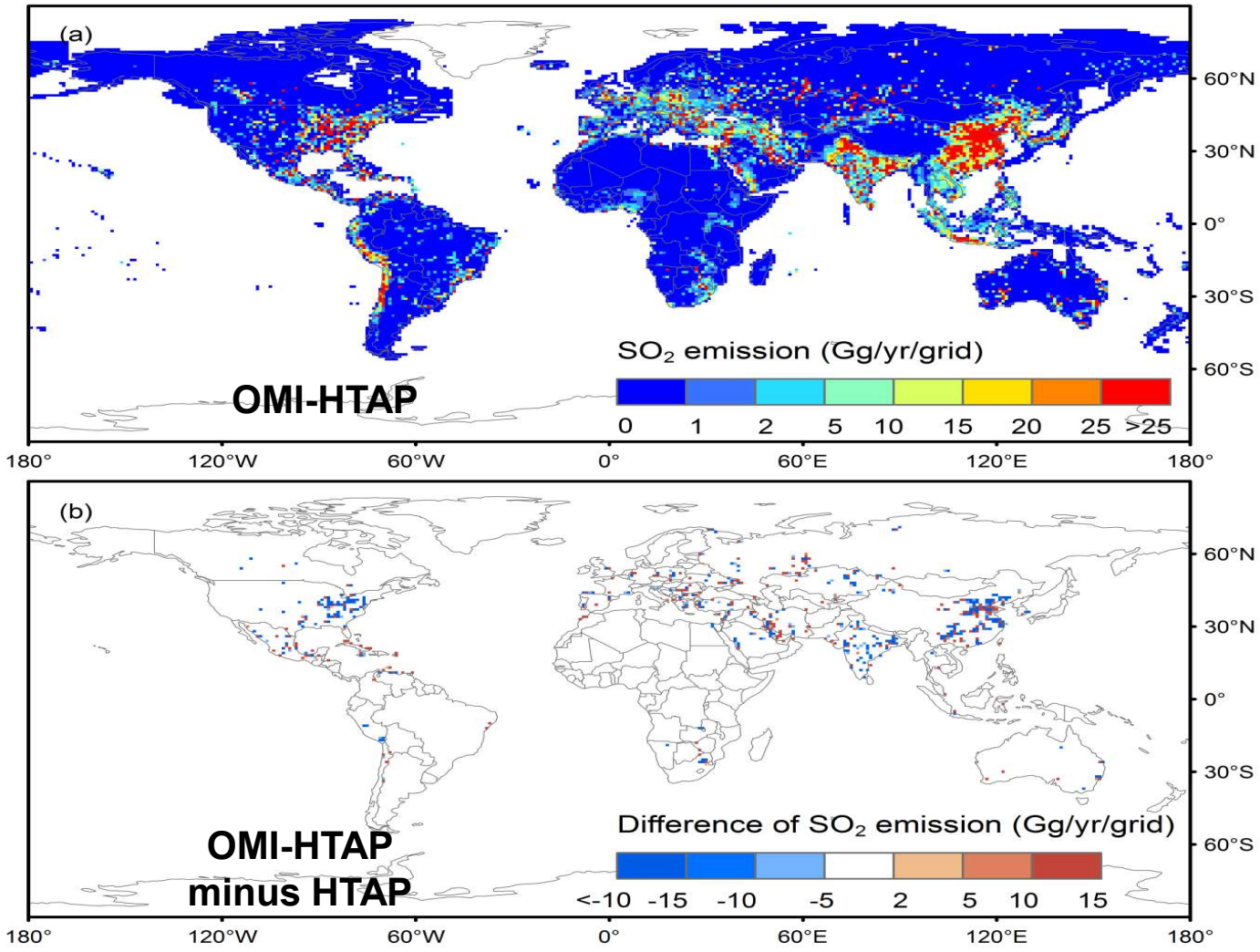
High resolution 500 x 500 m² emission monitoring



Model run: Massimo Vieno

- Nano-satellites add-on to the current Copernicus satellites for 500 x 500 m2 NO2 as indicator of pollution sources
- Add NO2 sensor to EU Copernicus CO2 mission for improving detection of anthropogenic CO2 emissions (NO2 as indicator for anthropogenic CO2 emissions)
- Copernicus sentinel 5 Next Generation, 1x1 km2 high resolution emission monitoring
- High Altitude Pseudo Satellites for monitoring high resolution pollution over e.g. Rotterdam area

Combine bottom-up with satellite observations: New global SO_2 emission inventory OMI-HTAP



A new global anthropogenic SO_2 emission inventory OMI-HTAP based on both satellite-derived and bottom-up emissions

-Add missing sources detected by OMI: higher values over Middle East, Mexico and Russia

-Correct misallocations of large point sources

GEOS-5 simulating SO_2 shows better agreement with in-situ measurements when driven by OMI-HTAP

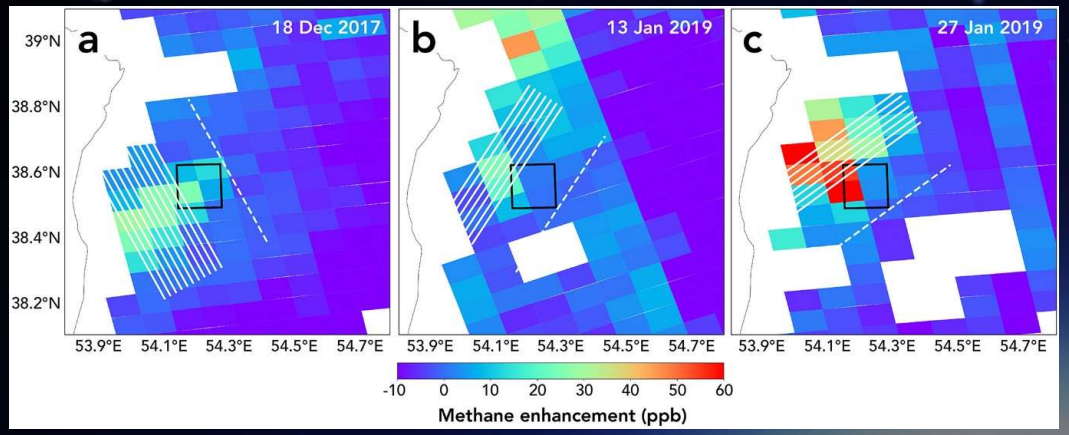
Liu, F., Choi, S., Li, C., Fioletov, V. E., McLinden, C. A., Joiner, J., Krotkov, N. A., Bian, H., Janssens-Maenhout, G., Darmenov, A. S., and da Silva, A. M.: A new global anthropogenic SO_2 emission inventory for the last decade: A mosaic of satellite-derived and bottom-up emissions, Atmos. Chem. Phys. Discuss., https://doi.org/10.5194/acp-2018-331, in review, 2018.

