Introduction on Earth Observation Activities at ESA, EUMETSAT and ECMWF

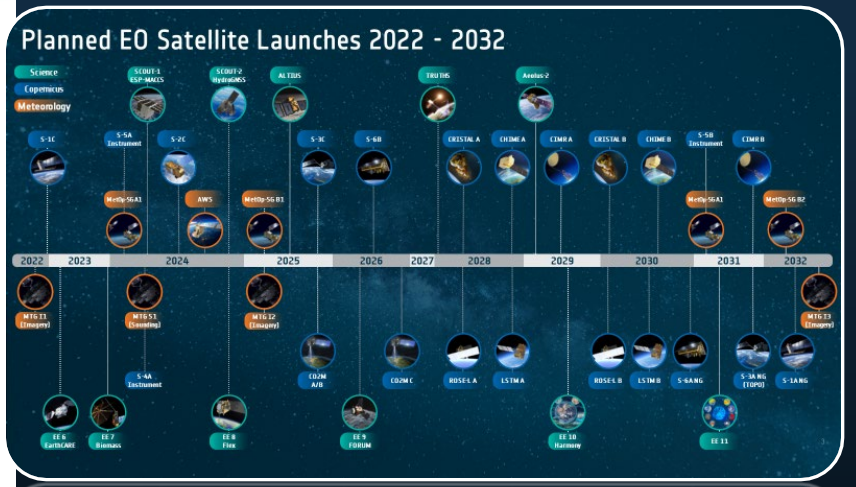
Christian Retscher, ESA
Fedrico Fierli, EUMETSAT
Mark Parrington, ECMWF

Fifth Joint School on Atmospheric Composition
September 14 – 29, 2023

https://atmostraining.info/, https://atmostraining2023.esa.int/

Achieving ESA's EO Vision

Building satellites



Managing Missions

Handling Data

Science

Emergency Response

Climate Change

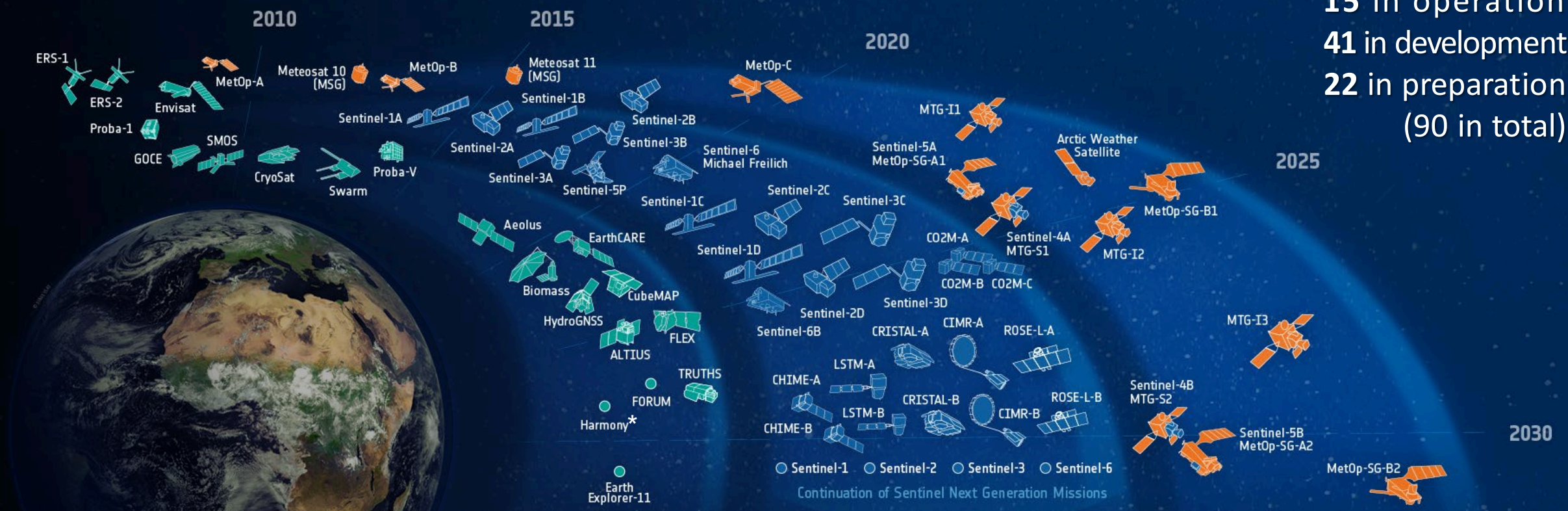
Commercialisation

Applying the Data

ESA's Earth Observation Mission

Satellites

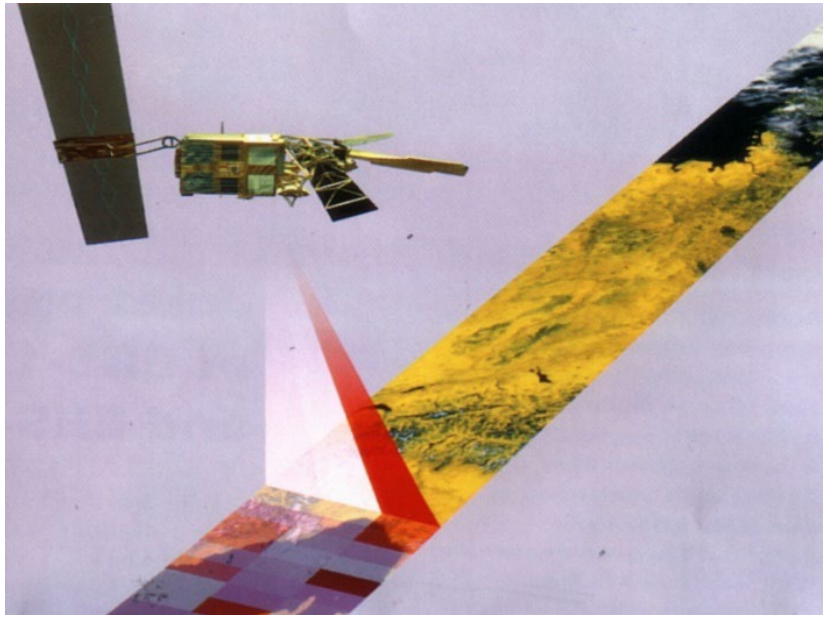
12 in heritage
15 in operation
41 in development
22 in preparation
(90 in total)

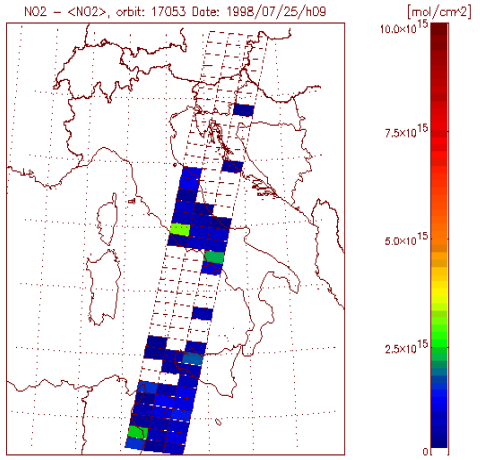


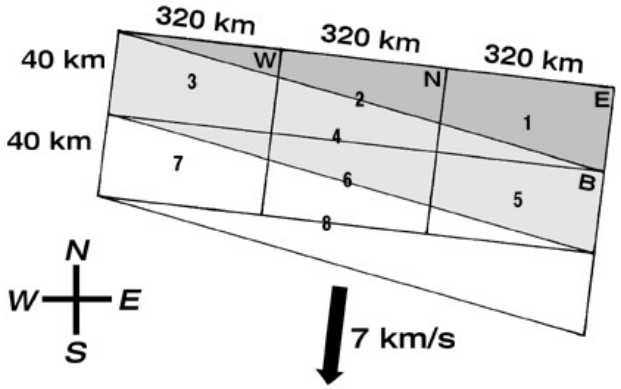
Science esa | Copernicus | Meteorology EUMETSAT

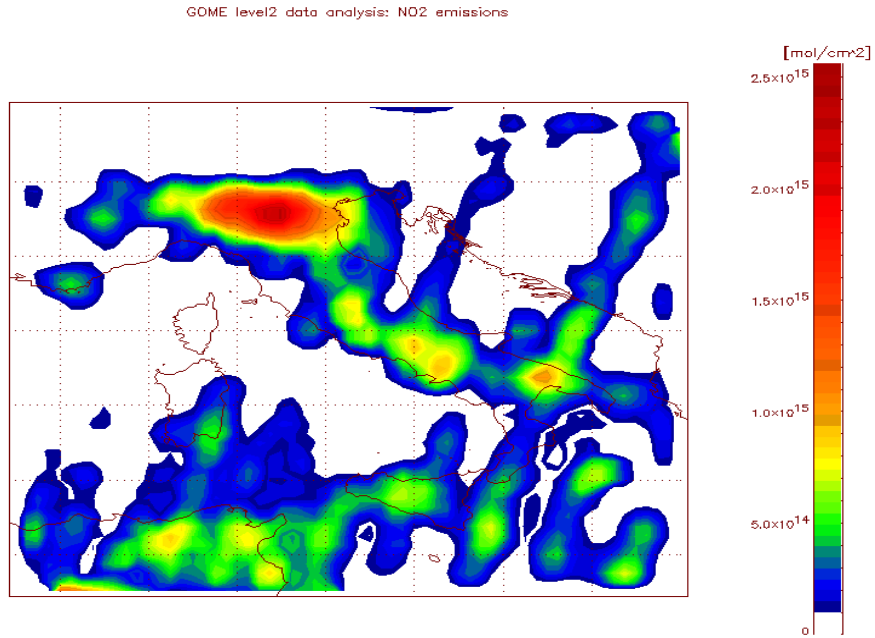
*Pending final mission selection

Heritage: ERS-2 Global Ozone Monitoring Experiment (GOME)









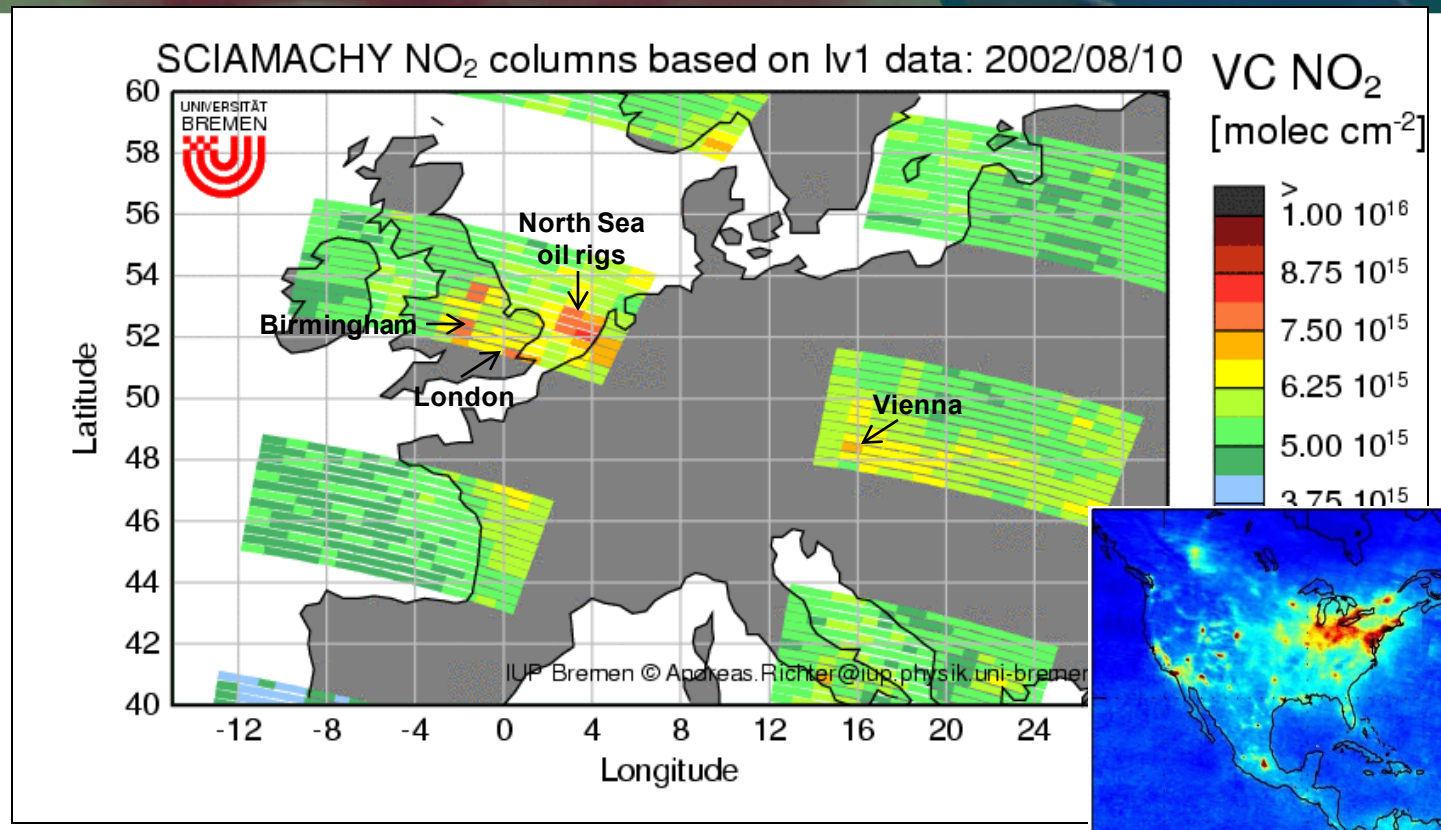
Nadir viewing spectrometer: GOME on ERS-2 **launched 1995** operational for 16 years; later similar instruments are SCIAMACHY and GOME-2

- **Spectral Coverage:** 240 - 790 nm
- **Spatial Resolution:** 40 x 320 km, global coverage 3d

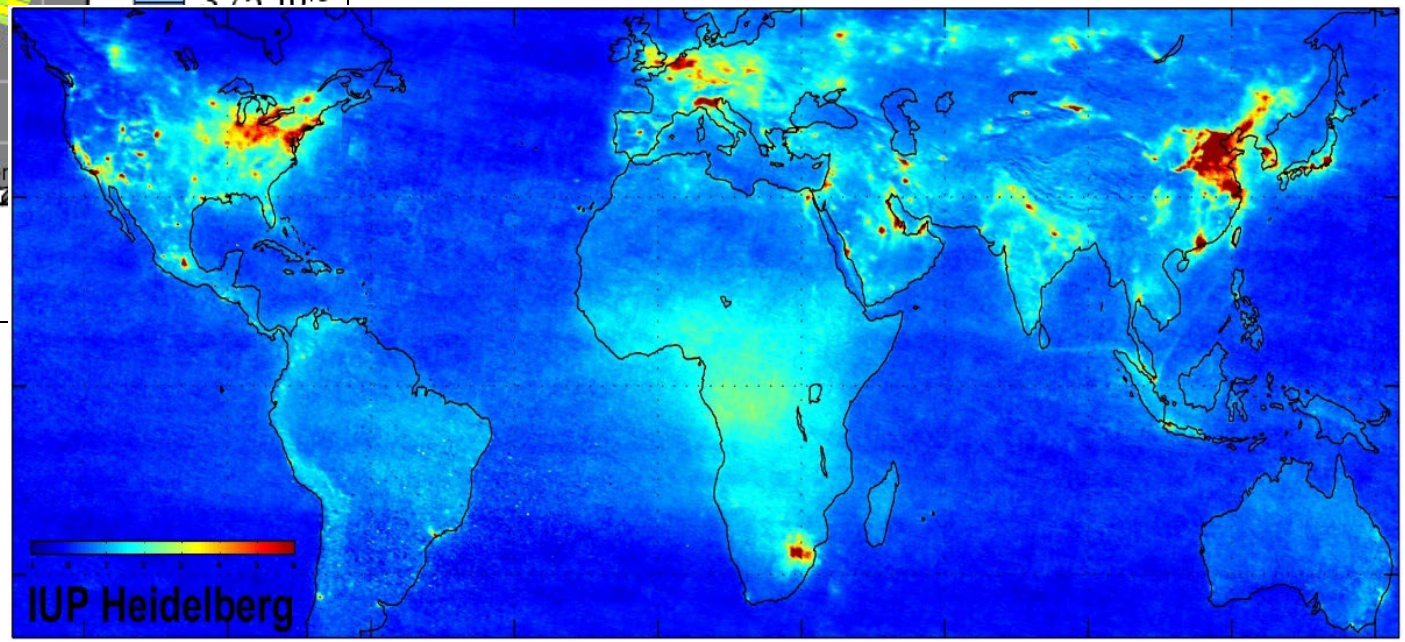
Industrial Air Pollution over the Mediterranean Sea derived from GOME NO_2 measurements – Credits: EMPA

- **Single Acquisition (left):** 25/07/1998 NO2
- **3 months average (right):** June - August 1998

Heritage: Envisat SCIAMACHY NO_2 measurements

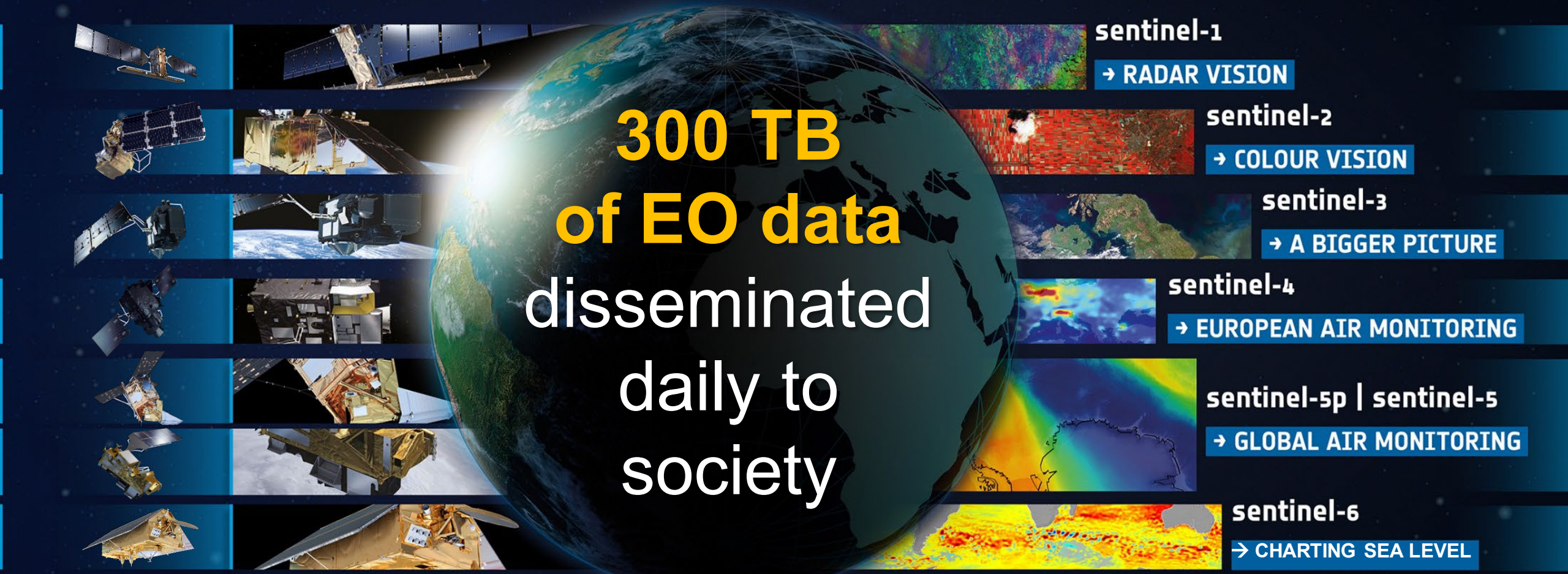


SCIAMACHY Nitrogen Dioxide (NO_2) Measurements averaged over 18 months (mid 2002 – end 2003)



NO2 -> 'Dirty atmosphere'
= Air pollution

Copernicus Sentinels (First Generation)



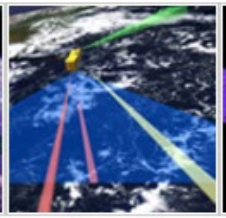
300 TB of EO data disseminated daily to society

