Air quality and greenhouse gas observations from Space: indicators of human activity

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KNMI and TU Delft

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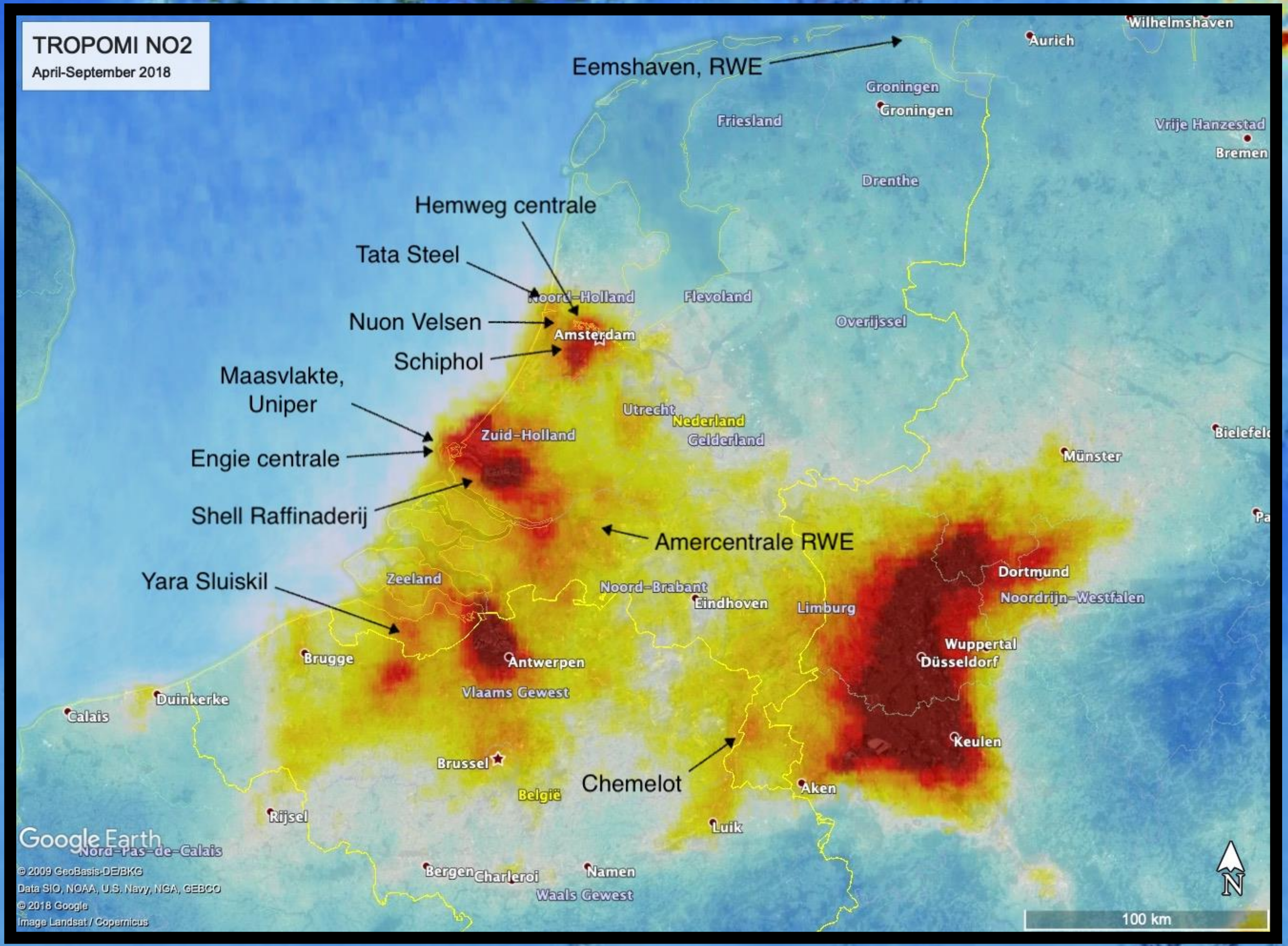
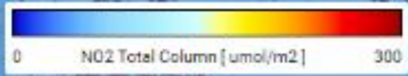
EUMETSAT, September 28, 2022



TROPOMI NO_2 Tropospheric Column
April-September 2018

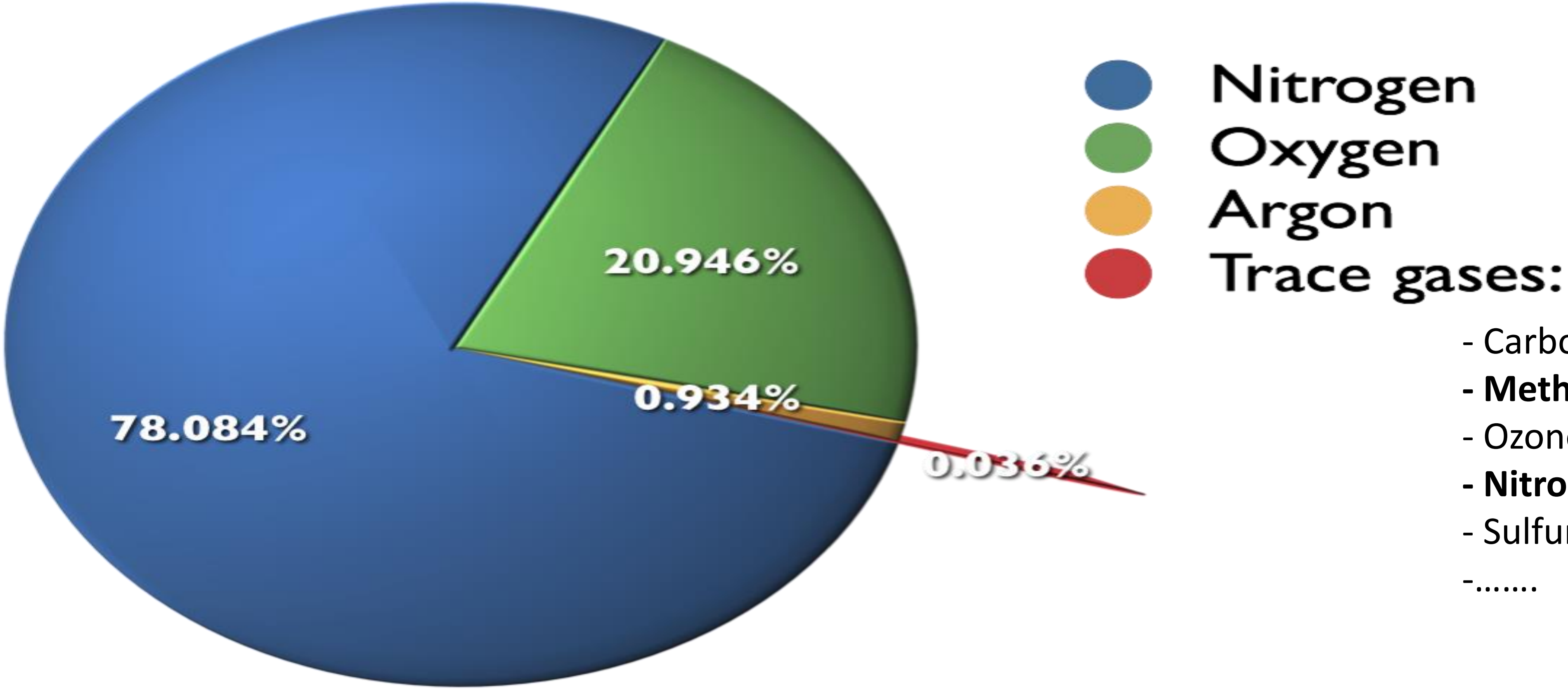


The “Anthropocene” Dutch Nobel Prize winner Paul Crutzen †

stitute
ure and the

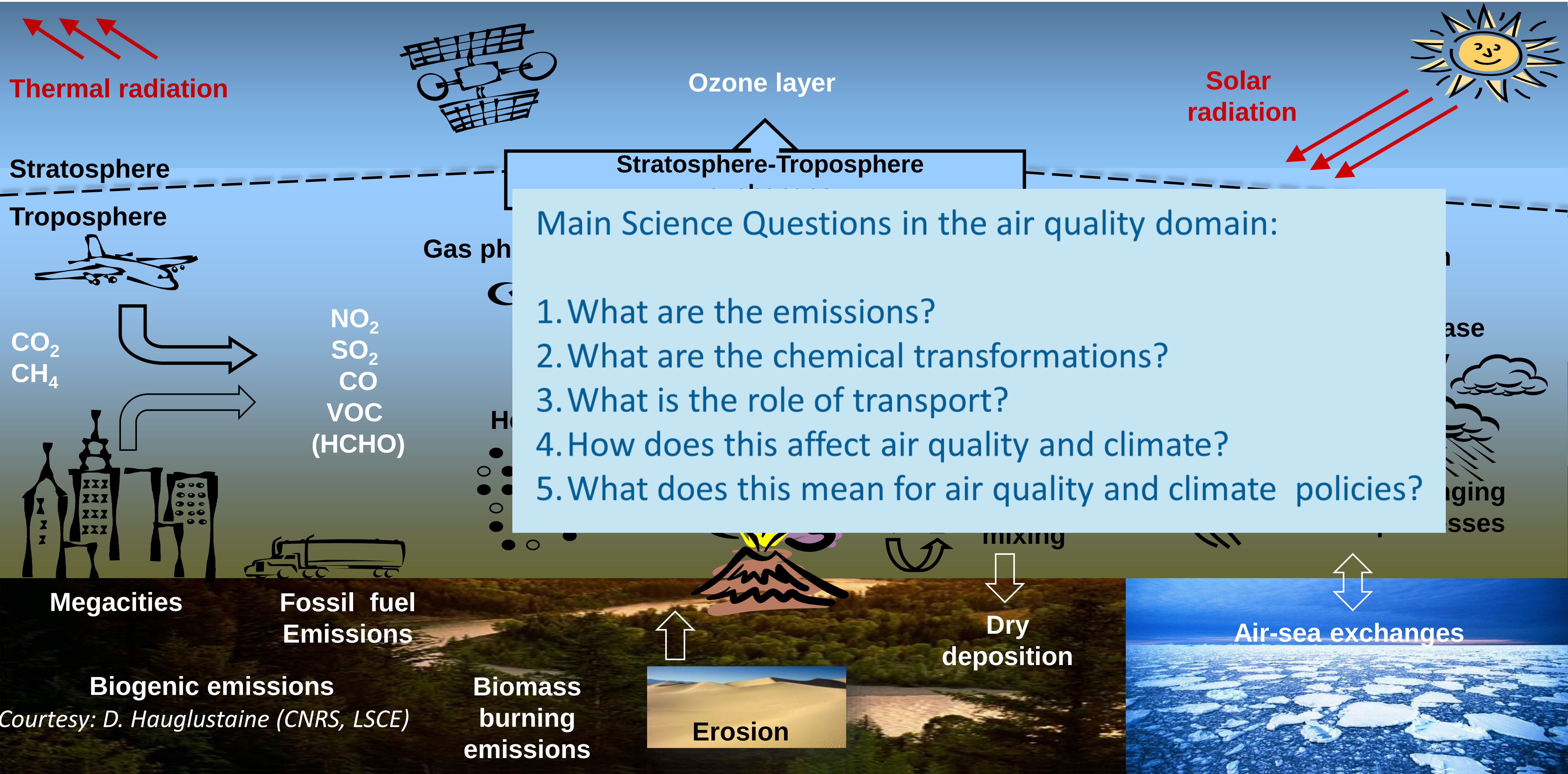
- Ozone Layer
- Air Quality
- Climate
- Biodiversity

Atmospheric composition: gases



- Carbon dioxide (CO_2)
- **Methane (CH_4)**
- Ozone (O_3)
- **Nitrogen dioxide (NO_2)**
- Sulfur dioxide (SO_2)
-…….

Atmospheric Chemistry: fascinating and challenging



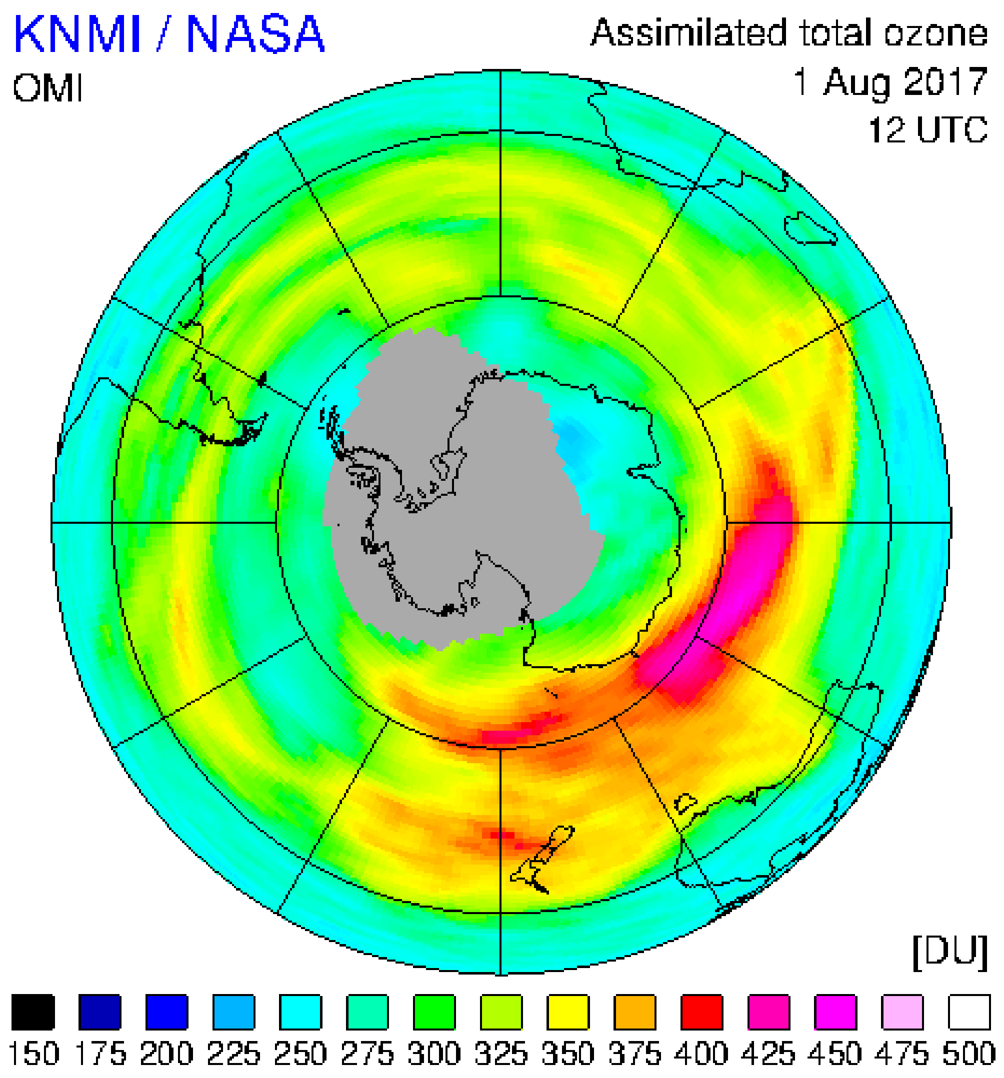
Courtesy: D. Hauglustaine (CNRS, LSCE)

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?

Montreal Protocol: also important for climate change

Royal Netherlands Meteorological Institute
Ministry of Infrastructure and the Environment



Ozone hole measured by OMI for 2017

- Satellite measurements form the basis of assessing the effect of the Montreal Protocol
- Without Montreal Protocol climate change would have been worse
- At the time the Protocol was set we were not aware of this

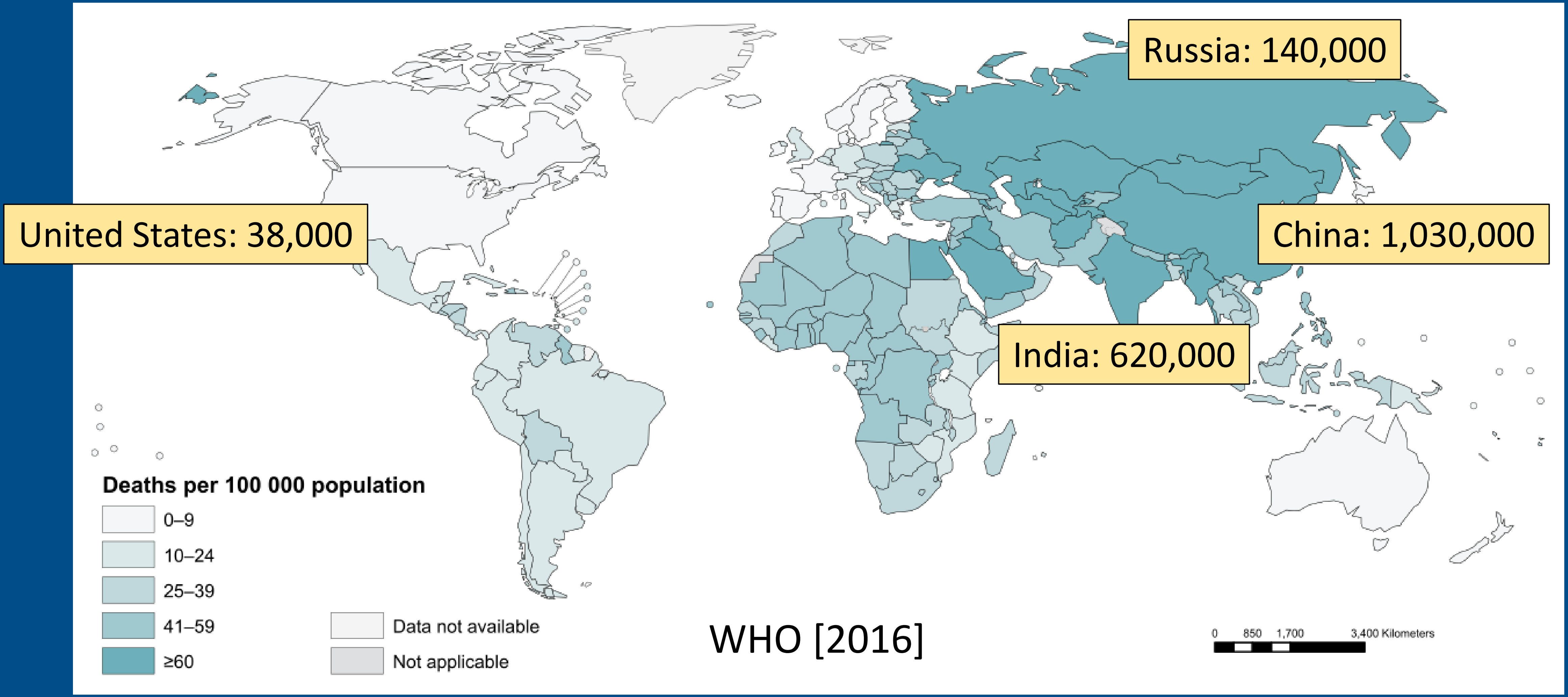
Velders et al, PNAS, 2007

Air Pollution

Chinese city on a clean and polluted day

Courtesy David G. Streets, Atm. Env. 41 (2007) 480-492

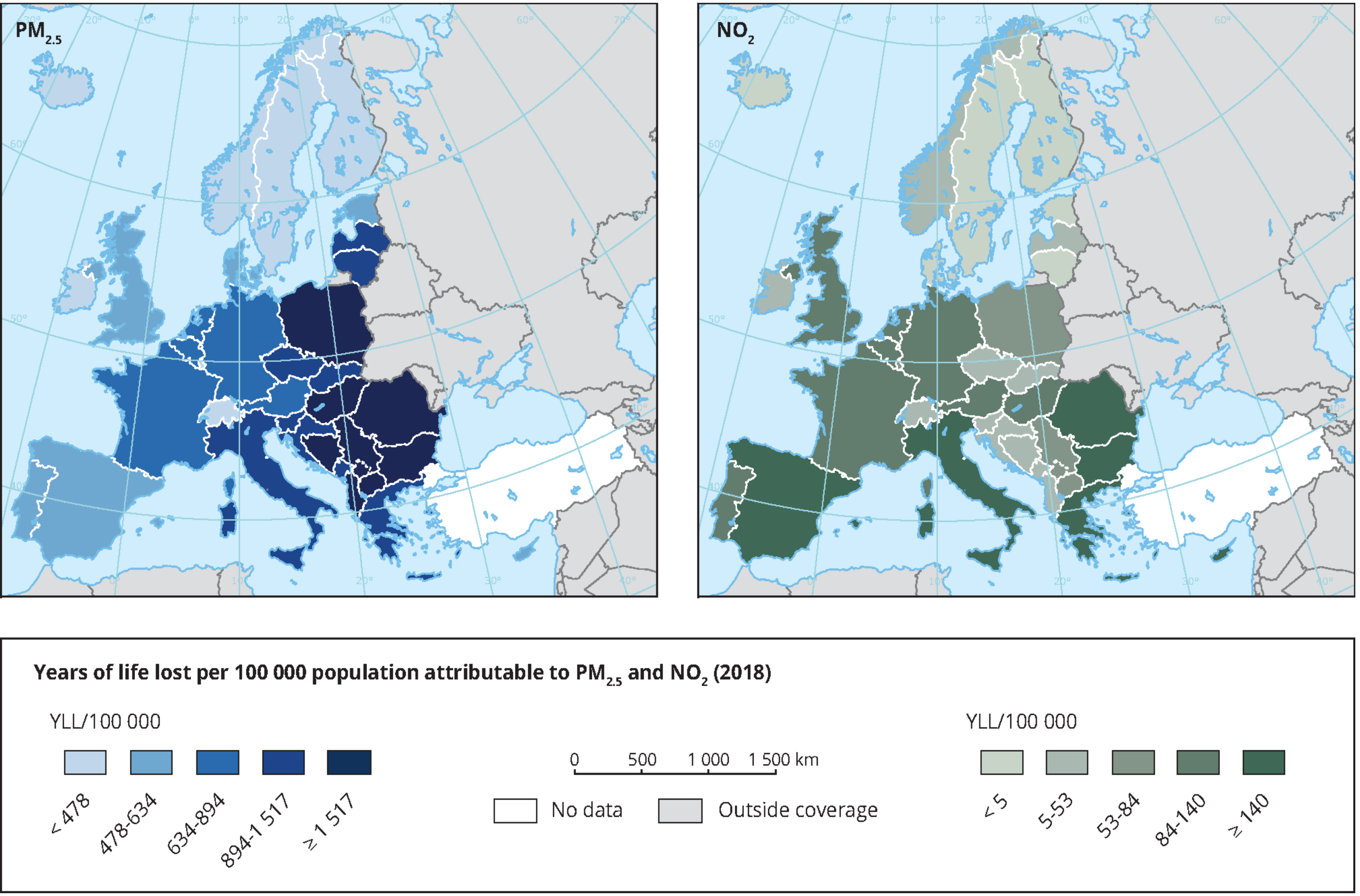
Air Pollution Accounts for 4.2 Million Premature Deaths per Year



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



- 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)

European Environmental Agency 2018

Years of life lost per 100 000 population attributable to 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

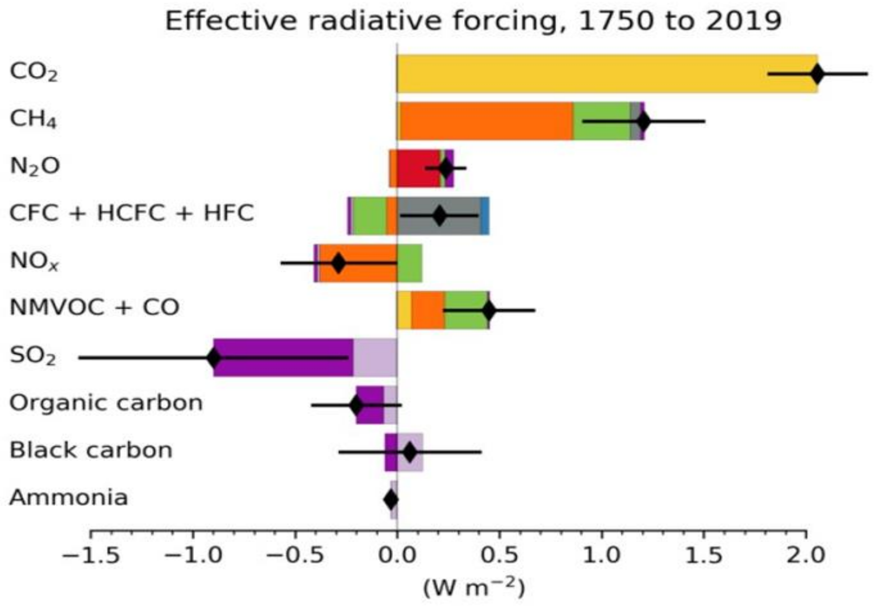
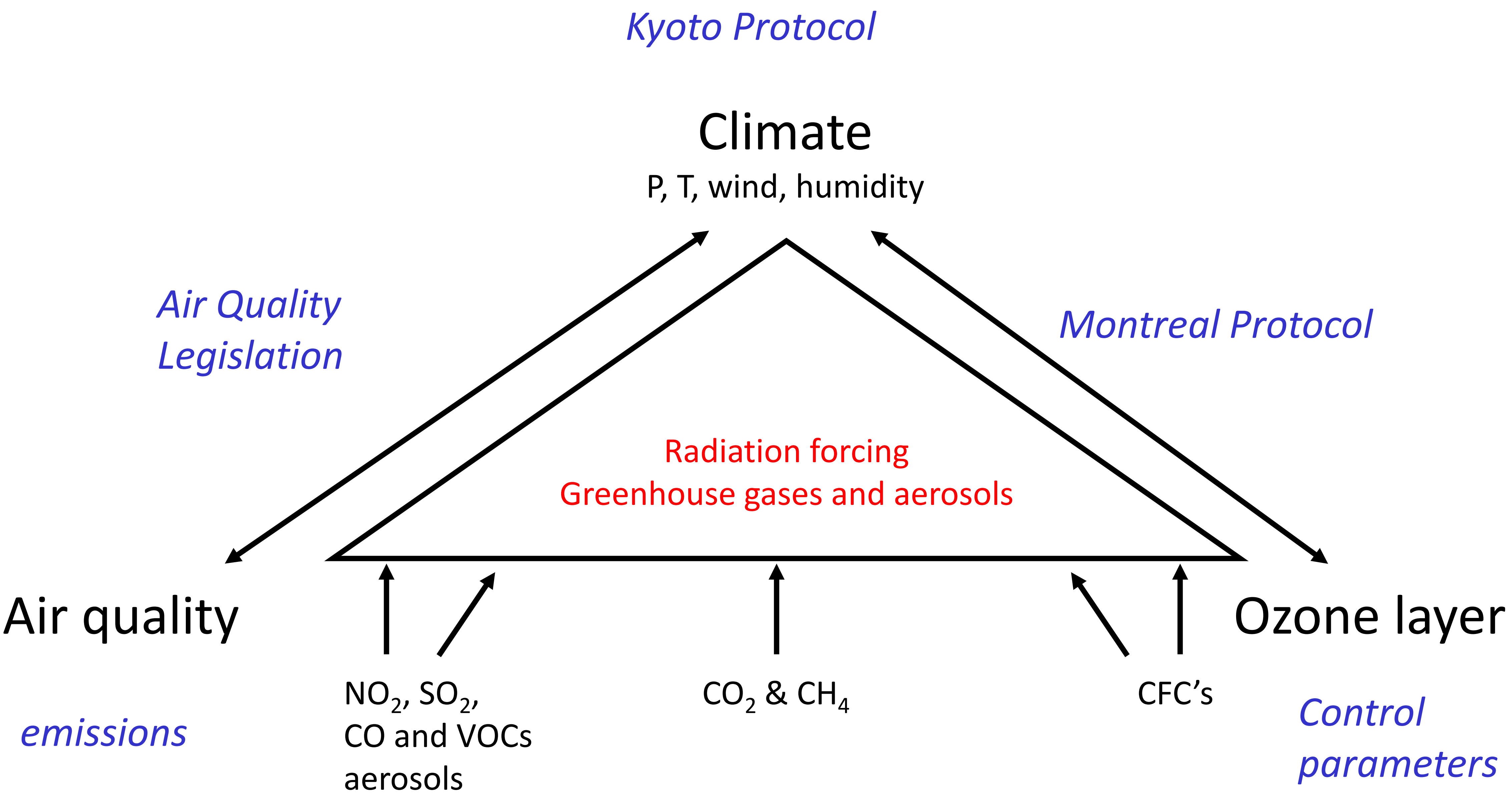
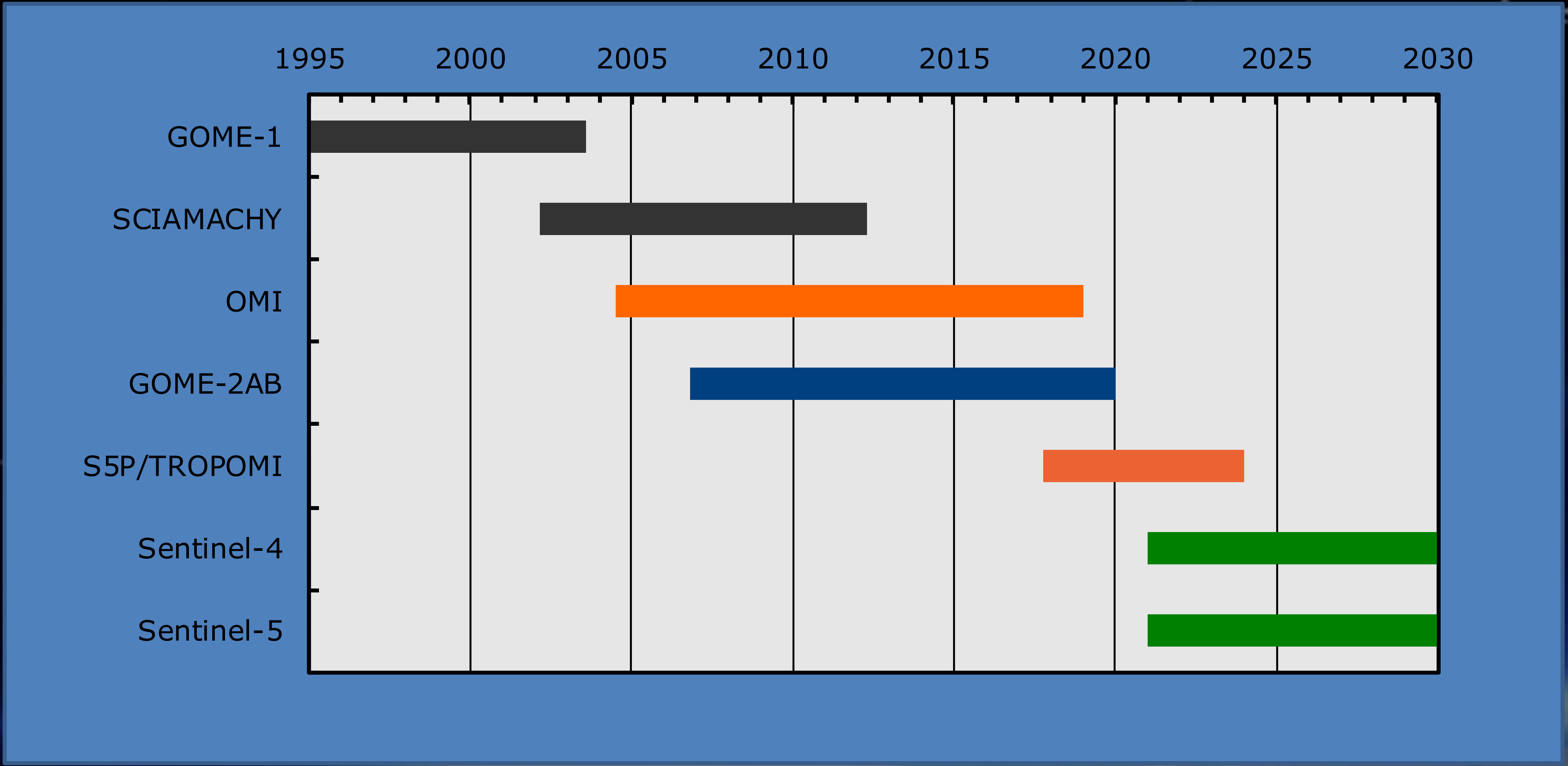