CH_4 Emissions from Oil and Gas

TROPOMI

LEAKS

Turkmenistan

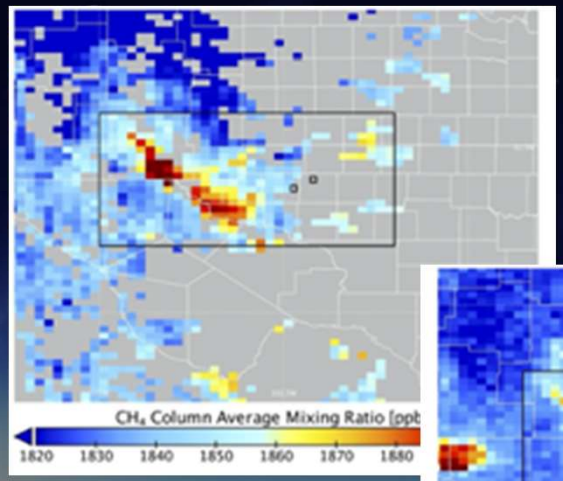


Varon et al., Geophysical Research Letters, First published: 25 October 2019, DOI: (10.1029/2019GL083798)

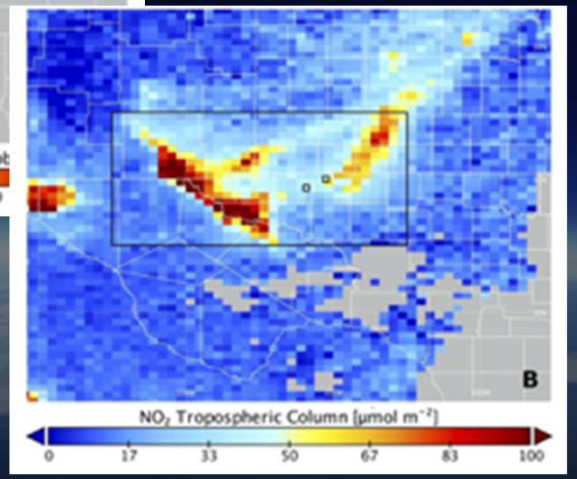
REGULAR OPERATIONS

Permian, 31 Jan 2019

CH_4



NO_2



De Gouw et al, Nature Scientific Report, 2020

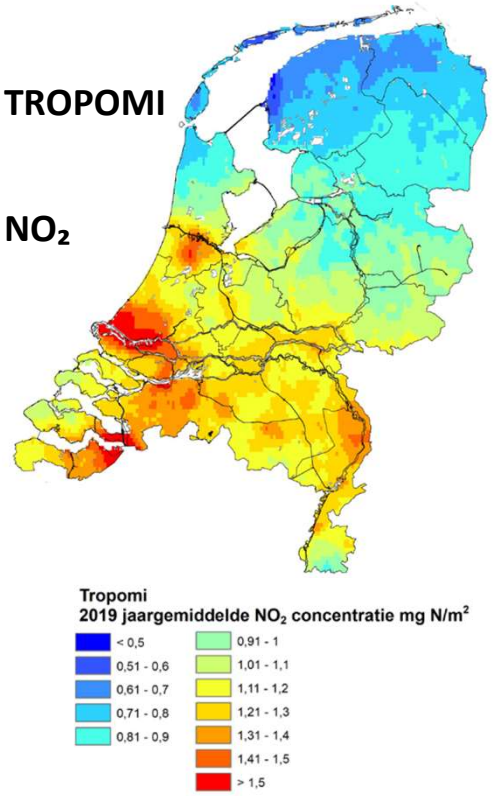
Nitrogen Cycle : measuring NH_3 and NO_x on farm scale resolution from space (500 x 500 m^2) proposal for Earth Explorer ESA mission, December 2020

Lead-Investigator: Pierre Coheur (ULB); co-Lead Investigator Pieternel Levelt (KNMI, TUD)

Lieven Clarisse (ULB), Martin Van Damme (ULB), Henk Eskes (KNMI), Pepijn Veefkind (KNMI and TUD), Cathy Clerbaux (LATMOS, France), Michel Van Roozendael (BIRA-IASB, Belgium), Frank Dentener (JRC, Italy) , Jan Willem Erisman (Leiden University, The Netherlands), Martijn Schaap (TNO, The Netherlands; TU Berlin, Germany), Mark Sutton (CEH, United-Kingdom)