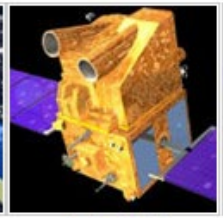
Earth Explorers

→ THE EUROPEAN SPACE AGENCY

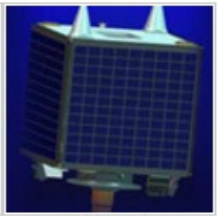
Third Party Missions

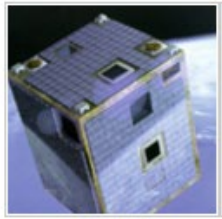

ALOS

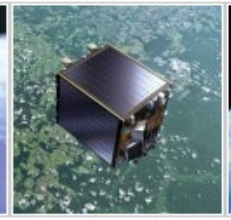

Aura OMI


CartoSat-1

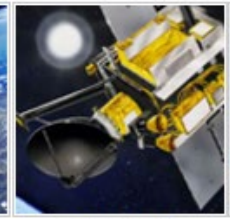

COSMO-SkyMed

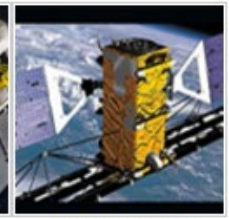

Deimos-1


Proba-1


Proba-V


QuickBird

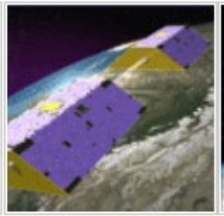

QuikSCAT


RADARSAT-2


Deimos-2

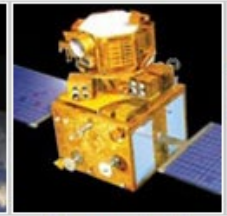

GeoEye-1

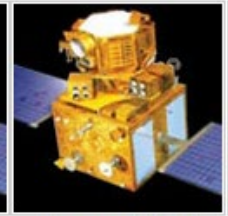

GOSAT

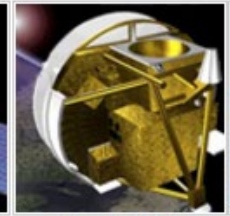

GRACE


IKONOS


RapidEye


ResourceSat-1


ResourceSat-2


SciSat-1/ACE


SeaSat


IRS-1C

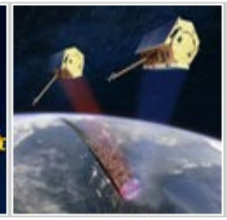

IRS-1D

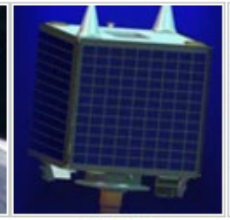

JERS-1


KOMPSAT-1

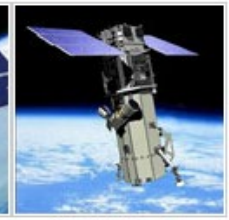

KOMPSAT-2


SPOT


TerraSAR-X and TanDEM-X

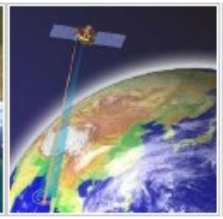

UK-DMC

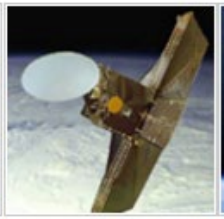

WorldView-1

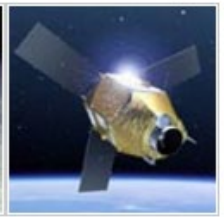

WorldView-2

Landsat TM/ETM


Landsat OLI/TIRS


OceanSat-2


Odin


Pleiades-HR

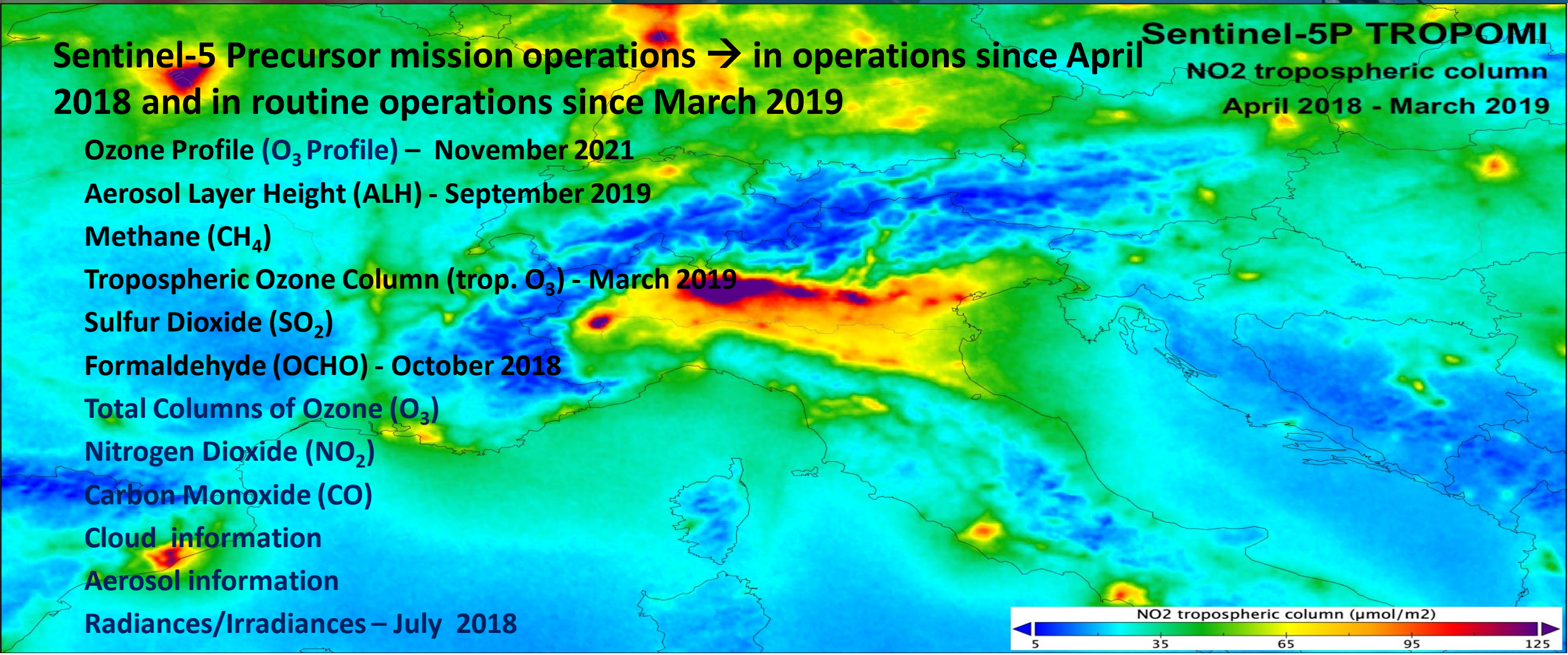

WorldView-3

Data access:
https://earth.esa.int/eogateway/search?text=&category=Missions&subFilter=Third%20Party%20Missions

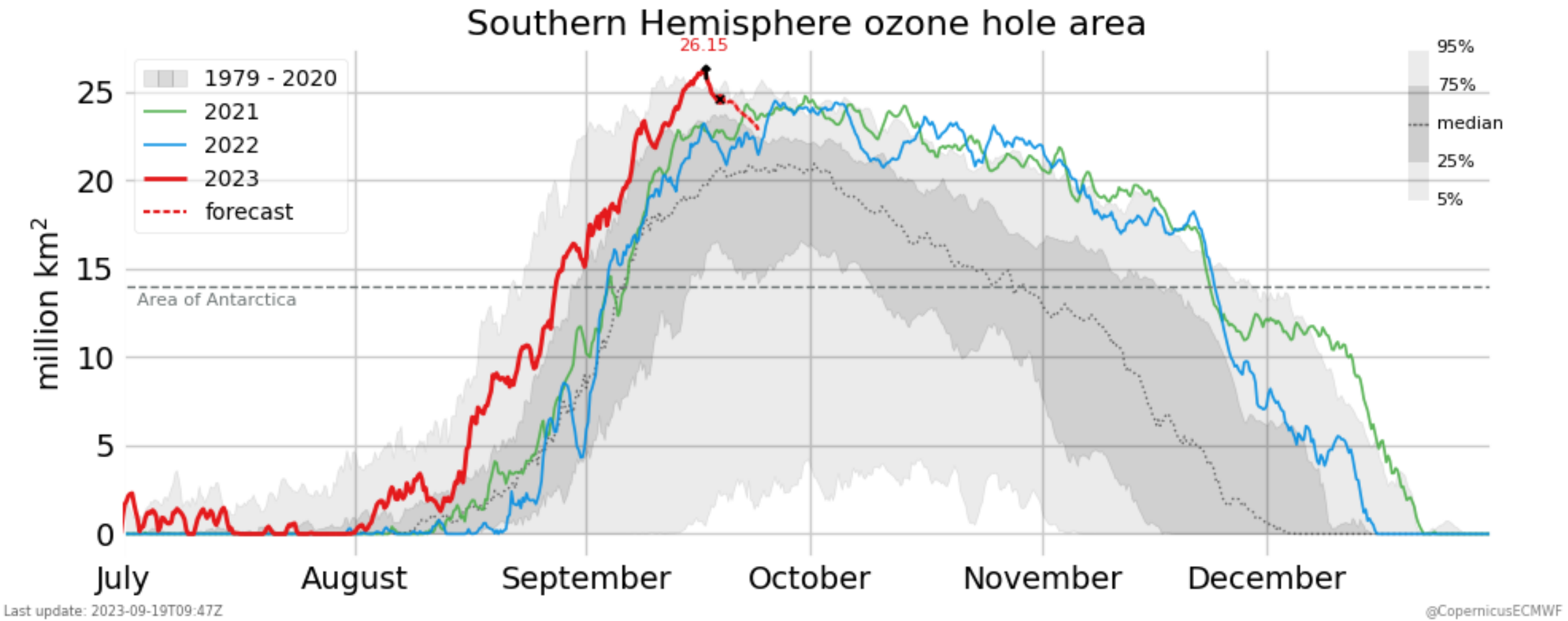
Copernicus Sentinel-5P Data Products

Sentinel-5 Precursor mission operations → in operations since April 2018 and in routine operations since March 2019

- Ozone Profile (O_3 Profile) – November 2021
- Aerosol Layer Height (ALH) - September 2019
- Methane (CH_4)
- Tropospheric Ozone Column (trop. O_3) - March 2019
- Sulfur Dioxide (SO_2)
- Formaldehyde (OCHO) - October 2018
- Total Columns of Ozone (O_3)
- Nitrogen Dioxide (NO_2)
- Carbon Monoxide (CO)
- Cloud information
- Aerosol information
- Radiances/Irradiances – July 2018



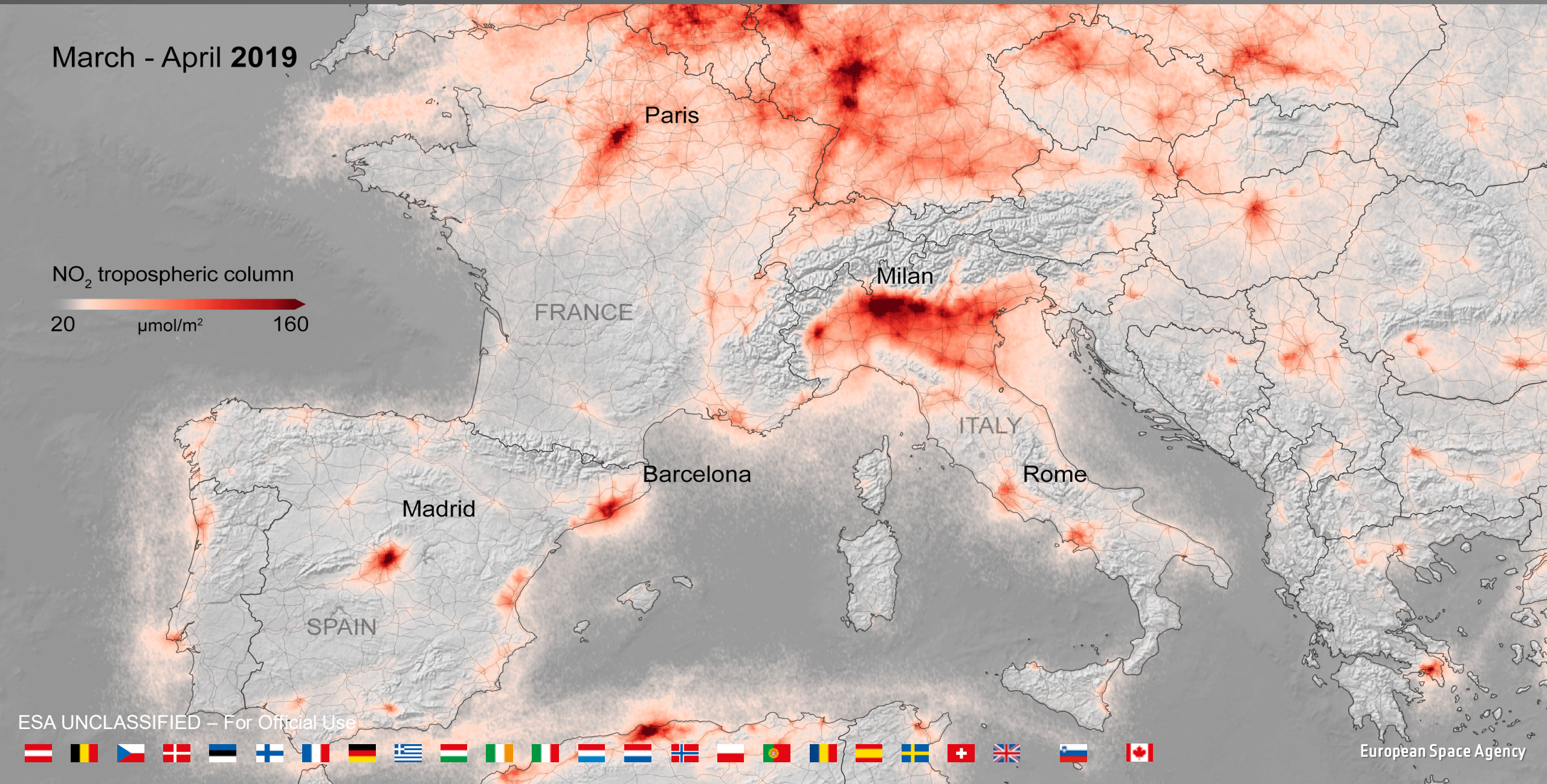
Sentinel-5P Ozone Monitoring



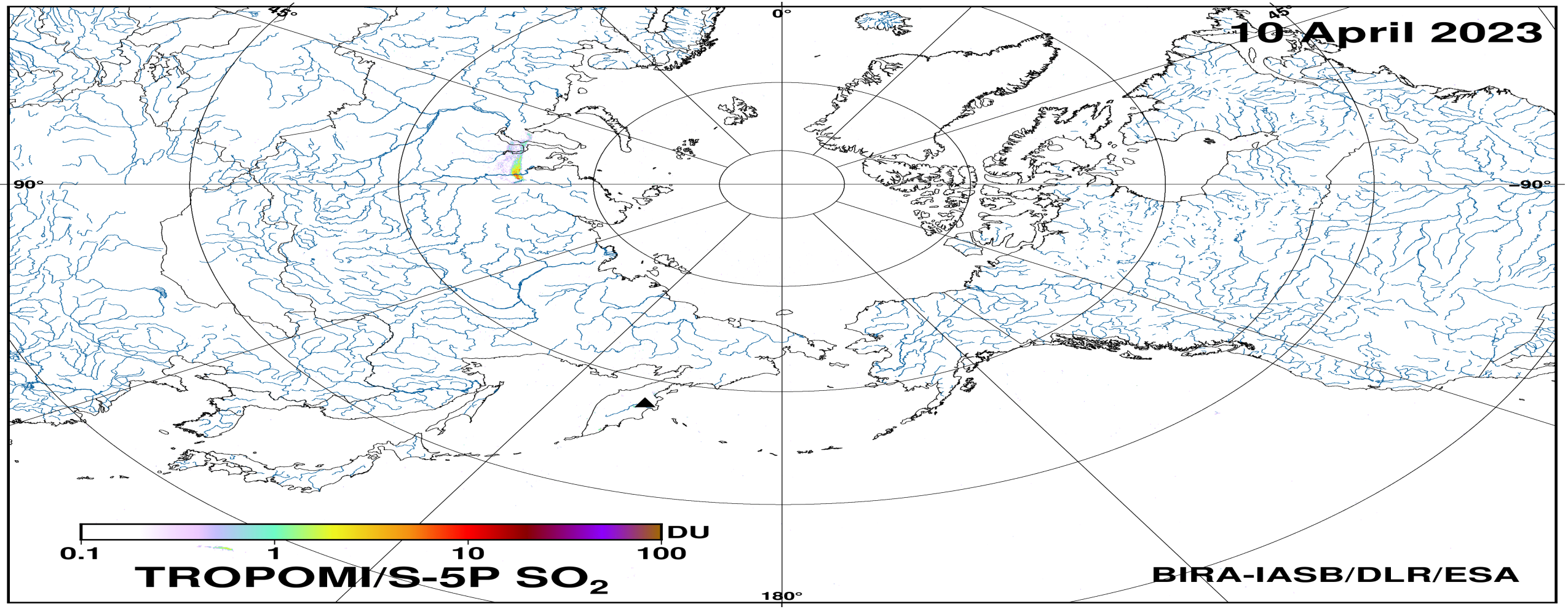
https://atmosphere.copernicus.eu/monitoring-ozone-layer

CAMS ozone monitoring includes a few TCO3 observations in addition to S5p

Dropping Air Pollution in Europe



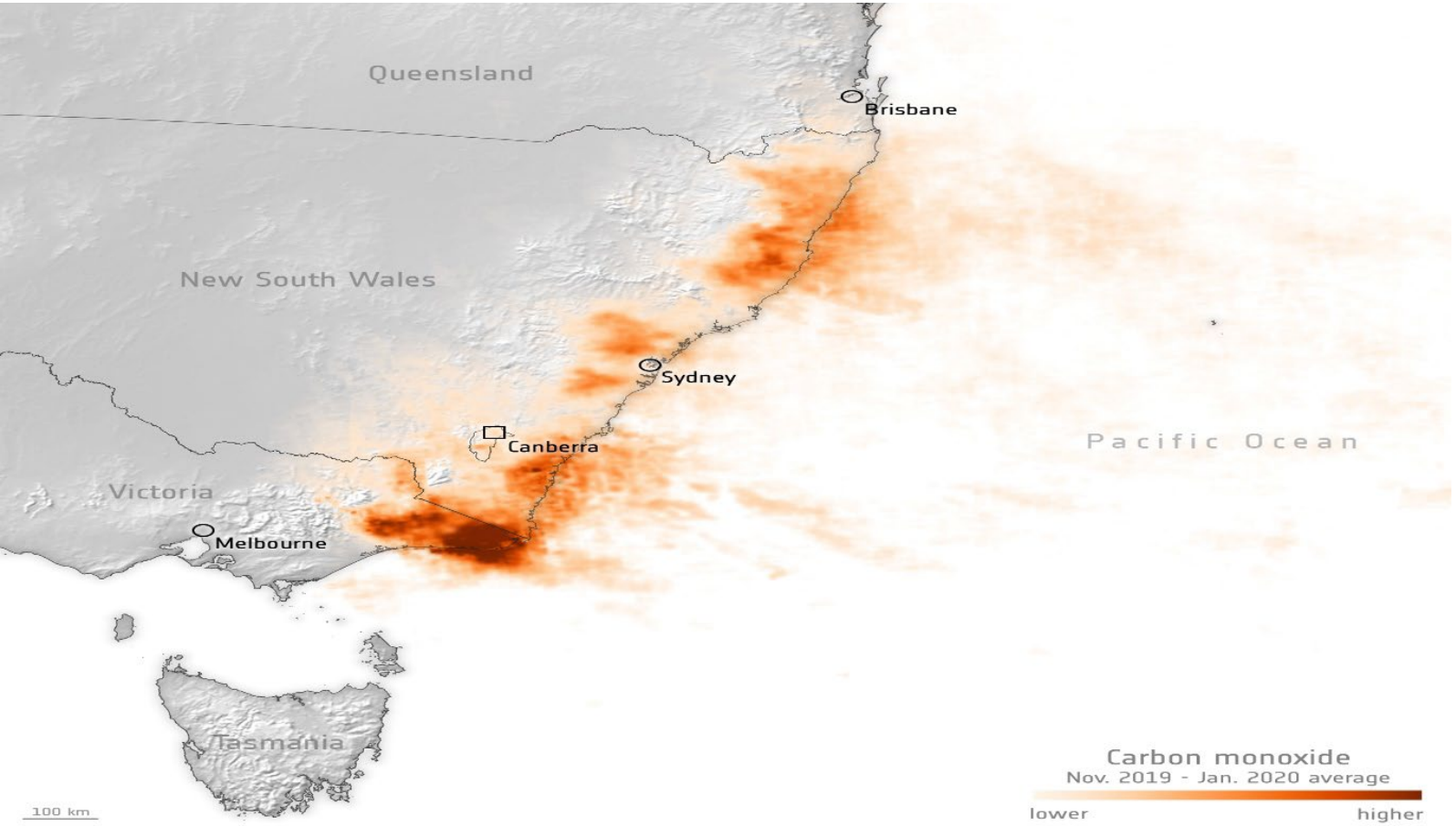
Sentinel-5P Air Pollution Monitoring Volcanic Emissions