Figure 6.12: Contribution to effective radiative forcing (ERF) (left) and global mean surface air temperature (GSAT) change (right) from component emissions between 1750 to 2019 based on CMIP6 models

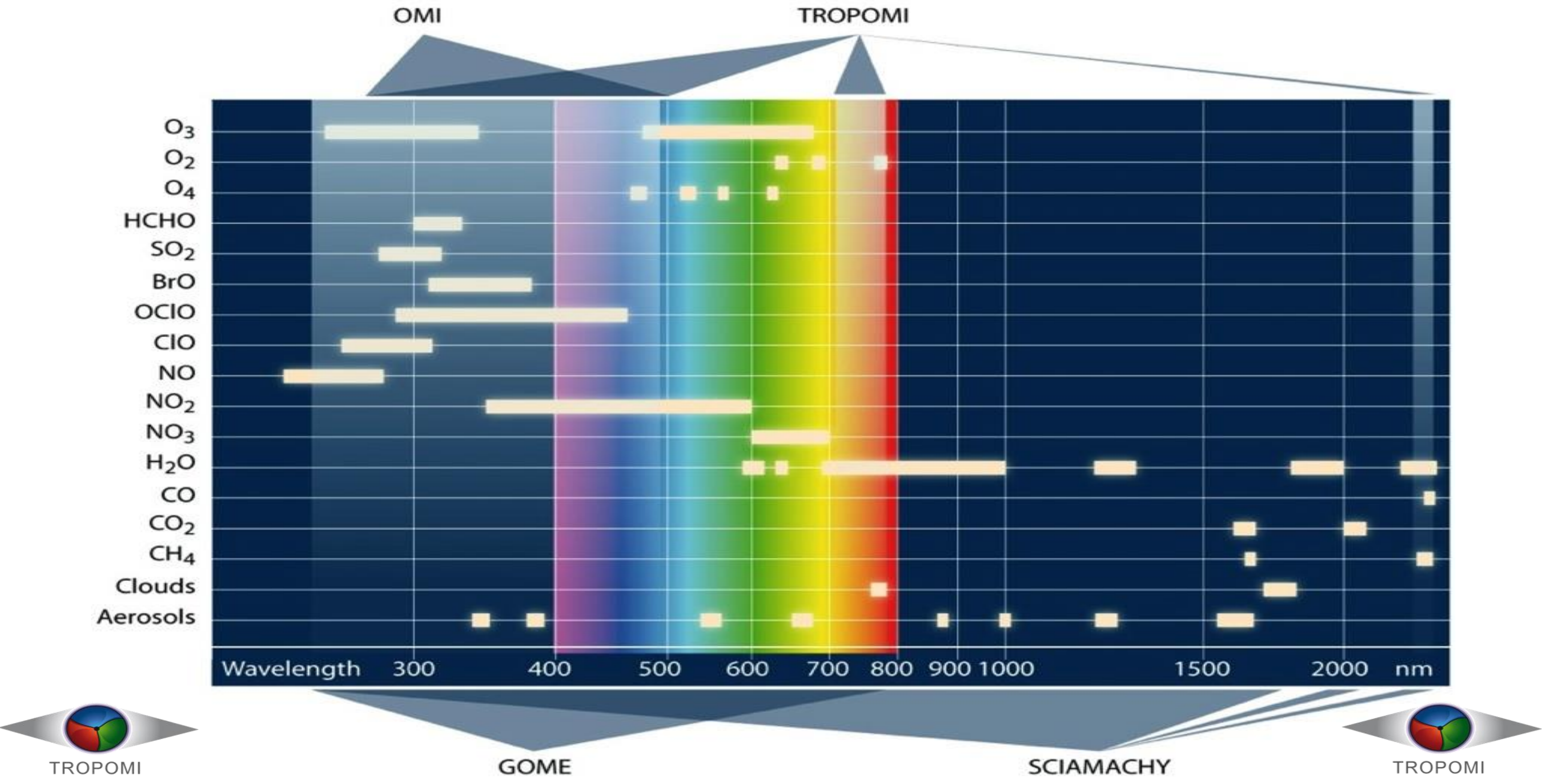
- Climate change is driven by changes in the atmospheric composition
- COP 21 & 26 addresses the emission control of long-lived greenhouse gases
- For the short and medium term, also the short-lived components (SLCF) - air pollutants - are important


Kyoto Protocol
Climate
P, T, wind, humidity
Air Quality
Legislation
Montreal Protocol
Radiation forcing
Greenhouse gases and aerosols
Air quality
Ozone layer
emissions
NO_2, SO_2,
CO and VOCs
aerosols
CO_2 & CH_4
CFC's
Control
parameters

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



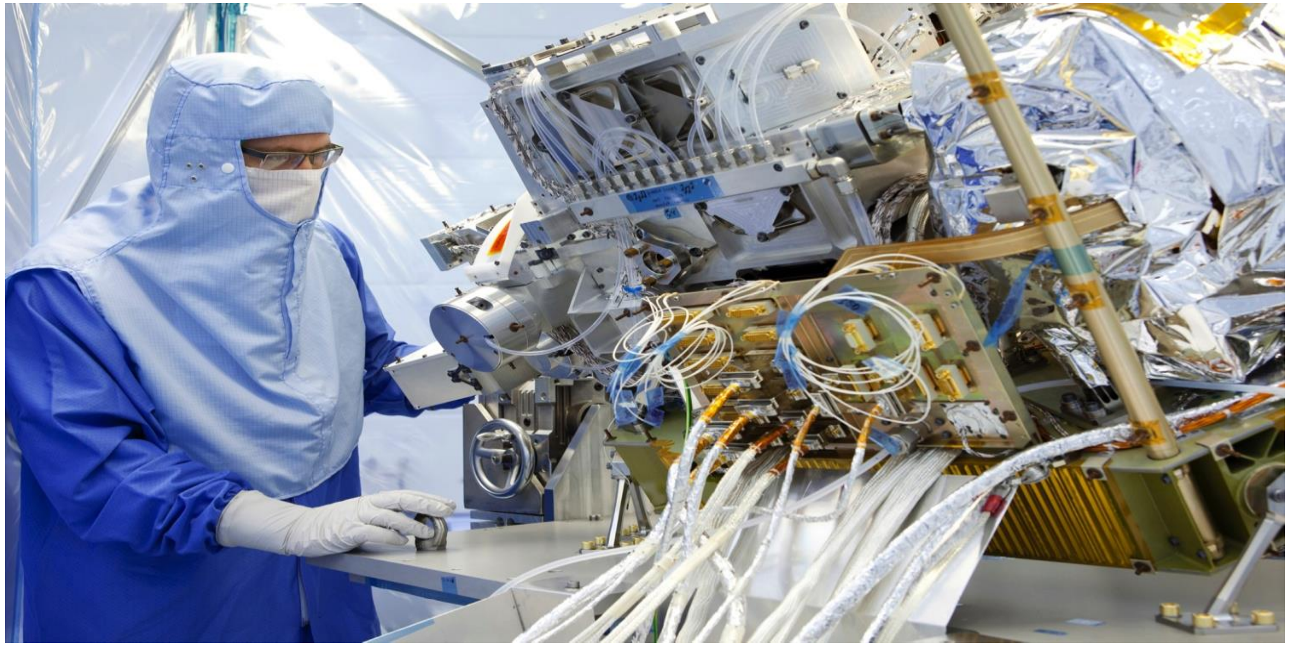
OMI
TROPOMI
O3
O2
O4
HCHO
SO2
BrO
OClO
ClO
NO
NO2
NO3
H2O
CO
CO2
CH4
Clouds
Aerosols
Wavelength 300 400 500 600 700 800 900 1000 1500 2000 nm
GOME
SCIAMACHY
TROPOMI
TROPOMI

Netherlands Leading role in OMI & TROPOMI

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

13 x 24 km2 & daily global coverage

OMI received the NASA/USGS Pecora Award 2018!



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

3,5 x 5 km2 & daily global coverage

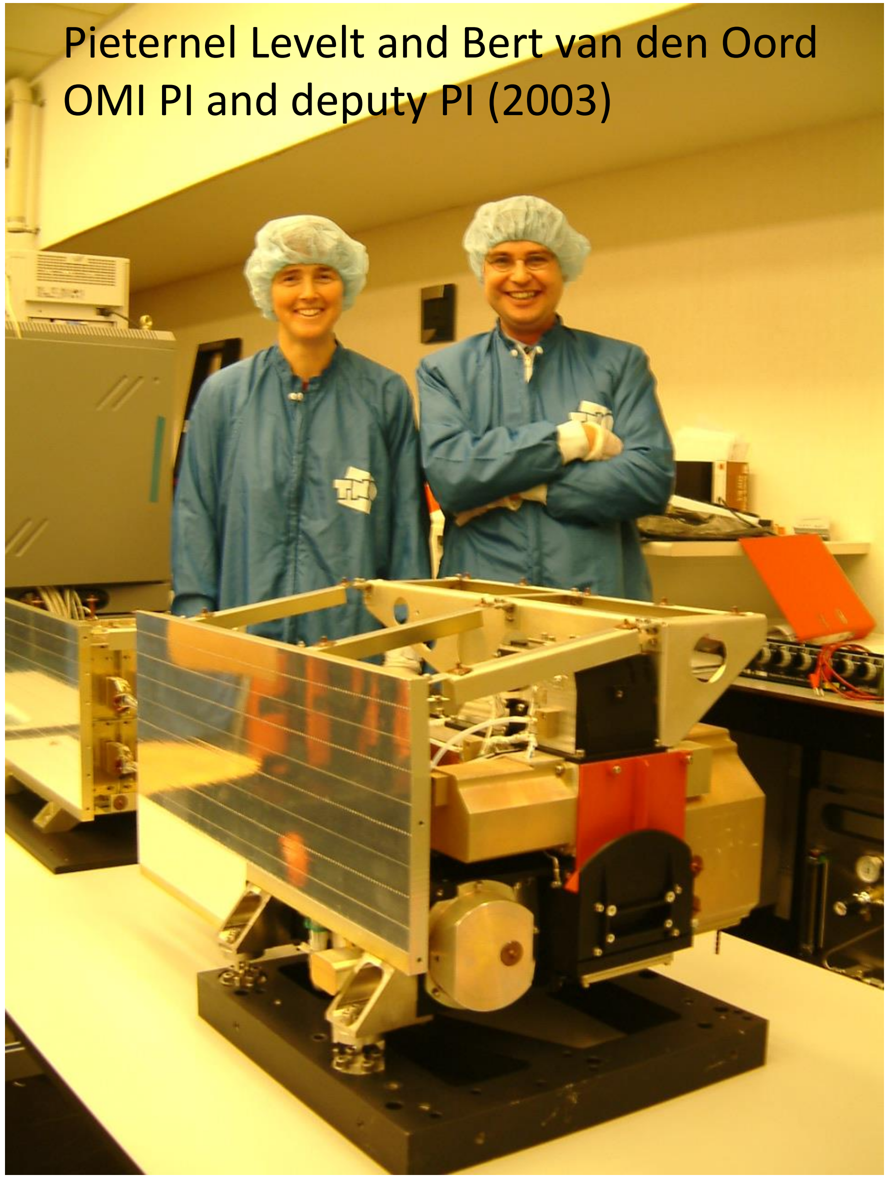
KNMI: PI institute for OMI and TROPOMI

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

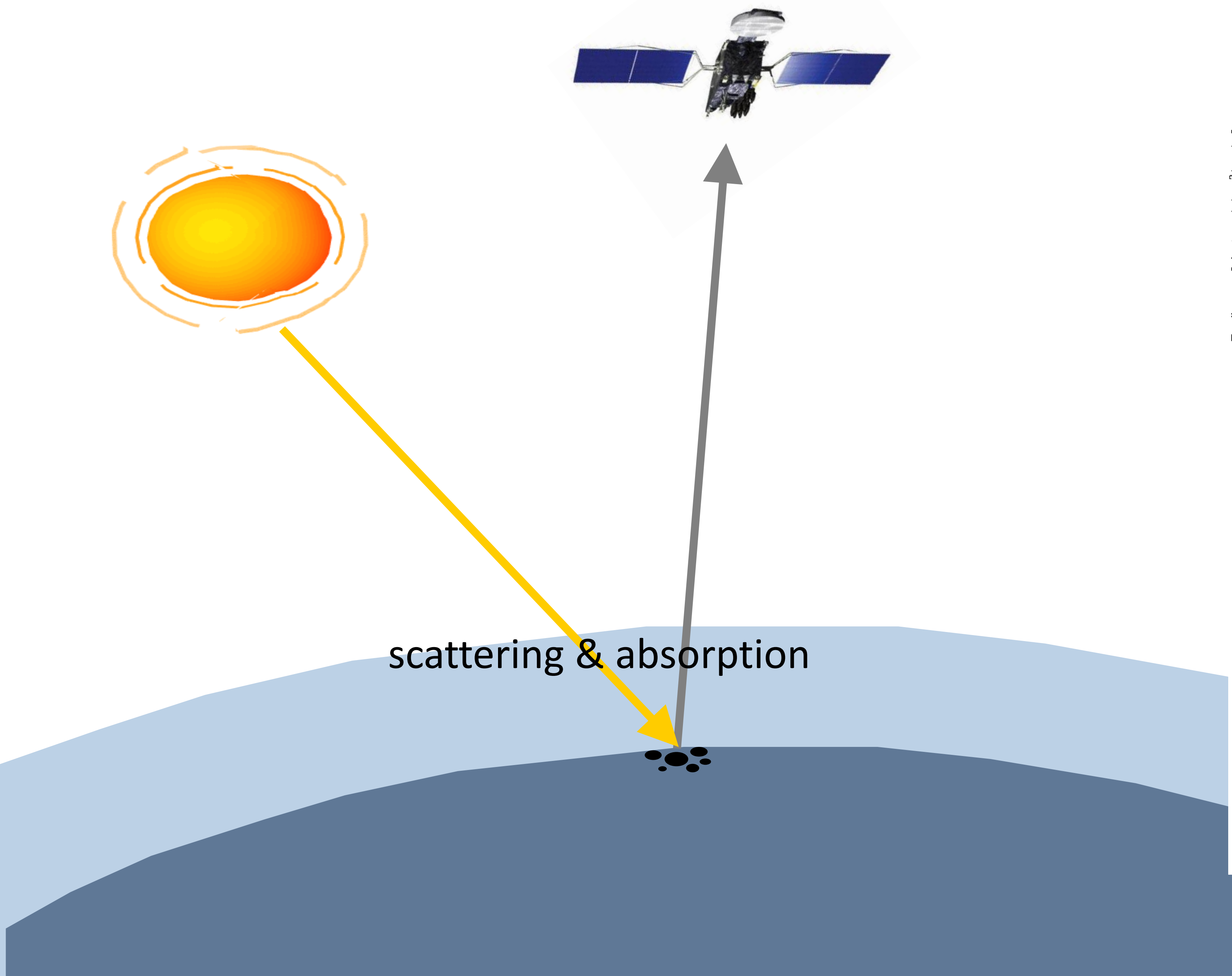
- *Levelt, P.F., et al The Ozone Monitoring Instrument, IEEE Trans. Geo. Rem. Sens., Special Issue on the EOS-Aura mission, 44 (5), 1199-1208, May 2006.*
- *Levelt, P.F., et al.: The Ozone Monitoring Instrument: Overview of fourteen years in space, Atmos. Chem. Phys. Discuss., Atmos. Chem. Phys., 18, 5699–5745, https://doi.org/10.5194/acp-18-5699-2018, 2018.*

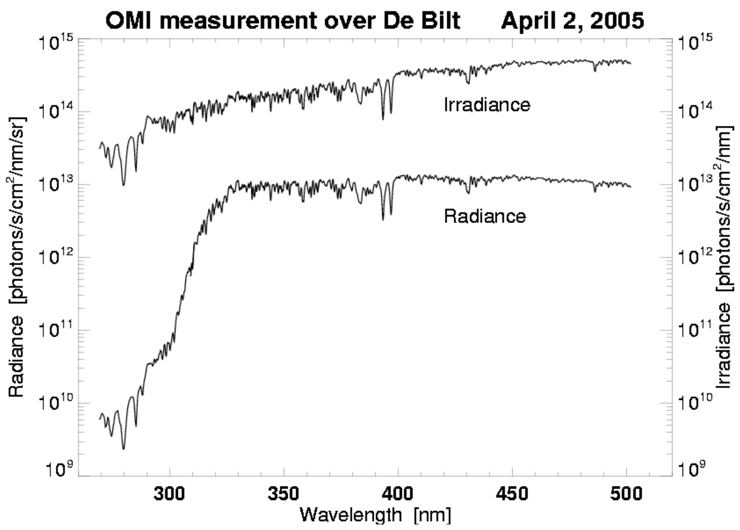


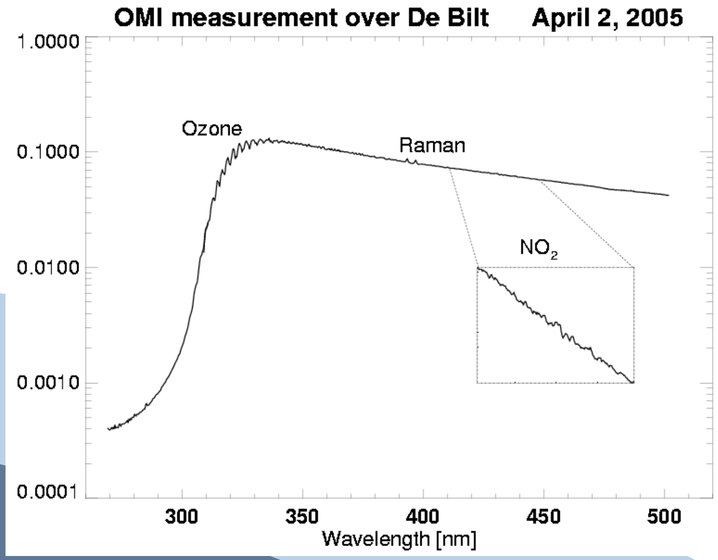
Pieternel Levelt and Bert van den Oord
OMI PI and deputy PI (2003)

Measurement Technique

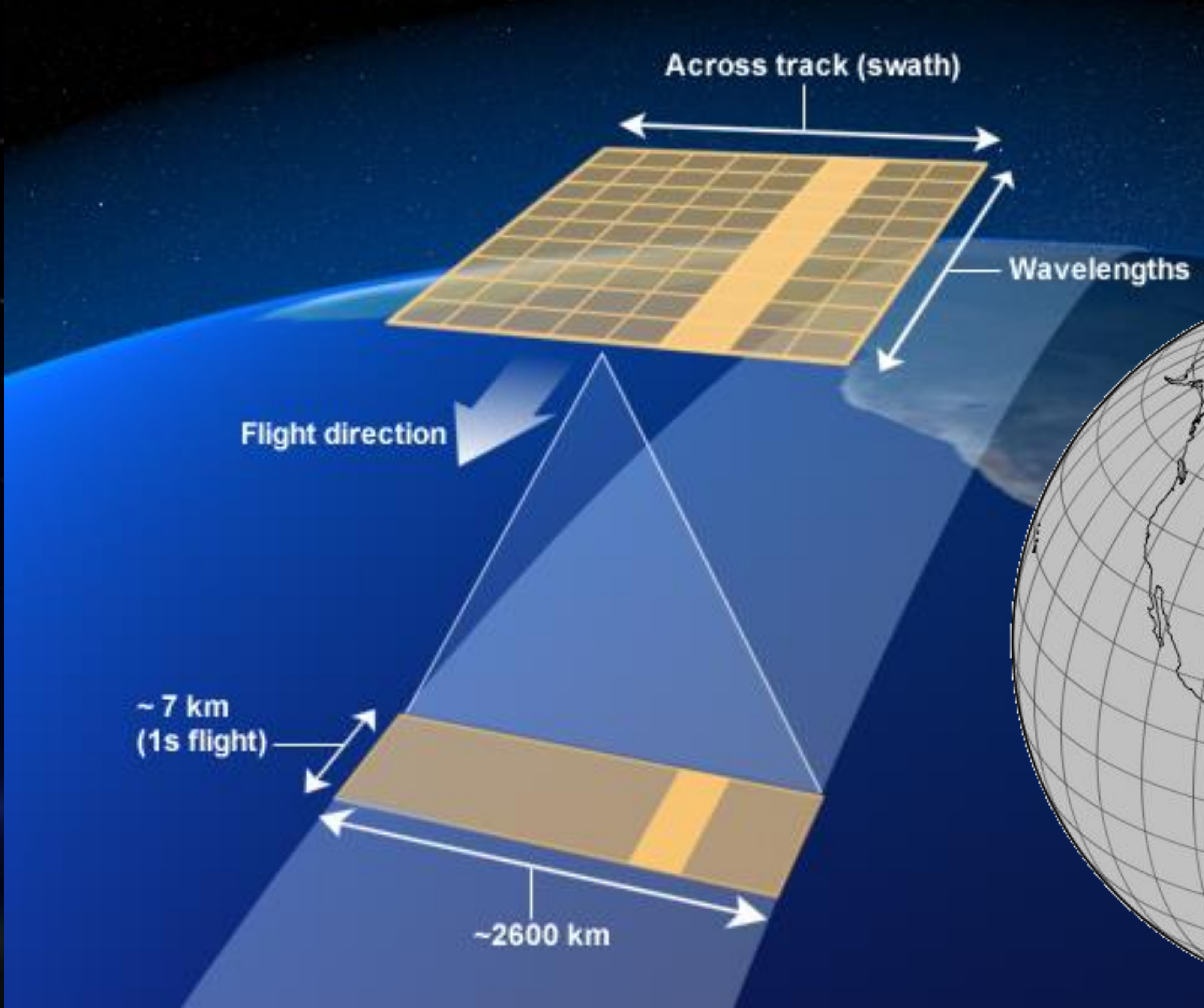
Royal Netherlands
Meteorological Institute
Ministry of Infrastructure and the Environment