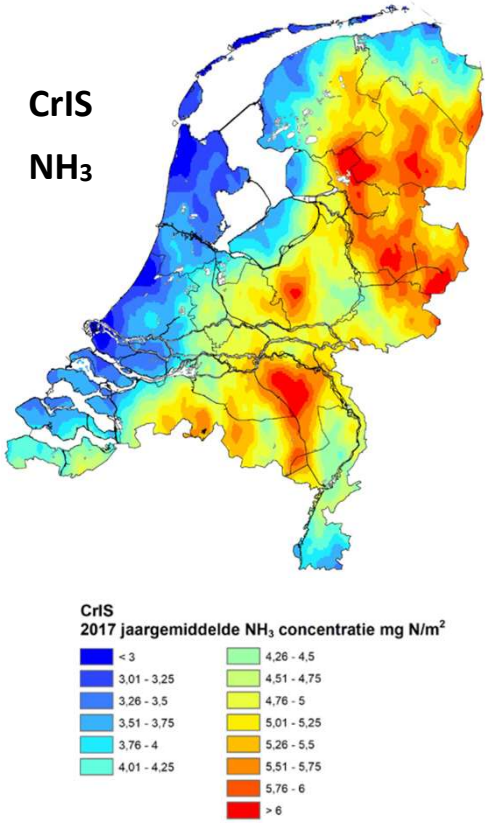
TROPOMI

NO_2



CrIS

NH_3

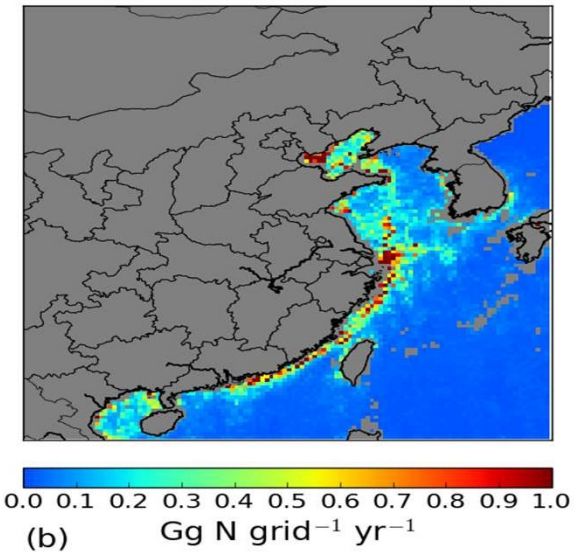


Mission Objectives

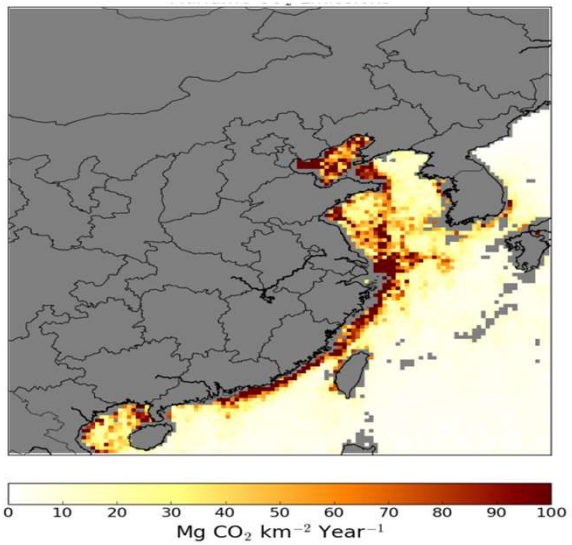
1. *Quantify the* **emissions** *of NH_3 and NO_x on the landscape scales*, and to attribute the relative contributions of natural, industrial, agricultural, fire, transport and household sources.
2. *Quantify the contribution of reactive nitrogen to* **air pollution**.
3. *Constrain the atmospheric* **dispersion and surface deposition** *of reactive nitrogen* and its impacts on ecosystems and the carbon cycle.
4. *Reduce uncertainties in the contribution of reactive nitrogen to* **climate forcing** via a better understanding of gas phase chemistry, secondary aerosol formation and interactions between biogeochemical cycles.

CO_2 emissions: CO_2/NO_x and CO_2 Monitoring from space (EU Copernicus/ESA)

NO_x emissions



CO_2 emissions

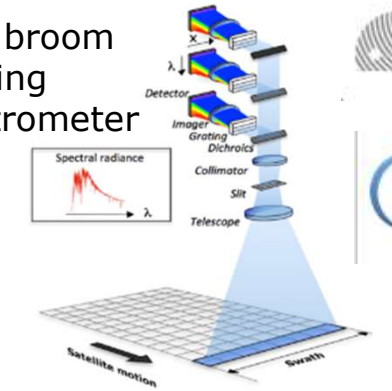


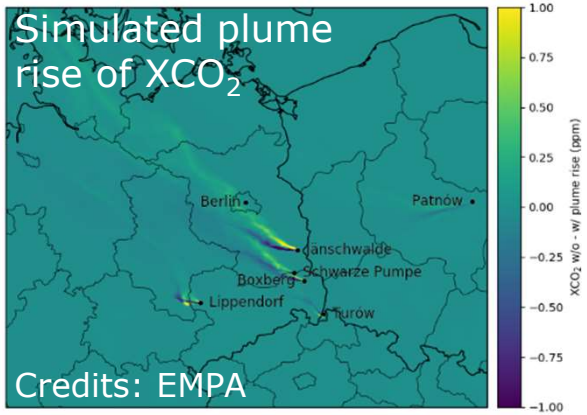
- Satellite-derived maritime NO_x emissions are revealed that were hidden below the NO_2 outflow of the Chinese mainland.
- The NO_x emissions are derived from OMI observations with the KNMI algorithm DECSO.
- The known NO_x/CO_2 ratio of ship emissions are used to derive CO_2 emissions of ships.