Sentinel-5P SO_2 measurements emitted by the Russian volcano Shiveluch

Sentinel-5P Air Pollution Monitoring Bush-Fires in Australia

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



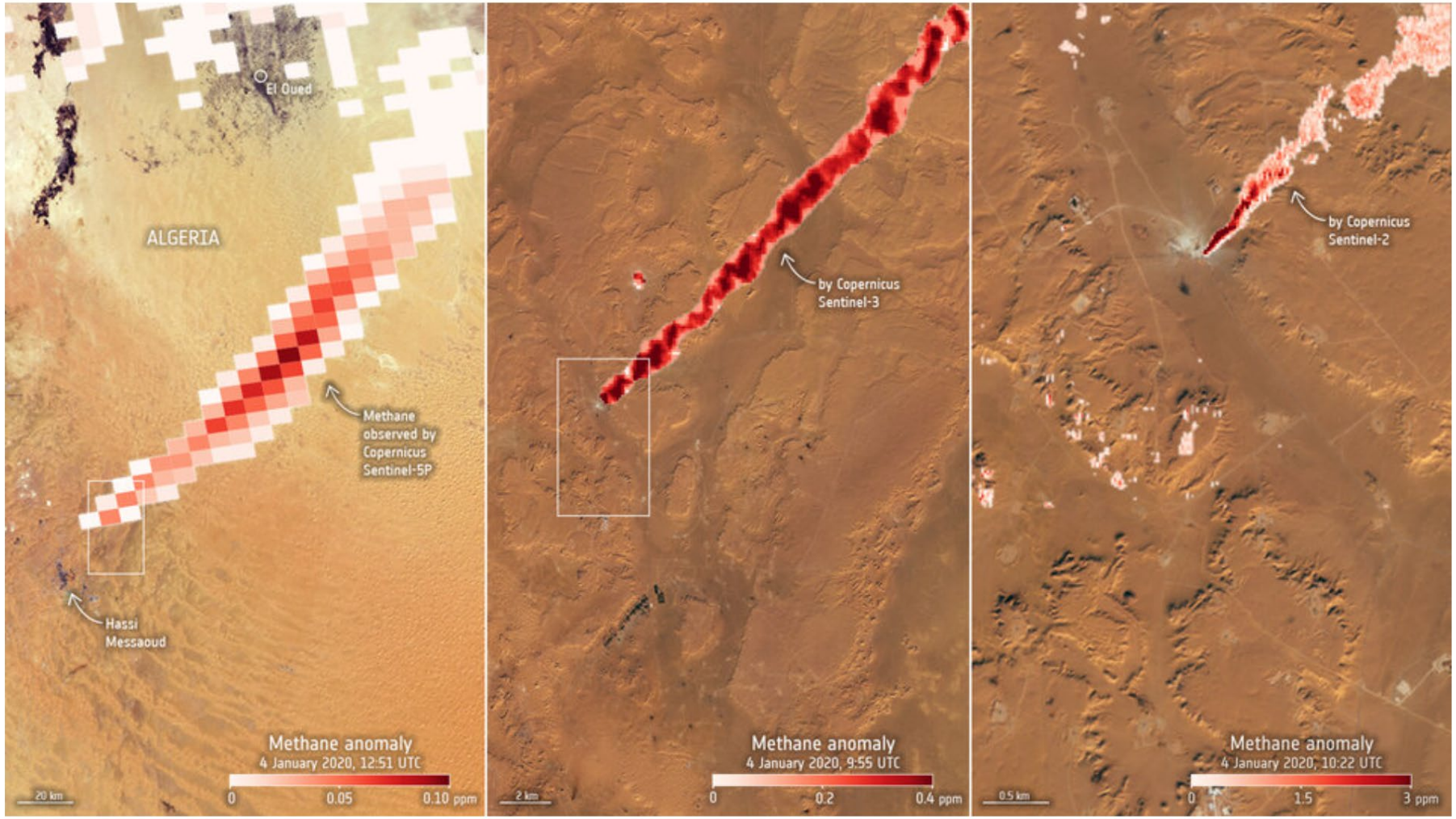
these bushfires (Nov. 2019 – Jan. 2020) released CO equivalent to 715 million tonnes of CO2 in just three months

van der Velde, I.R., van der Werf, G.R., Houweling, S. *et al.* Vast CO_2 release from Australian fires in 2019–2020 constrained by satellite. *Nature* **597,** 366–369 (2021). https://doi.org/10.1038/s41586-021-03712-y

CO measurements - Credits: contains modified Copernicus data (2019/20) processed by SRON

Latest Research on CH4:
Trio of Sentinel satellites detect super-emitters

https://www.esa.int/Applications/Observing_the_Earth/Copernicus/Trio_of_Sentinel_satellites_map_methane_super-emitters



Machine learning algorithm on Sentinel-5P plume detection

Sentinel-2 image to zoom in on the plumes' origins and pinpointed the exact location of the leak to be an oil/gas well, while Sentinel-3 showed the leak continued for six days.

When analysing these leaks, both Sentinel-2 and Sentinel-3 provided similar estimates of methane emissions

Schuit et. al.
https://acp.copernicus.org/articles/23/9071/2023/

Near the Hassi Messaoud oil/gas field in Algeria, continuous methane emission from a leaking facility for six days.

EO4Society: Advancing EO Methods and Techniques
Sentinel-5p+ Innovation Projects

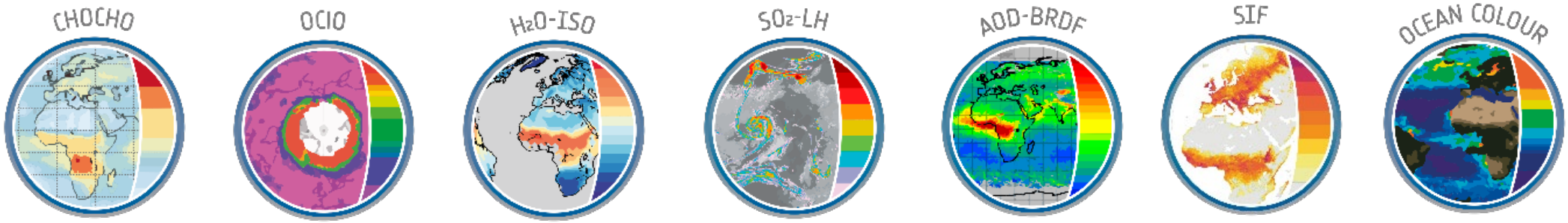
List of S5p+I products, developed: 2019 - 2022/23

- Glyoxal – CHOCHO
- Chlorine Dioxide - OClO
- Water Vapor Isotopologues - H2O-ISO
- Sulphur Dioxide Layer Height - SO2-LH
- Aerosol Optical Depth and Surface - AOD/BRDF
- Solor Induced Fluorescence - SIF
- Ocean Color

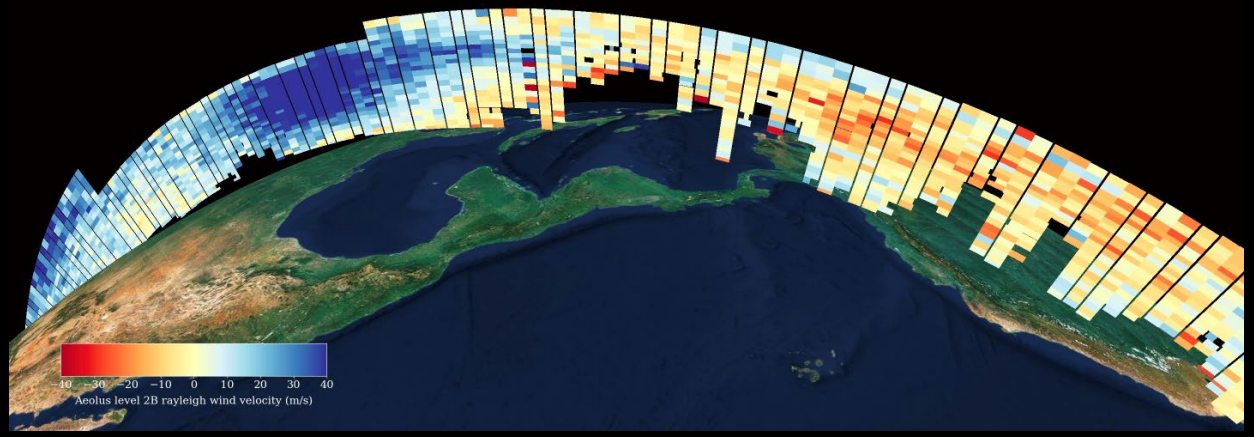
Many of these products are now available through the S5p **Product Algorithm Laboratory (PAL)**
https://data-portal.s5p-pal.com/

S5p+I & PAL developed by:
BIRA, IUP-UB, DLR, KNMI, SRON, ULeicester, KIT, UBergen, AUTH, UOxford, GRASP, Catalyst, Noveltis, UPValencia, LSCE, AWI, UVictoria, FCIENCIAS, S&T

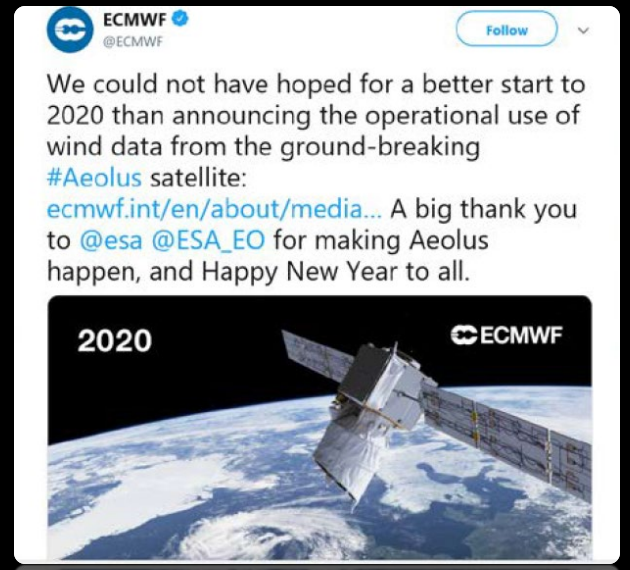
https://eo4society.esa.int/tag/sentinel-5p-innovation+atmosphere-science-cluster/



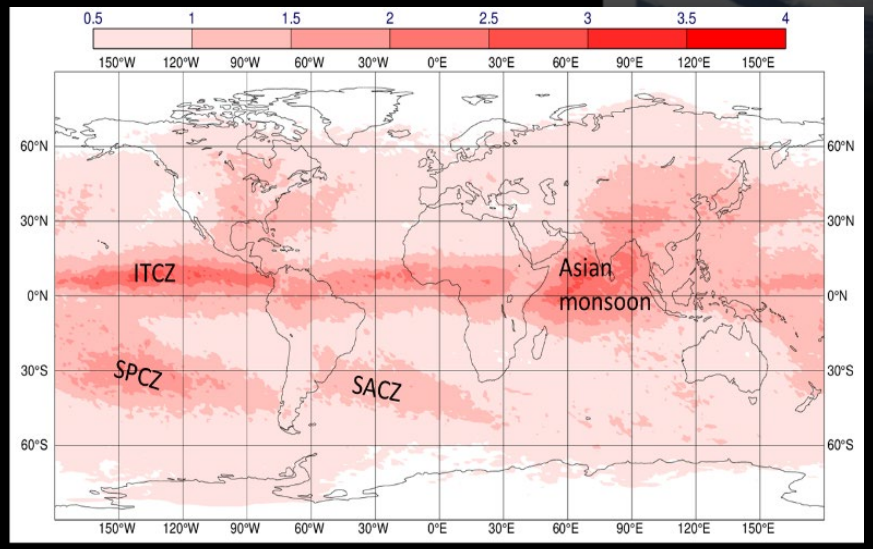
Aeolus addresses our ‘Blind Spot’ - Wind



Aeolus gauges hurricane Lota wind velocities 17 November 2020

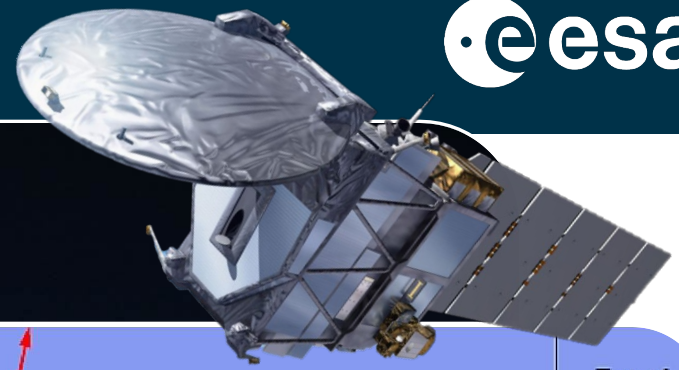


- Improving NWP Models’ forecast accuracy with data now operationally used by ECMWF
- Deepening Understanding of Climate Science
- Spurring insight into the atmospheric energy, water, aerosol and chemistry cycles



Positive impact (red) when assimilating Aeolus winds from 4 April to 19 August 2020 (M. Rennie – ECMWF)

Earth Explorer 6 EarthCARE



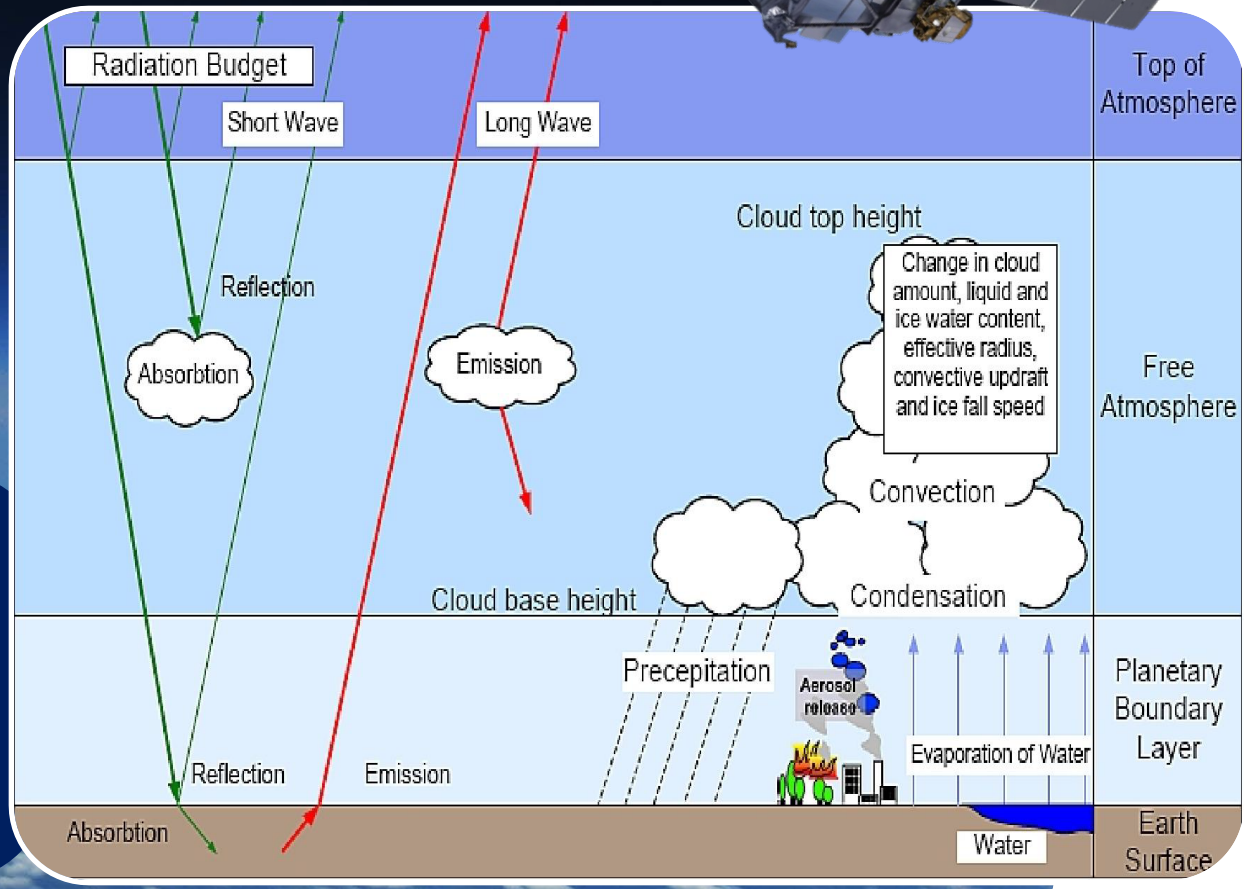
Study of natural & anthropogenic Climate Change

Joint ESA/JAXA(NICT) mission

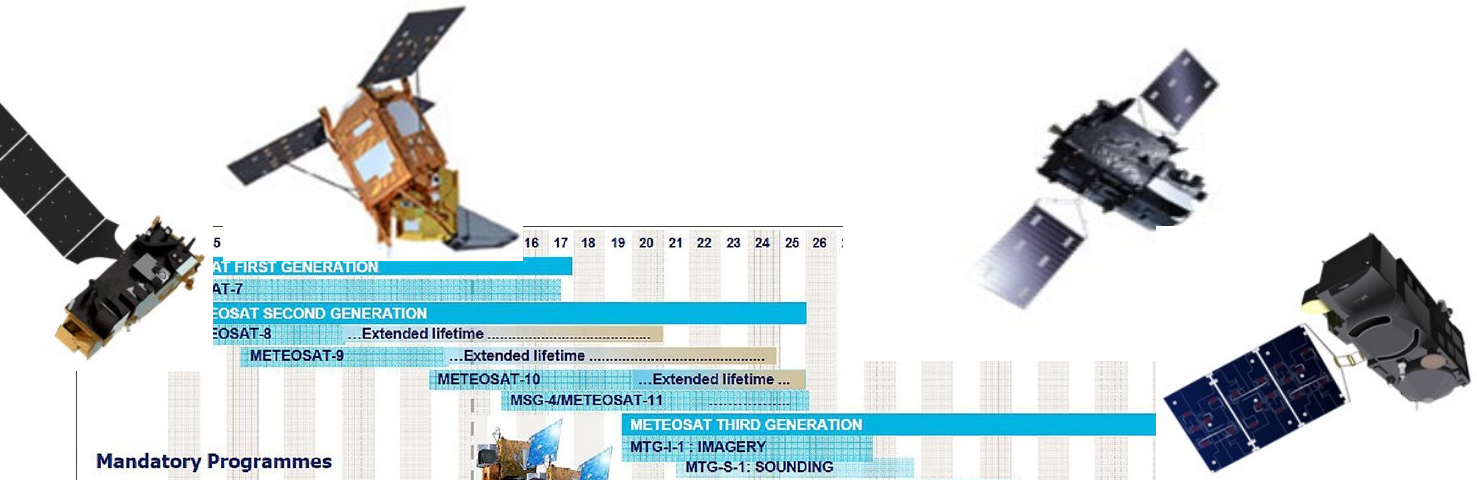
- Building on ESA's ERM (Earth Radiation Mission) and JAXA's ATMOS-B1 satellite projects
- Unique global measurements of vertical profiles of clouds, aerosols, temperature and humidity profiles simultaneously with the Top-of-Atmosphere radiance

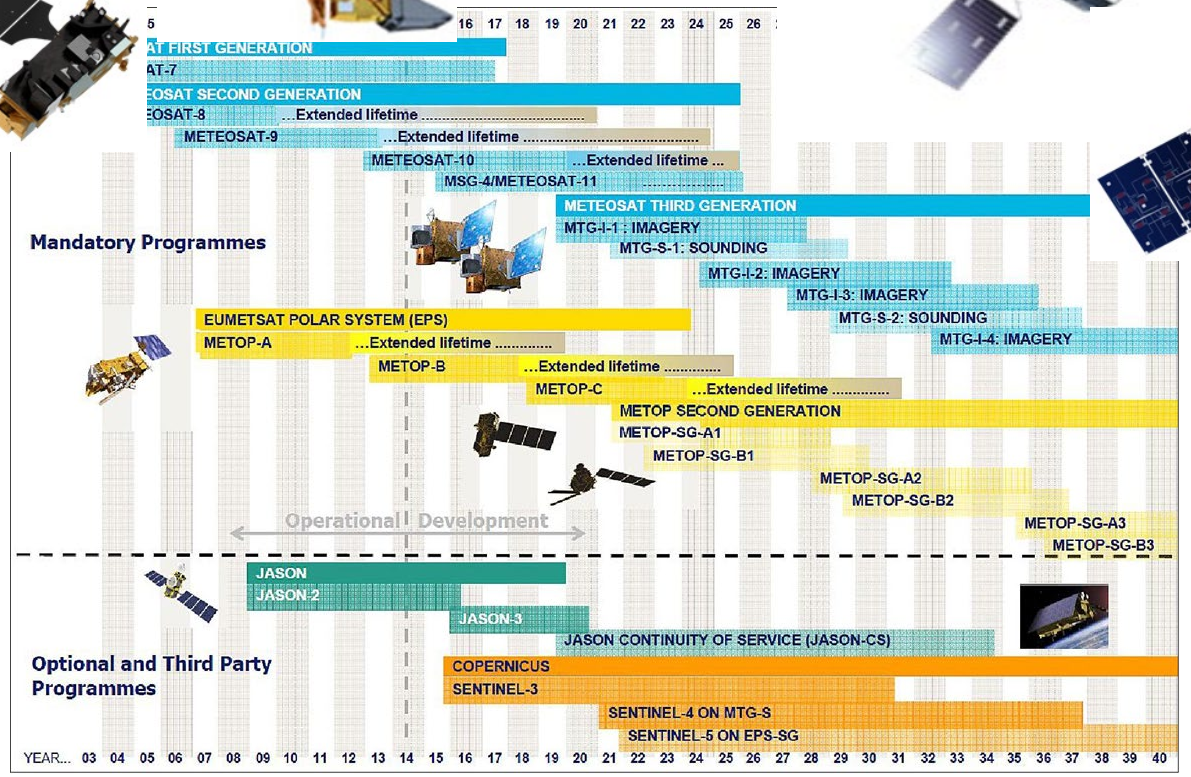
Synergistic active/passive instrument suite for vertical cloud profile retrievals

- UV Lidar for cloud and aerosol optical depth
- Cloud Profiling Radar for micro- and macroscopic properties of clouds
- Broadband Radiometer for top of atmosphere radiance