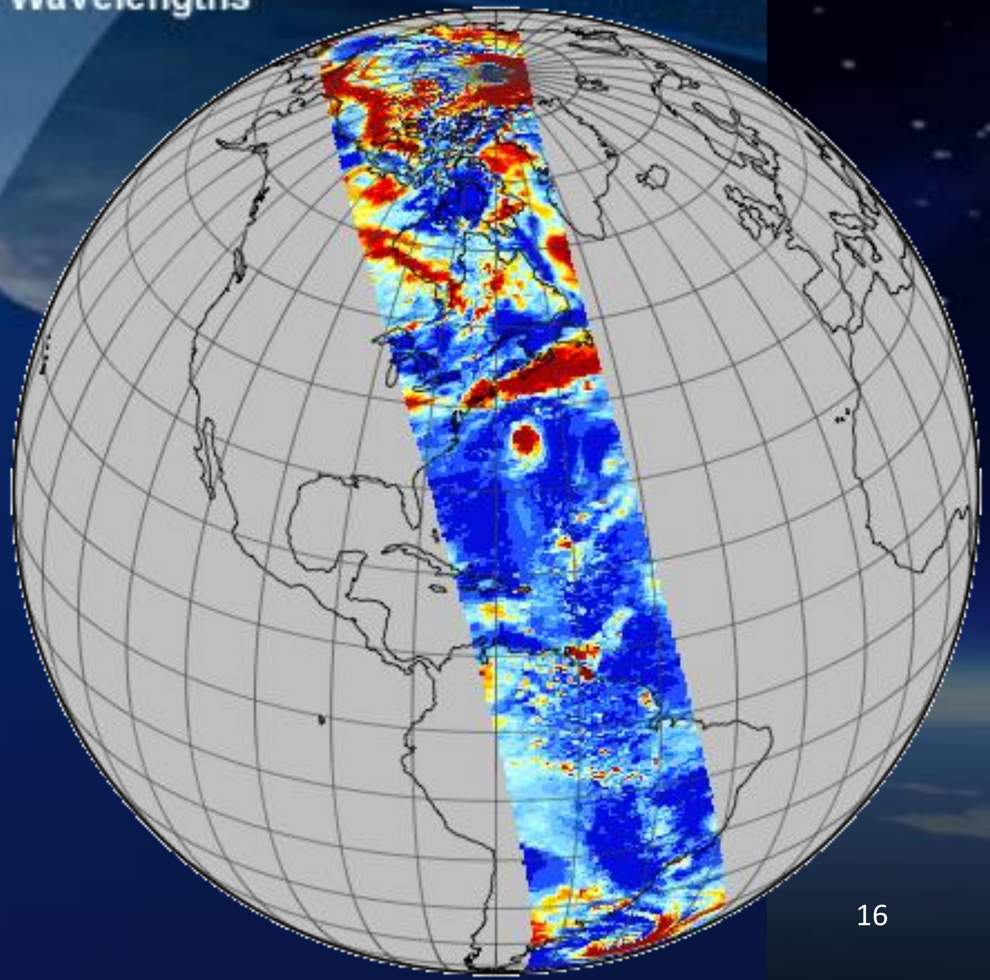






OMI and TROPOMI Measurement Principle

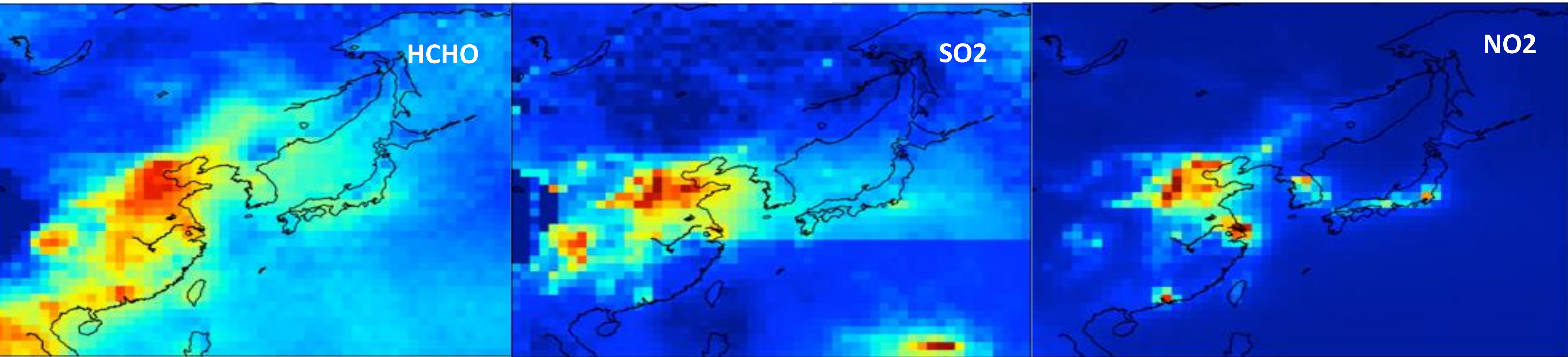




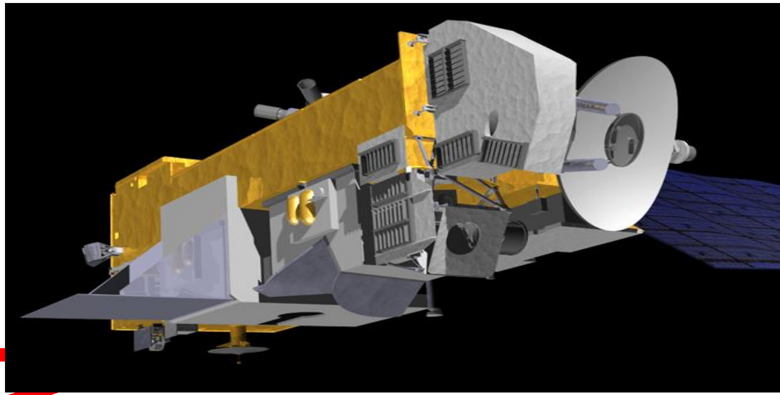
OMI lead to new findings in Air Quality Domain

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

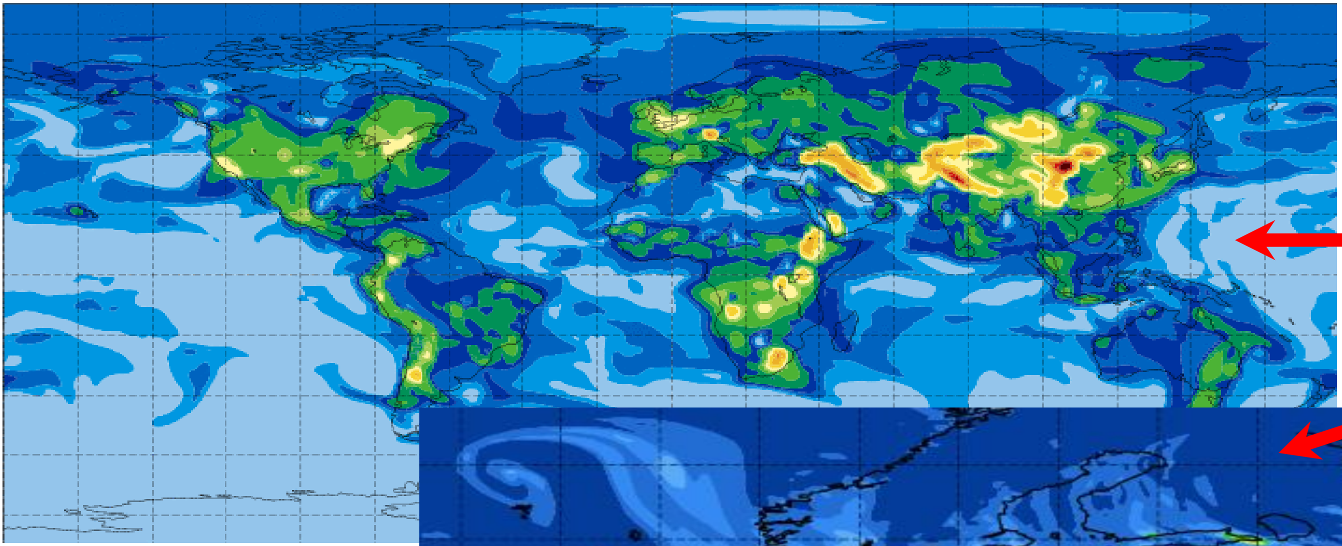
Product	Application
Ozone column	*Ozone layer monitoring / NWP*
Ozone profile	*Ozone layer monitoring / Tropospheric ozone*
NO_2	*Air quality / Emission monitoring*
SO_2	*Volcanic eruptions / Air quality / Emission monitoring*
Formaldehyde	*Air quality / Emission monitoring*
BrO	*Polar chemistry / stratospheric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

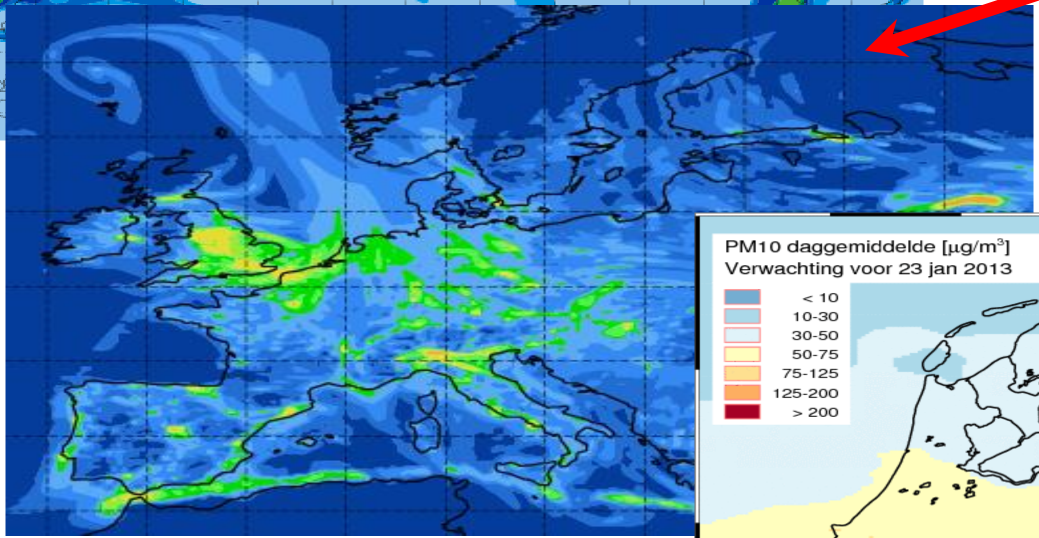


EU Copernicus Atmosphere: Air Quality product chain

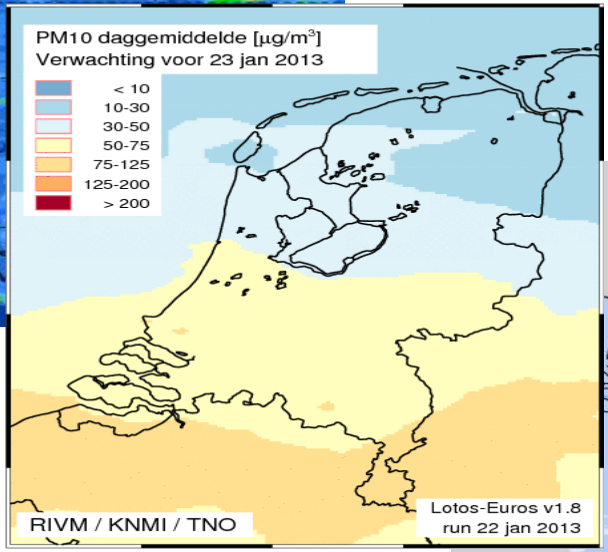


OMI NRT contributions

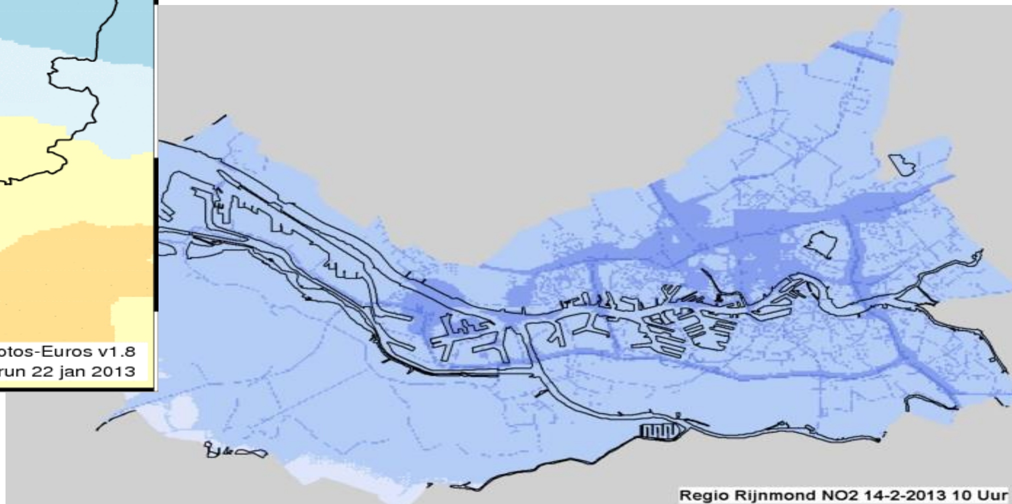




National forecasts:
Nesting in MACC regional



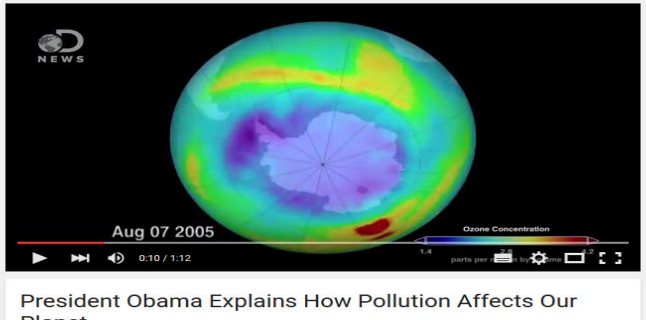
Couple to
city-scale models

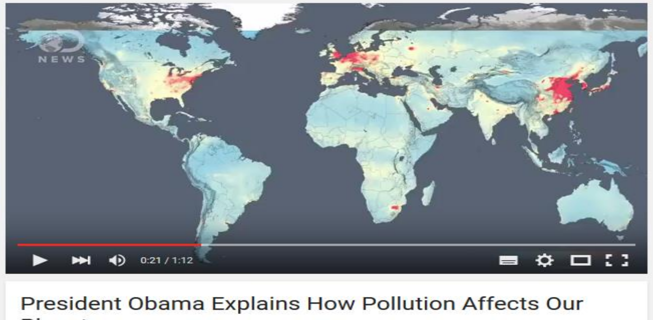


Use of
CAMS-global analyses as
boundary conditions for
CAMS-Europe

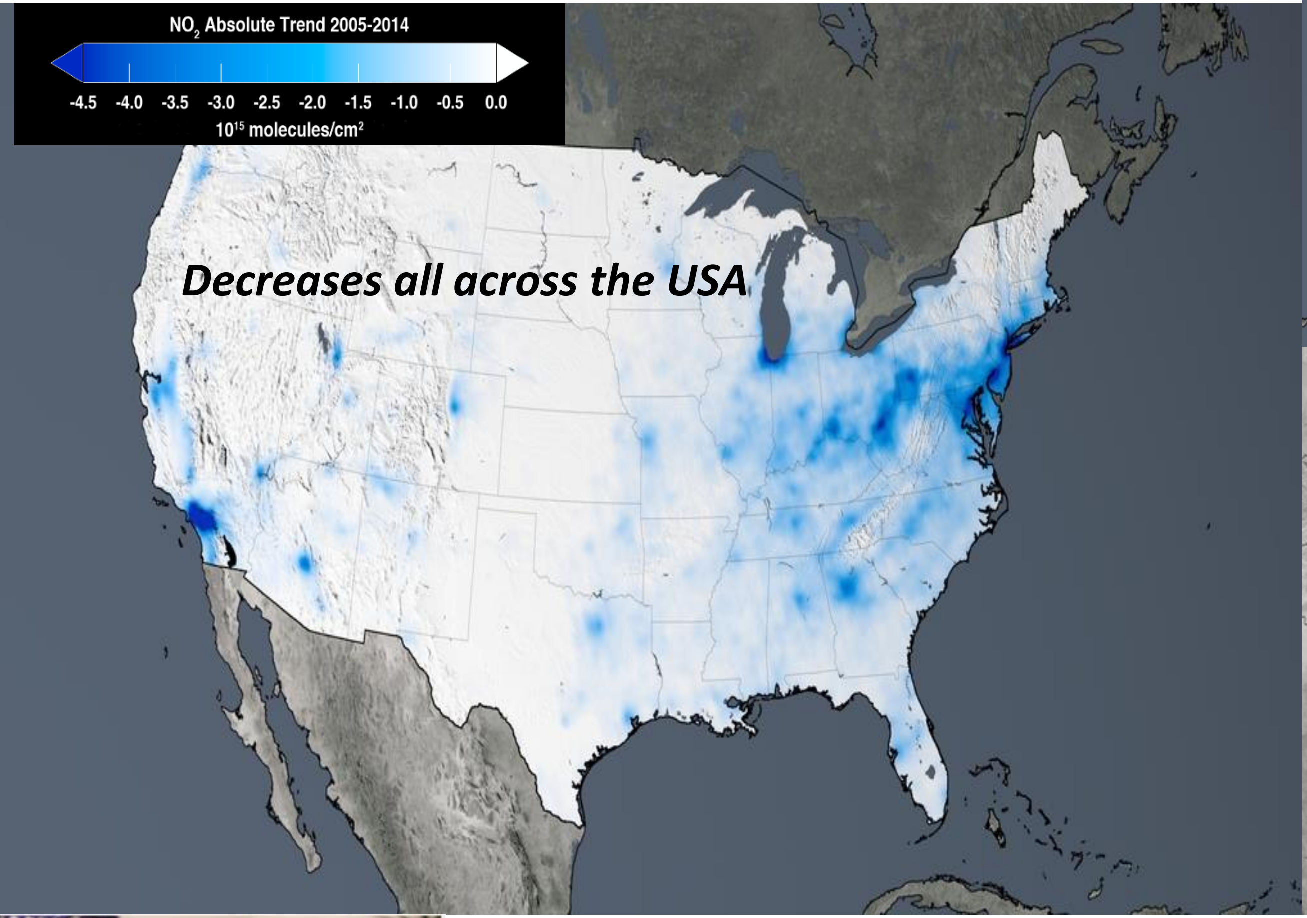
President Barack Obama about OMI NO_2 and emission control

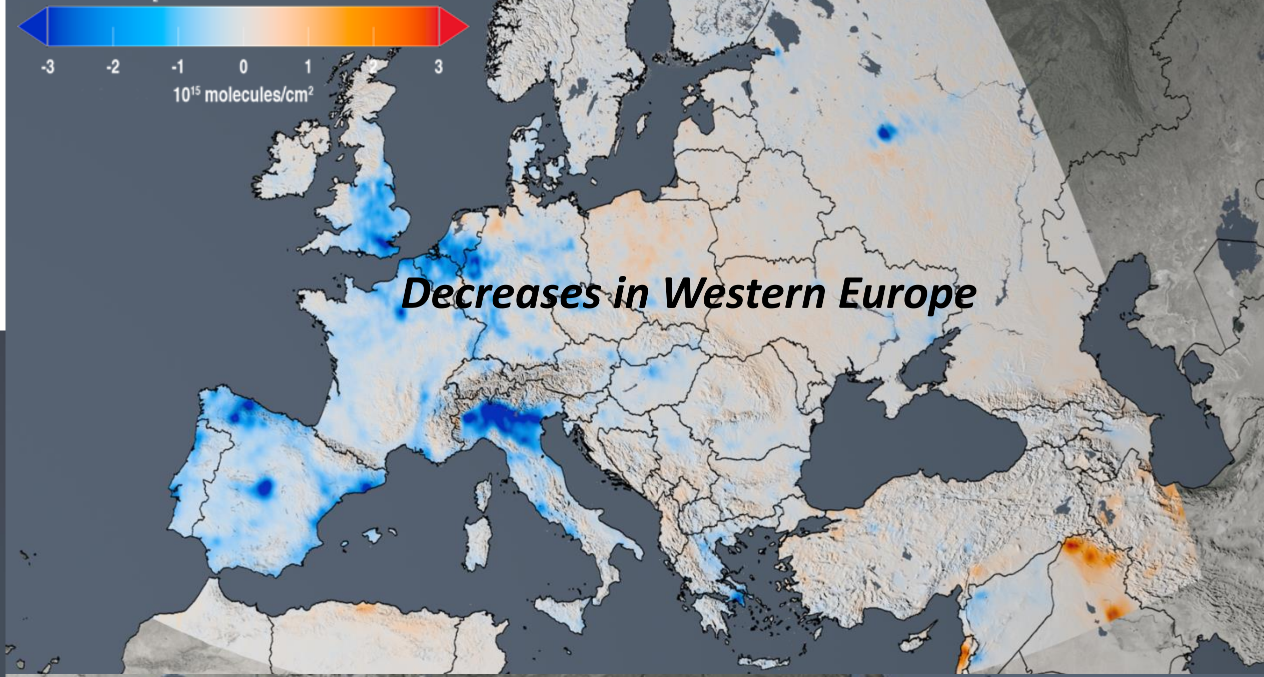
Science Channel, April 12, 2016

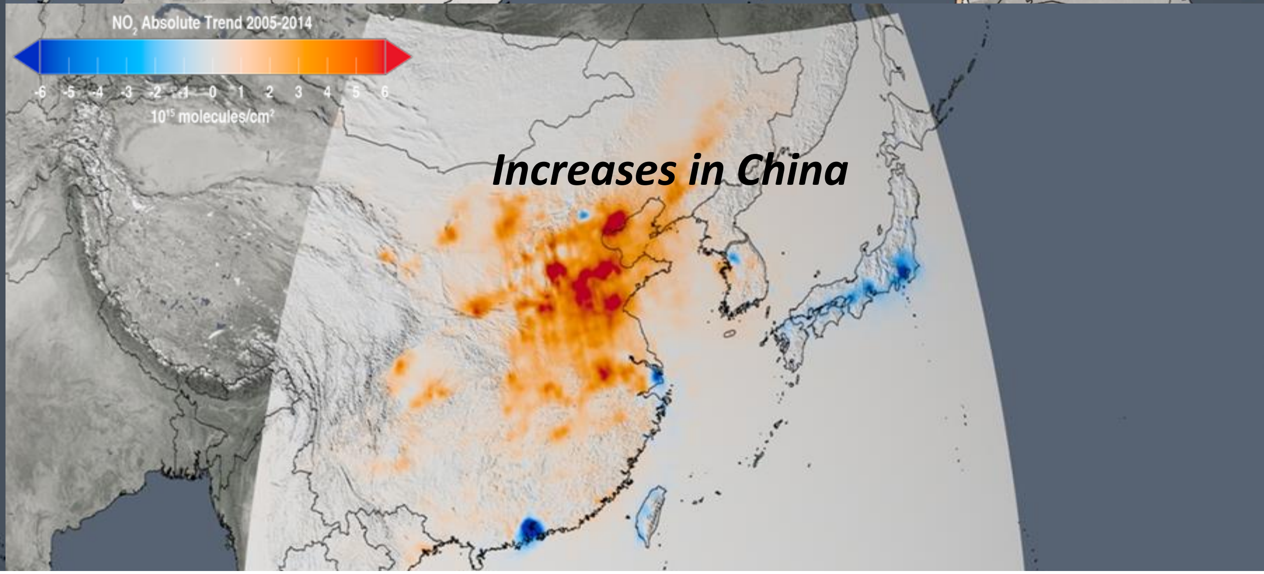




OMI: 2005 compared to 2014 (NASA/KNMI)

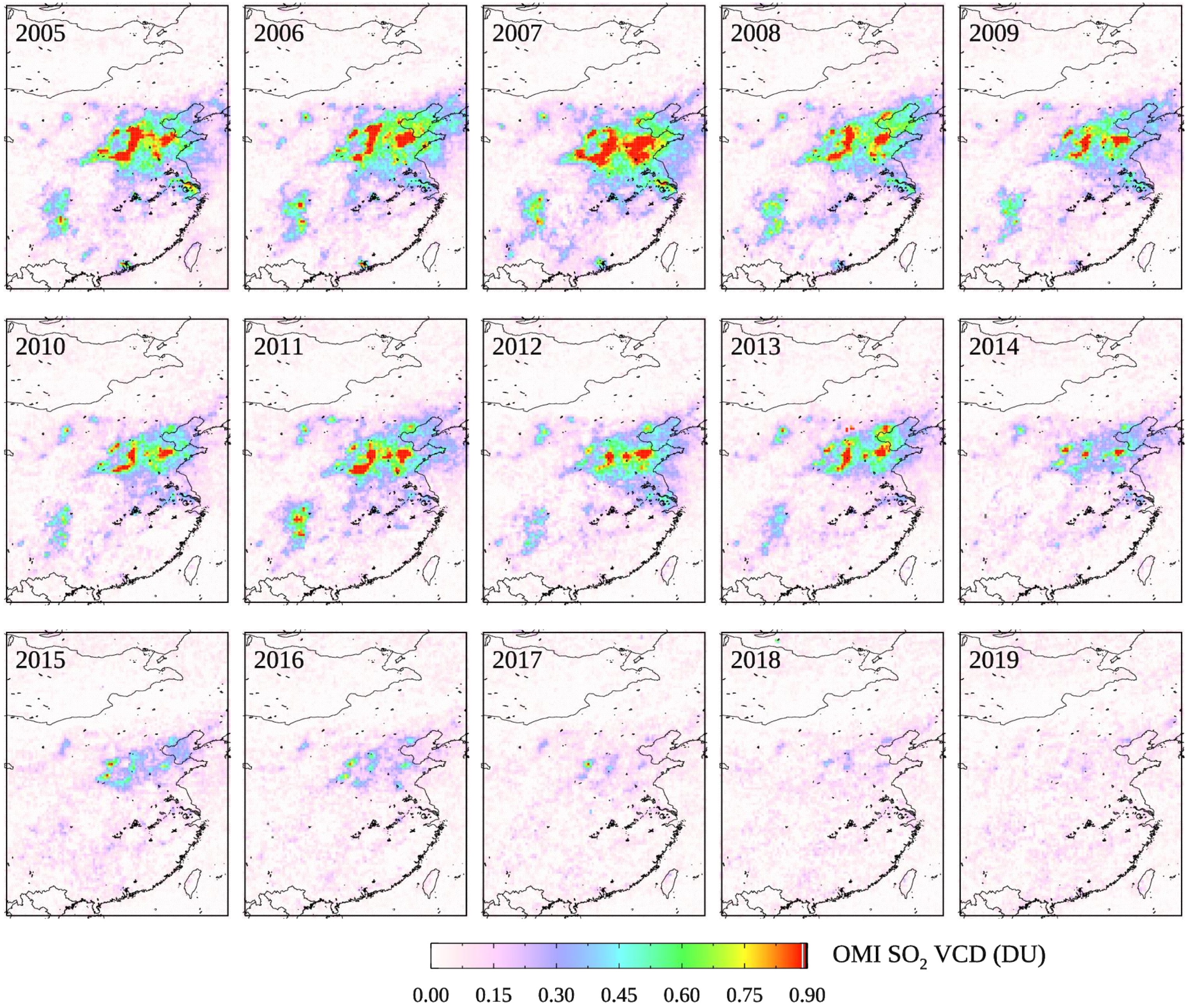






President Barack Obama
about OMI NO_2 and emission control
Science Channel, April 12, 2016

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



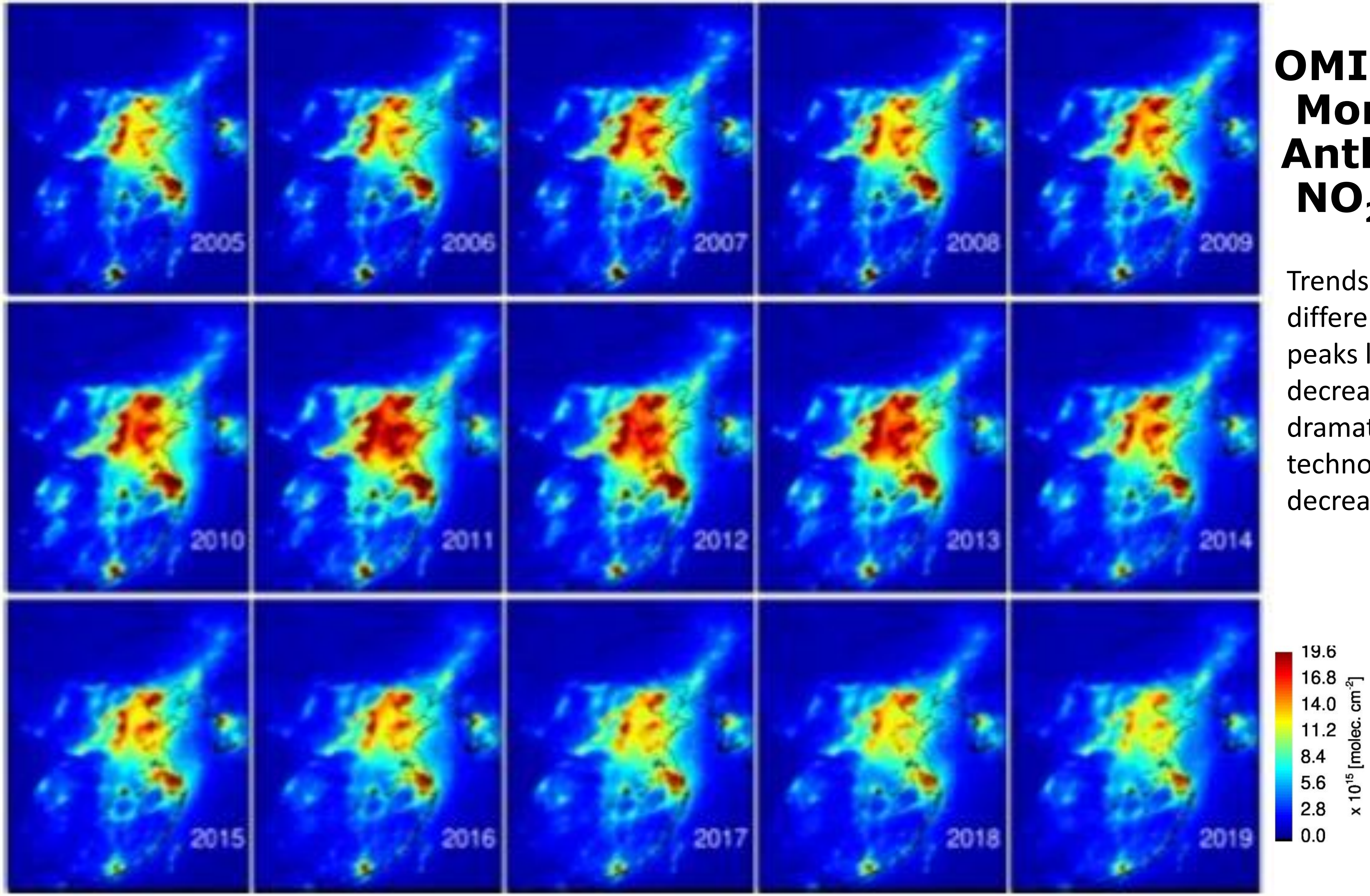
OMI Long-term Monitoring of Anthropogenic SO_2 Pollution

Mean warm season (April to October) OMI SO_2 vertical column densities (VCDs) over eastern China from 2005-2019 [*Li et al., AMT* 2020].