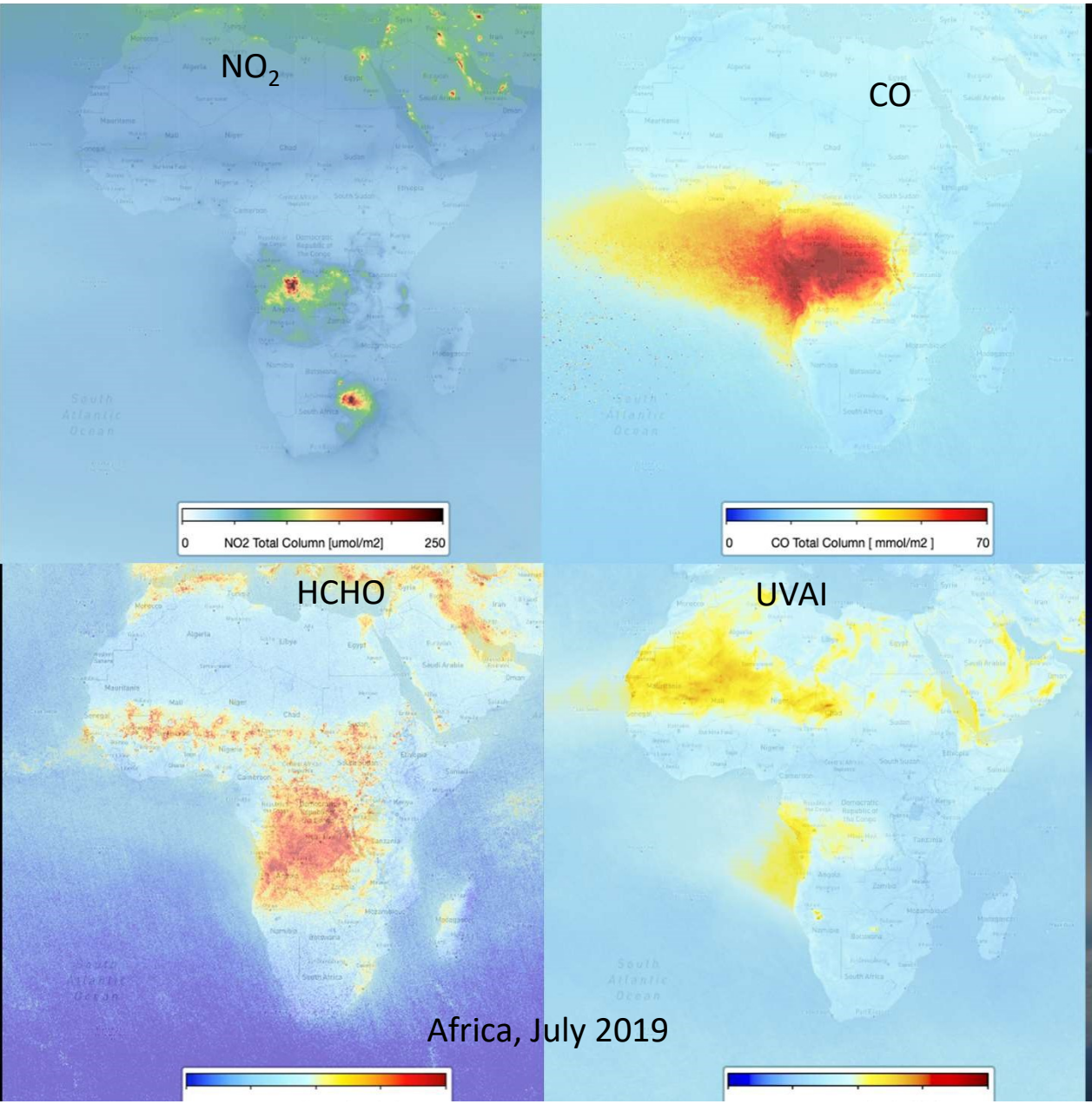
Ding et al., Maritime NO_x emissions over Chinese seas derived from satellite observations, GRL, 2018

CO_2 monitoring from space

Push broom imaging spectrometer







Africa

TROPOMI

Population is expected to double in 2050 (now 1.1 billion)

4th industrial revolution: will lead to huge increase in air pollutants and green house gases

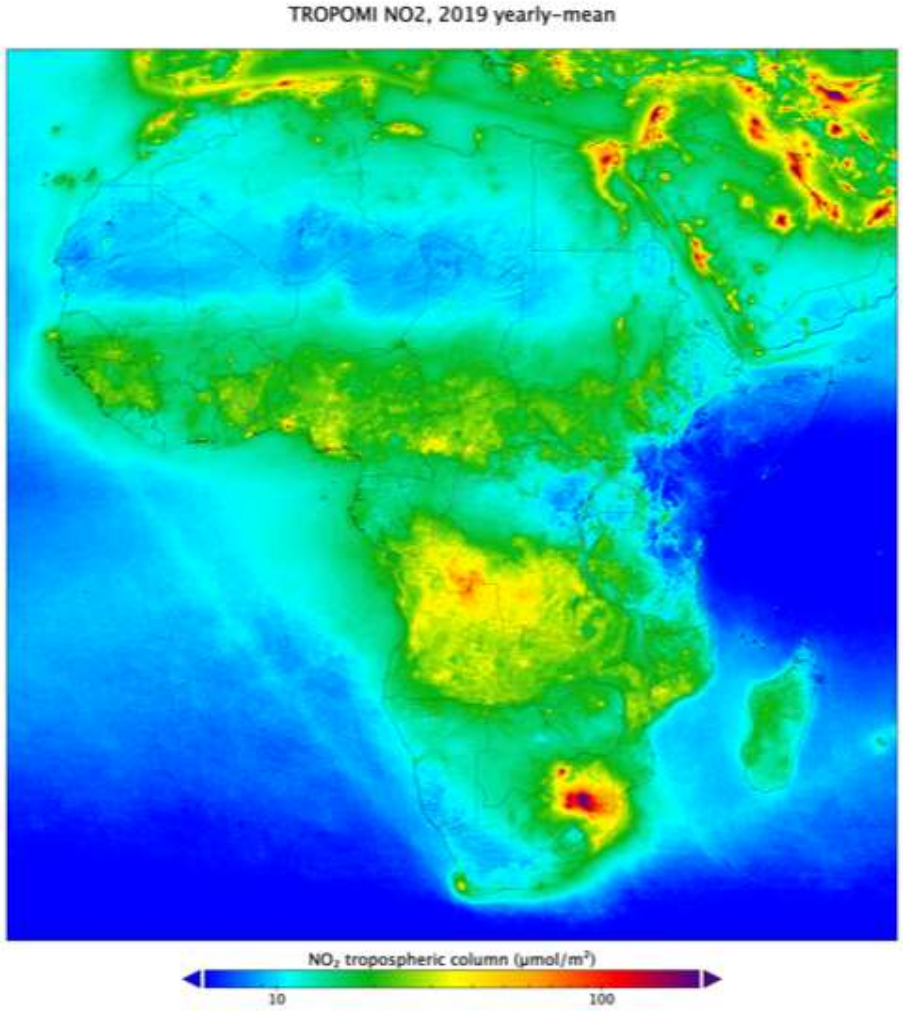
NCAR-ACOM has all available capacity on atmospheric chemistry: lab, modelling, ground based, satellite, aircraft campaign