A huge step forward for monitoring environment and climate

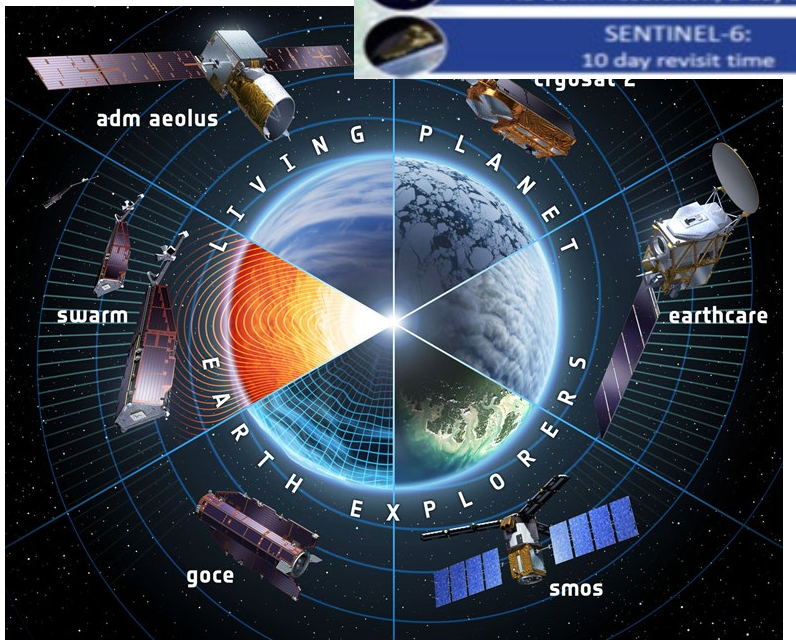




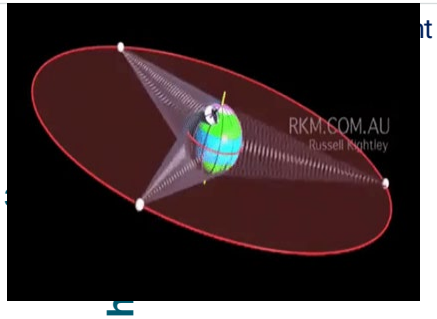
EUMETSAT Copernicus Europe's eyes on Earth

esa

SENTINEL-1: 4-40m resolution, 3 day revisit at equator	S1A and 1B in orbit
SENTINEL-2: 10-60m resolution, 5 days revisit time	S2A and 2B in orbit
SENTINEL-3: 300-1200m resolution, <2 days revisit	S3A and S3B in orbit
SENTINEL-4: 8km resolution, 60 min revisit time	1st Launch 2022
SENTINEL-5p: 7-68km resolution, 1 day revisit	S5P in orbit
SENTINEL-5: 7.5-50km resolution, 1 day revisit	1st Launch 2023
SENTINEL-6: 10 day revisit time	1st Launch 2020



Copernicus Sentinels operated by EUMETSAT



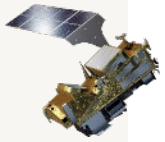
YEAR... 07 08 09 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31 32 33 34 35 36 37 38 39 40

METEOSAT THIRD GENERATION

MTG-S-1: SOUNDING

MTG-S-2: SOUNDING

SENTINEL-4 on MTG-S



EUMETSAT POLAR SYSTEM SECOND GENERATION (EPS-SG)

METOP-SG A: SOUNDING AND IMAGERY

SENTINEL-5 on METOP-SG A

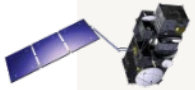
Monitoring atmosph composition

JASON (HIGH PRECISION OCEAN ALTIMETRY)

JASON-2

JASON-3

SENTINEL-6 (JASON-CS)



COPERNICUS

SENTINEL-3 A/B/C/D

Monitoring the ocean

YEAR... 07 08 09 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31 32 33 34 35 36 37 38 39 40

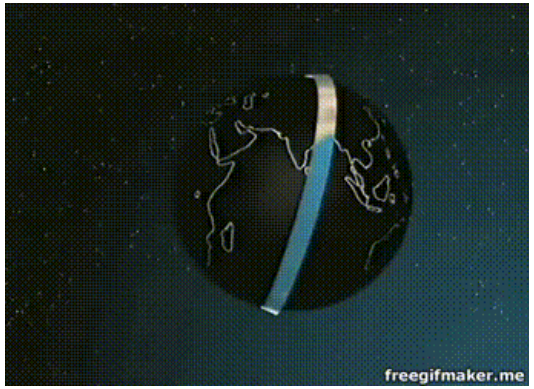
Programs are divided by orbit type ☺

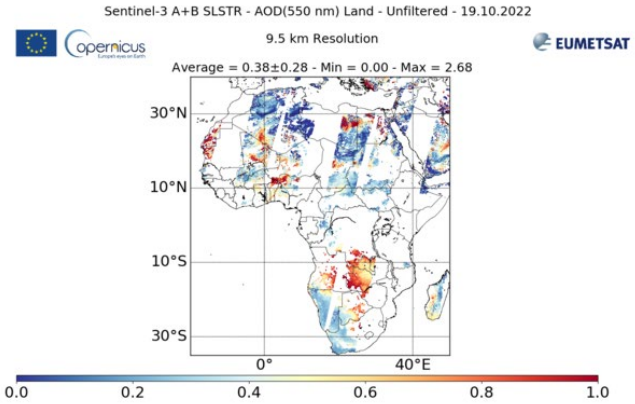
Why monitoring from space?

- Use data and algorithms instead of eyes
- Observe and measure from a distance without modifying the target
- Access to spatial and temporal scales impossible without the contribution of satellite
- Consistency of measurements worldwide

- *Low earth orbits (circling the earth)*

Advantages:
More near to Earth -> Higher spatial resolution
Used also for Active Obs.(Radar/Lidar) and PMW
Disadvantages:
Poorer time resolution -> needs of constellation

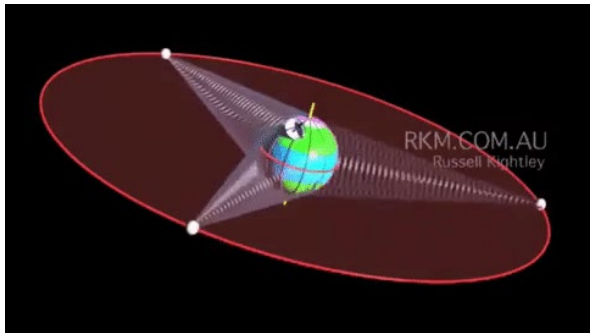


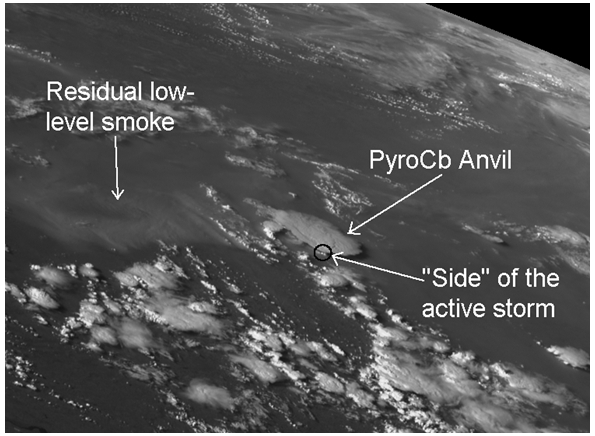


- *Geostationary (fixed position above earth)*

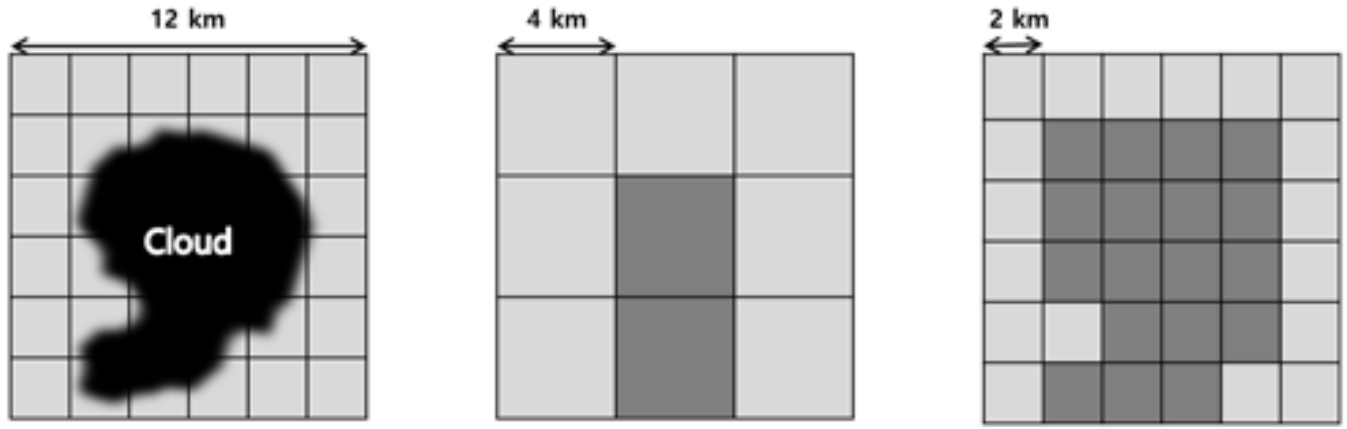
Advantages:
Better time resolution

Disadvantages:
One side of the Earth -> needs of constellations
large viewing angles at the borders -> geometrical distorsions
Only VIS/IR and passive Obs.

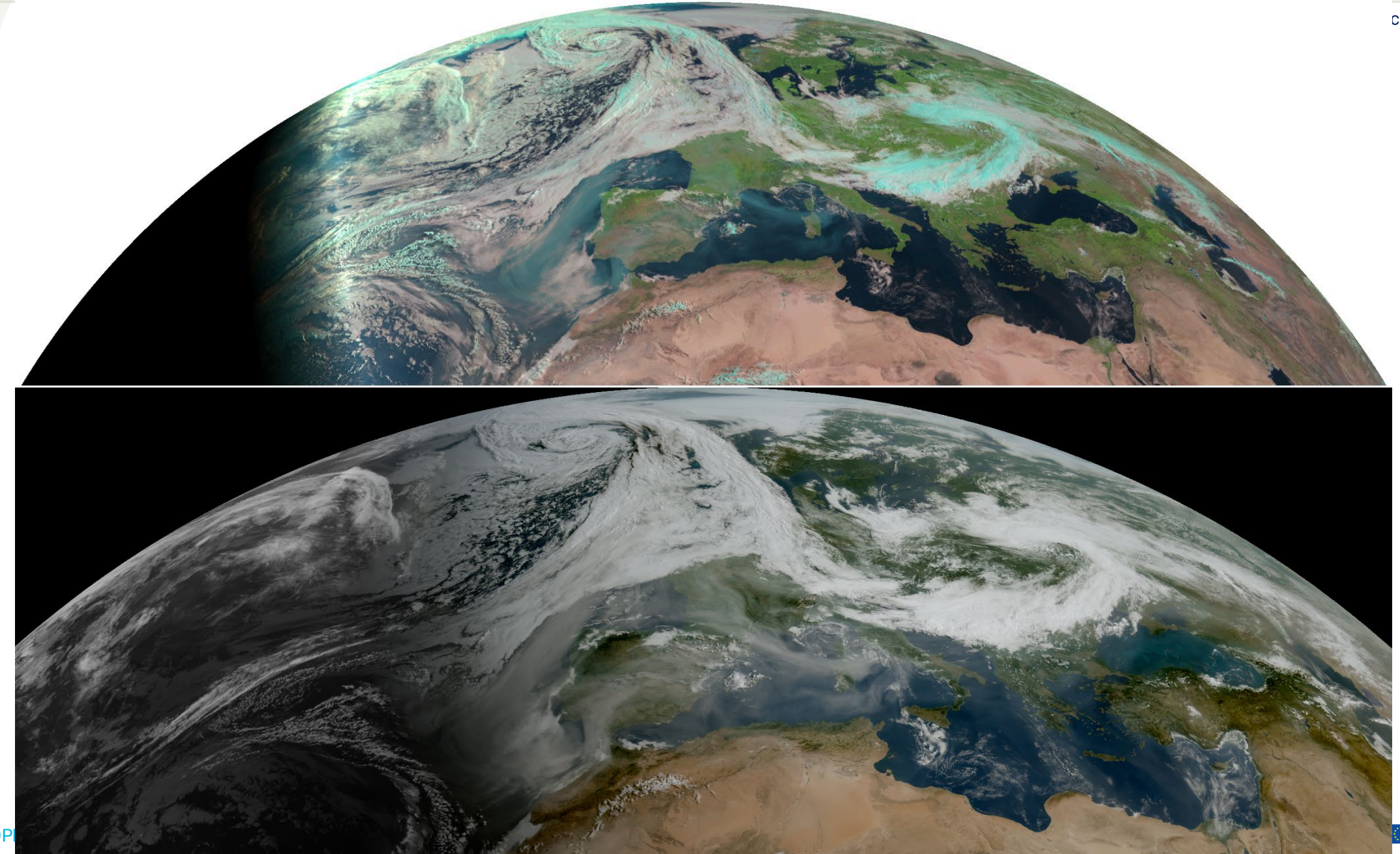




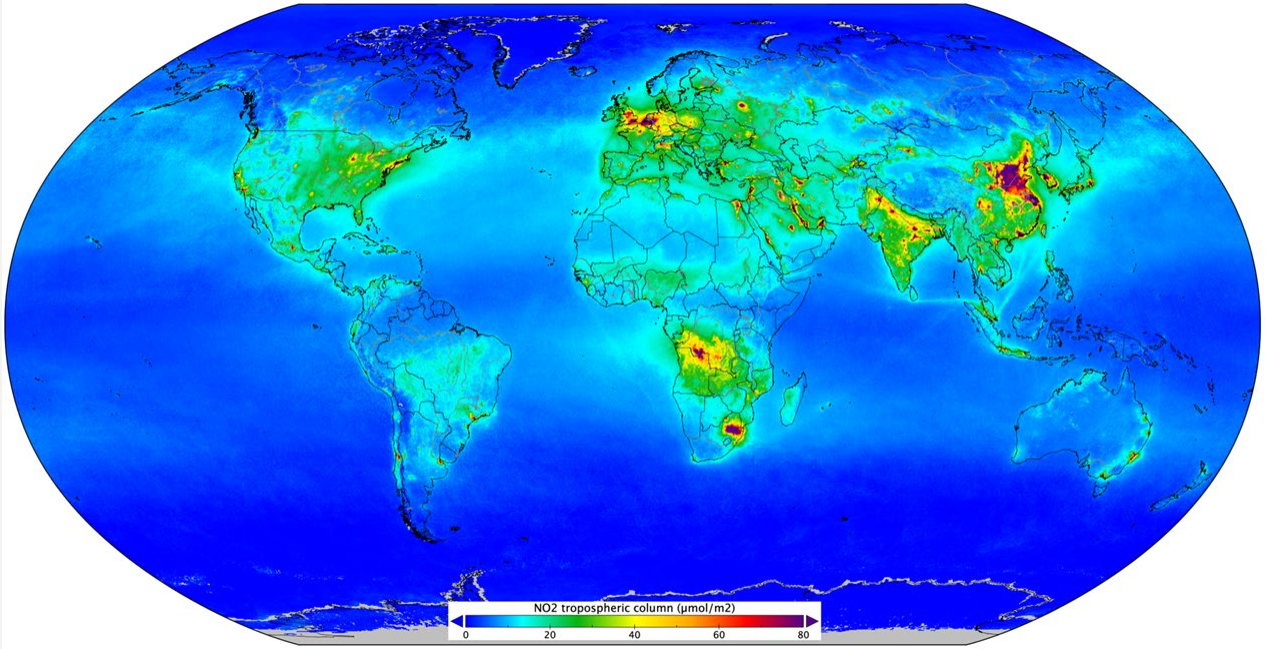
A question of resolution …



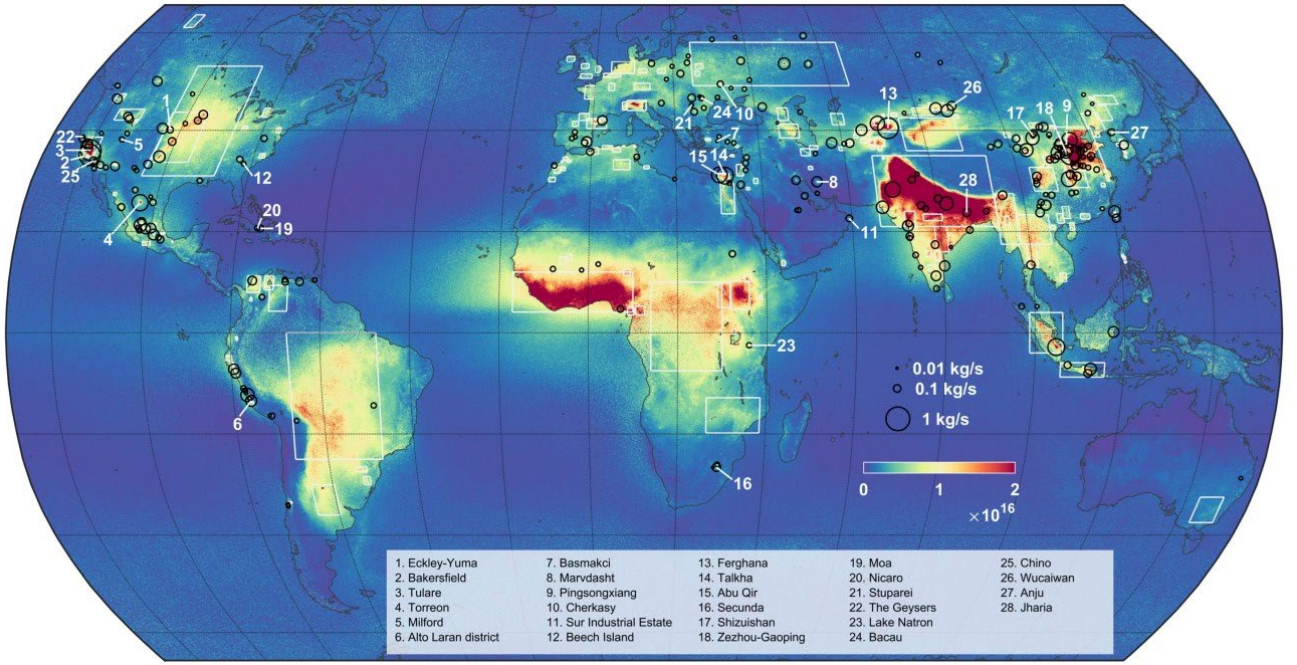
Resolution –Third vs Second Gen … MTG data are preliminary



Satellite monitor pollutants and support observational effort

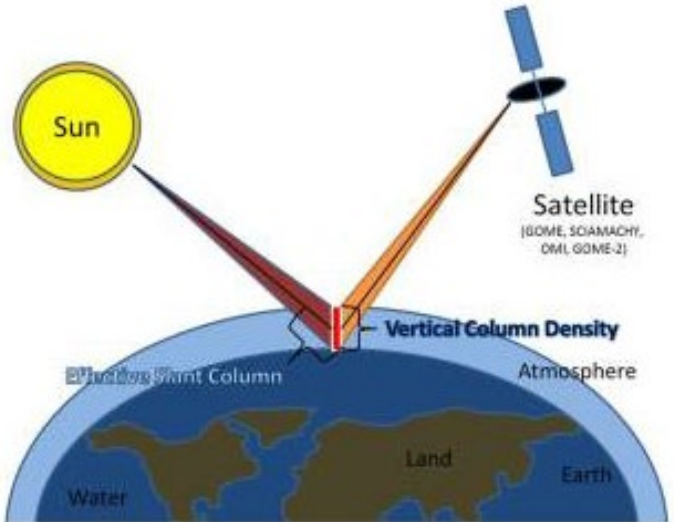


Nitrogen Dioxide from 1 month TROPOMI data
© Copernicus program



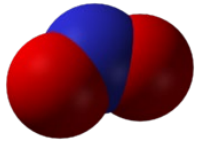
Ammonia fluxes based on 9 years of IASI data
© Martin Van Damme and Lieven Clarisse/ULB

Products for Trace Gas: EUMETSAT and Sentinels



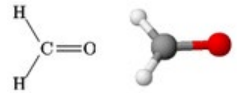
Product	Metop GOME-2	Sentinel 5 and 5p	Metop IASI	Metop-SG IASI-NG	MTG-S S4/UVN
	PRESENT			FUTURE	
O_3 total column	√	√	√	√	√
O_3 profile (incl. troposphere)	√	√	√	√	
O_3 tropospheric column	√				√
NO_2 total column	√	√			√
NO_2 tropospheric column	√	√			√
SO_2	√	√	√	√	√
SO_2 Layer Height		√	√	√	
HCHO	√	√			√
CHOCHO	√	√			√
BrO	√	√			
OClO		√			
HNO_3			√	√	
NH_3			√	√	
CO		√	√	√	
CH_4		√	√	√	
SIF	√	√			
CO_2					
H_2O	√	√			√
UV Products	√	√			√

Carbon monoxide (CO) is present in small amounts (about 80 ppb) in the Earth's atmosphere.
About half of the carbon monoxide in Earth's atmosphere is from the burning of fossil fuels and biomass (such as forest and bushfires)
Most of the rest of carbon monoxide comes from chemical reactions with organic compounds emitted by human activities and plants.