Continued but slower decrease in SO_2 pollution over China since 2016 (figure on left).

Courtesy: Can Li (U. Maryland, ESSIC) and OMI SO_2 group at GSFC

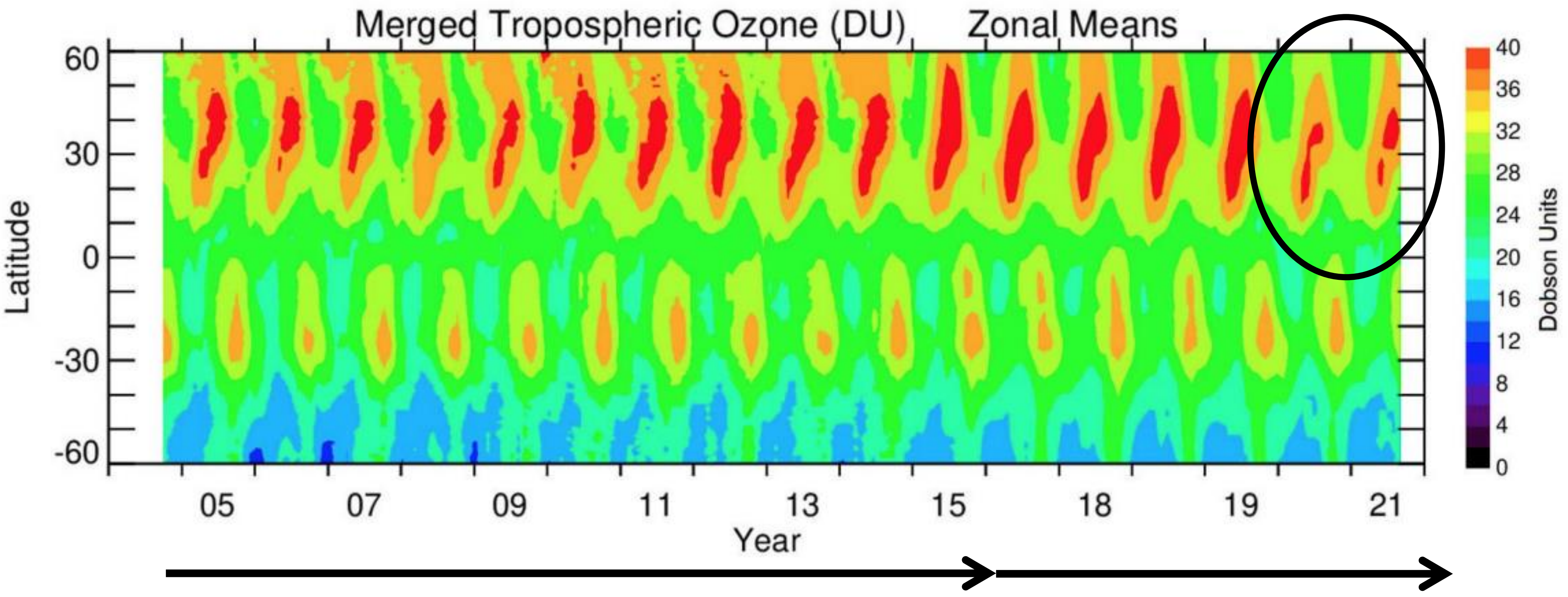
OMI Long-term Monitoring of Anthropogenic NO_2 Pollution



Trends somewhat different from SO_2, peaks later in time and decrease is not as dramatic (different technologies used to decrease emissions).

Courtesy: Lok Lamsal, USRA, and NO_2 group at GSFC

Trends in global tropospheric ozone inferred from OMI & MLS and other instruments (OMPS, EPIC)

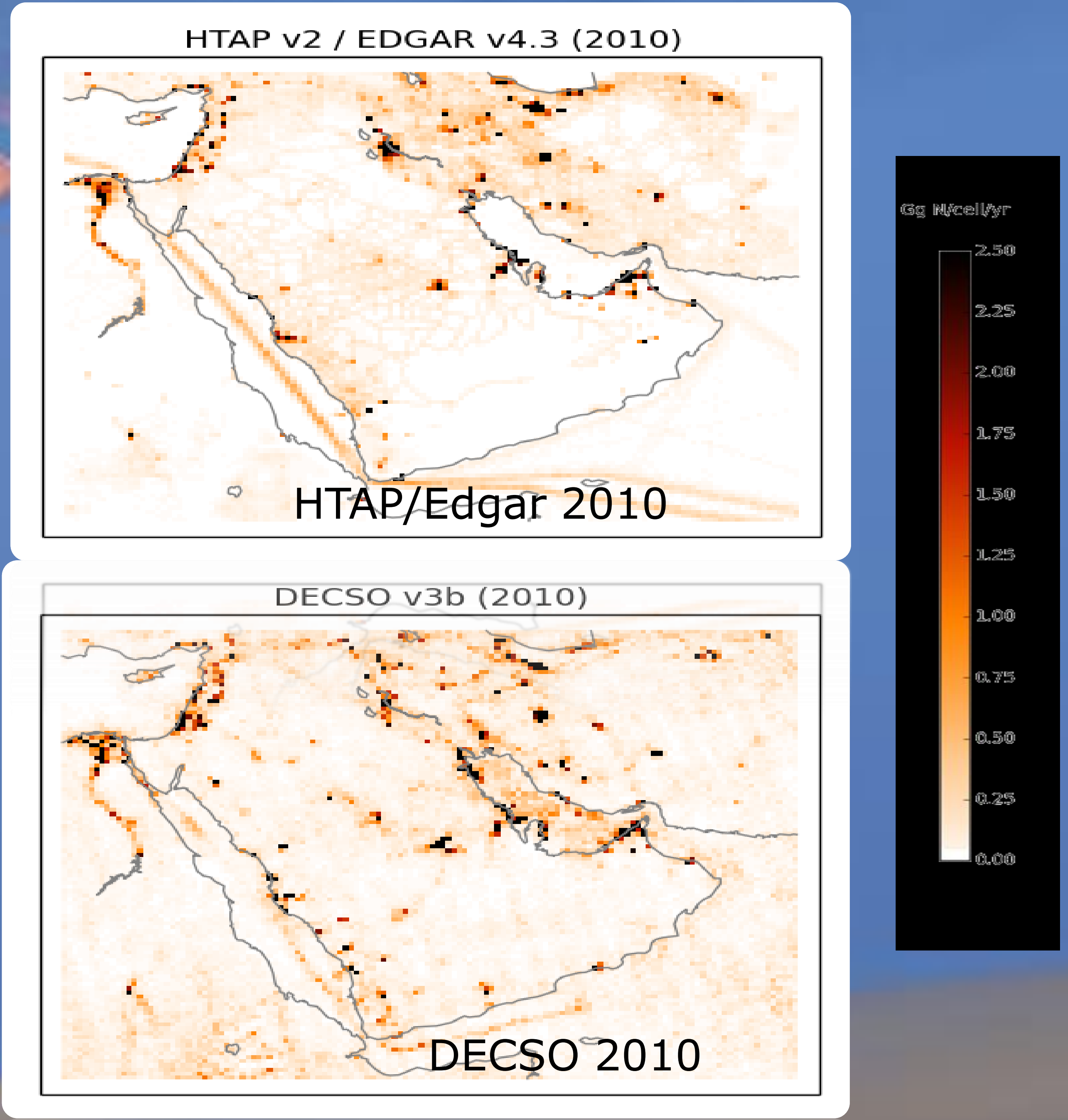


From Ziemke et al., GRL, 2022

- Tropospheric ozone decreases in the NH in 2020 and 2021 produced the lowest recorded tropospheric ozone in the NH since at least year 2005
- NO_2 measurements suggest that the NH tropospheric ozone losses in both 2020 and 2021 were largely of anthropogenic origin

Slide courtesy : Joanna Joiner, NASA GSFC

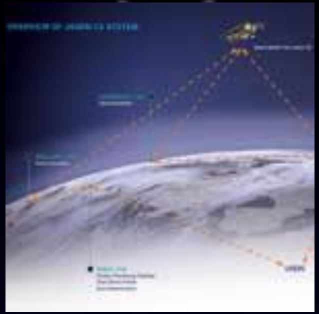
Top-down emission estimates based on satellite data



Daily emission estimates constrained by satellites: DECSO algorithm from KNMI

Bas Mijling , Ronald van der A
KNMI

EU Copernicus Sentinels



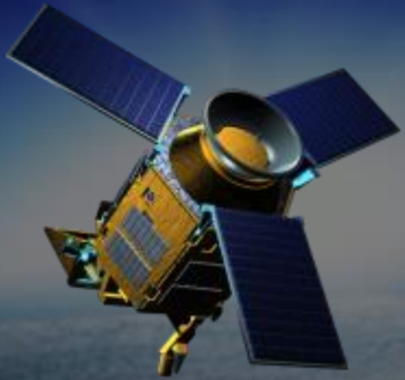
Sentinel 6

Sentinel 1

Sentinel 5

Sentinel 2

Sentinel 4



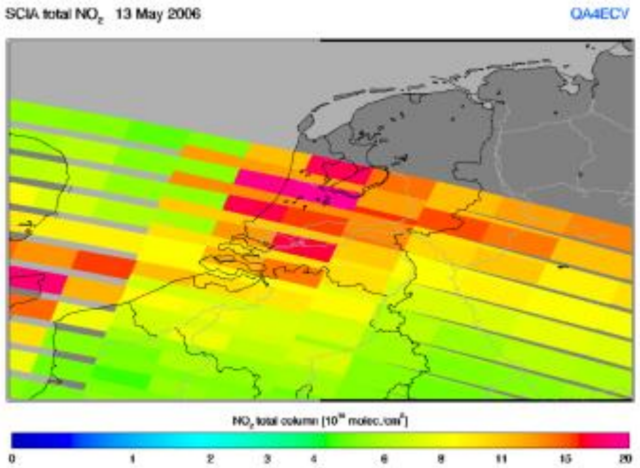
Sentinel 5P

Sentinel 3

From OMI to TROPOMI

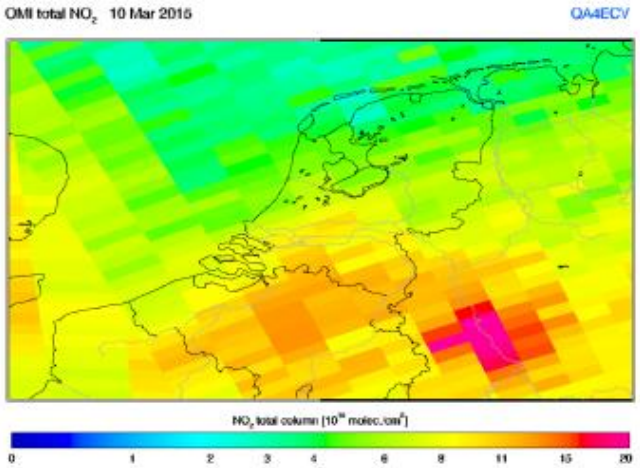
- **16 x higher spatial resolution**
  3,5 x 5,5 km^2 vs. 13 x 24 km^2
- **1-5x higher sensitivity** per ground pixel
- **CO and Methane (7 x 5,5 km^2)**
  SWIR band added
- **Better cloud information**
  oxygen A band added

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



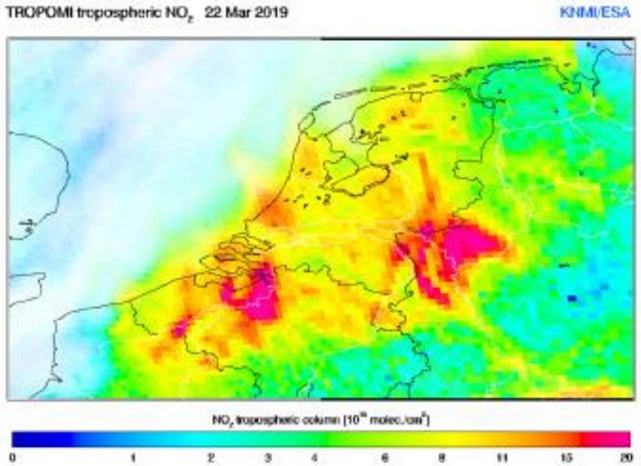
SCIAMACHY
13 May 2006

30 x 60 km^2
6 day global coverage



OMI
10 March 2016

13 x 24 km^2
Daily global coverage

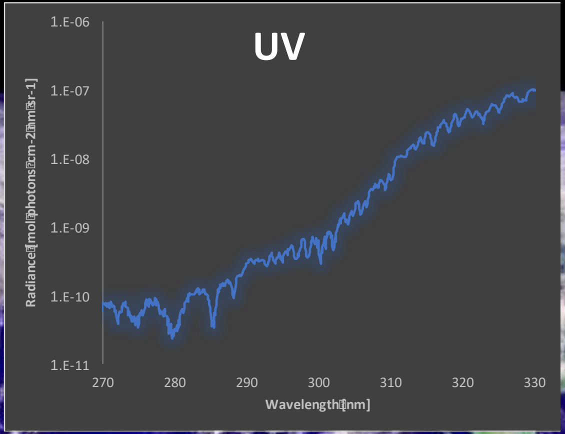


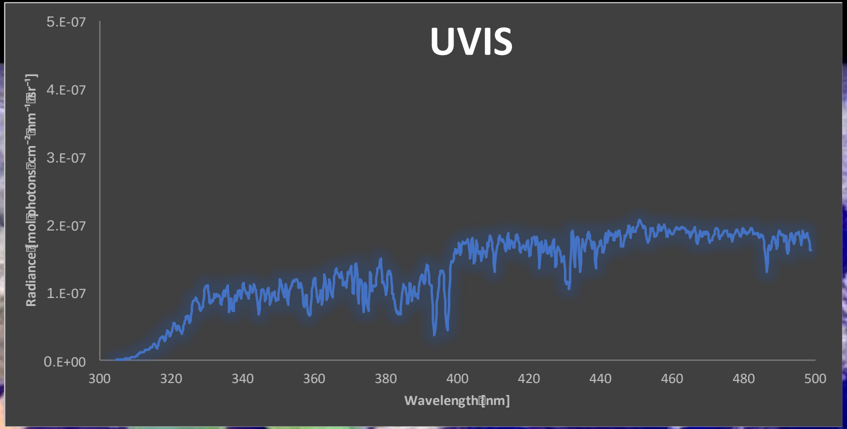
TROPOMI
22 March 2019

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

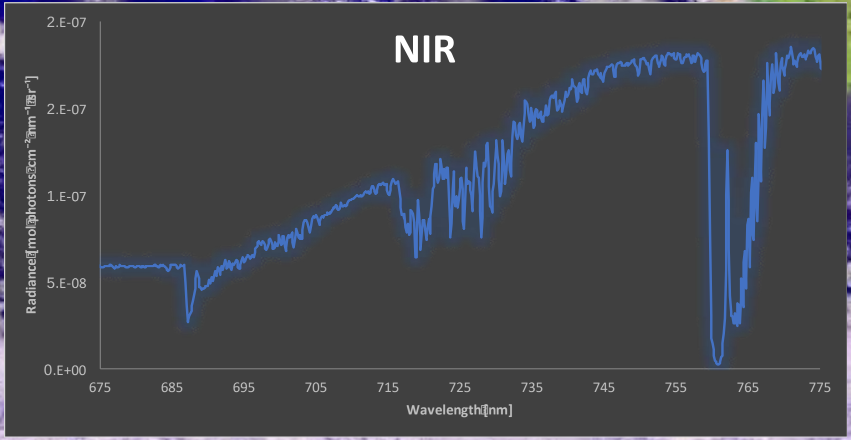
TROPOMI Launch Successful!

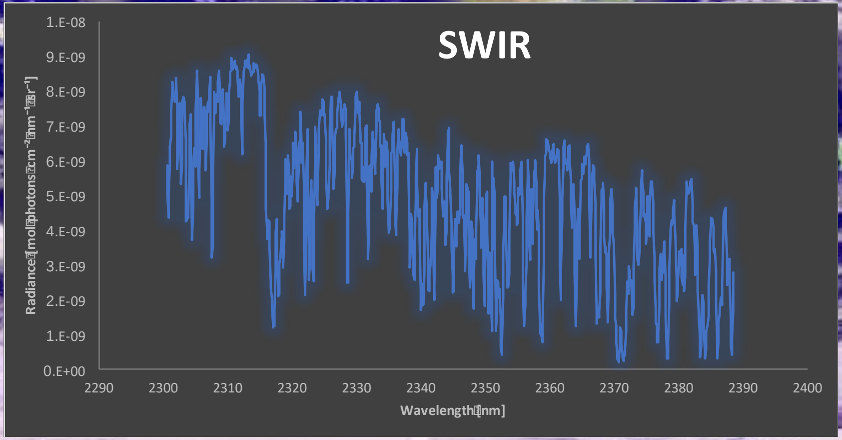
Friday October 13, 2017





- 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





TROPOMI Operational Data Products

TROPOMI

Parameter	Data Product	Vertical Resolution	Bias	Random
Ozone	Ozone Profile	6 km	10-30%	10%
	Total Ozone	total column	3.5-5%	1.6-2.5%
	Tropospheric Ozone	trop column	25%	10%
NO_2	Stratospheric NO_2	strat column	<10%	0.5e15
	Tropospheric NO_2	trop column	25-50%	0.7e15
SO_2	SO_2 enhanced	total column	30%	0.15-0.3 (0.06-0.12) DU
	Total SO_2	total column	30-50%	1-3 (0.4-1.2) DU
Formaldehyde	Total HCHO	total column	40-80%	1.2e16 (4e15)
CO	Total CO	total column	15%	<10%
Methane	Total CH_4	total column	1.5%	1%
Cloud	Cloud Fraction	total column	<20%	0.05
	Albedo (Optical Thickness)	total column	<20%	0.05 (10)
	Cloud Height (Pressure)	total column	<20%	<0.5 km (<30hPa)
Aerosol	Aerosol Layer Height	total column	<100hPa	<50hPa
	Aerosol Type	total column	~1 AAI	<0.1 AAI
Surface UV	Provided by FMI in frame of the Finnish Sentinel Collaborative Ground Segment			

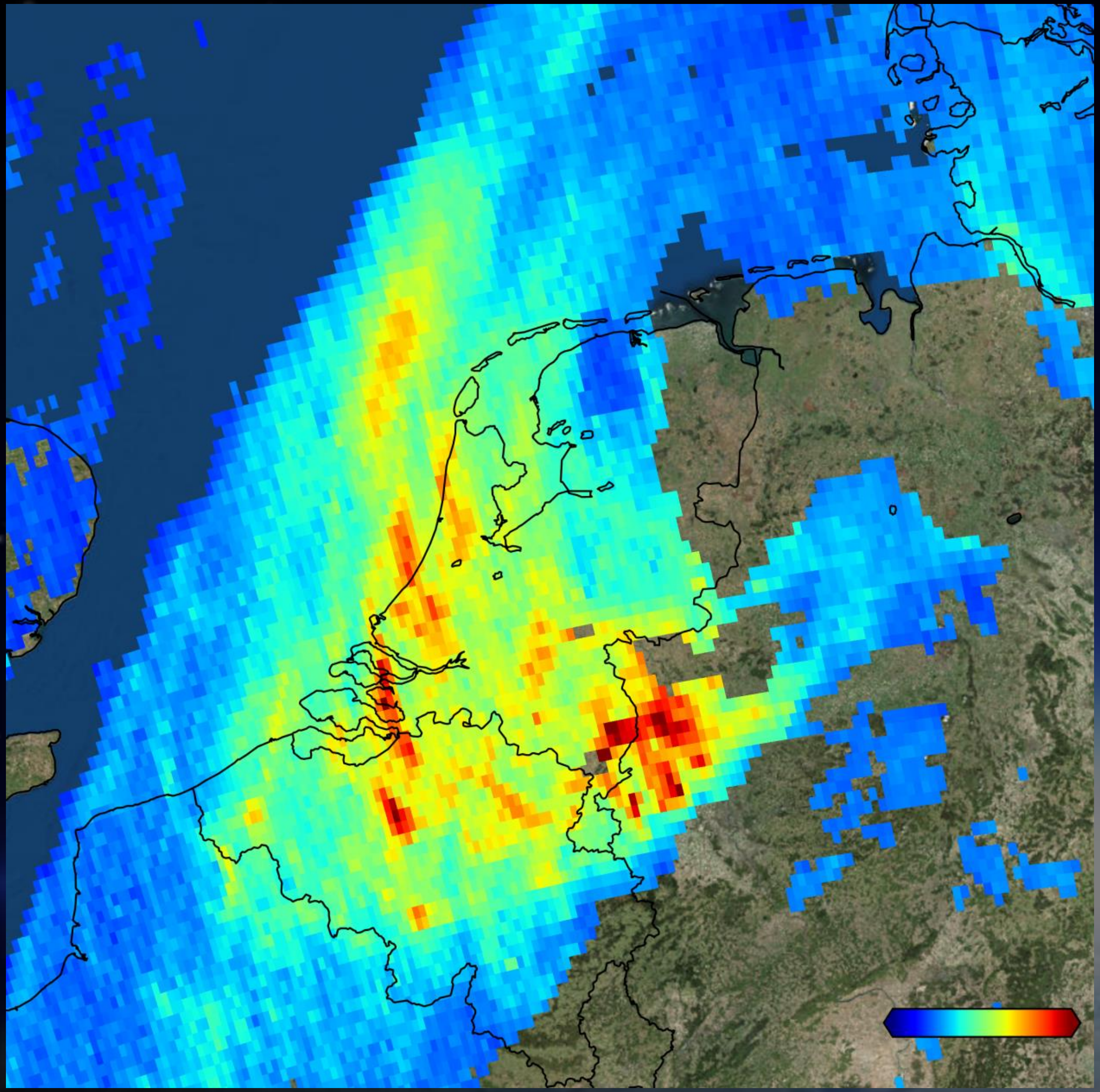
KNMI | DLR | BIRA-IASB | SRON | RAL | IUP-Bremen | MPIC | FMI