Involve other NCAR and USA labs: e.g. NCAR-EOL, NASA, NOAA

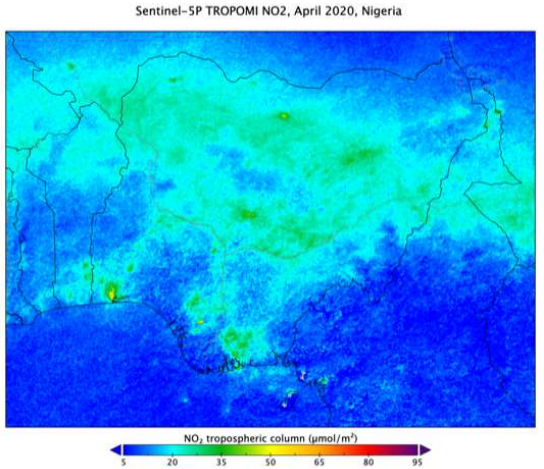
Capacity Building and possibility to involve Minority Serving Institutions across the USA (when interested)

Investigate Potential for GEOstationary satellite (TEMPO/sentinel-4)

TROPOMI NO_2 measurements over Africa

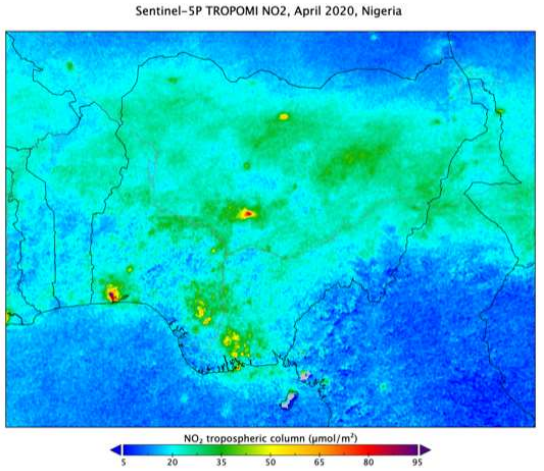


TROPOMI NO2 yearly mean 2019



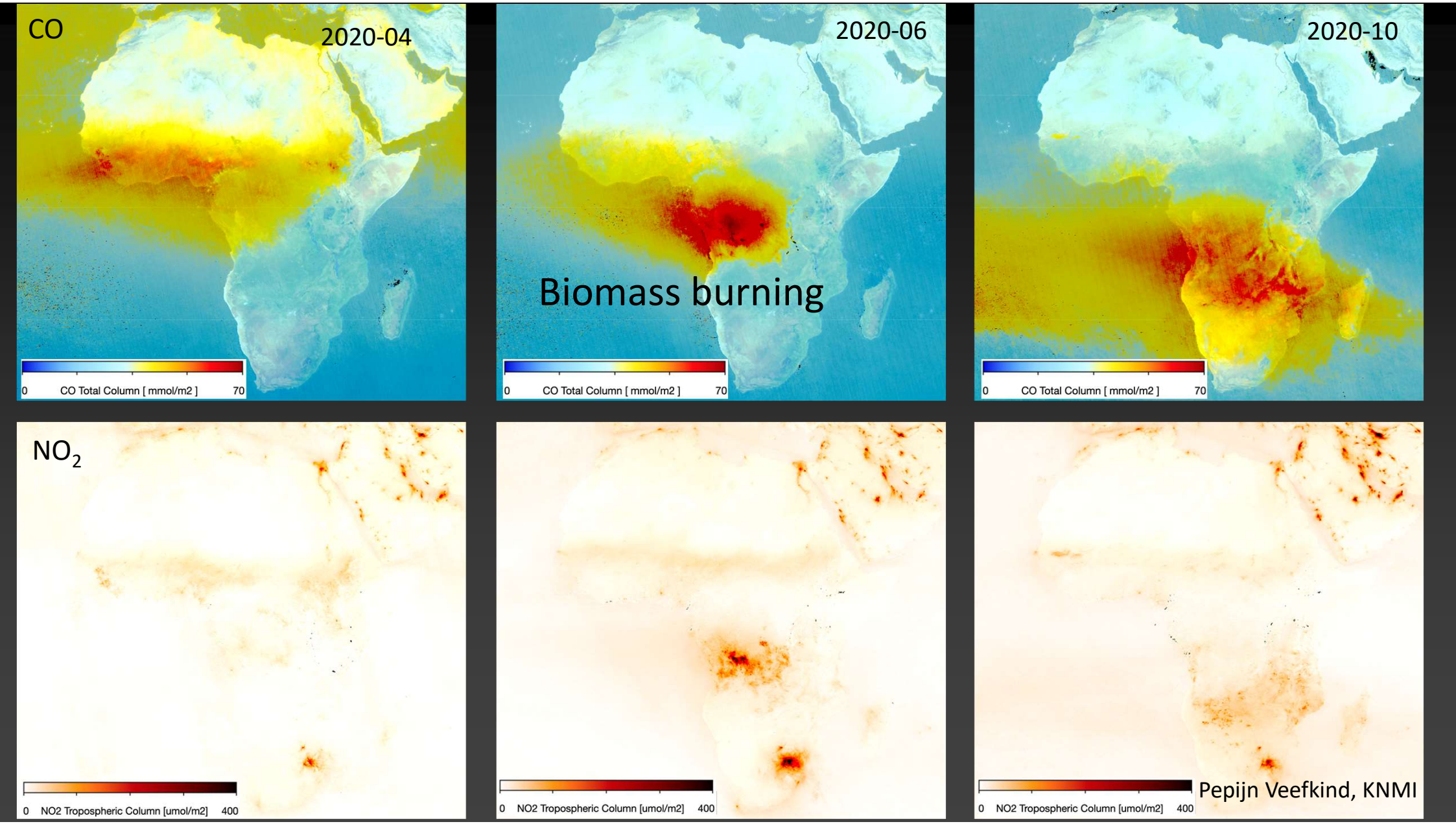
COVID Lockdown

TROPOMI NO_2
April 2020
Nigeria



TROPOMI NO_2
April 2019
Nigeria

Henk Eskes, KNMI


CO
2020-04
0 CO Total Column [mmol/m2] 70
2020-06
Biomass burning
0 CO Total Column [mmol/m2] 70
2020-10
0 CO Total Column [mmol/m2] 70
NO2
0 NO2 Tropospheric Column [umol/m2] 400
0 NO2 Tropospheric Column [umol/m2] 400
0 NO2 Tropospheric Column [umol/m2] 400
Pepijn Veefkind, KNMI

Summary

- OMI & TROPOMI: revolutionized air pollution measurements from space
- COVID lock down measures and its impact on air quality: a learning curve
- Satellite measurements will become a key observation for emission monitoring
- Future: going towards the imaging domain (500 x 500 m2)
- Africa : important continent to study since large increase in pollution is expected

backup

Royal Netherlands Meteorological Institute
Ministry of Infrastructure and the Environment

Main Science Questions in the air quality domain:

1. What are the emissions?
2. What are the chemical transformations?
3. What is the role of transport?
4. How does this affect air quality and climate?
5. What does this mean for air quality and climate policies?

First acknowledged death due to air pollution

Southwark Coroner's Court found that air pollution "made a material contribution" to Ella's death

BBC News 18 December 2020

A landmark decision

BBC NEWS

Ella Adoo-Kissi-Debrah: Air pollution a factor in girl's death, inquest finds

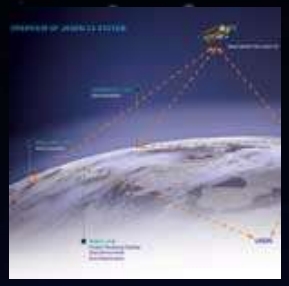
18 hours ago

Ella Adoo-Kissi-Debrah lived 25 metres from the South Circular Road in south-east London

A nine-year-old girl who died following an asthma attack has become the first person in the UK to have air pollution listed as a cause of death.