Nitrogen dioxide (NO2) is produced from oxidation of monoxide (NO) that is in turn produced by combustion – high temperatures to break nitrogen and oxygen molecules

HCHO Formaldeheide also produced in fires
Synthesis product – potentially toxic

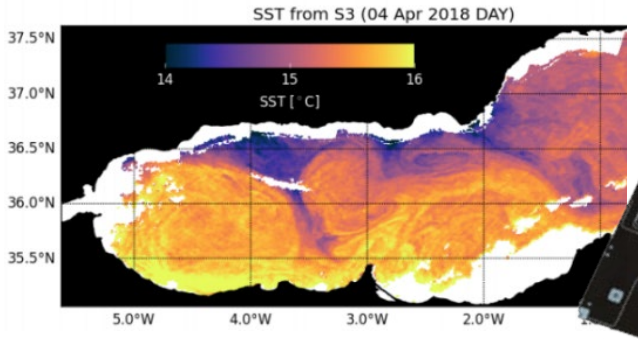


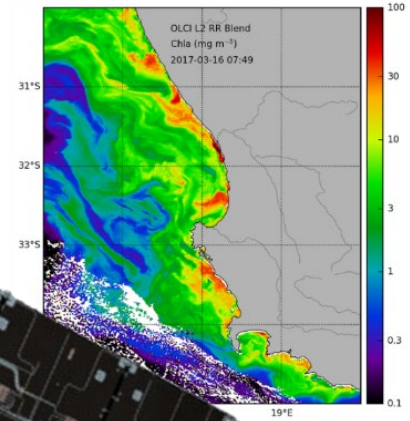
NH3 – Ammonia produced in livestock- also
Synthesis product – potentially toxic

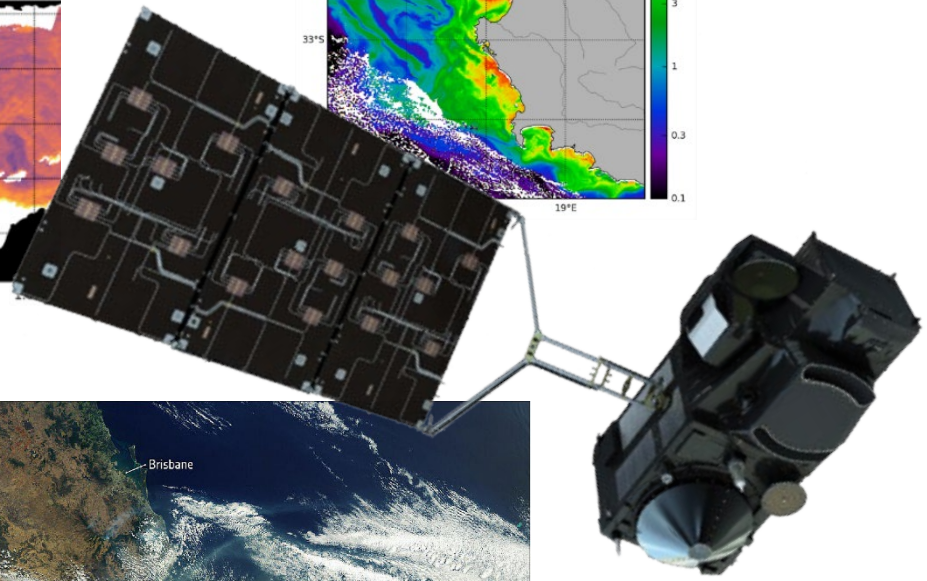
Sentinel-3: Synchronous ocean and atmosphere data

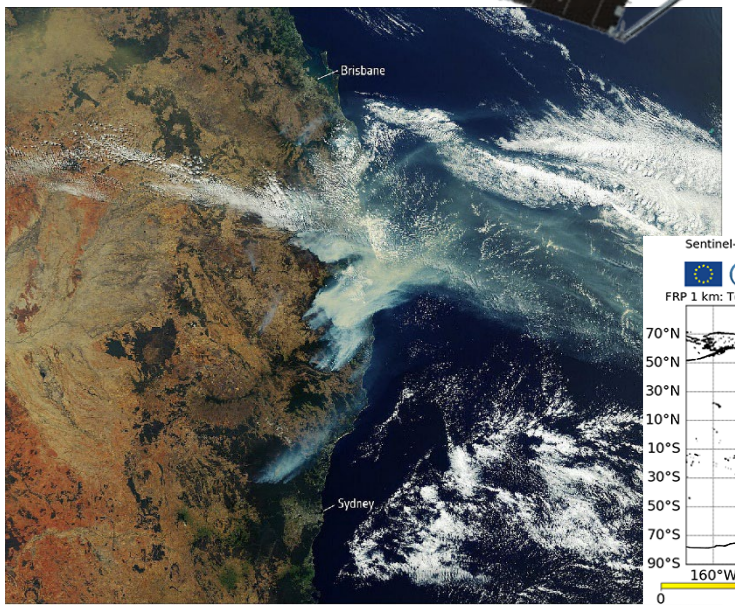
copernicus.eumetsat.int

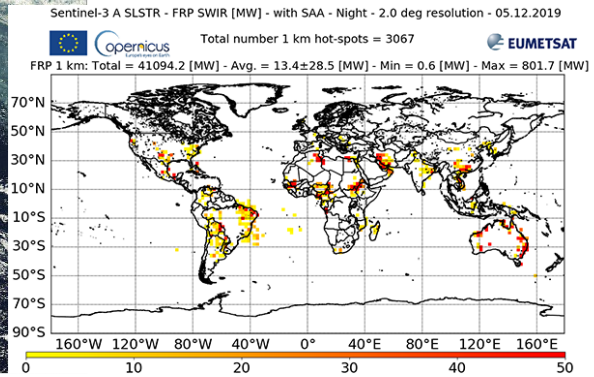
- ~ Daily data from 3 instrument packages:
  - OLCI
  - SLSTR
  - Altimetry (SRAL)
- Wide variety of relevant products:
  - Ocean colour, chlorophyll, TSM
  - Aerosols, Fire Radiative Power
- Many relevant applications:
  - Carbon cycling, sediment dynamics, waves/wind, air quality fires, dust, volcanic eruptions.





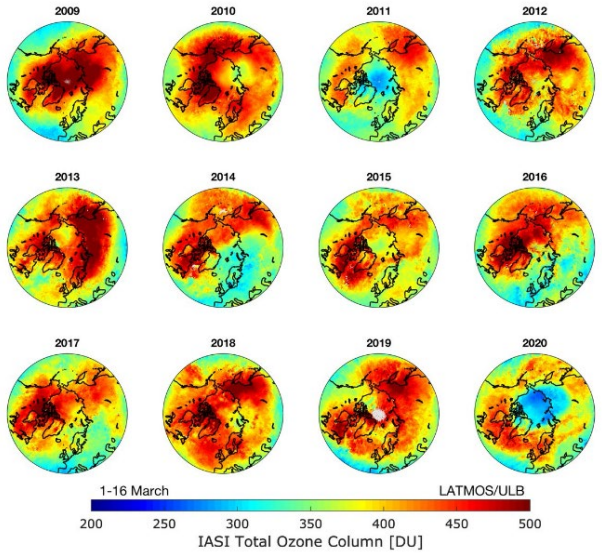


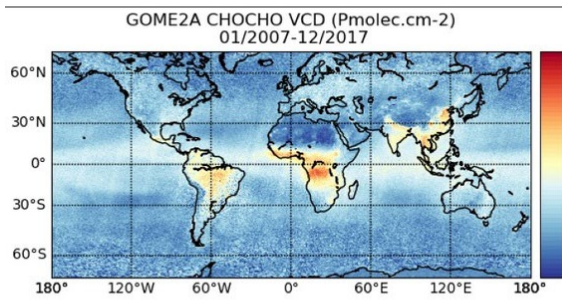


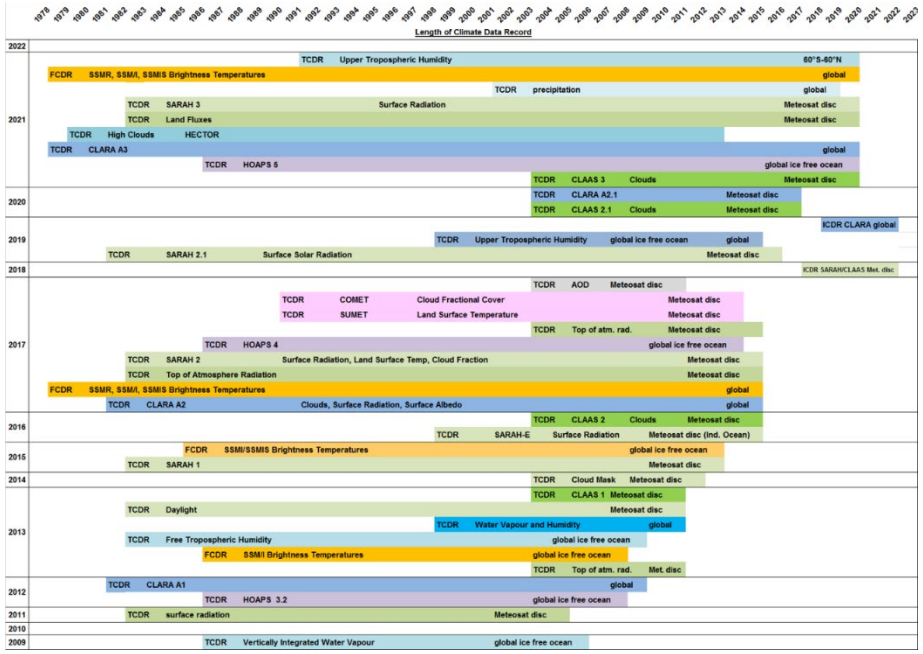


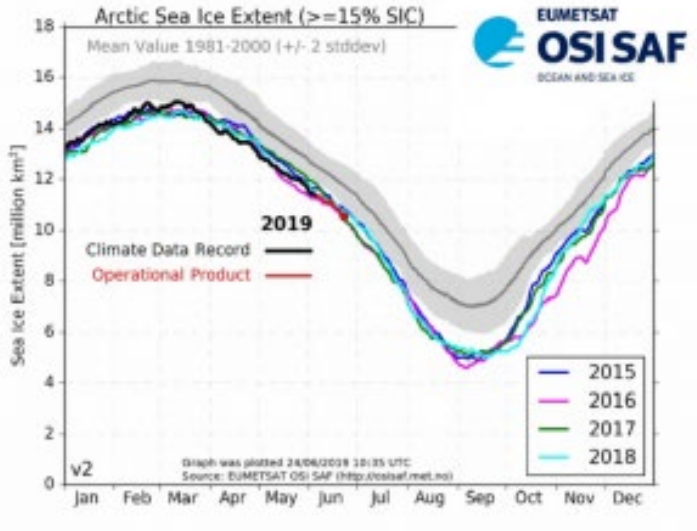
Continuity – Monitoring and Climate applications

EUMETSAT AC SAF
ATMOSPHERIC COMPOSITION MONITORING

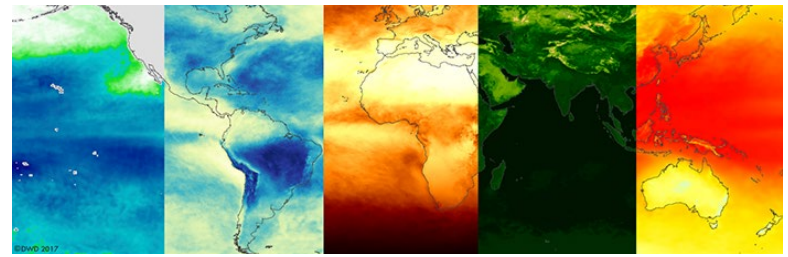








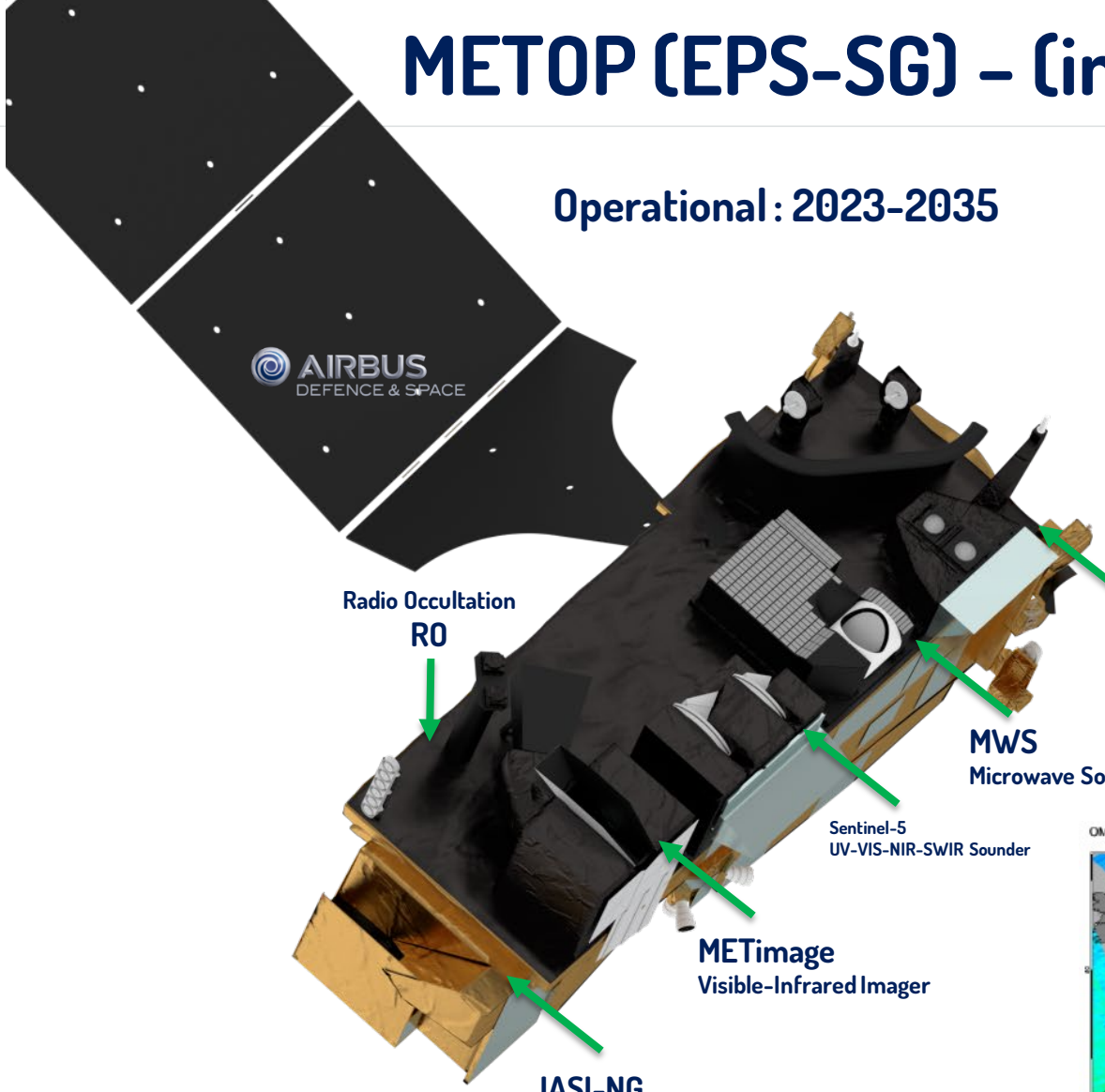
EUMETSAT CM SAF
CLIMATE MONITORING



cnrs
Deutscher Wetterdienst
Wetter und Klima aus einer Hand
DWD
Met Office
Ilmatieteen laitos
Meteorologiska institutet
Finnish Meteorological Institute
SMHI
EUMETSAT
Royal Netherlands Meteorological Institute
Ministry of Infrastructure and Water Management
Schweizerische Eidgenossenschaft
Confédération suisse
Confederazione Svizzera
Confederaziun svizra
Swiss Confederation
Federal Department of Home Affairs FDHA
Federal Office of Meteorology and Climatology MeteoSwiss
RMI

METOP (EPS-SG) – (incl. Sentinel 5)

Operational : 2023-2035



Radio Occultation
RO

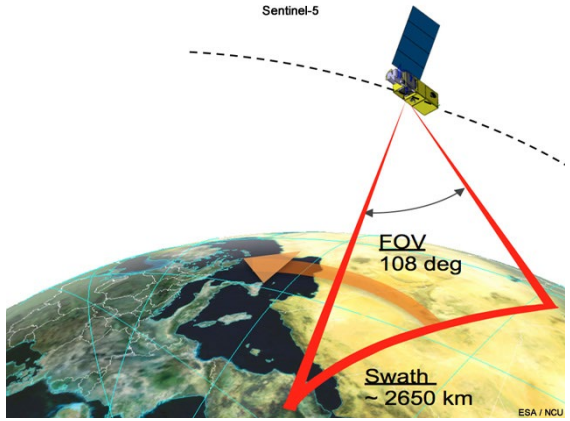
3MI
Multi-viewing,
-channel,
-polarisation Imager

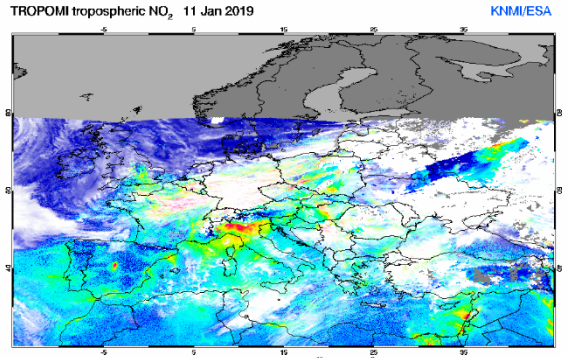
MWS
Microwave Sounder

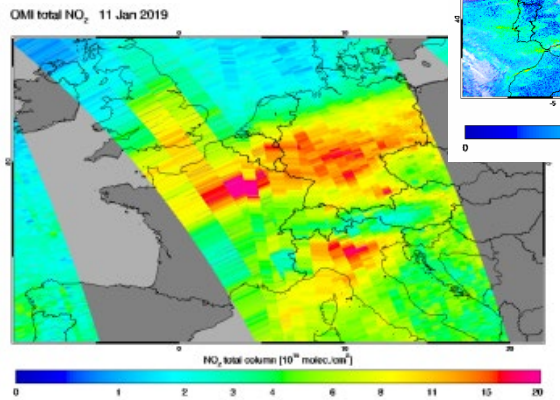
Sentinel-5
UV-VIS-NIR-SWIR Sounder

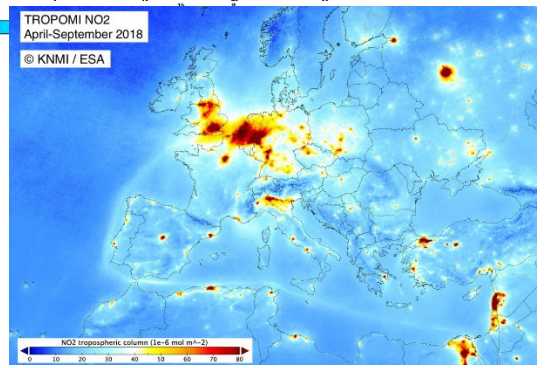
METimage
Visible-Infrared Imager

IASI-NG
Infrared Atmospheric Sounding Interferometer
– New Generation



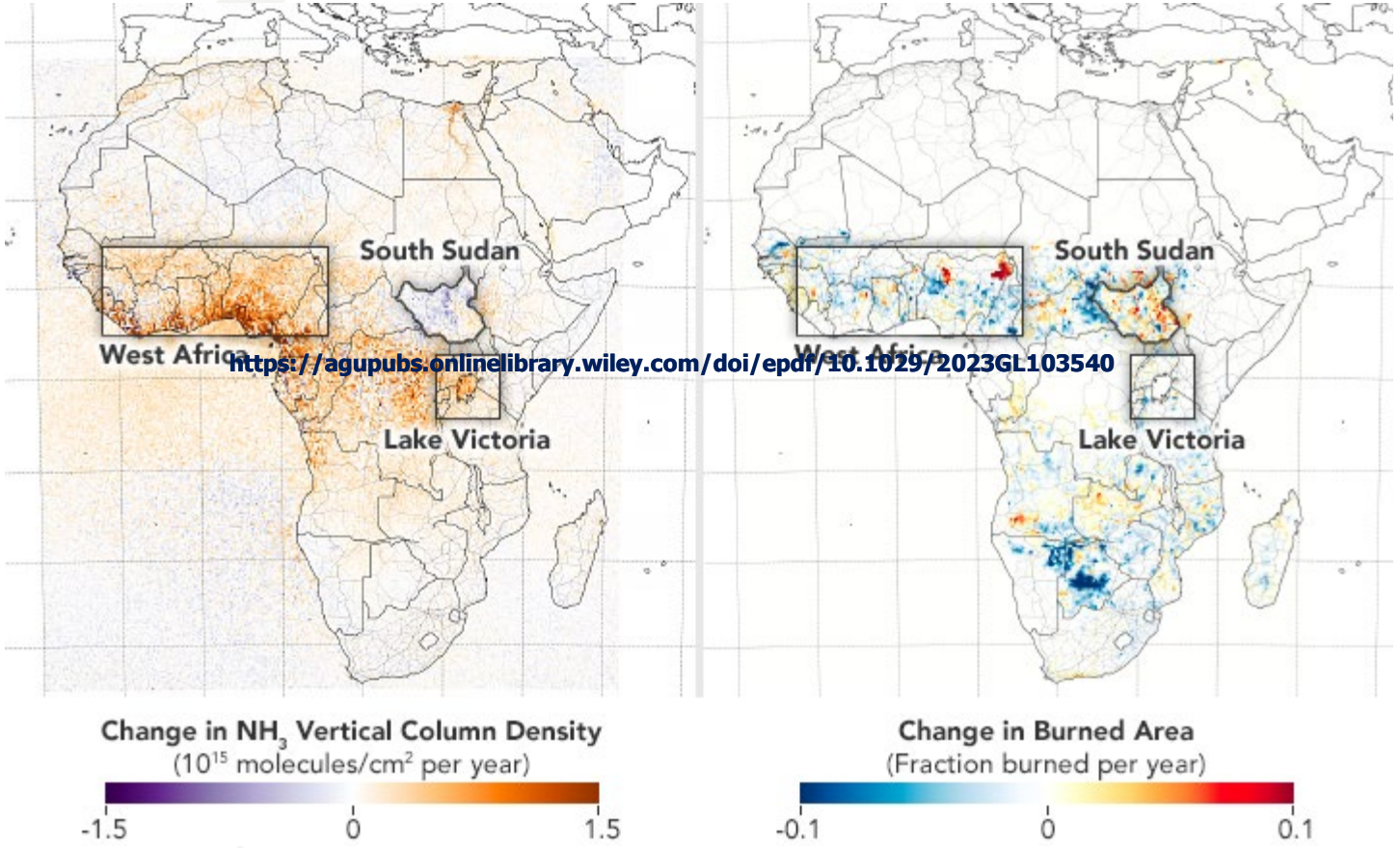






Example: Changes in ammonia concentrations

What does it means – support air quality monitoring
Analysis of 7 years of IASI data from https://acp.copernicus.org/articles/21/16277/2021/



https://agupubs.onlinelibrary.wiley.com/doi/epdf/10.1029/2023GL103540

Meteosat Third Generation (MTG): Mission overview

- **Imagery missions (MTG-I):**
  1. Full disk imagery every 10 minutes in 16 spectral bands with the Flexible Combined Imager (FCI). Fast imaging of European weather every 2.5 minutes
  2. Day/night Lightning Imager (LI)