First NO_2 measurements after launch from S5p/TROPOMI

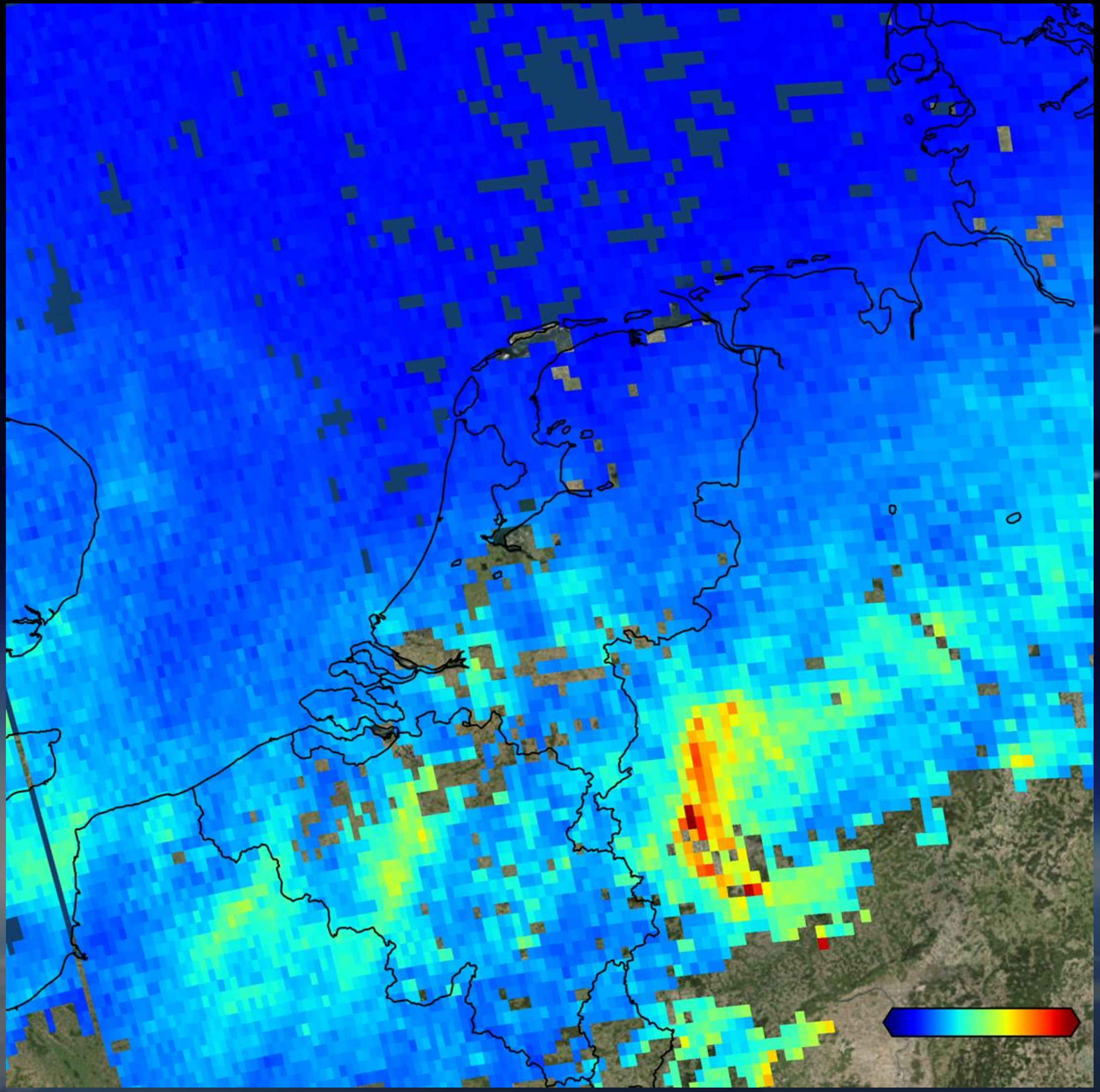
KNMI/NSO/ESA

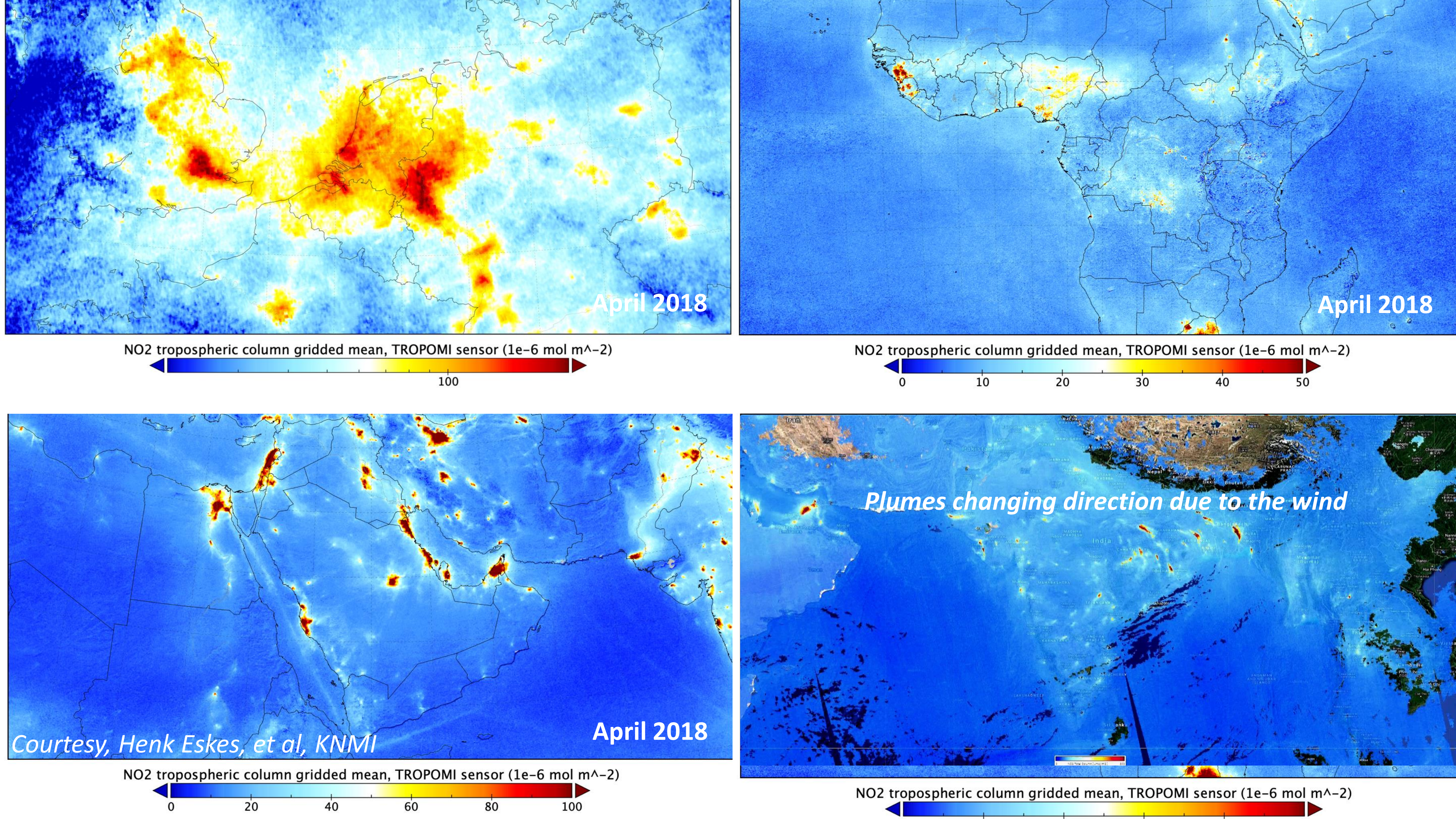
TROPOMI

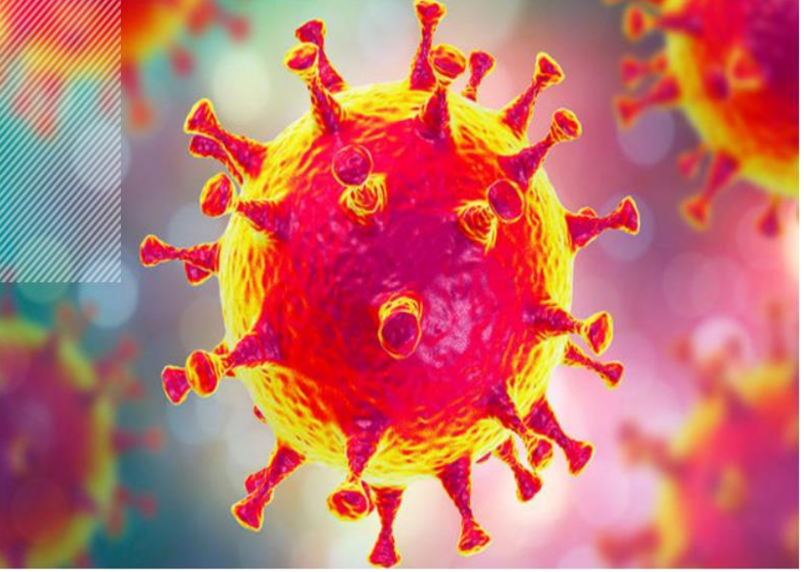
NO_2 07-11-2017



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
April 2018
Courtesy, Henk Eskes, et al, KNMI
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.

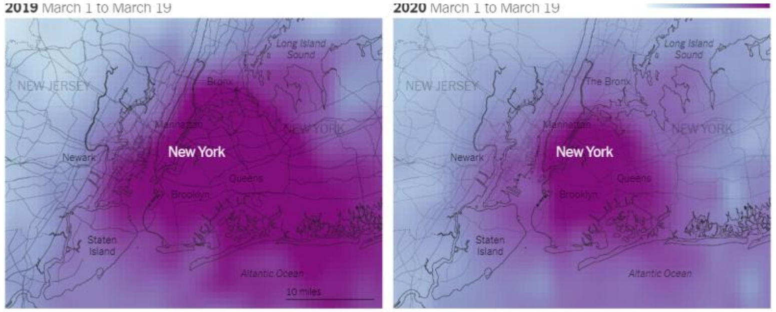
Quirin Schiermeier **Nature Physics news item**

ENGLISH ESPAÑOL 中文

The New York Times

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

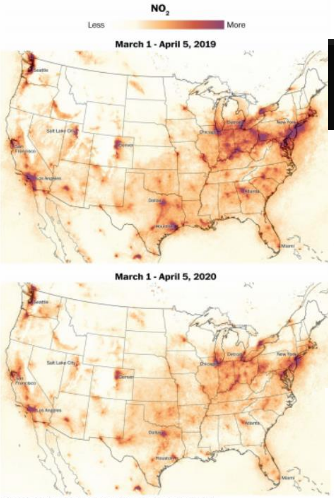
By Brad Plumer and Nadja Popovich March 22, 2020



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.



Source: Sentinel-5P satellite data provided by Descartes Labs
LAUREN TIERNEY/THE WASHINGTON POST

The Washington Post
Democracy Dies in Darkness

Capital Weather Gang

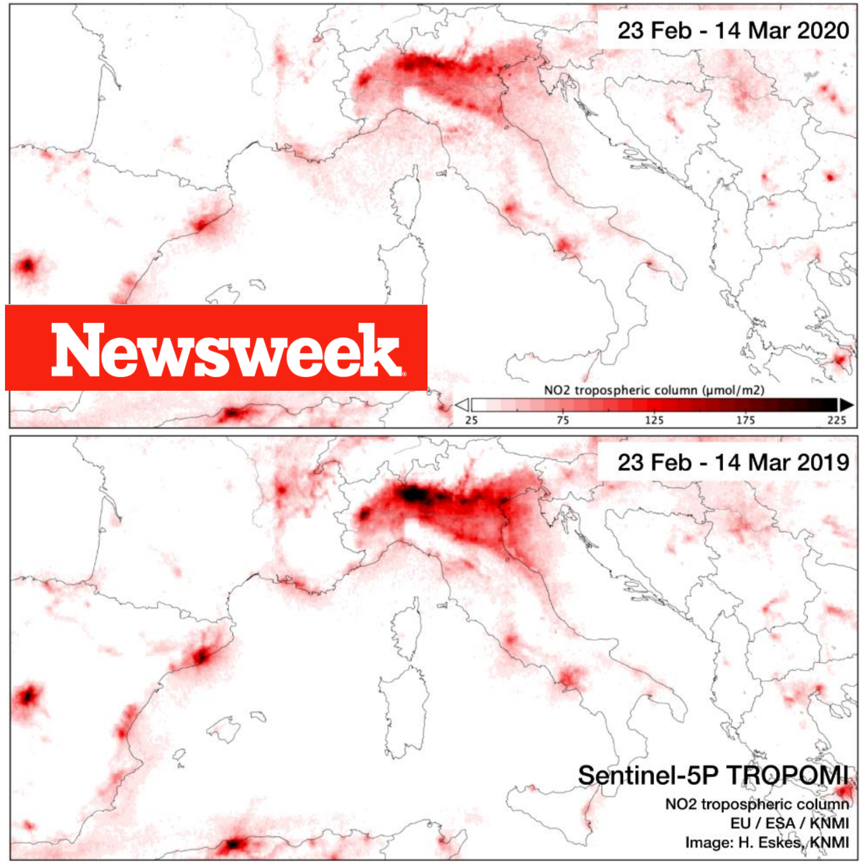
The silver lining to coronavirus lockdowns: Air quality is improving

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

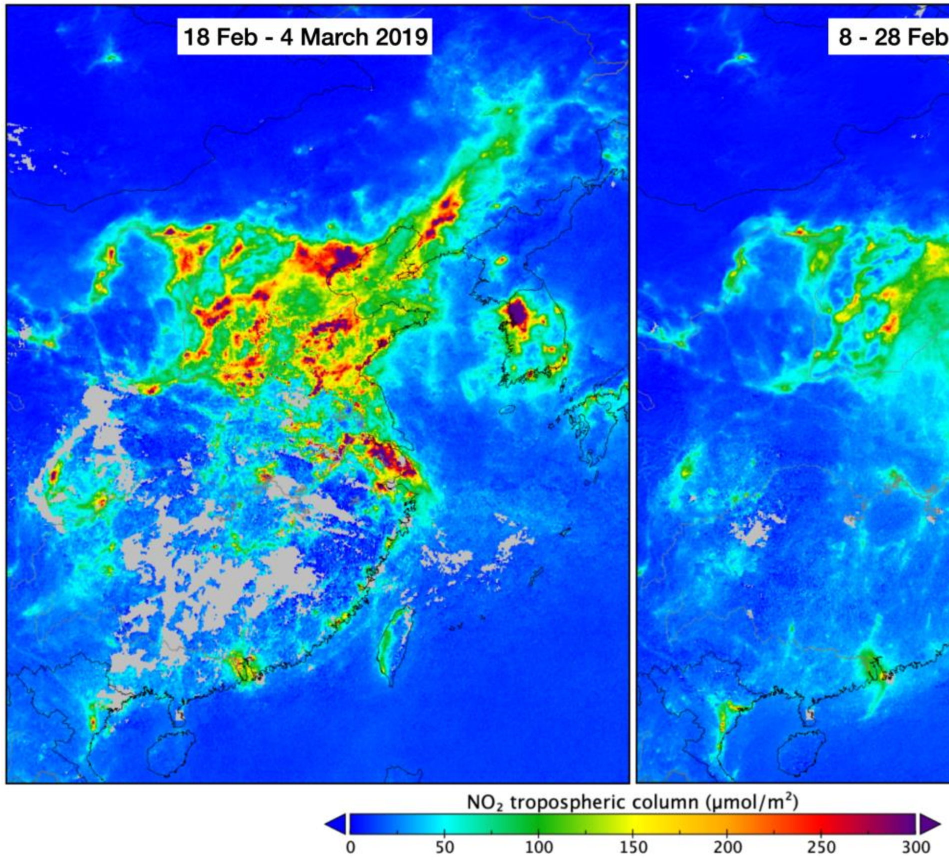


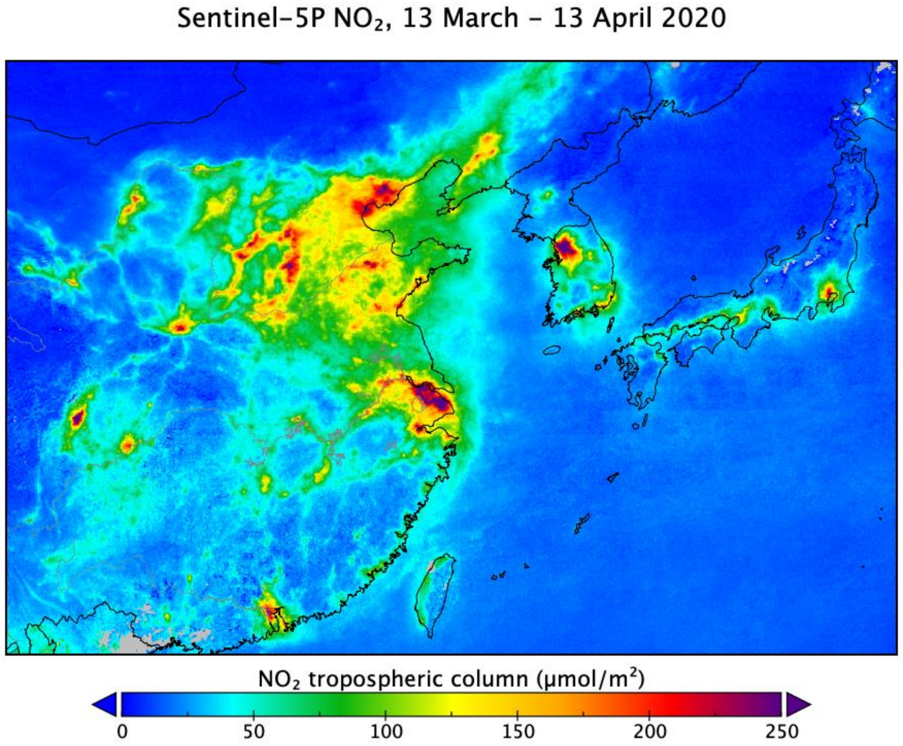
Pieternel Levelt from the Dutch Met office KNMI and Delft University of Technology in the Netherlands, echoed DeCarlo's comments telling Newsweek that there have been significant reductions in nitrogen dioxide over China and northern Italy in particular.

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**

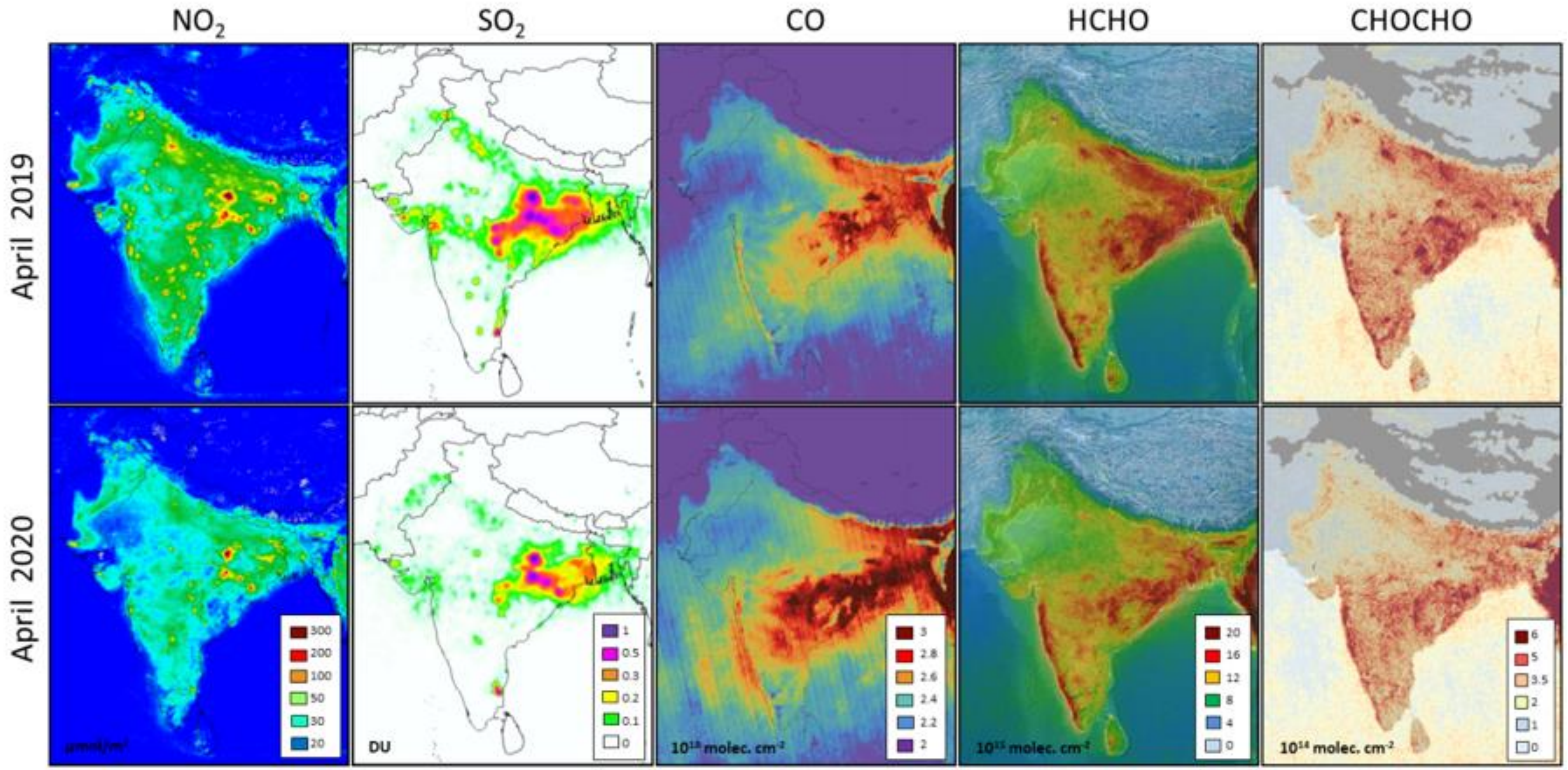




Courtesy Henk Eskes et al, KNMI

Sentinel 5p/TROPOMI

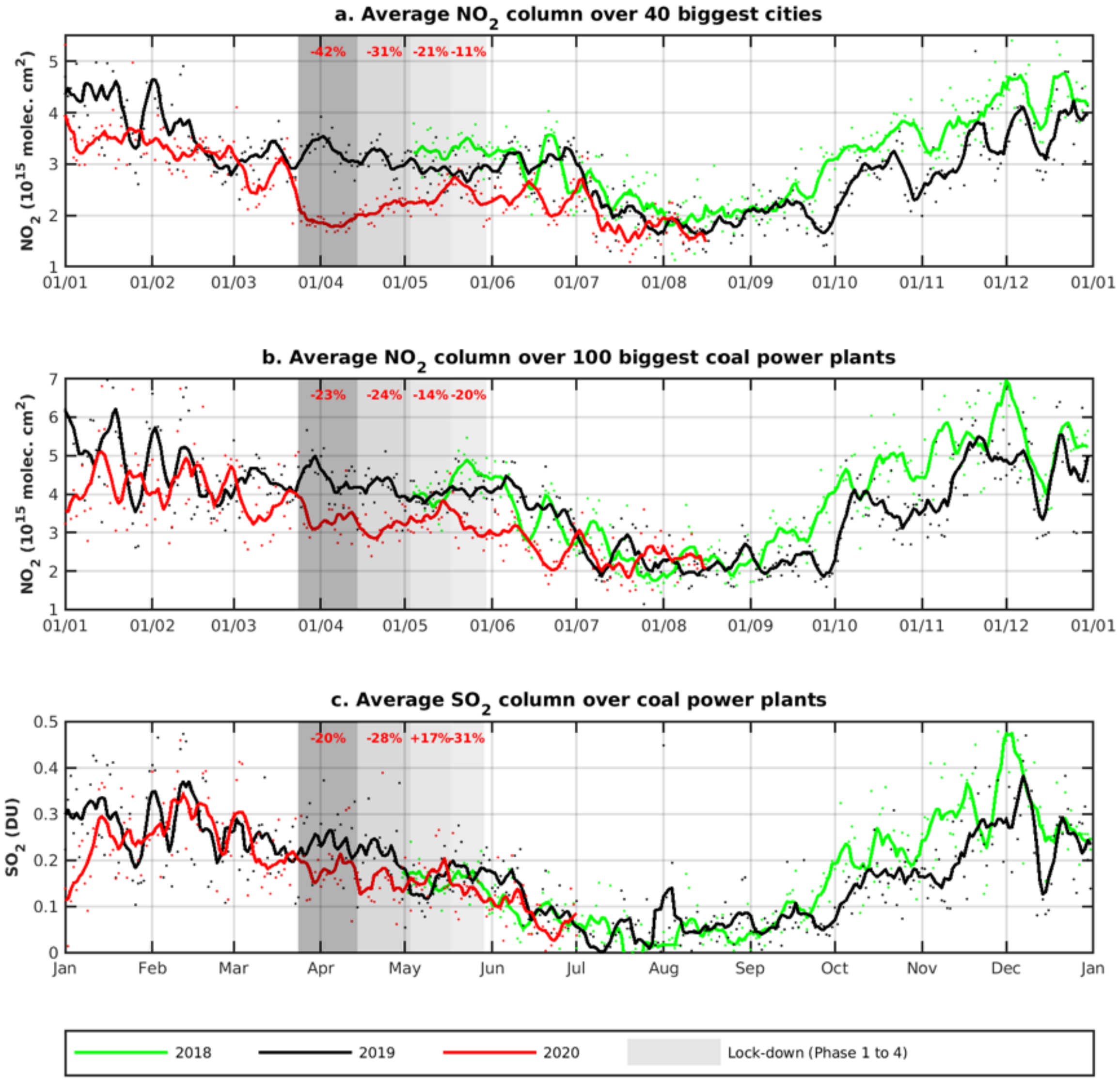
TROPOMI NO_2, SO_2, CO, HCHO, CHOCHO COVID lockdown impact (comparison February 2019 with 2020) over India



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

Levelt, et al, ACP, 2022

TROPOMI NO_2, and SO_2 over Indian cities and powerplants



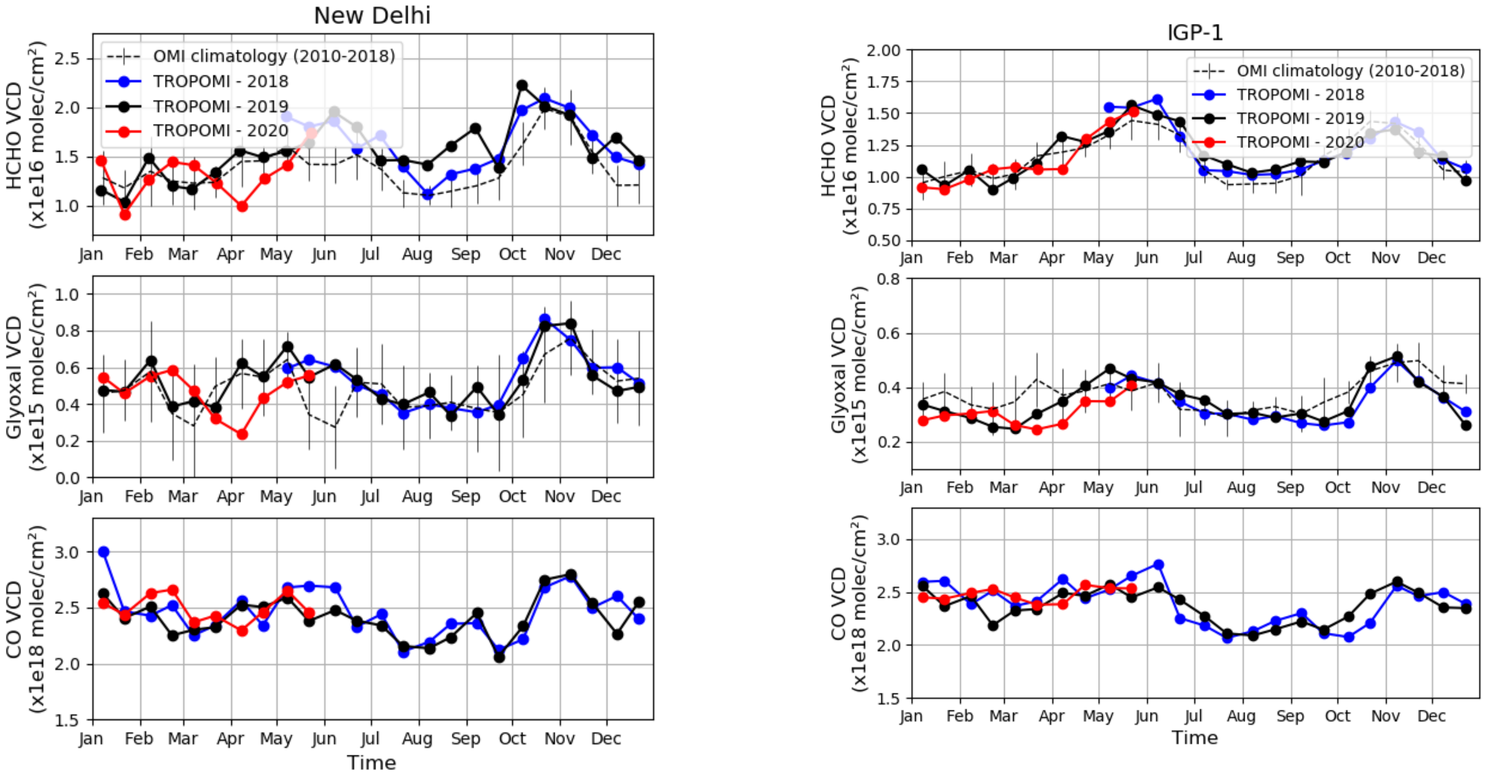
Average tropospheric NO2 concentrations for 2018 (green), 2019 (black) and 2020 (red) :

- 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.

Levelt, et al, ACP, 2022

New Delhi and Indo-Gangetic plane as observed by TROPOMI



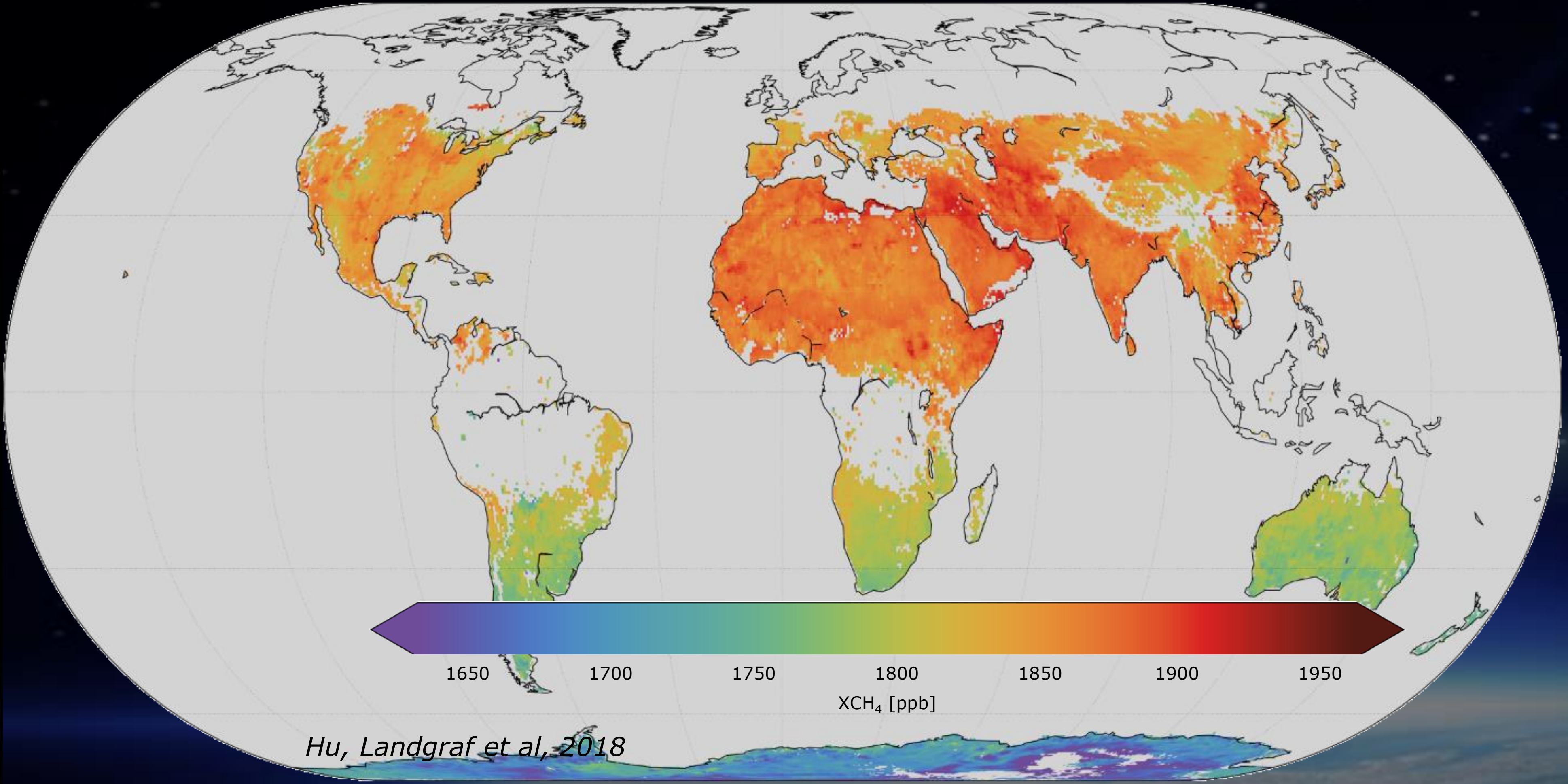
Time evolution of HCHO, CHOCHO, and CO over Indo-Gangetic plain and New Delhi (2020 in red, 2019 in black, 2018 in blue).