EU Copernicus Sentinels

Sentinel 5

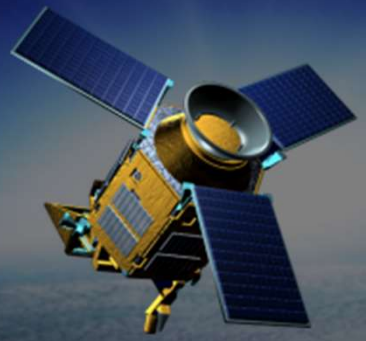


Sentinel 6

Sentinel 1

Sentinel 2

Sentinel 4



Sentinel 5P

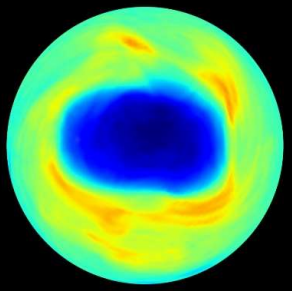
Sentinel 3

TROPOMI

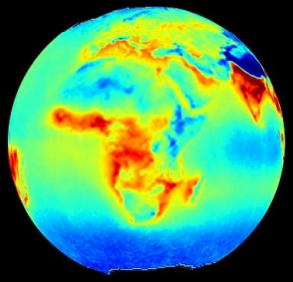
Global revisit time

0 24h

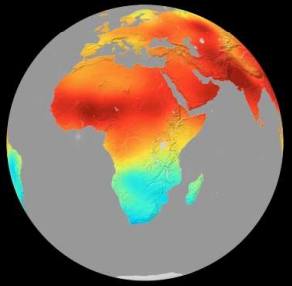
Nitrogen dioxide



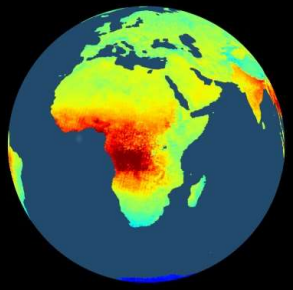