- **Sounding mission (MTG-S):**
  1. 3D mapping of water vapour, temperature with Hyperspectral Infrared Sounder (IRS)
  2. Air quality monitoring and atmospheric chemistry in synergy with Sentinel-4 / Ultraviolet Visible & Near-infrared

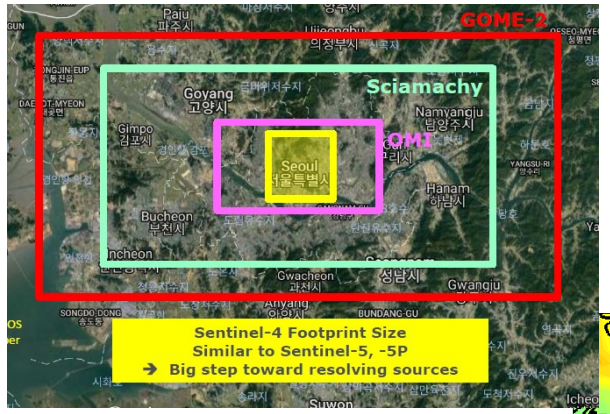
- **Start of operations in 2022 and 2024**
- **Operational exploitation: 2022–2042**

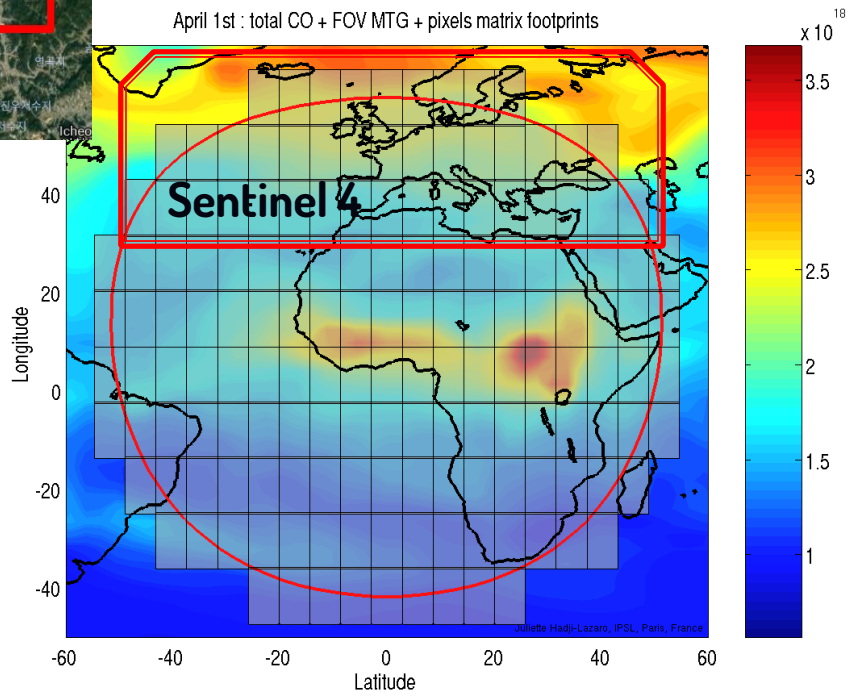
Example: MTG-S Sounding Mission – Sentinel 4

The spatial resolution ~ 8 x 8 km
with hourly temporal resolution

First Geostationary over EU

Focus on air quality with the main data products being O_3, NO_2, SO_2, HCHO, and aerosol optical depth.



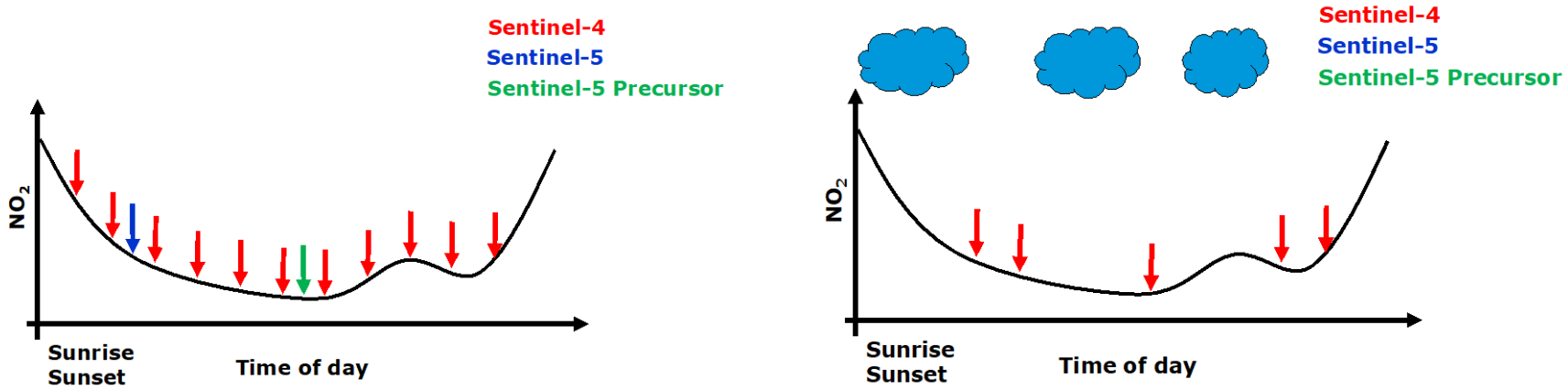


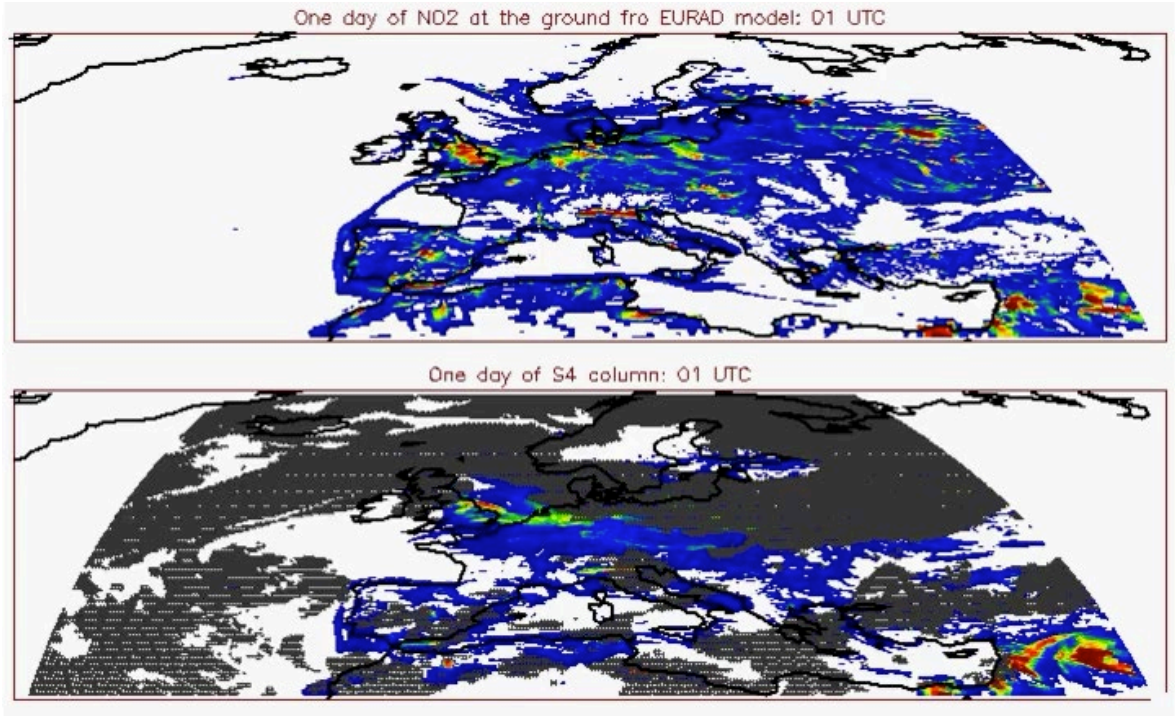
Start of operations: 2023

Operational : 2023-2042

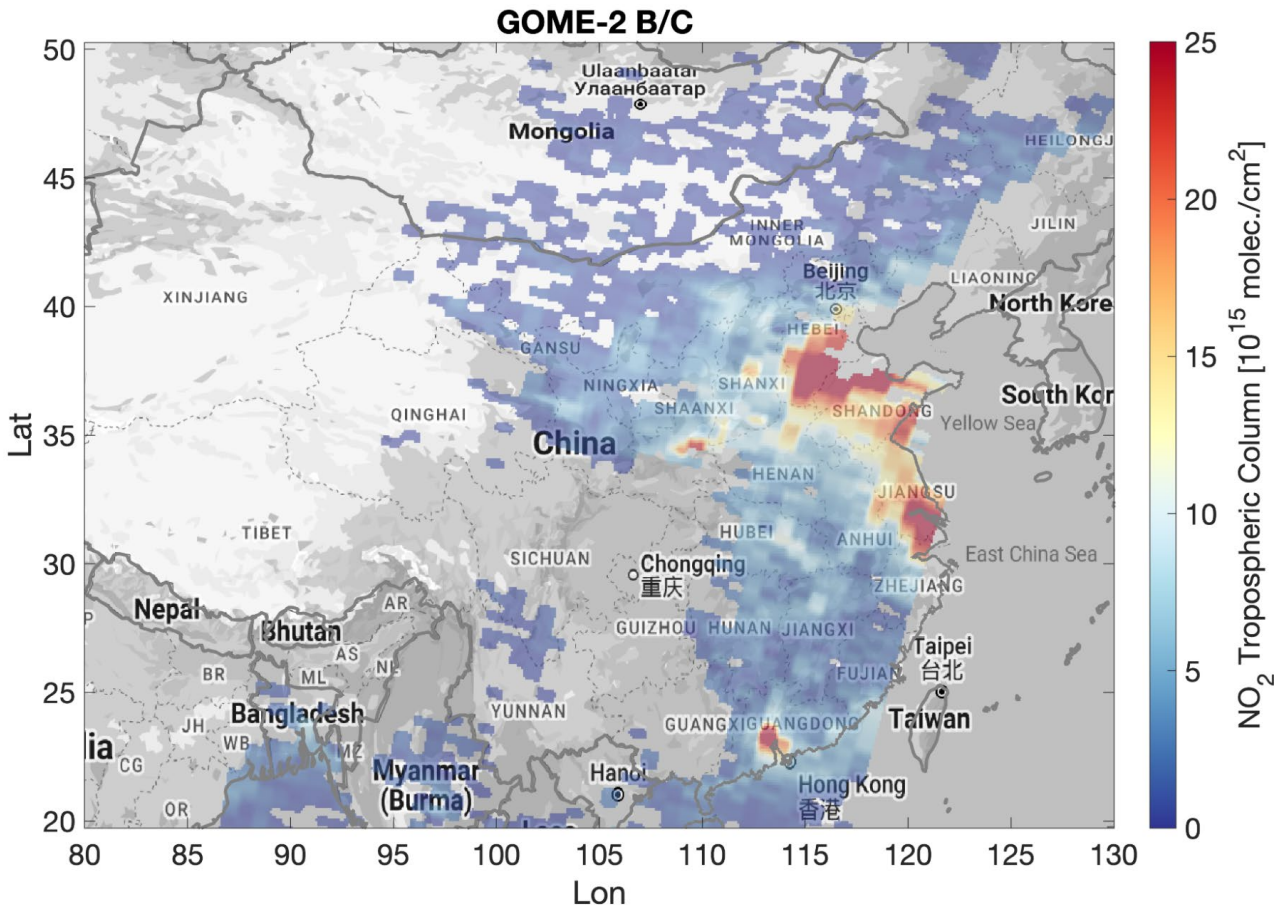
Synergy with the instruments on the EUMETSAT Meteosat Third generation

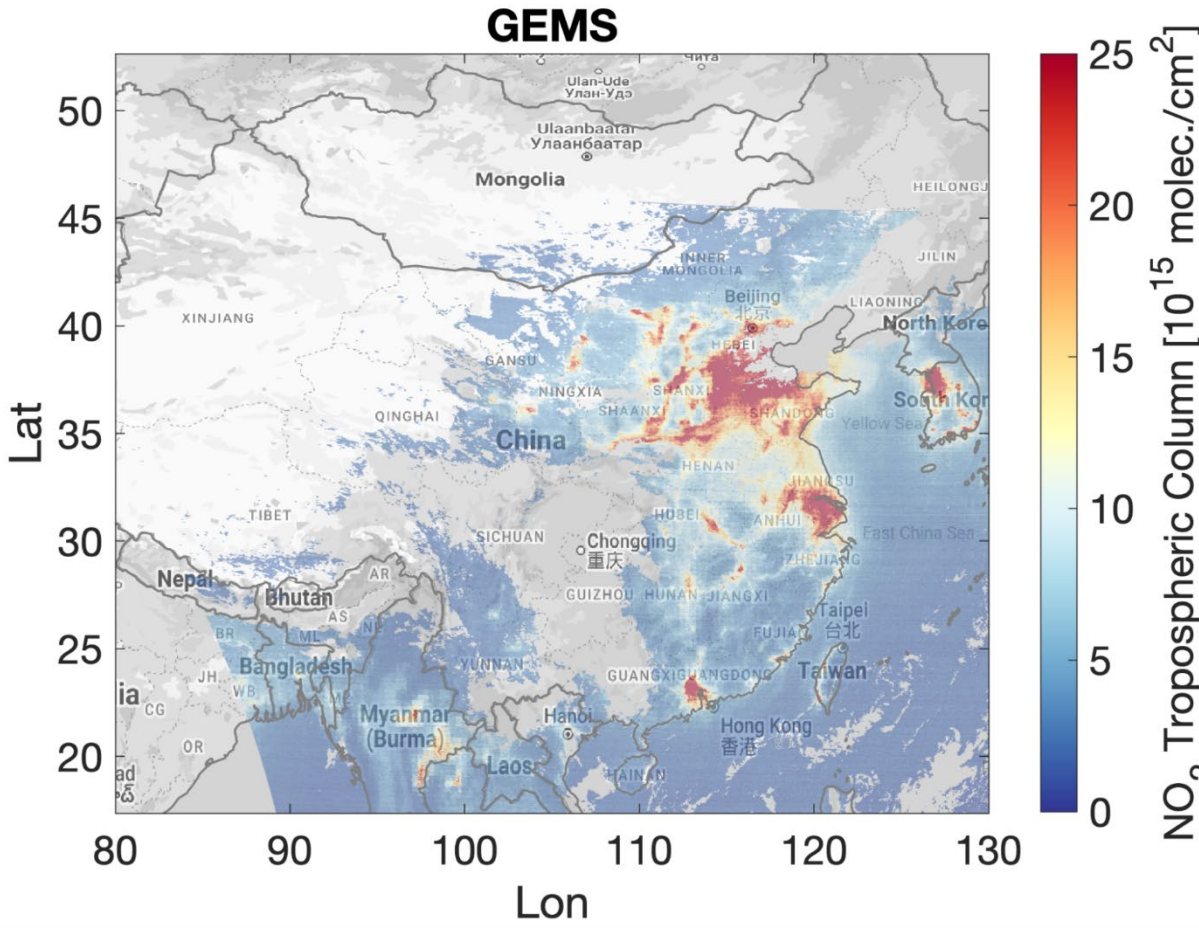
Example: Better coverage with multiple satellites