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

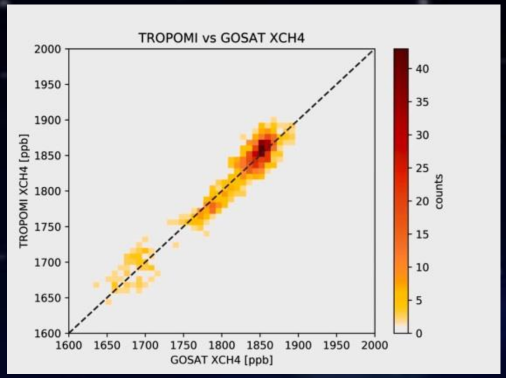
Levelt, et al, ACP, 2022

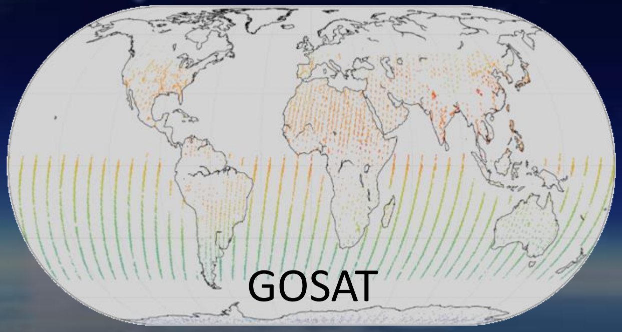
Methane XCH4

12 Nov – 30 dec 2017



TROPOMI-GOSAT comparison



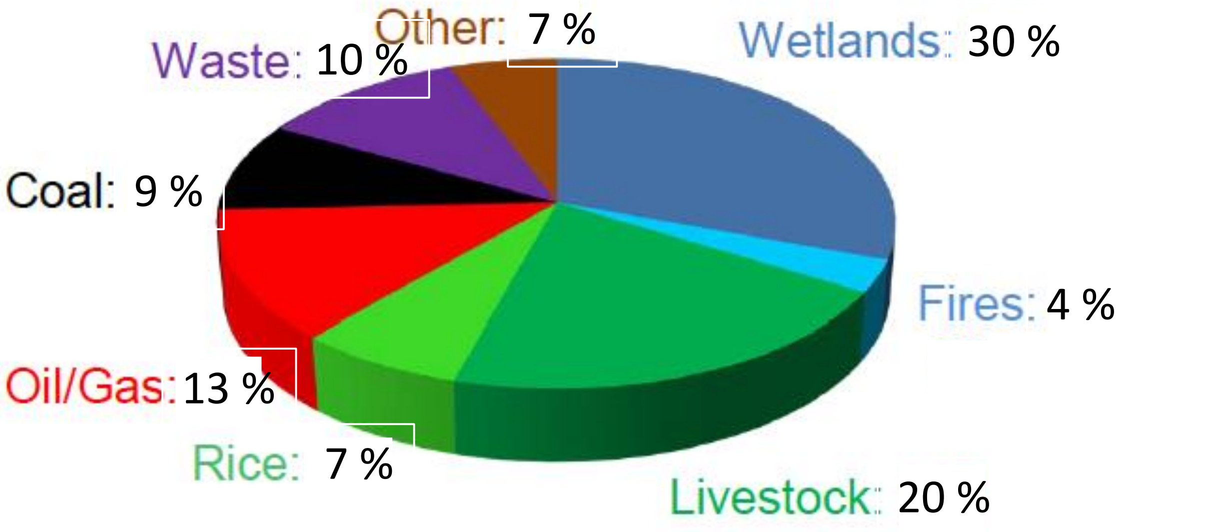


TROPOMI **1000 x** more measurements than GOSAT!!

Credits: SRON

Methane Sources

~ 40% natural



Global totals (Tg/y), EDGAR4.2 and LPJ wetlands

Joint EU-US Press Release on the Global Methane Pledge

Brussels, 18 September 2021

The European Union and the United States announced today the Global Methane Pledge, an initiative to reduce global methane emissions to be launched at the UN Climate Change Conference (COP 26) in November in Glasgow.

President **Biden** and European Commission President Ursula **von der Leyen** urged countries at the US-led Major Economies Forum on Energy and Climate (MEF) to join the Pledge and welcomed those that have already signaled their support.

In **Glasgow** at the **UN Climate Summit methane was one of the main discussion points**.

Oil/Gas

Coal

Wetlands

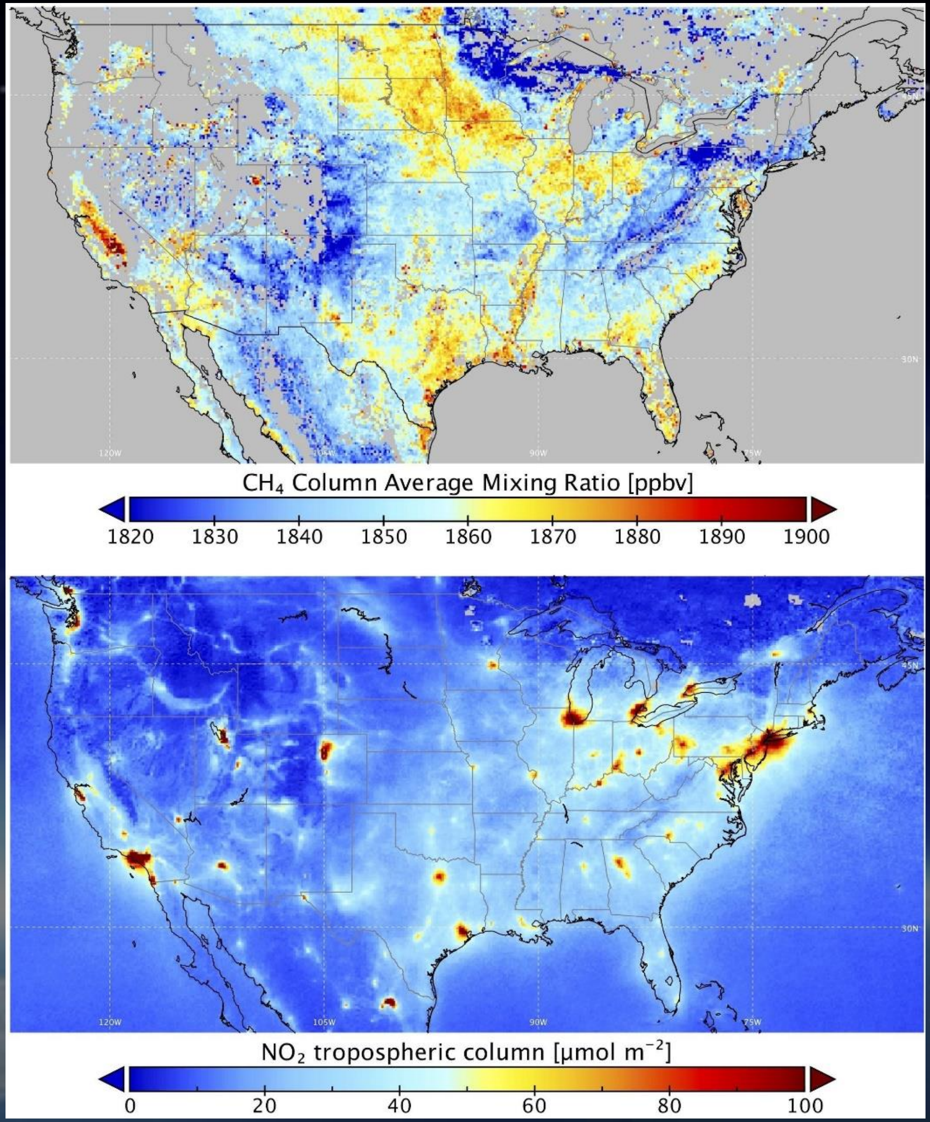
Cattle

Waste

Rice fields

Oil and Gas : TROPOMI NO2/Methane in the Permian basin

Joost de Gouw, Pepijn Veefkind et al., Nature Scientific Reports, January 2020



Average TROPOMI columns for (top) methane and (bottom) tropospheric NO_2 over the contiguous United States between 1 December 2018 and 31 March 2019. Retrieved columns have been binned on a 0.1°×0.125° latitude-longitude grid for this analysis.

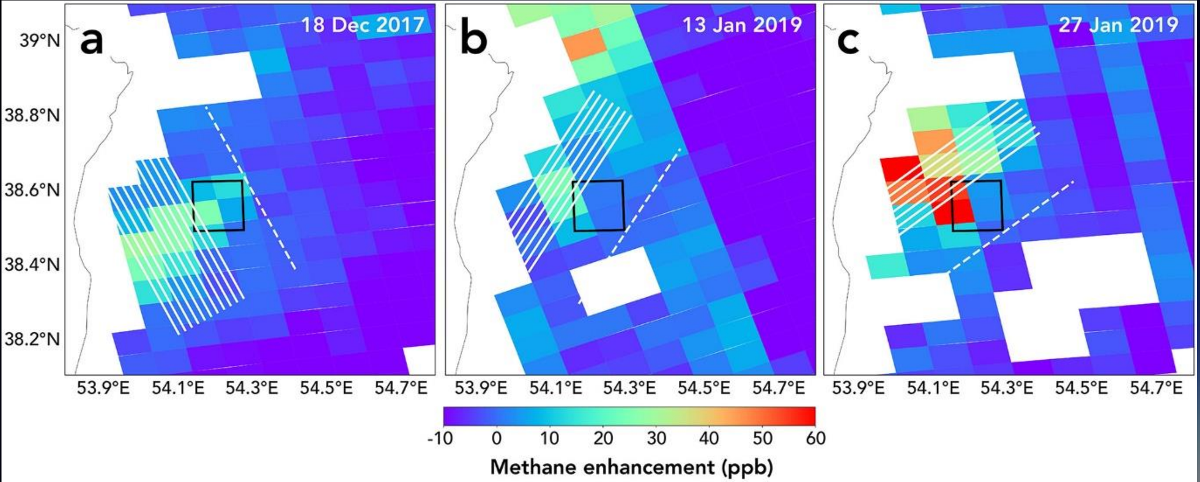
CH_4 Emissions from Oil and Gas

TROPOMI

TROPOMI

LEAKS

Turkmenistan

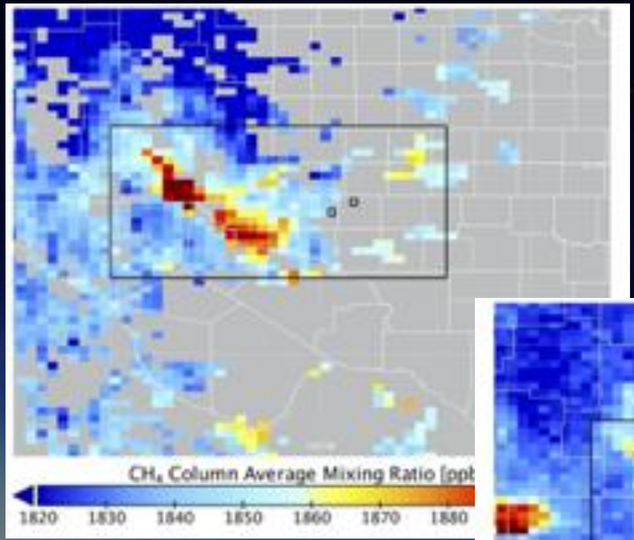


Varon et al., Geophysical Research Letters, First published: 25 October 2019, DOI: (10.1029/2019GL083798)

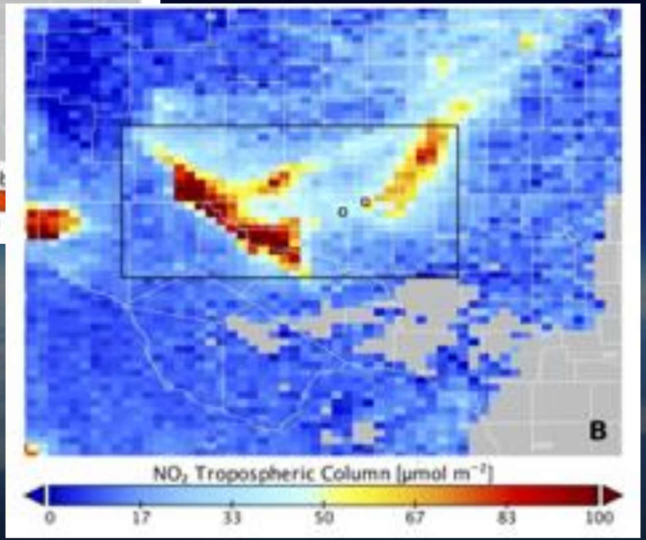
REGULAR OPERATIONS

Permian, 31 Jan 2019

CH_4



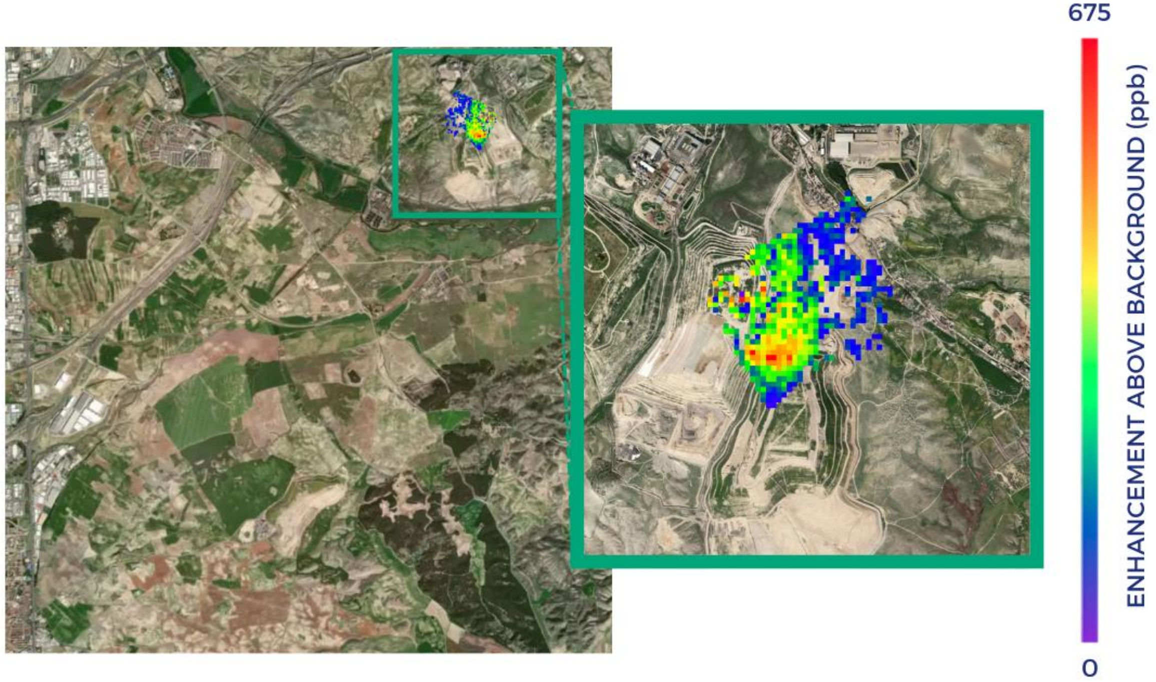
NO_2



De Gouw et al, Nature Scientific Report, 2020

ESA Satellites detect large methane emissions from Madrid landfills

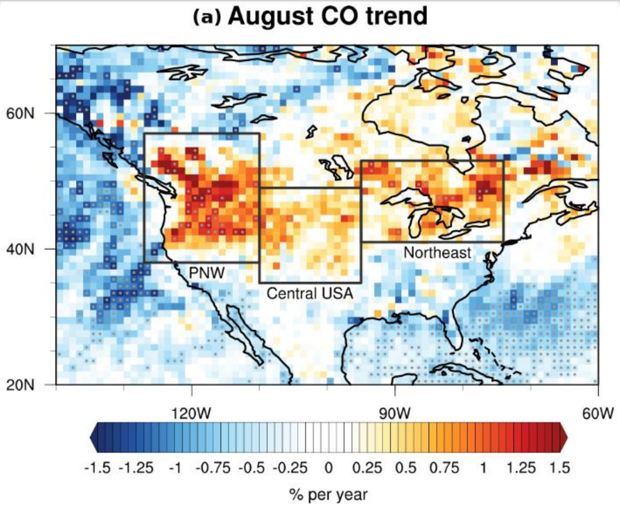
https://www.esa.int/Applications/Observing_the_Earth/Satellites_detect_large_methane_emissions_from_Madrid_landfills

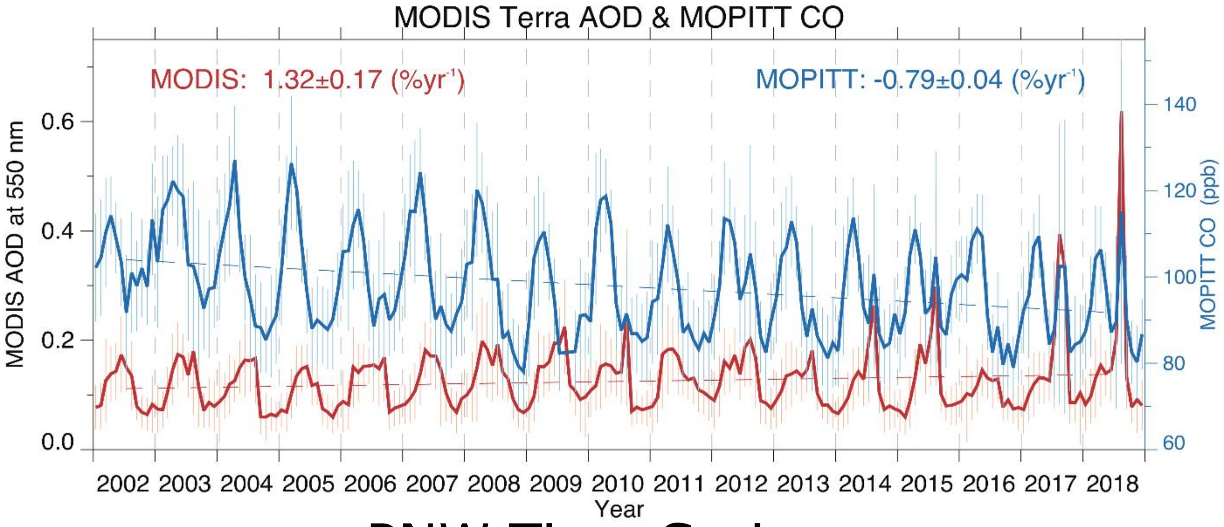


High-resolution satellites have detected substantial quantities of methane leaking from adjacent landfill sites close to the centre of Madrid, Spain. Using data from the Copernicus Sentinel-5P mission combined with GHGSat's high-resolution commercial imagery, scientists from the SRON Netherlands Institute for Space Research and GHGSat discovered both landfill sites combined emitted 8800 kg of methane per hour in August 2021 – the highest observed in Europe by GHGSat

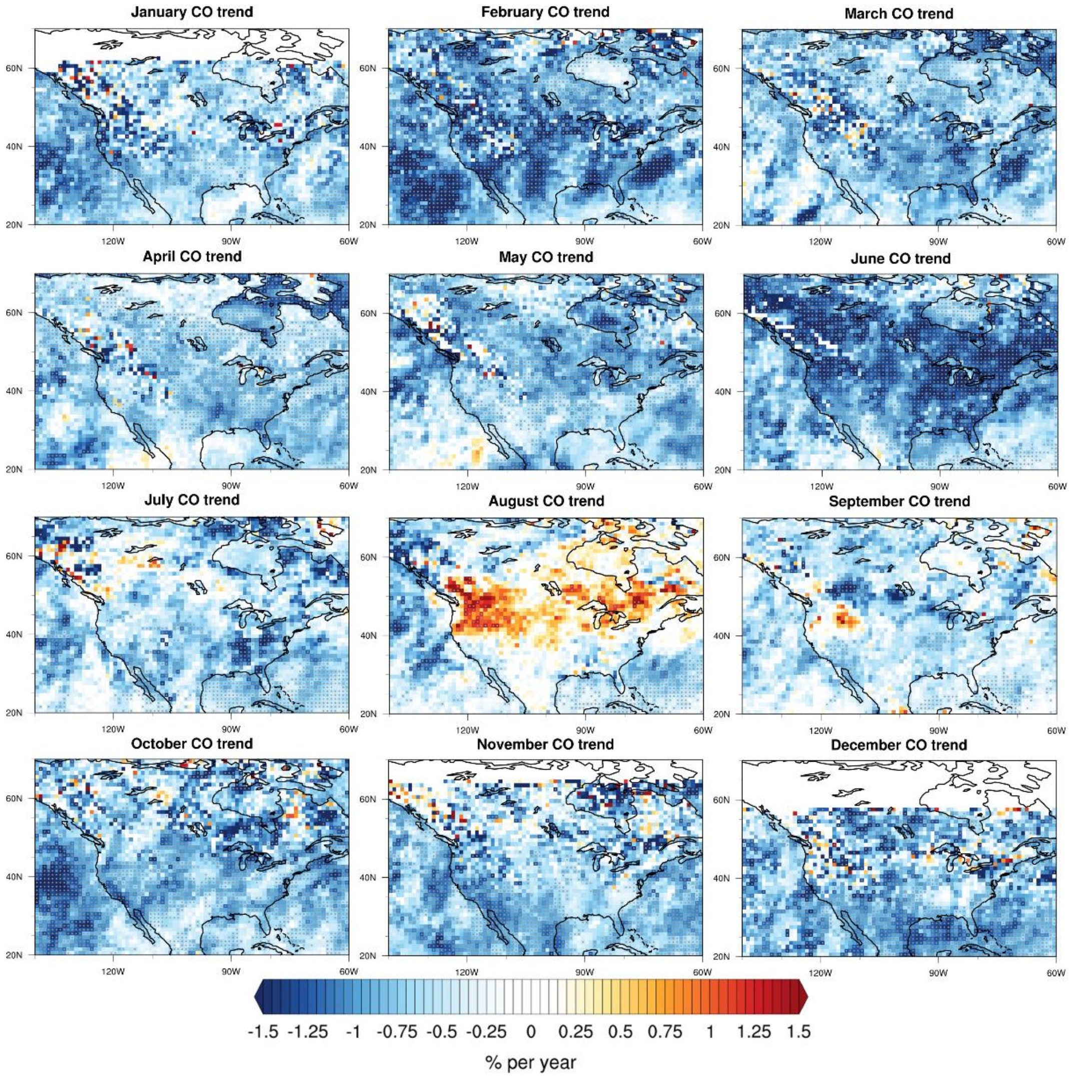
Change in CO seasonal cycle due to Pacific Northwest (PNW) Fire trends

August CO trends (2002-2018)
Boxes indicate PNW, Central and Northeast regions



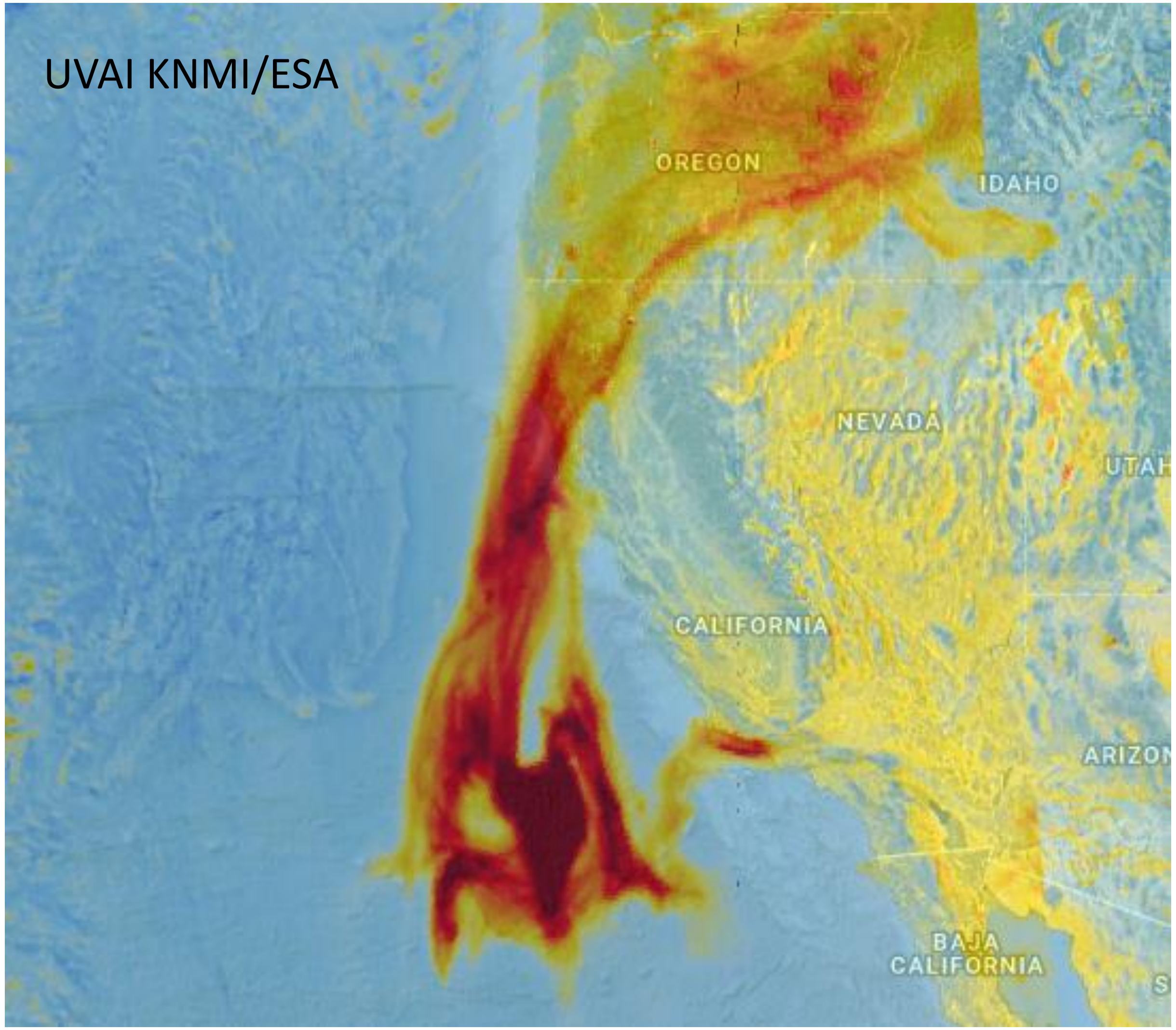


PNW Time Series



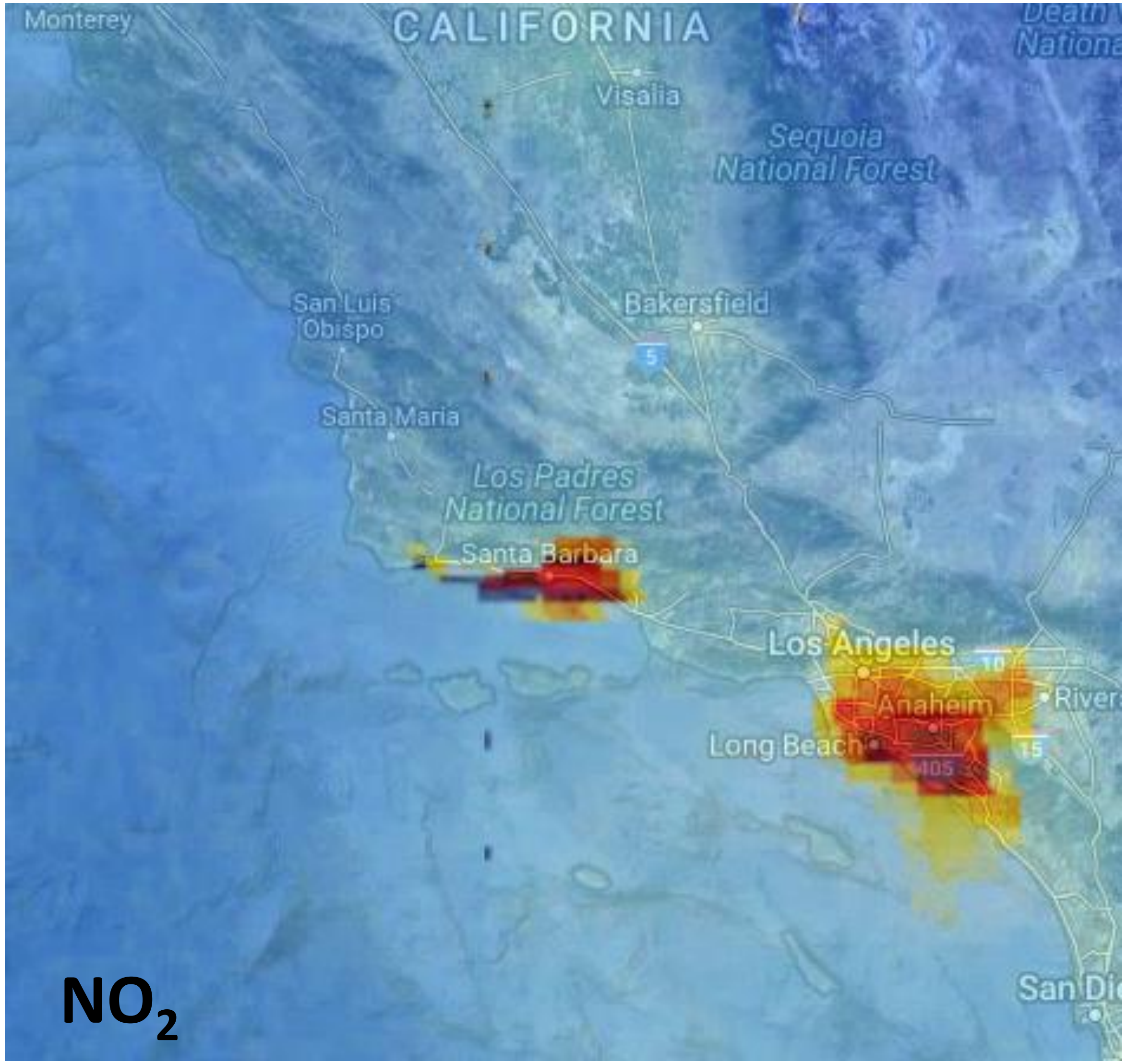
Buchholz et al., 2021, Nature Communications 2022