Ozone



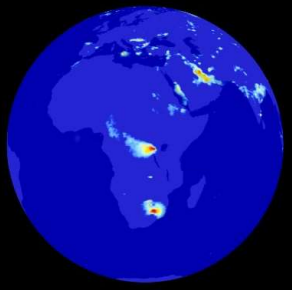
Formaldehyde



Methane

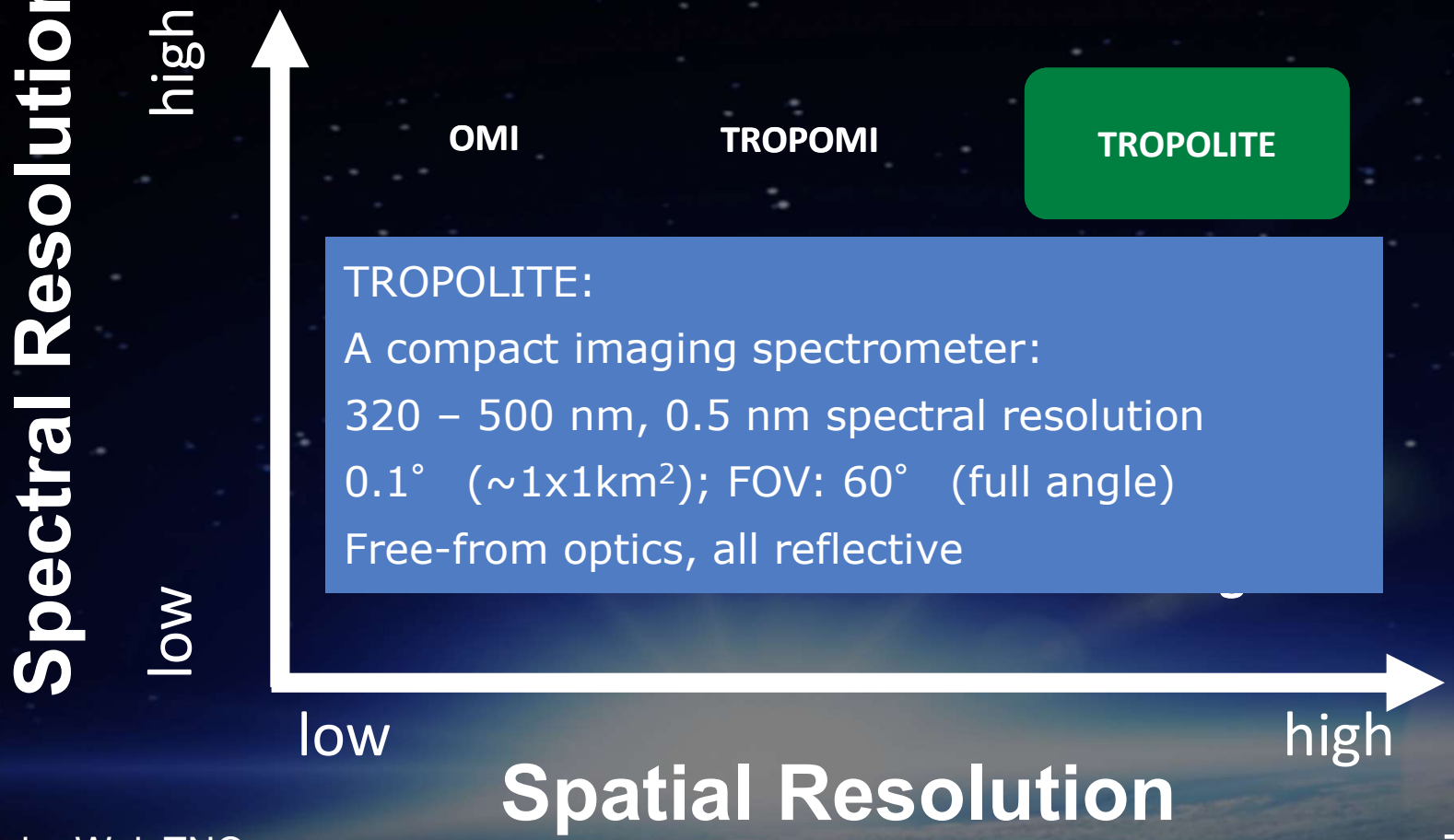


Carbon monoxide

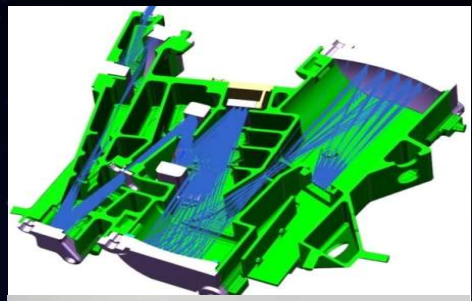


Sulphur dioxide

TROPOLITE: New developments: 1 x 1 km²
entering the image domain



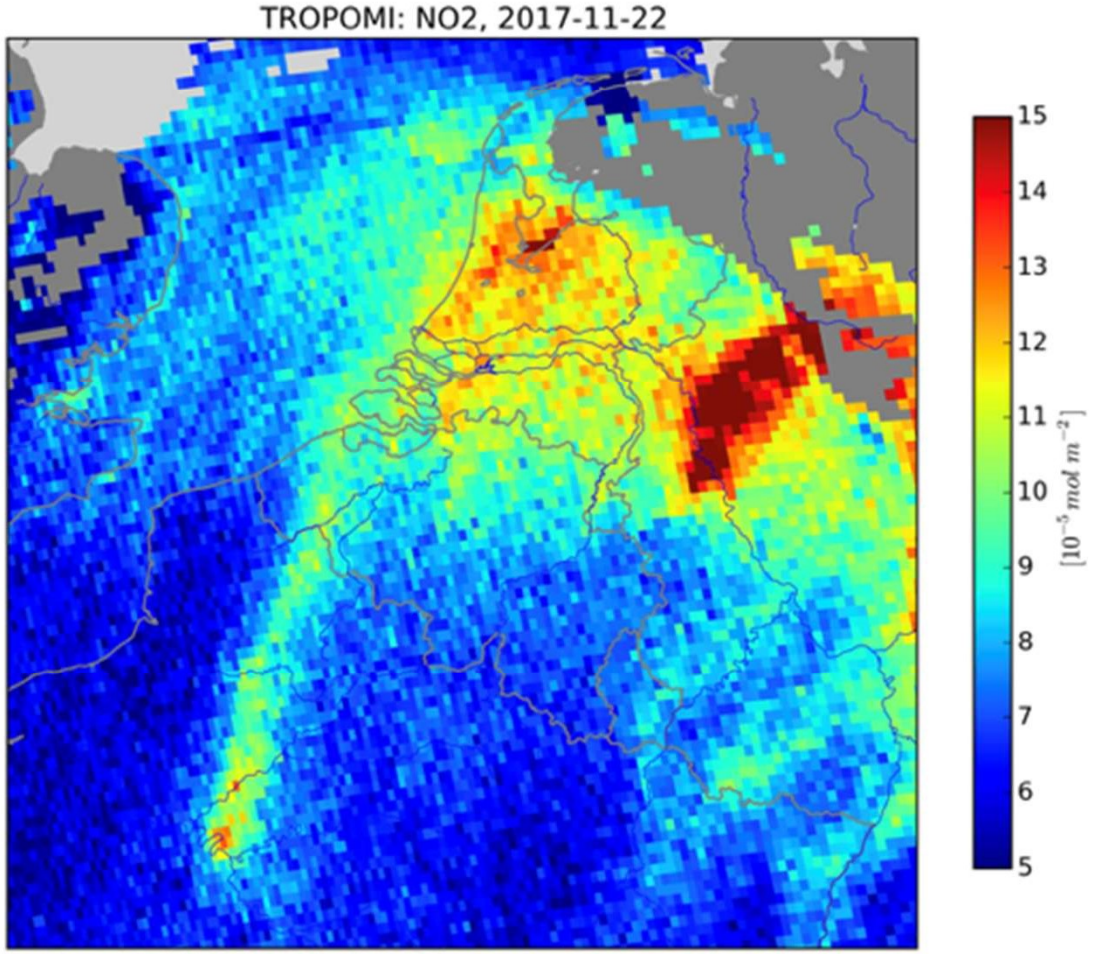
TROPOLITE:
A compact imaging spectrometer:
320 – 500 nm, 0.5 nm spectral resolution
0.1° (~1x1km²); FOV: 60° (full angle)
Free-from optics, all reflective



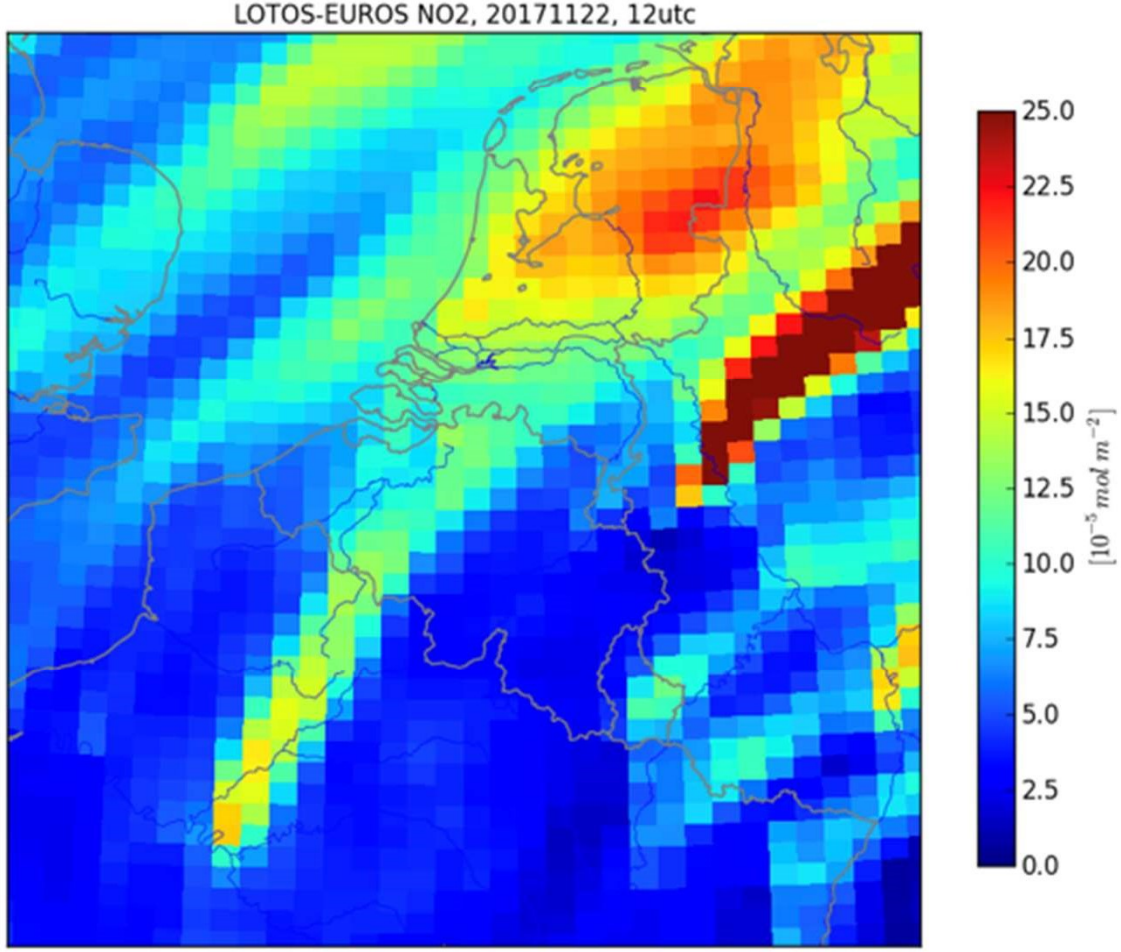
TROPOLITE on airplane above Berlin (TNO)

Goeij, van der Wal, TNO
Tim Vlemmix, X. Ge, TUDelft
Pepijn Veeflind, Pieternel Levelt, KNMI & TU Delft

TROPOMI



EUROS-LOTOS MODEL



Henk Eskes, KNMI