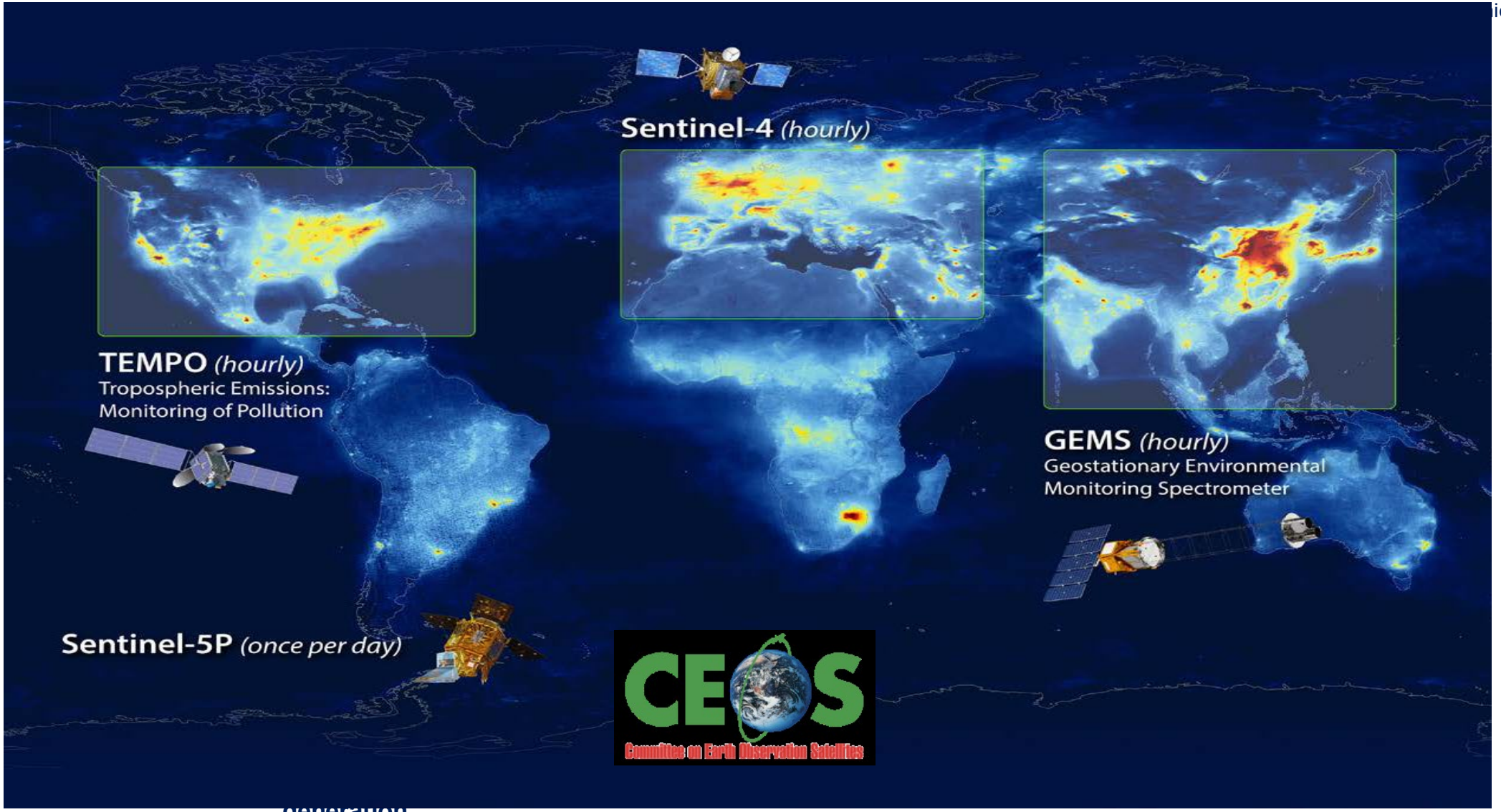


GEMS as Sentinel-4 precursor – LEO vs GEO



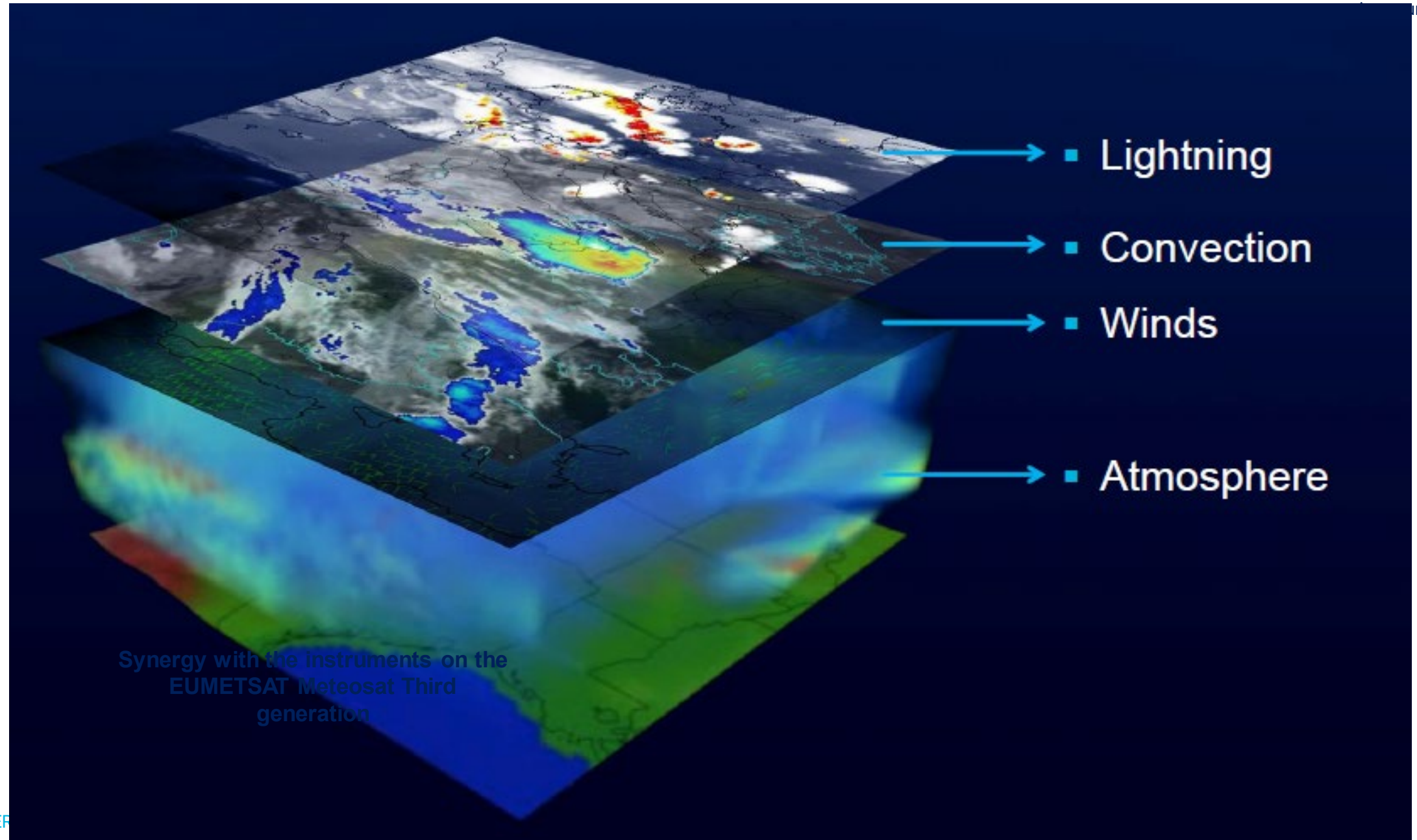


Sinergy – Constellation

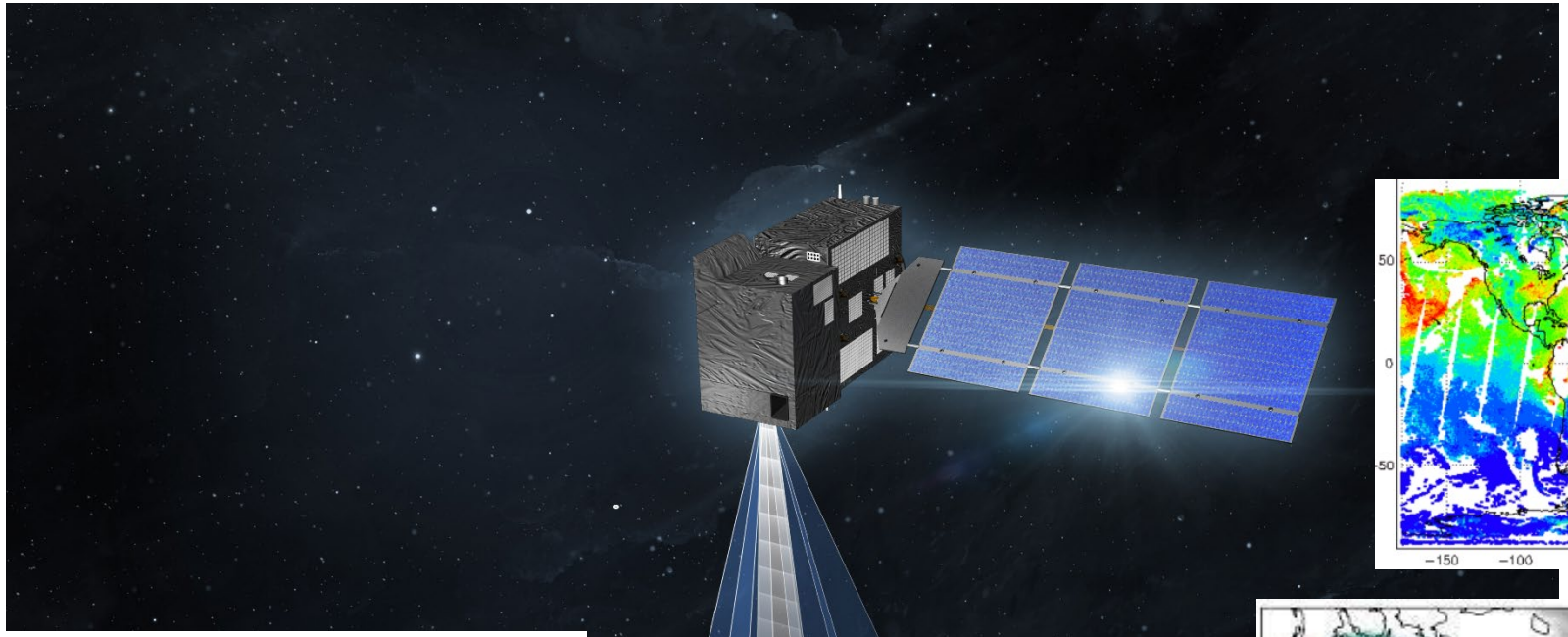


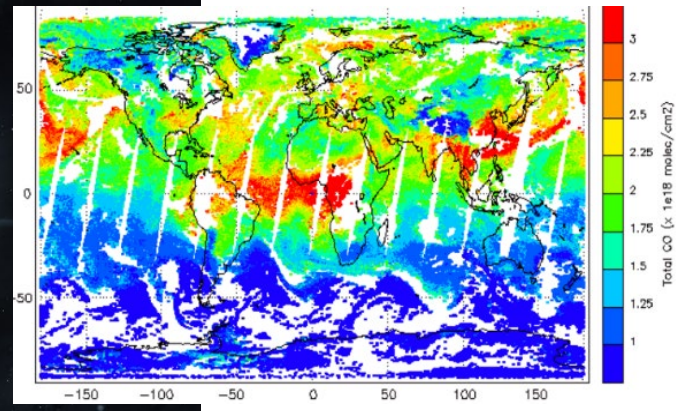
generation

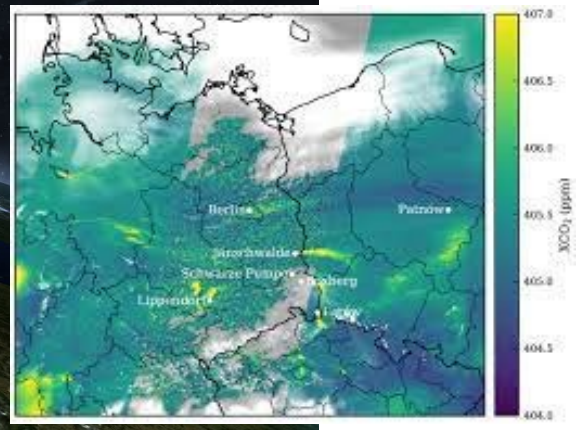
Sinergy – Weather Cube



Greenhouse gases – preparing for CO2M



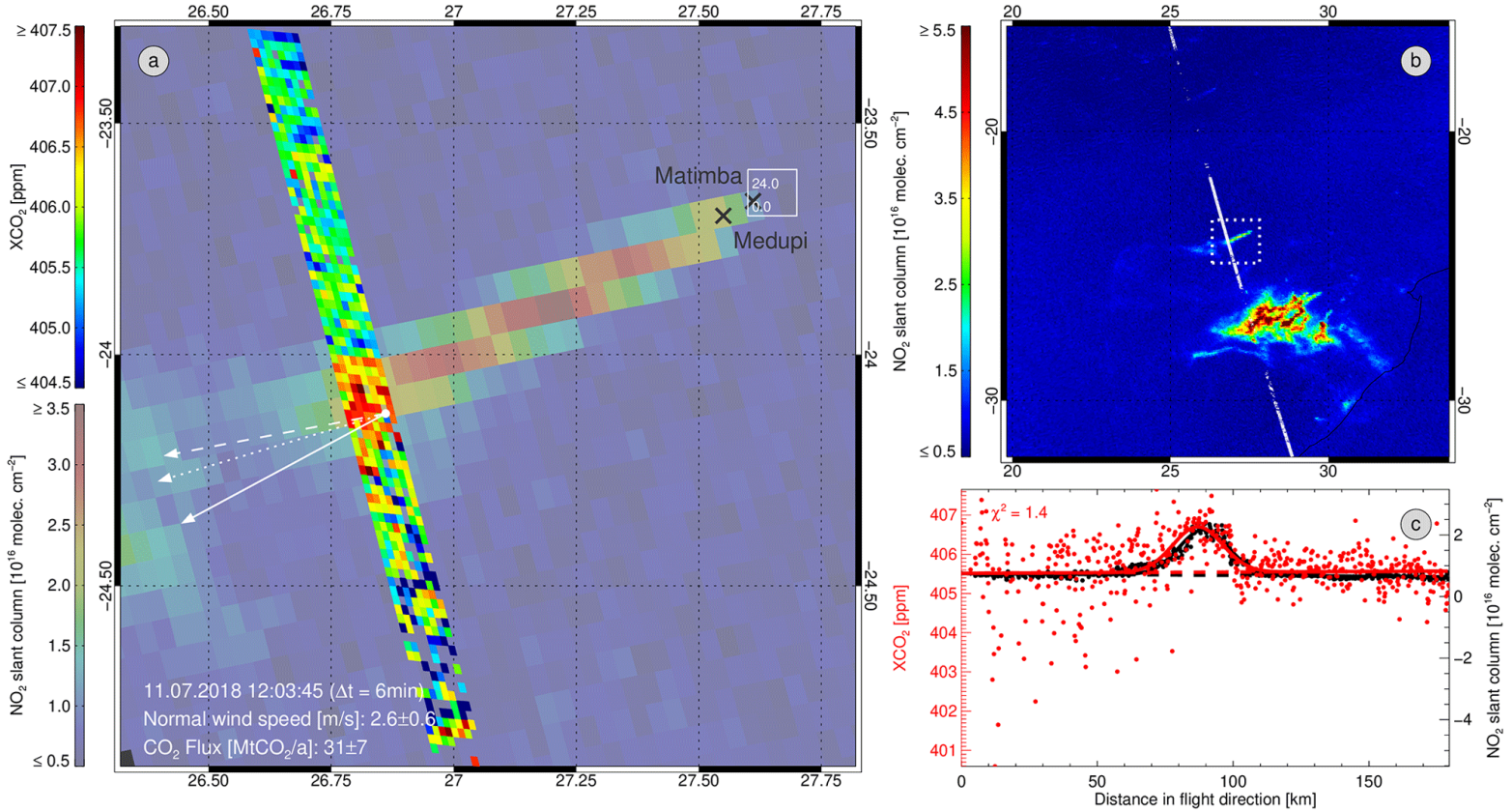




Product	Spatial resolution	Precision
CO2	4 km²	0.5 – 0.7 ppm
CH4	4 km²	10 ppb
NO2	4 km²	1.5x10¹⁵ molec/cm²
SIF*	4 km²	0.7 mW m⁻² sr⁻¹ nm⁻¹
Aerosol	16 km²	0.05 AOD, 500 m LH
Clouds	<5% of FOV	Water & cirrus clouds

VIS band also covers CHOCHO (glyoxal)
VIS & SWIR band also covers water vapour
*Top-of-Atmosphere Solar Induced Fluorescence

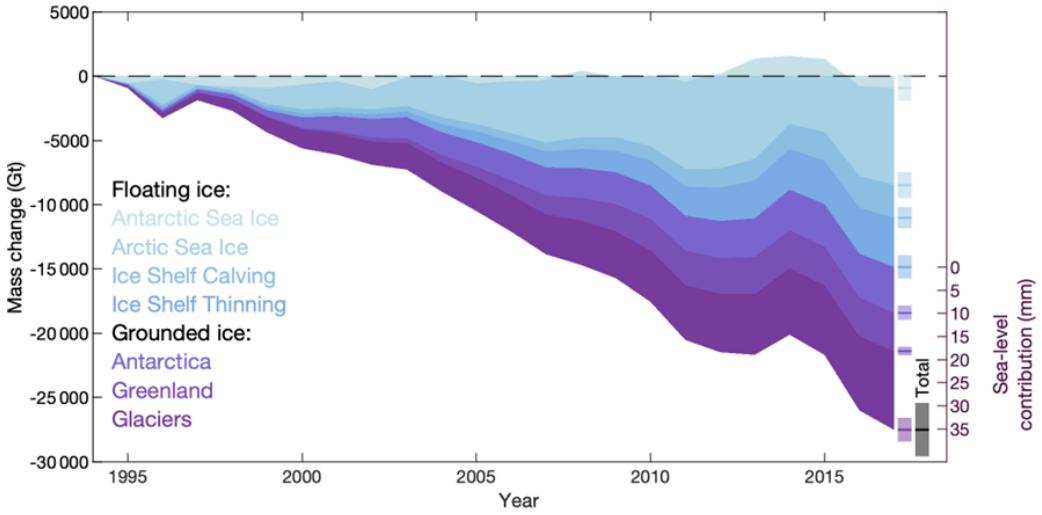
Example: Monitoring Carbon Dioxide

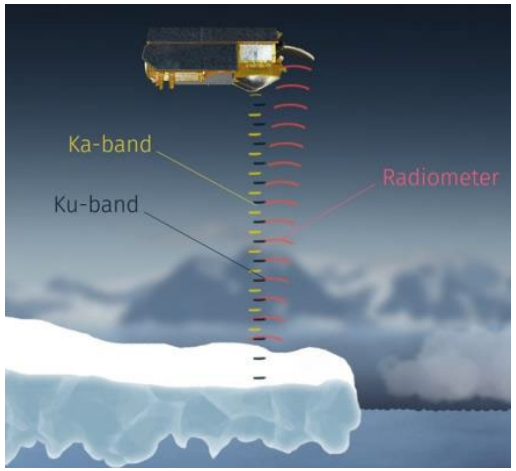


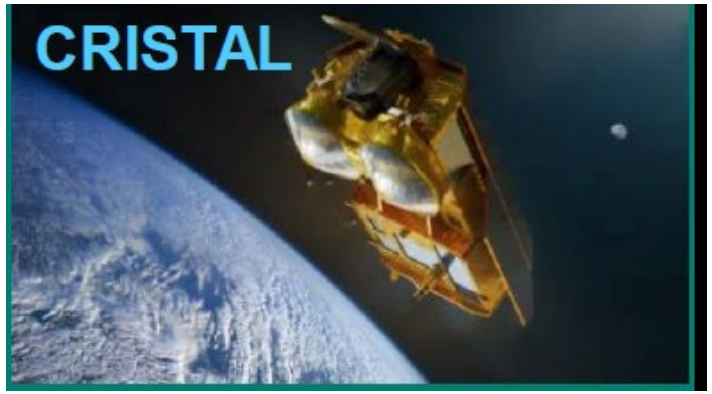
Experimental study on Matimba Power Station

Nitrogen Dioxide from TROPOMI data
© Copernicus program & CO2 from OCO2
Credit – Hakkarainen et al. 2020

Copernicus expansion missions – focus on cryosphere

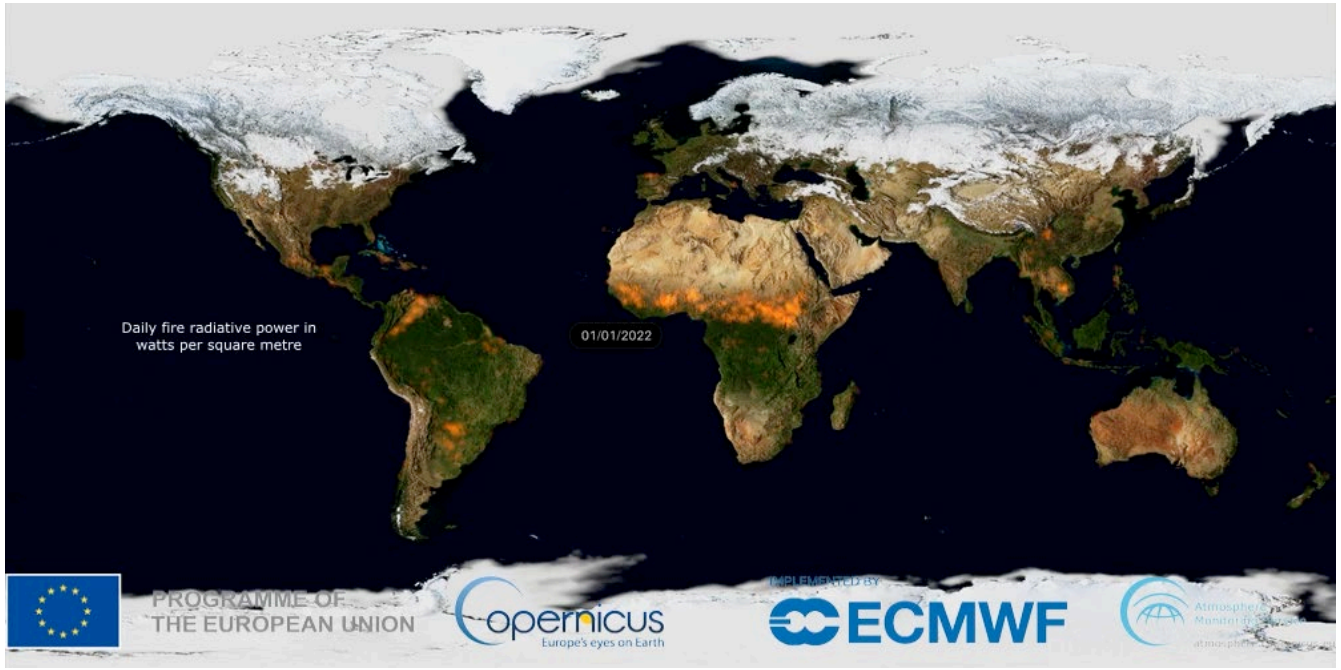




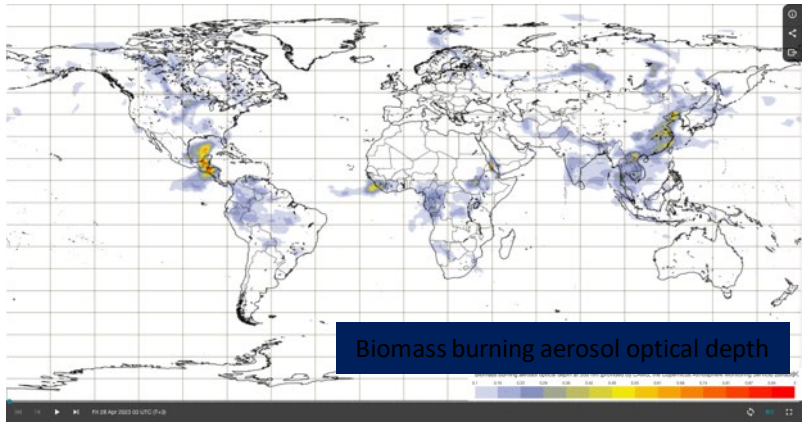


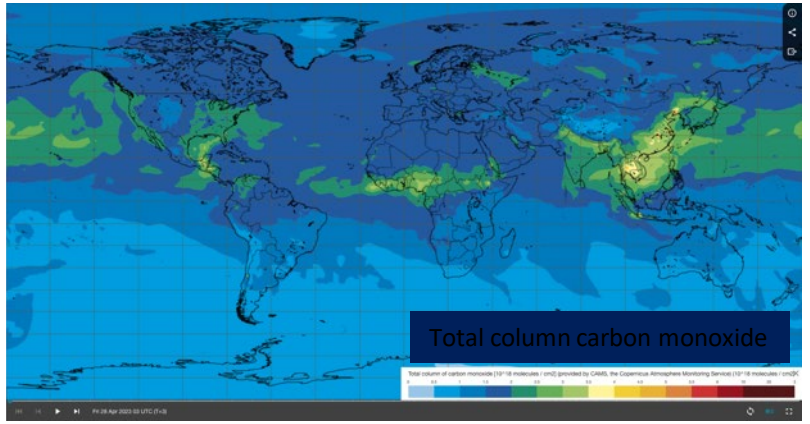
MONITORING WILDFIRE EMISSIONS

Wildfires are a significant source of atmospheric pollution, including carbon gases, volatile organic compounds and particulate matter, influencing global atmospheric composition and chemistry.