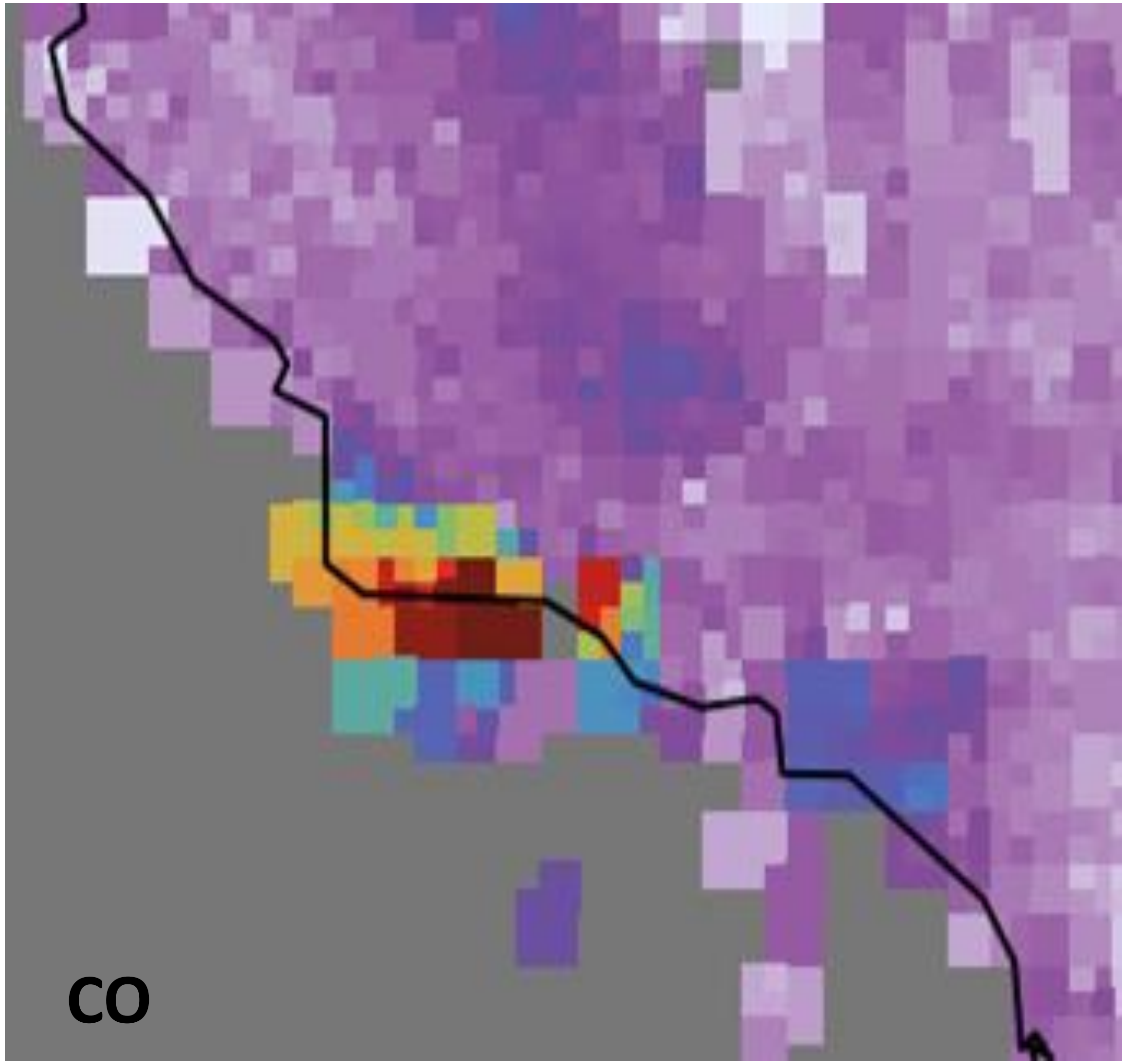
Forest Fires California 12-12-2017



Forest Fires California 12-12-2017

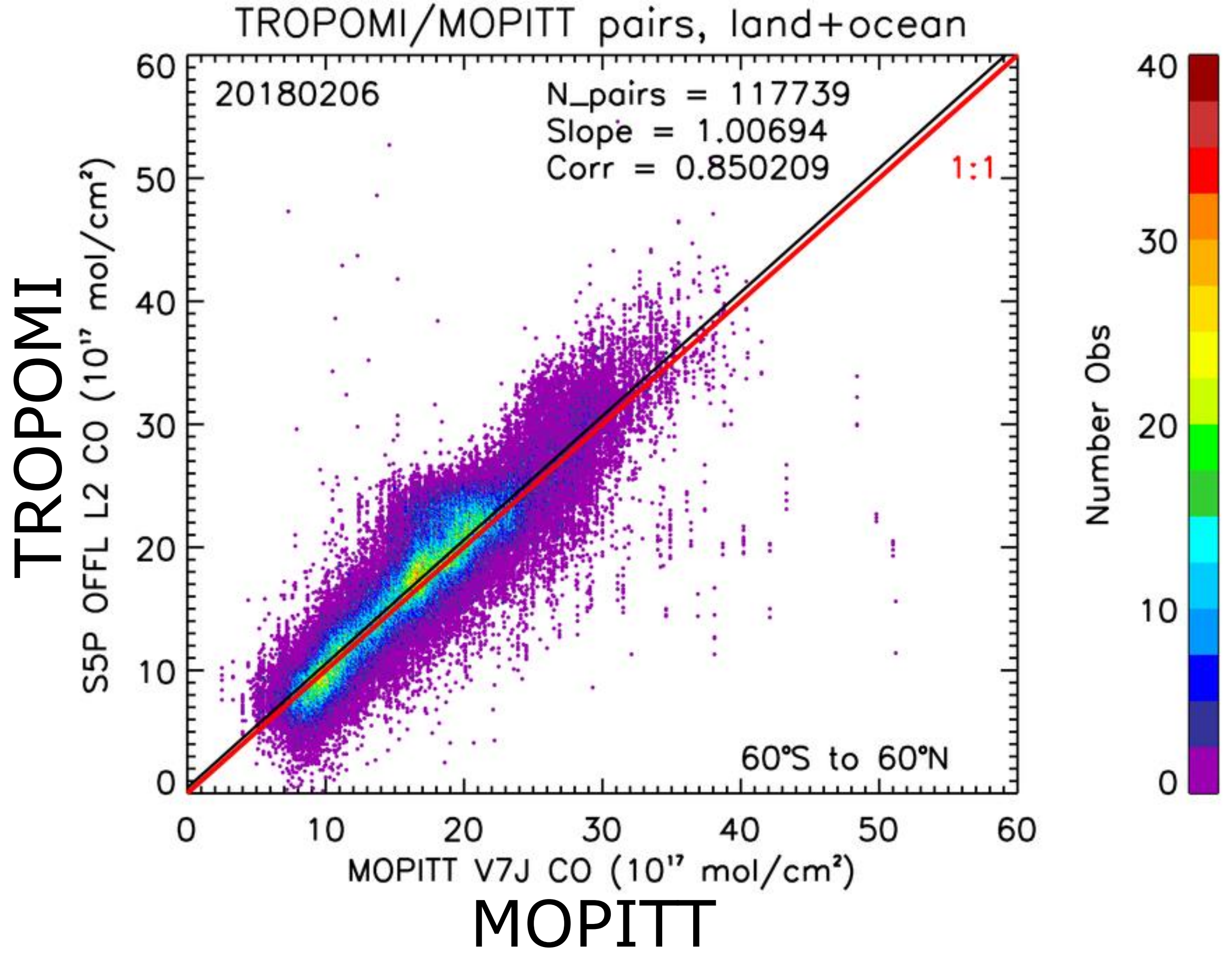
KNMI/SRON/ESA

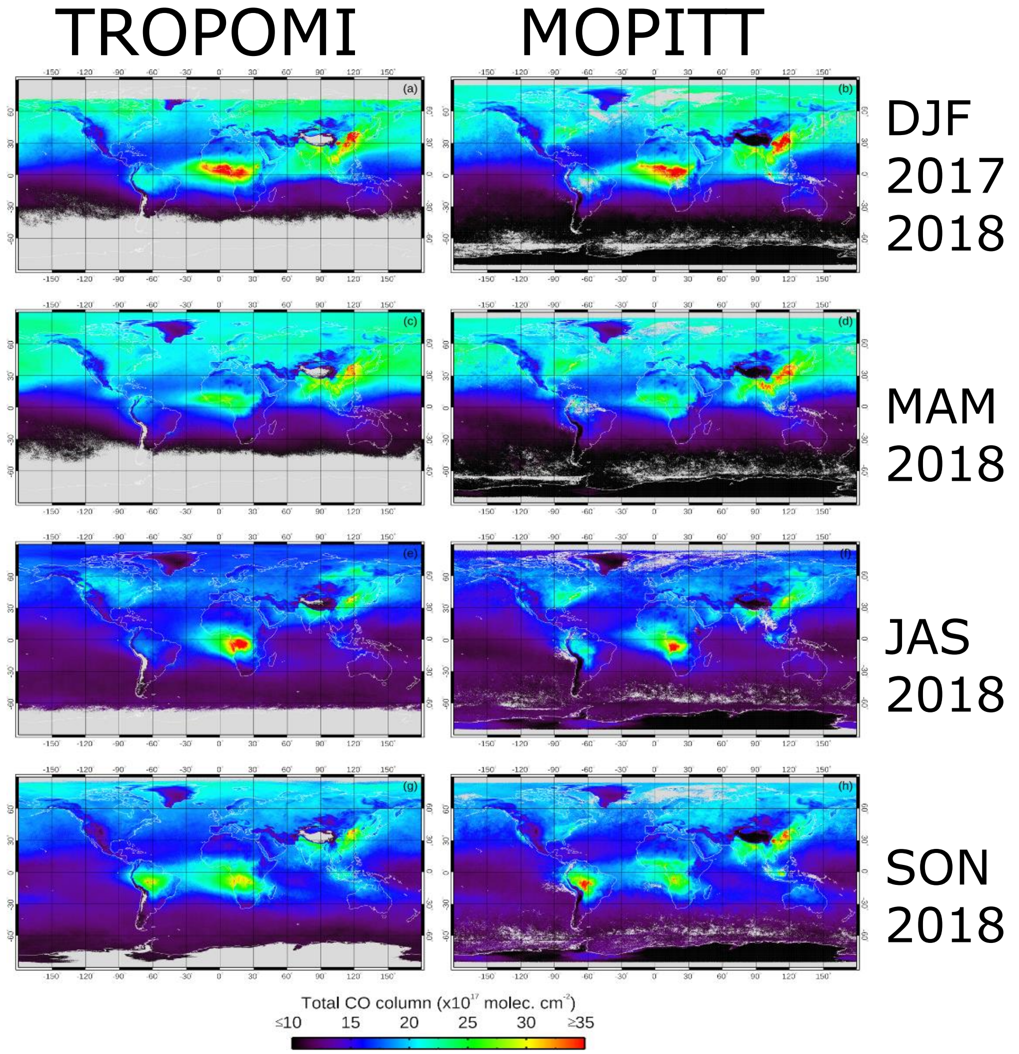




TROPOMI CO comparison to MOPITT

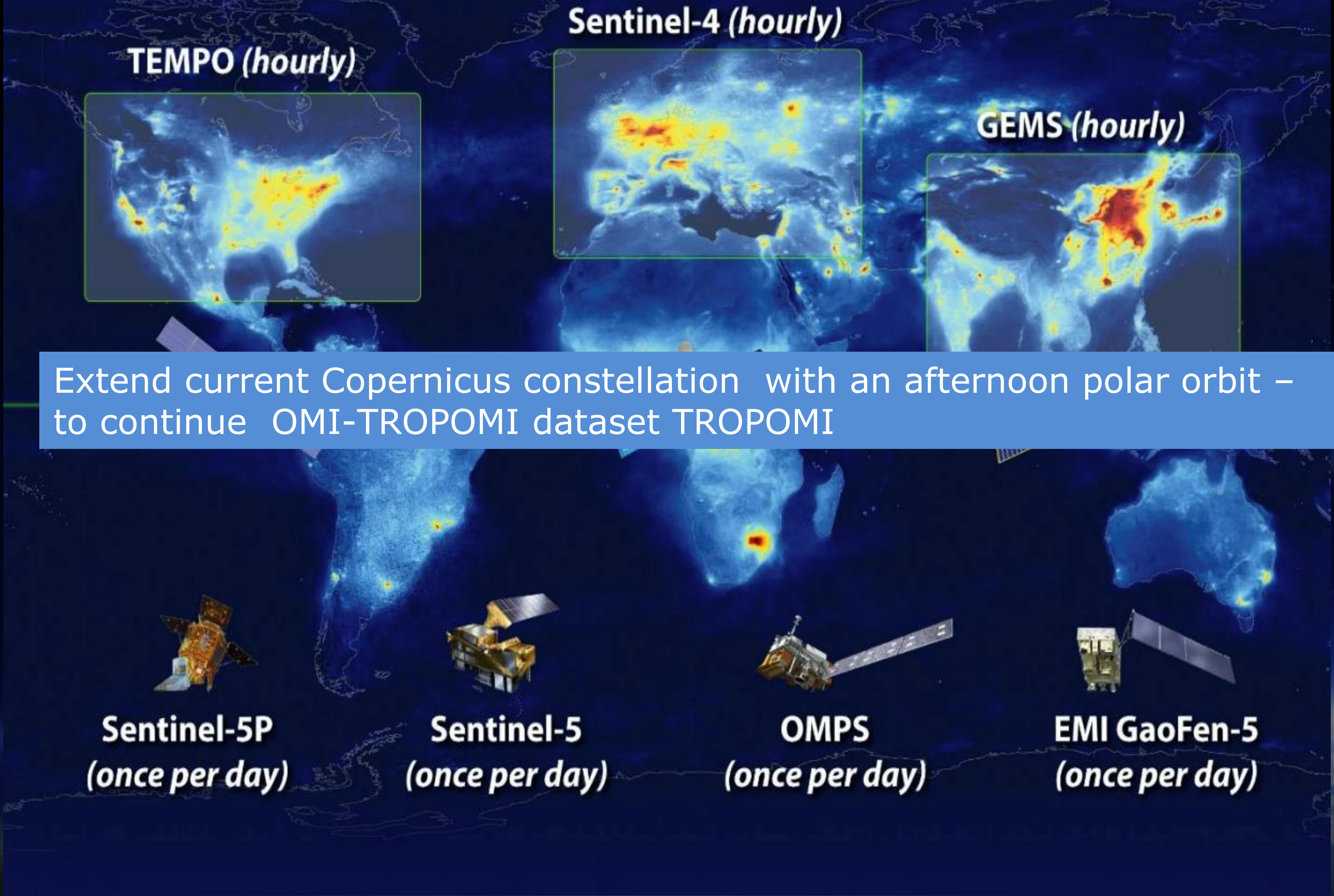
Single day comparison: 2018.02.06



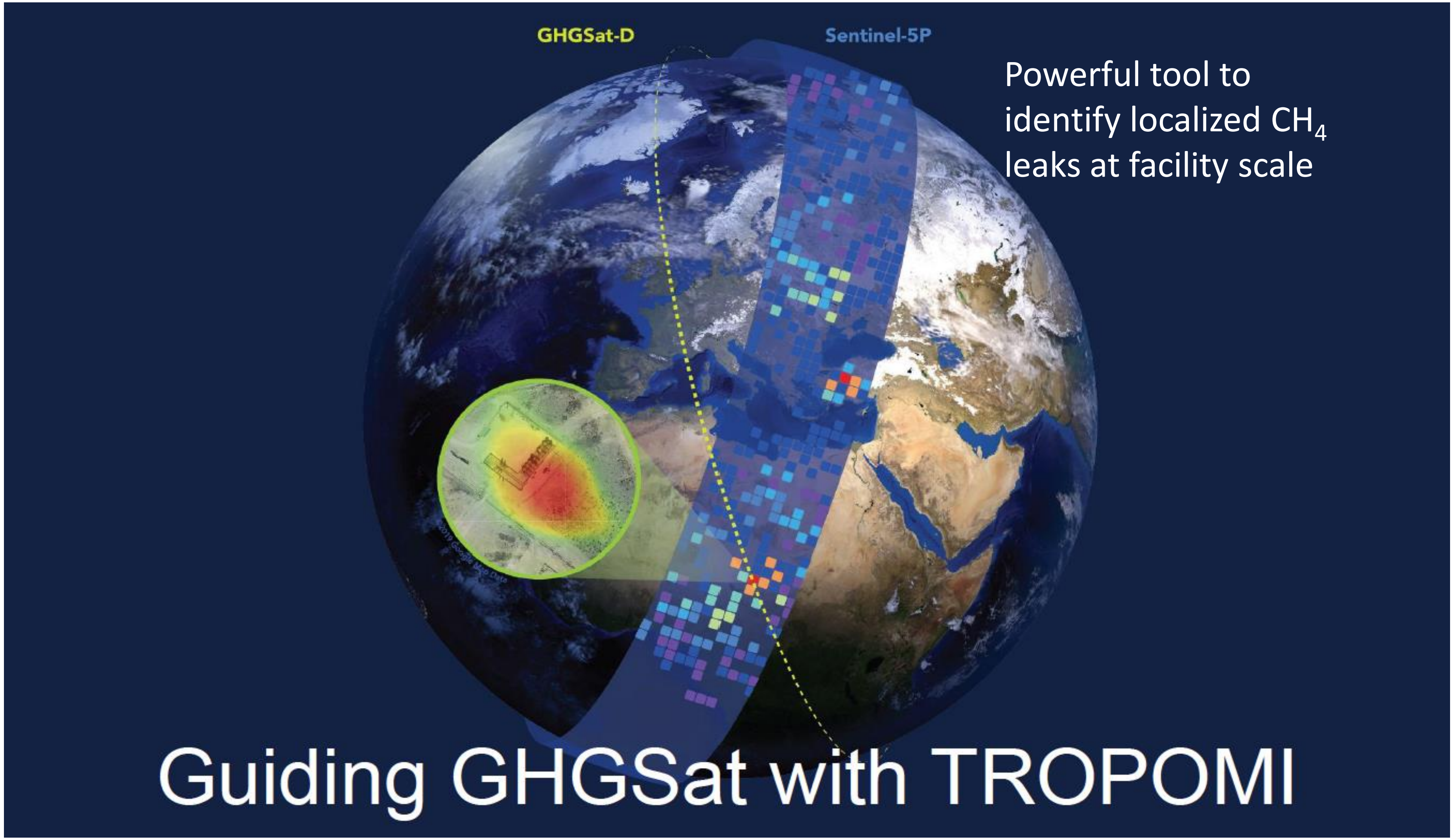


Global Atmospheric Chemistry Constellation

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



SYNERGY TROPOMI and commercial satellites

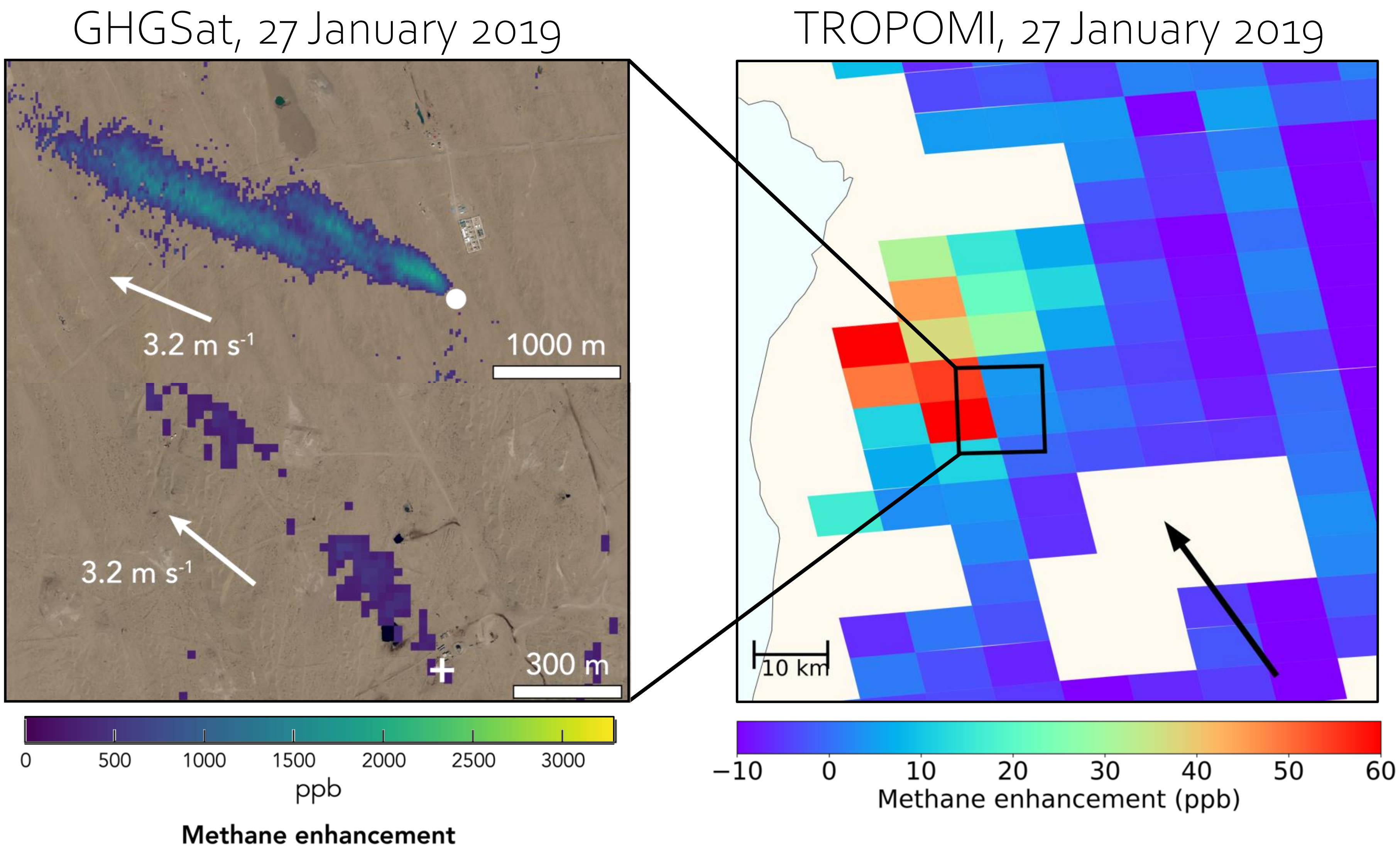


Powerful tool to identify localized CH_4 leaks at facility scale

GHGSat
GLOBAL EMISSIONS MONITORING

Satellite discovery of large gas leaks

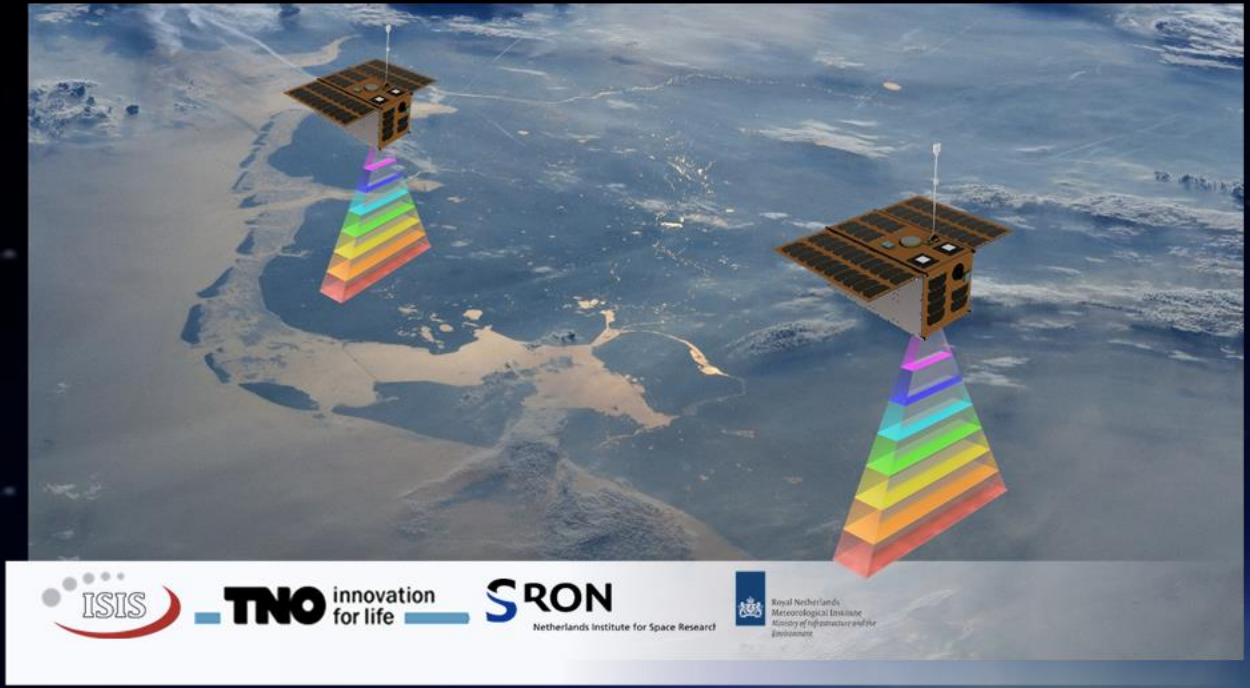
NOS News on television at 20:00, Friday November 22, 2019



Paper out now in GRL: Varon et al. (2019)

TANGO
a potential constellation of high spatial resolution emission monitoring

TROPOMI



TANGO (https://www.youtube.com/watch?v=hOS3cm1BKuU) will zoom in on user-selected targets with a spatial resolution of 300x300 m^2 for CH_4, CO_2 and NO_2

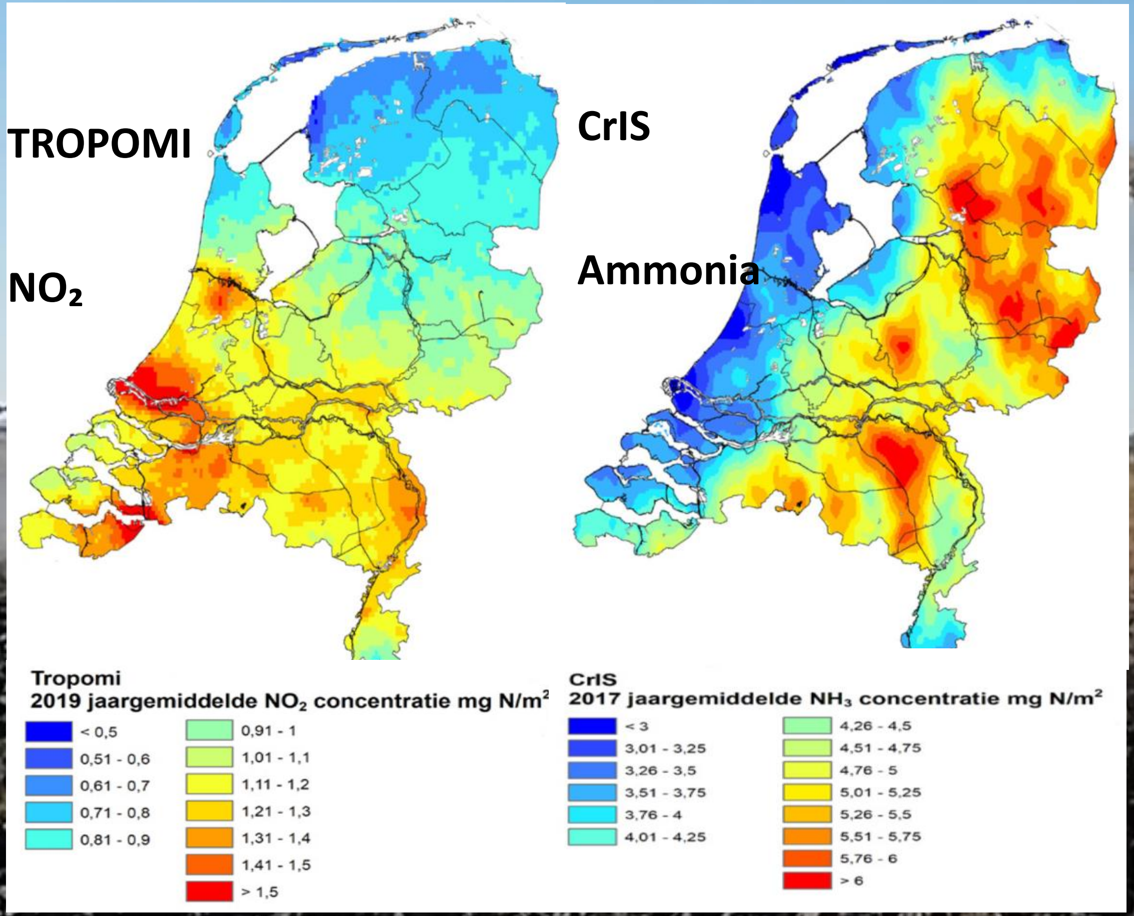
To be funded

EU supports UNEP in establishing an independent International Methane Emissions Observatory (IMEO). IMEO will play an important role in creating a sound scientific basis for methane emissions calculations and delivering the Global Methane Pledge in this regard. TANGO (still to be funded) could play an important role in this by forming together **a constellation of high spatial resolution emission monitoring of methane (& CO2) emissions.**

Nitrosat (ESA's Earth Explorer program):

Mapping reactive nitrogen (NH3 and NOx) on farm scale resolution from space (500x500 m^2)

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



Synchronized imaging of NH_3 and NO_2 at a spatial resolution of 500 x 500m^2 and a Bi-monthly revisit time for detecting seasonal impacts

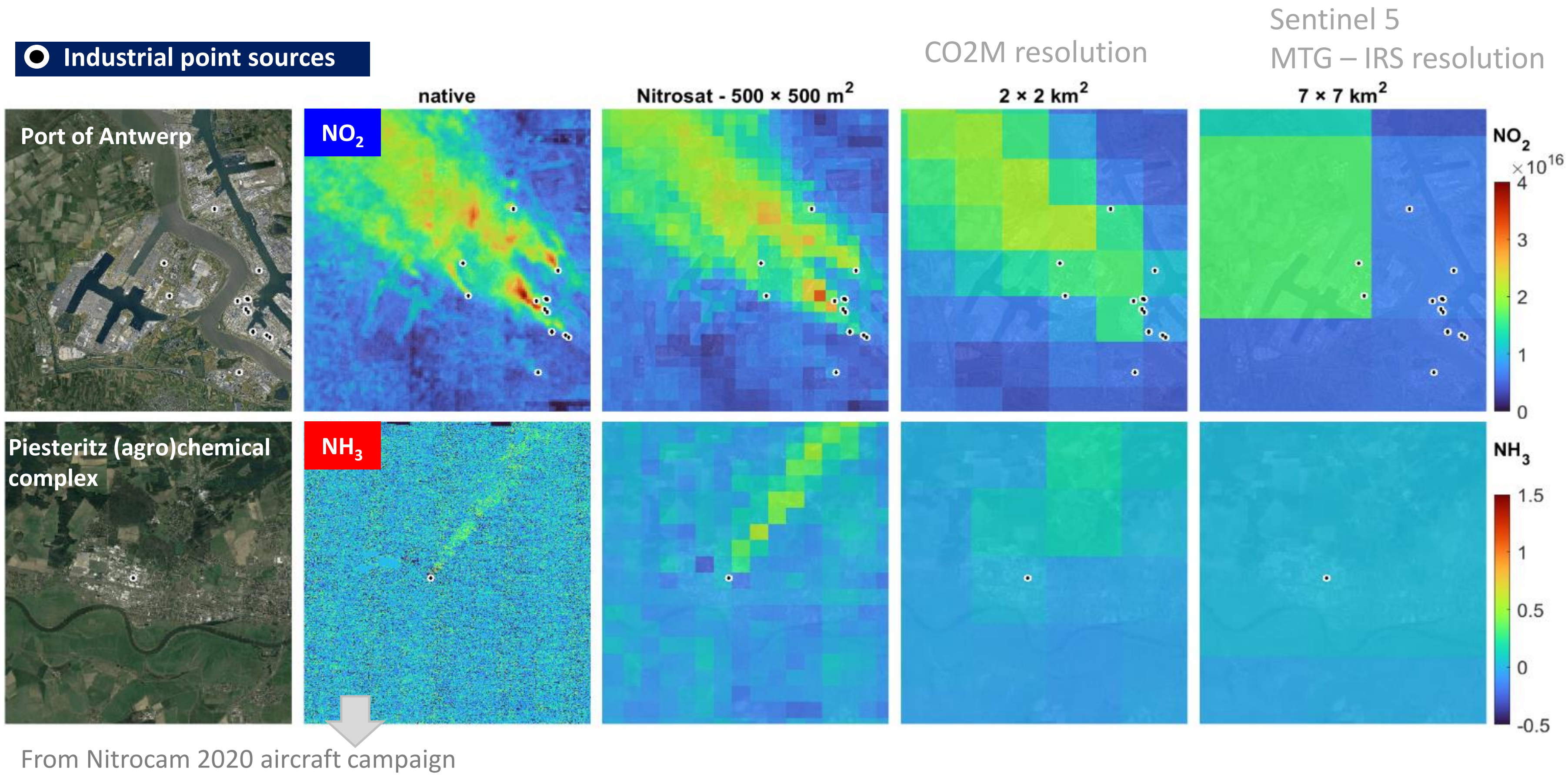
NH_3 Infrared imaging Fourier Transform Spectrometer

- 900-1000 cm^{-1} spectral range
- 0.625 cm^{-1} spectral sampling
- NeDT < 0.38 K

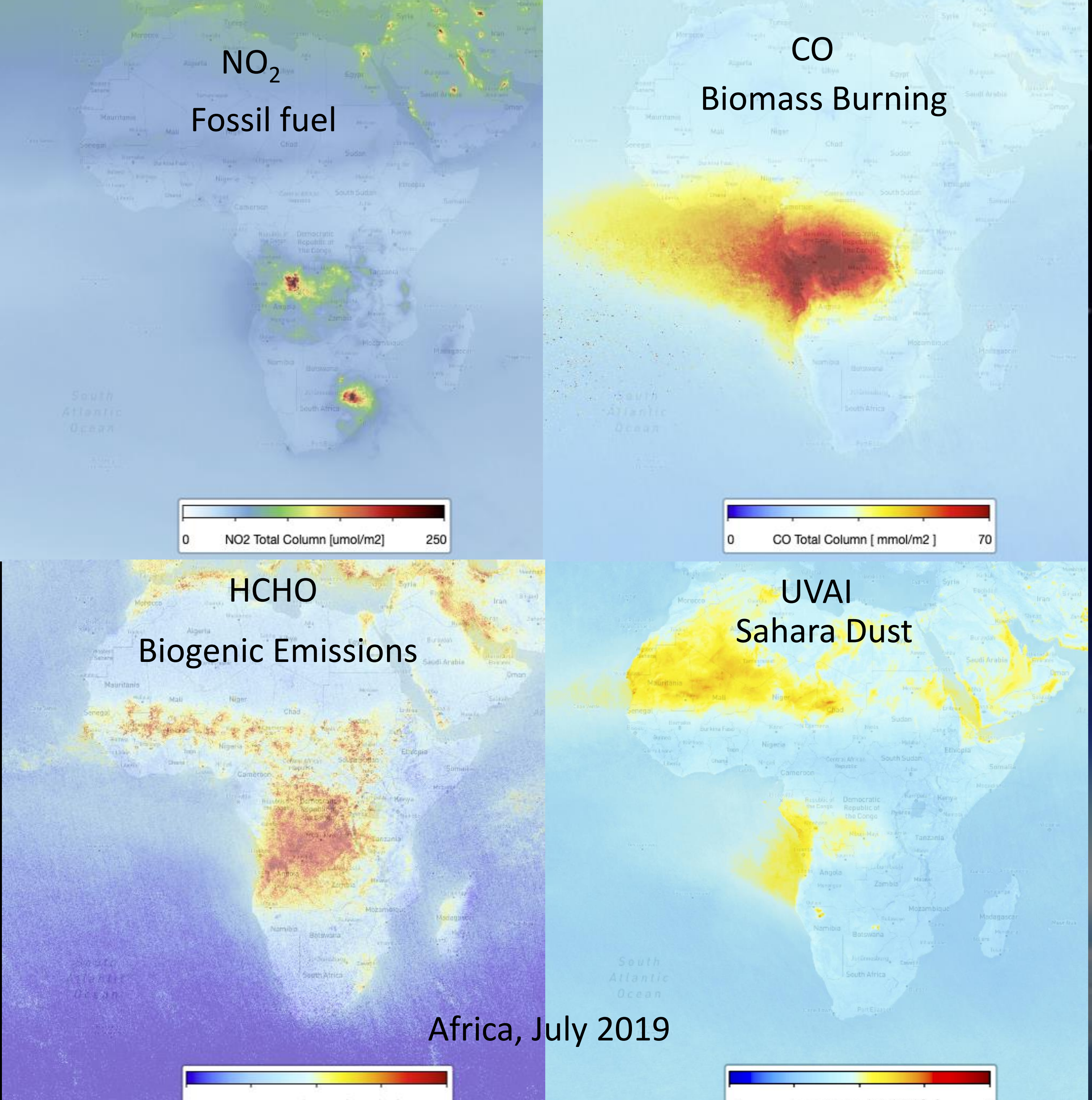
NO_2 Visible Imaging Pushbroom Spectrometer

- <405-500 nm spectral range
- 0.5 nm spectral resolution
- SNR 600-800 (cloud free)

Nitrocam aircraft campaign 2020
Science and mission objectives



Landscape scale: a remaining gap for measuring reactive nitrogen



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

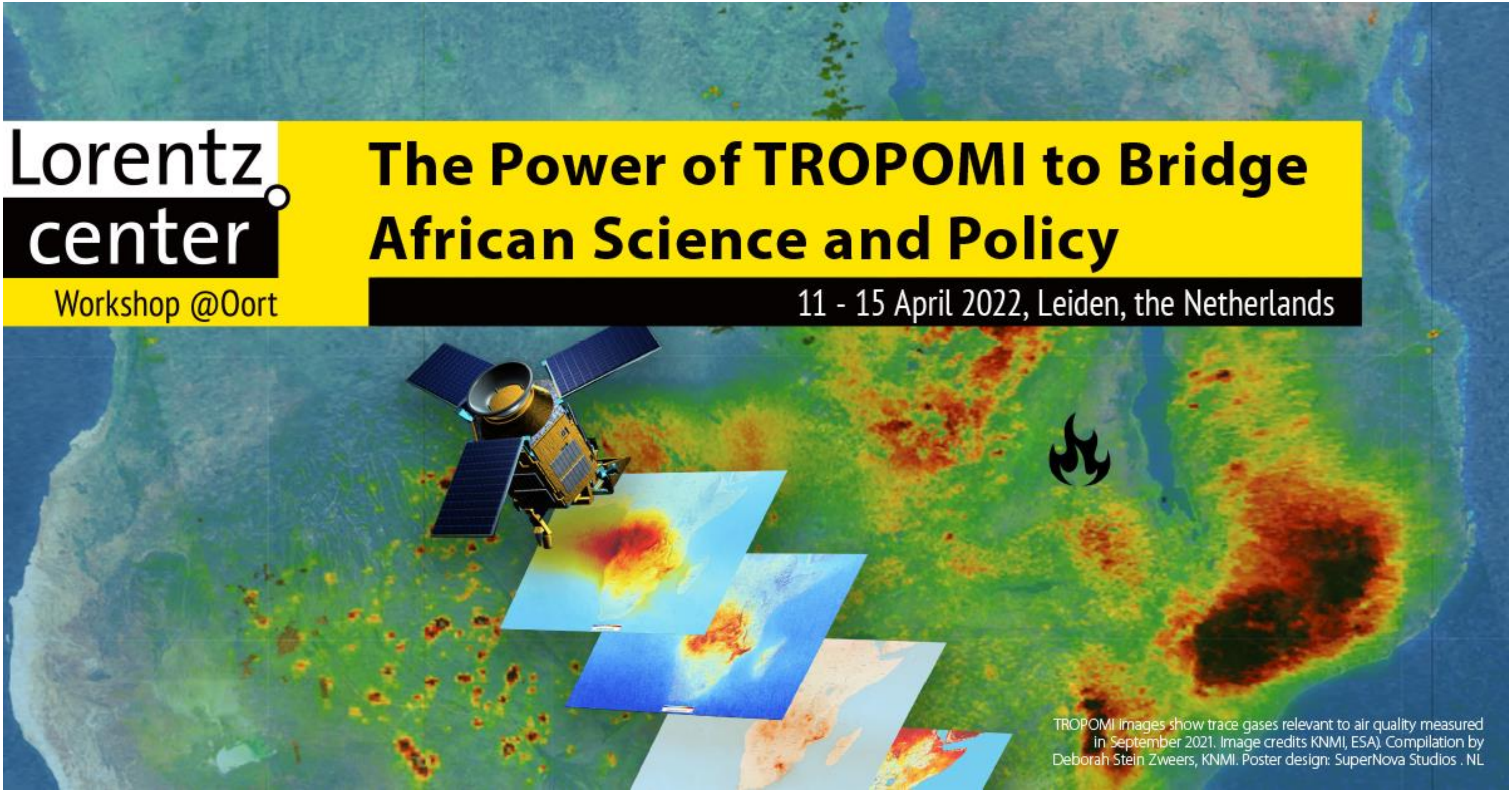
Workshops last 2 years:

Advancing air quality and carbon science in Africa (Ben Gaubert – March 2021)

Workshop on a pilot design for air quality in Africa (Solomon Bililing – June 2021)

Lorentz Workshop on Africa , April 11-15 , 2022 at Leiden University (KNMI, TU Delft, Africa Institute Leiden, NCAR)

IGAC: Long standing tradition with Africa subgroup including scientists from Africa


Lorentz center
Workshop @Oort
The Power of TROPOMI to Bridge African Science and Policy
11 - 15 April 2022, Leiden, the Netherlands
TROPOMI images show trace gases relevant to air quality measured in September 2021. Image credits KNMI, ESA). Compilation by Deborah Stein Zweers, KNMI. Poster design: SuperNova Studios . NL

NEW YORK TIMES: RACE TO THE FUTURE

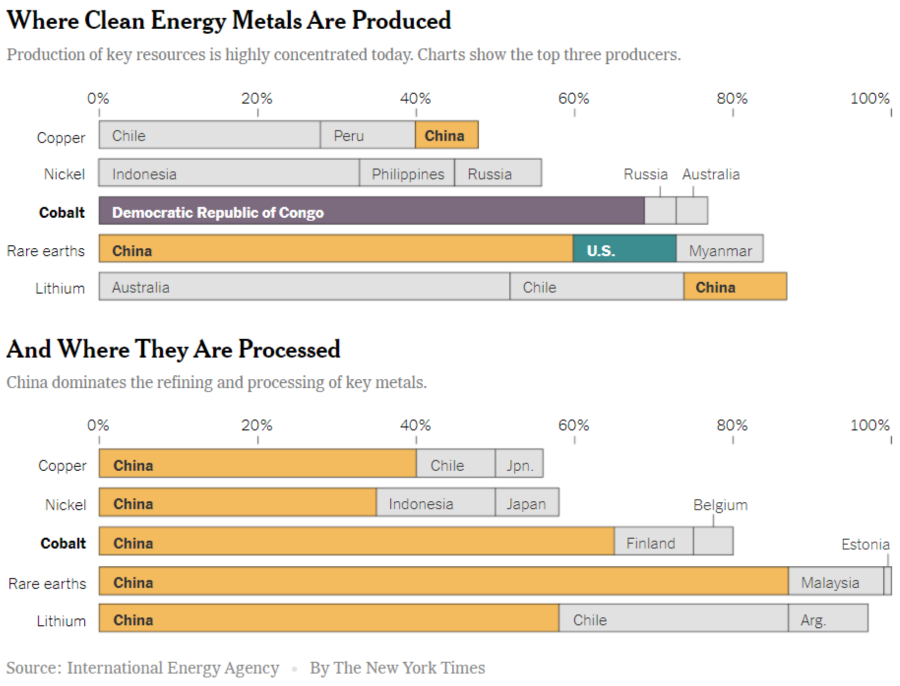
A Power Struggle Over Cobalt Rattles the Clean Energy Revolution (21 nov 2021)

Race to the Future: What to Know About the Frantic Quest for Cobalt (20 nov 2021)

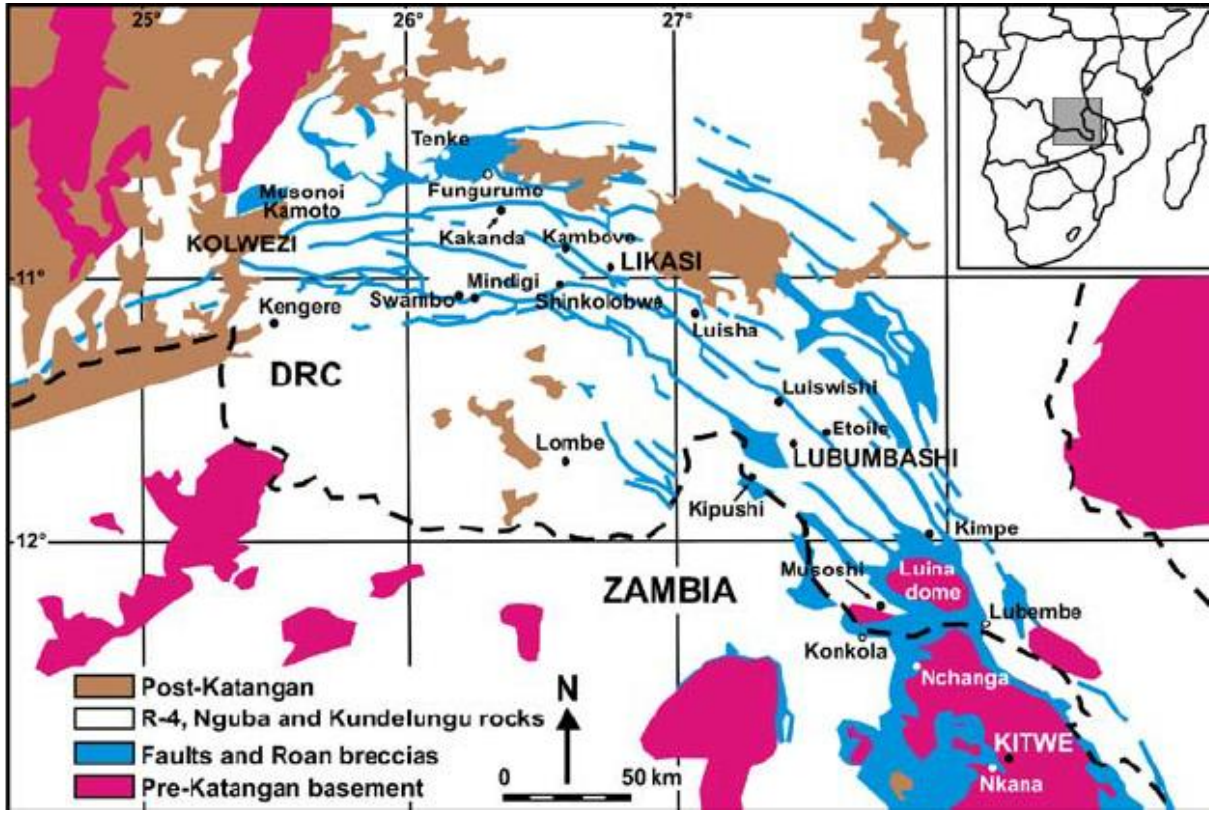
By Dionne Searcey, Michael Forsythe and Eric Lipton

An industrial cobalt and copper mine in mineral-rich Congo.

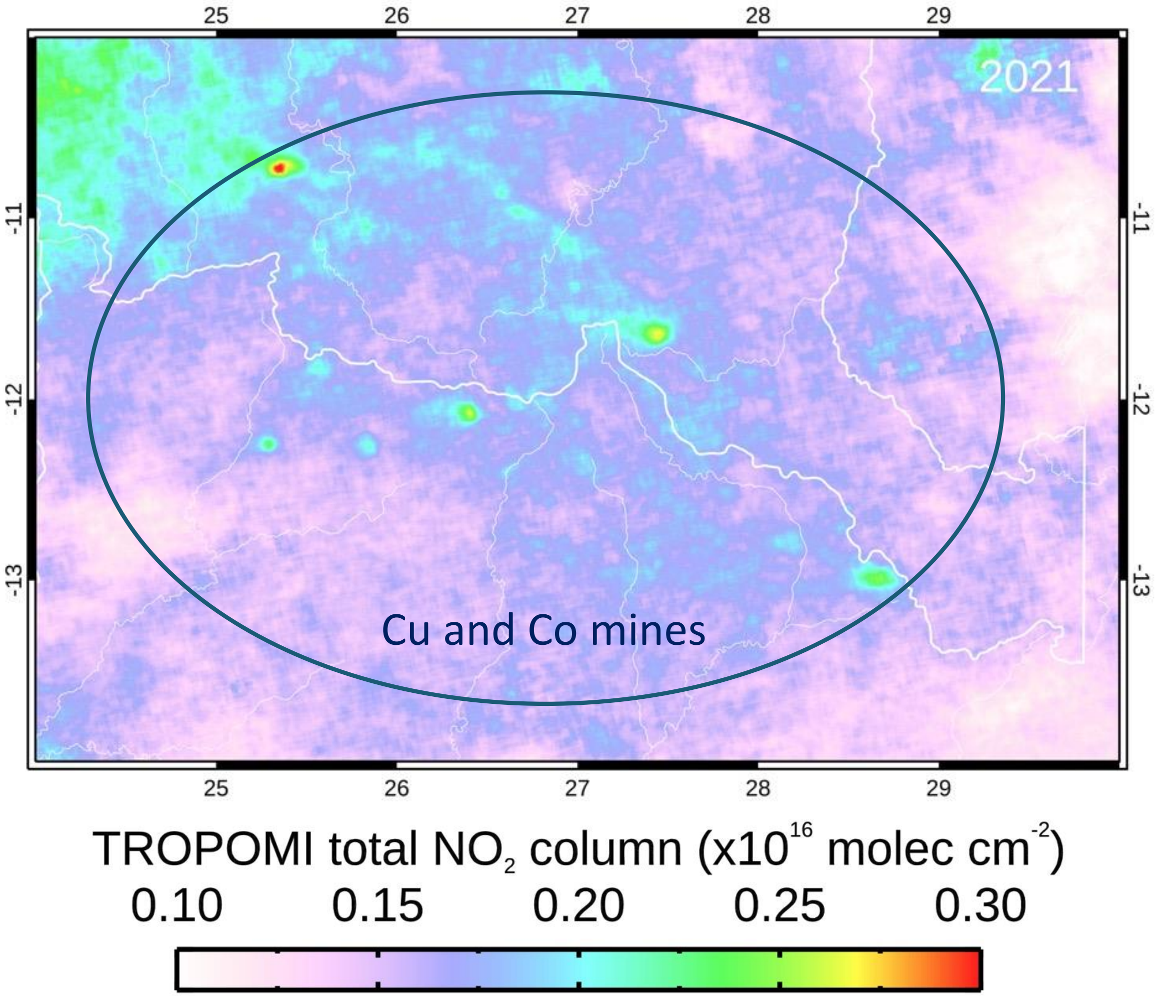
Credit Ashley Gilbertson for The New York Times



Results: TROPOMI NO2 captures mining activities for green energy over Africa.



(Geological map from Muchez *et al.*, 2008)



Sara-Eva Martinez-Alonso[1], Pieternel Levelt[1], Wenfu Tang[1], Helen Worden[1], Louisa Emmons[1], Henk Eskes[2], Pepijn Veefkind[2], Joost de Gouw[3] Nicolas Theys[4]
NCAR, KNMI, TU Delft, CU Boulder, BIRA

Summary

- The Netherlands has an international leading position in measuring the atmospheric composition from space:

  Dutch Clean Air initiative (KNMI, SRON, TUDelft and TNO)
- OMI and TROPOMI led to new findings in the air quality & health domain
- Air Quality and Greenhouse gas emissions can nowadays be monitored from space, important for the Paris agreement
- The Netherlands is working towards emission monitoring from space on a < 500 x 500 m2 spatial resolution.
- New satellite initiatives presented:
  - Nitrogen Deposition (ESA Earth Explorer- final selection 2025)
  - TROPOMI follow-on (KNMI, SRON, TNO, TUD, Airbuss)
  - TANGO (KNMI, SRON, TNO, ISIS)
  - Africa (NCAR, KNMI)
- **Emission regulation have been proven effective**

TROPOMI

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www.knmi.nl/omi

sentinels.copernicus.eu

#tropomi

Copernicus
Europe's eyes on Earth