Daily total Fire Radiative Power 1 Jan-31 Dec 2022

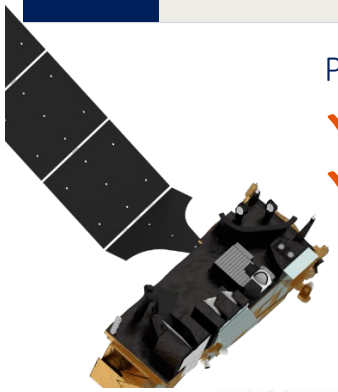




Example CAMS forecasts initialized 28 April 00 UTC valid for 03 UTC

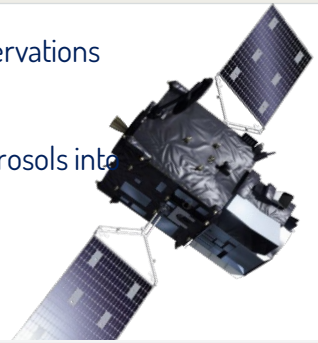
https://atmosphere.copernicus.eu/global-fire-monitoring

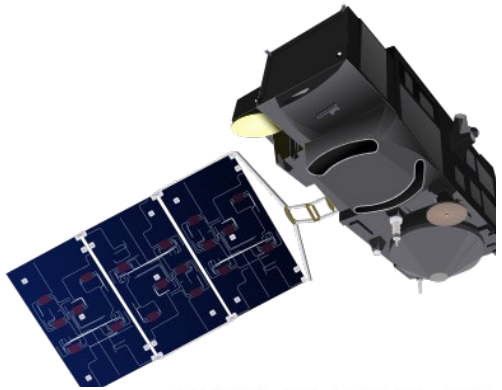
Example: Synergy of observational datasets to monitor wildfires

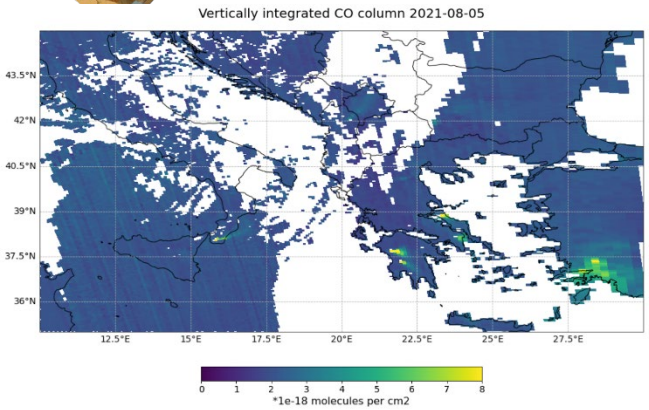


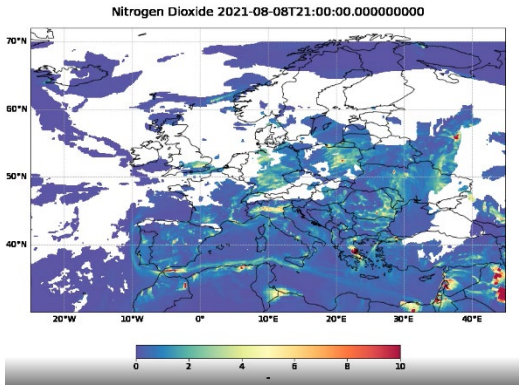
Pollutants, hot spots & intensity from satellite observations

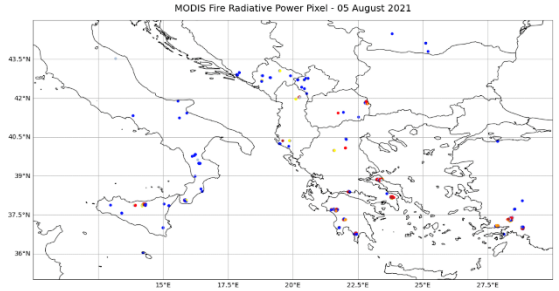
- ✓ Measurement of fire intensity
- ✓ Linked to emission of combustion gases & aerosols into the atmosphere

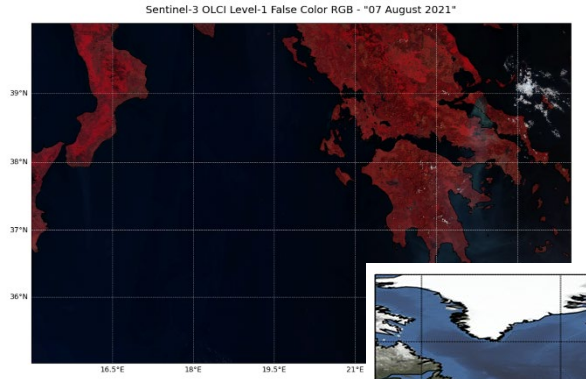


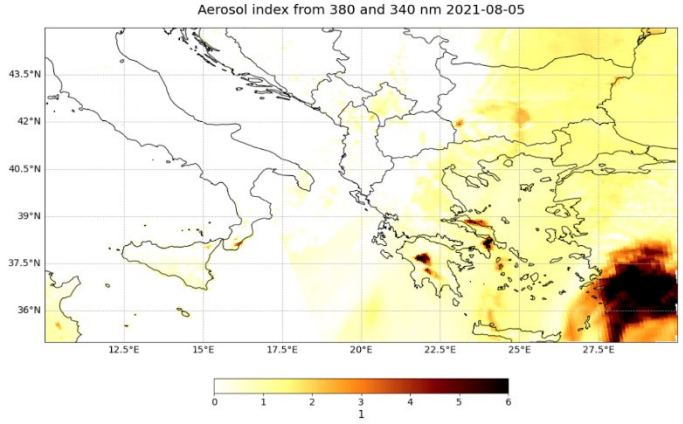








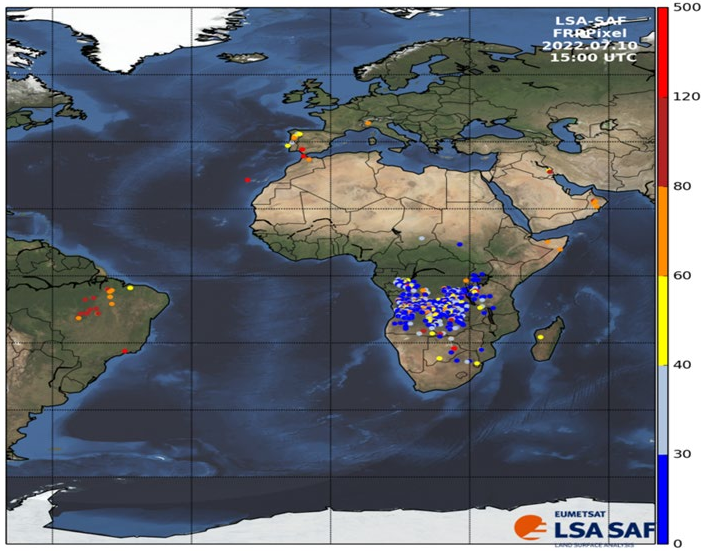




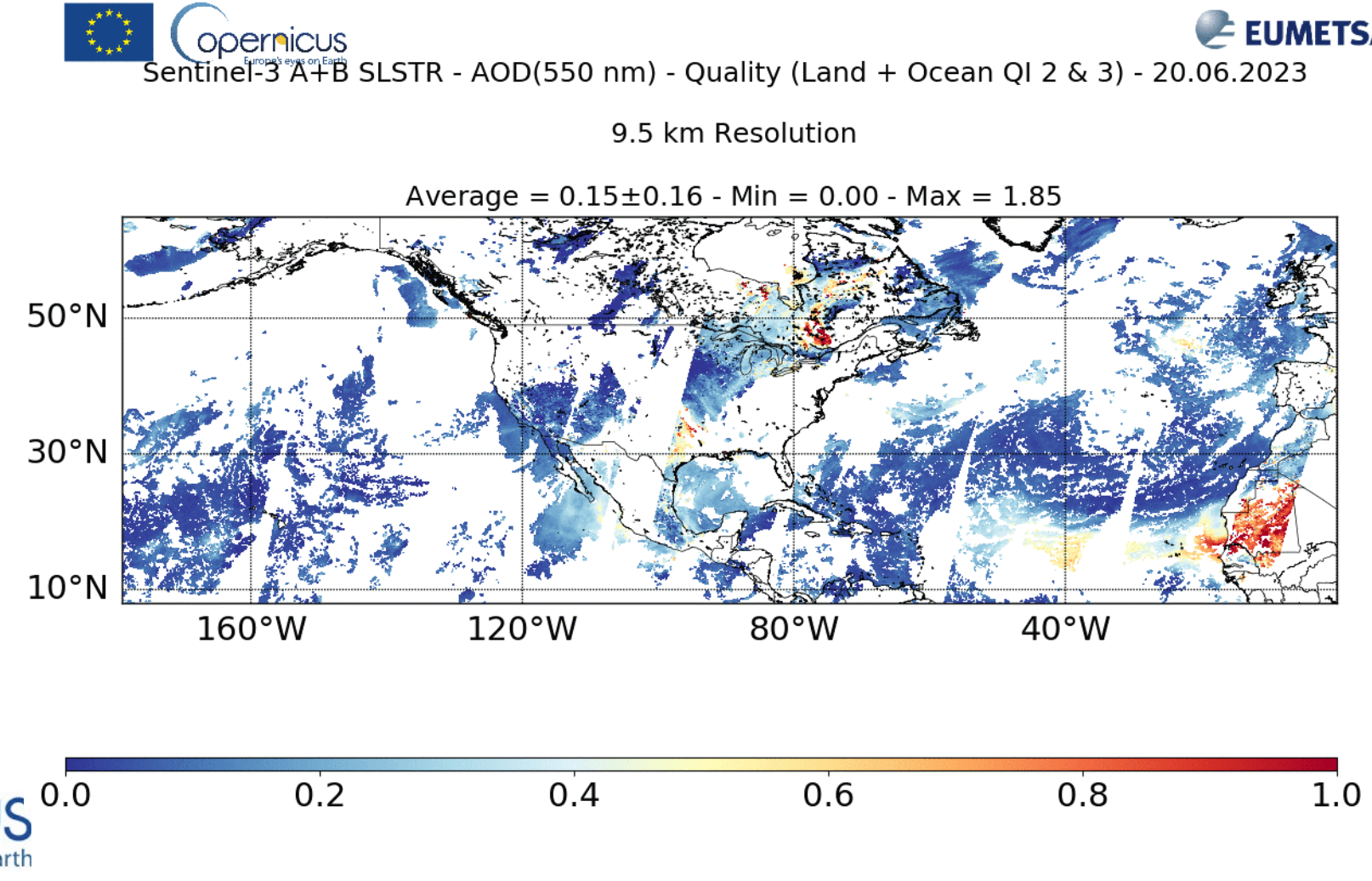
MSG/SEVIRI - every 15-minute allows:

- ✓ Strong seasonality
- ✓ Strong diurnal cycle

Fire Radiative Power

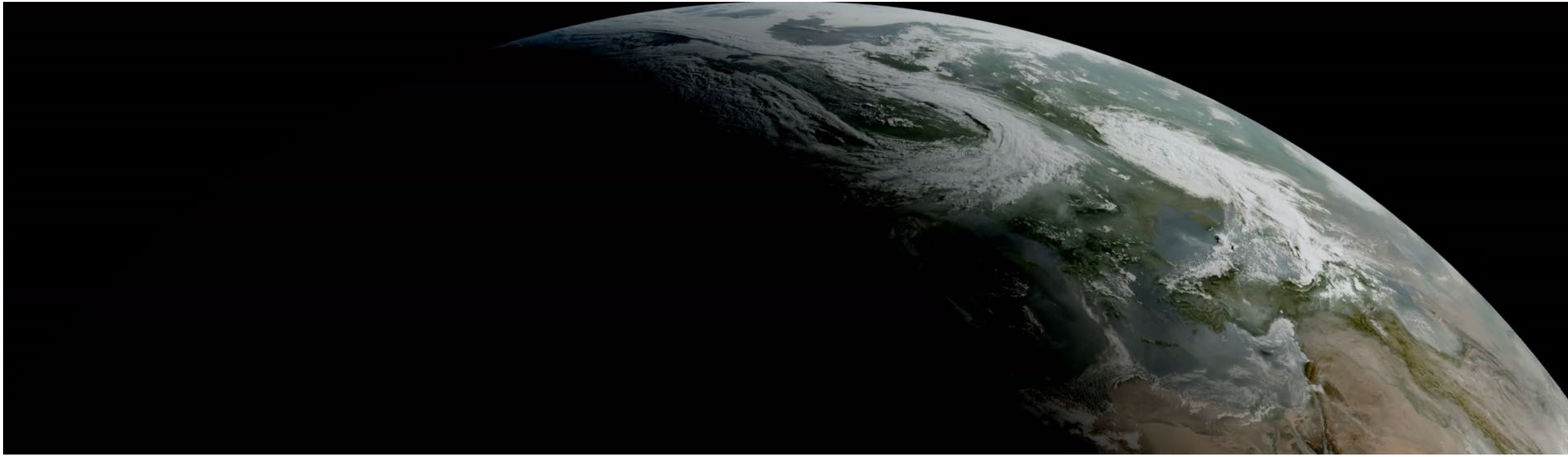


Monitoring from space: Sentinel-3 observations of Canadian wildfires



Monitoring from space: MTG observations of Canadian wildfires

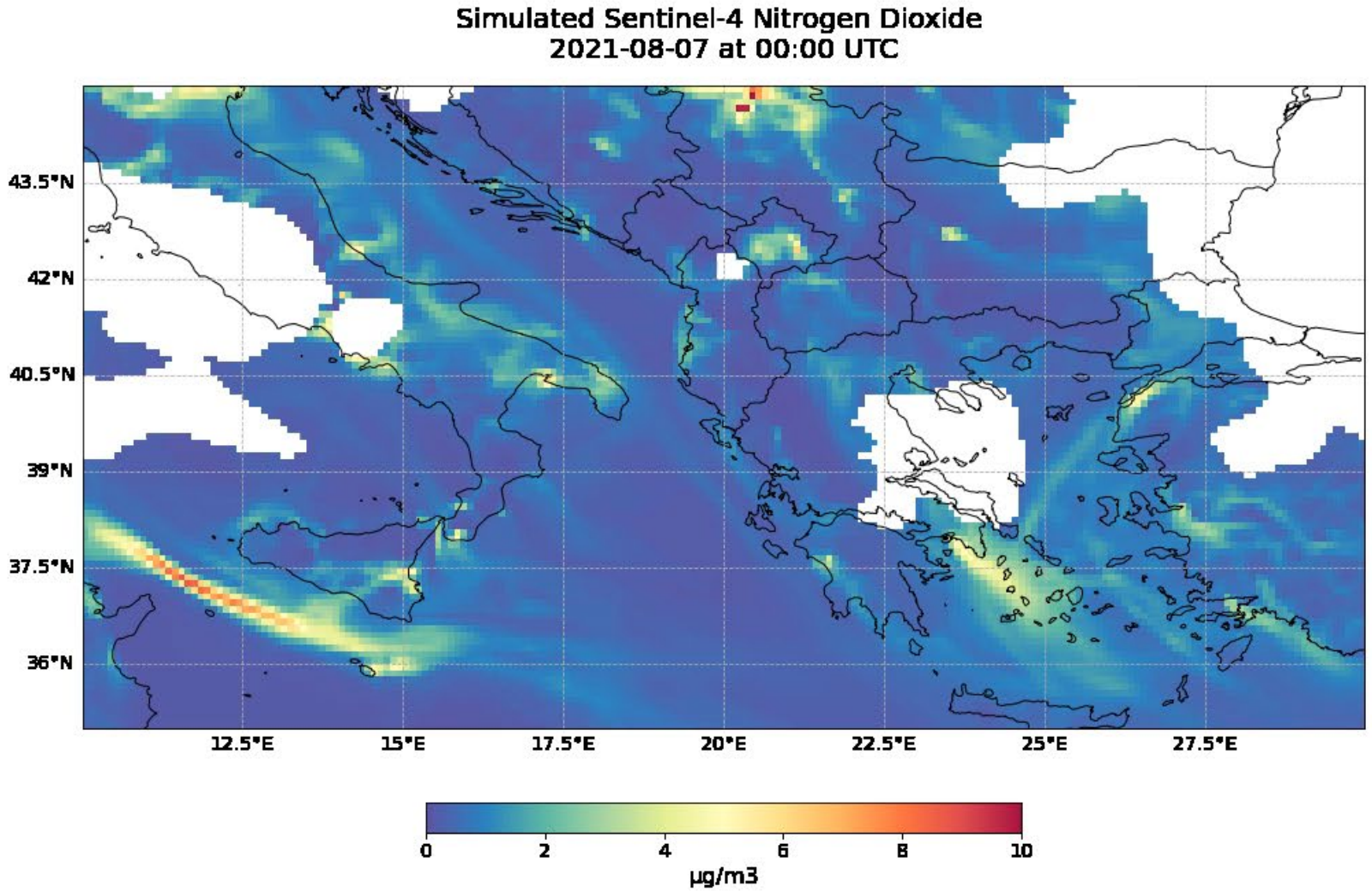
MTG data are preliminary



Monitoring from space: Sentinel-4

a whole new dimension will be explored by Sentinel-4:

daytime hourly air quality data over Europe

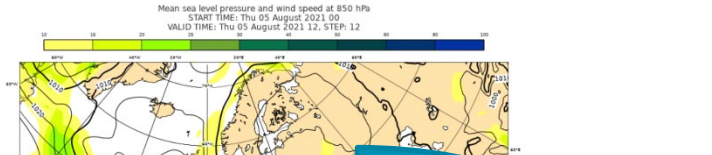


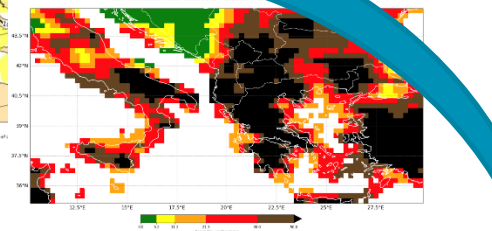
Part of an unique data value chain

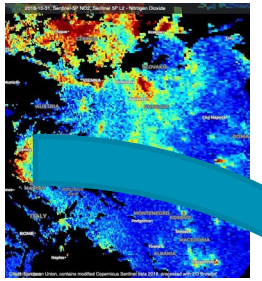
Bring to Users the concept of "Copernicus improves usability"

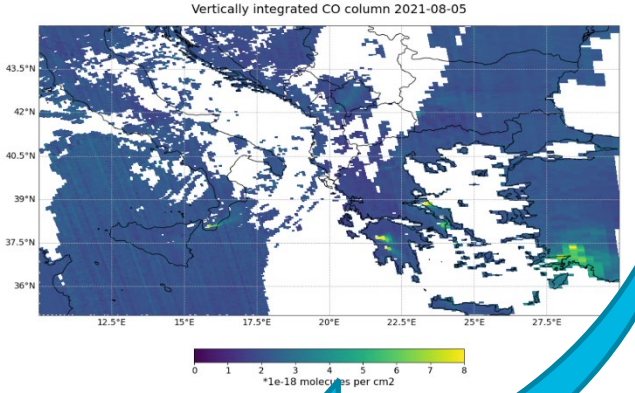
User journey encompassing:
→Forecast
→Monitoring and nowcasting
→Estimate of impacts

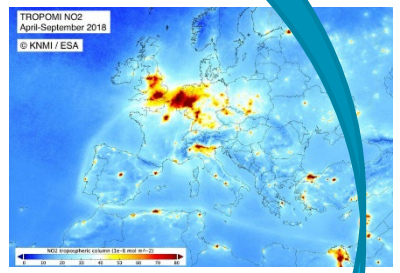
Integrated system:
→ Satellite and non satellite, models
→Support emission estimate
→Generate added value products
→Ensure Quality and usability

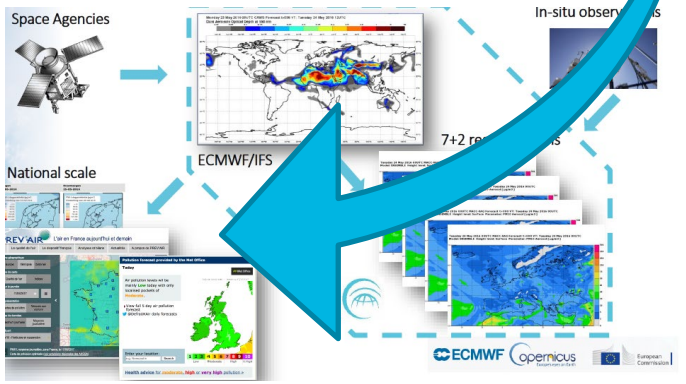


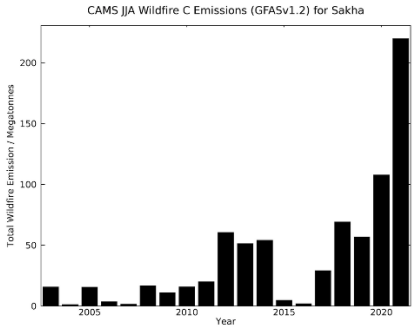


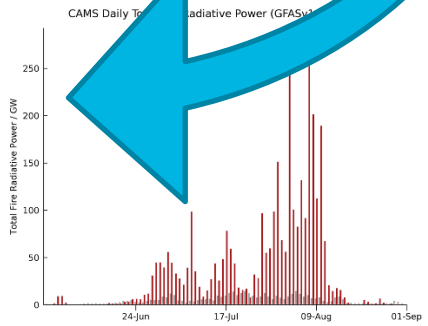






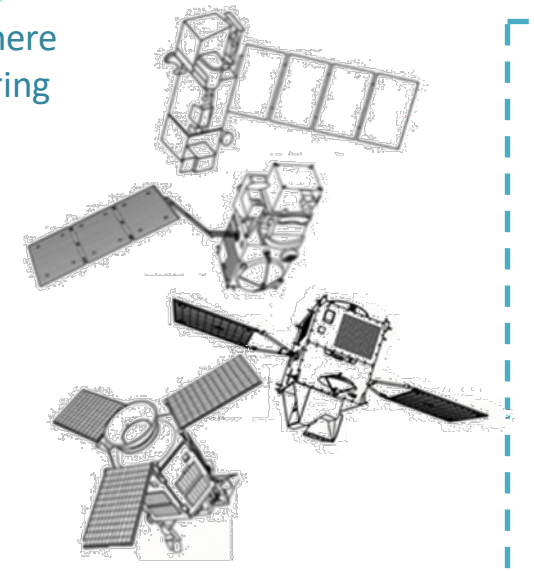




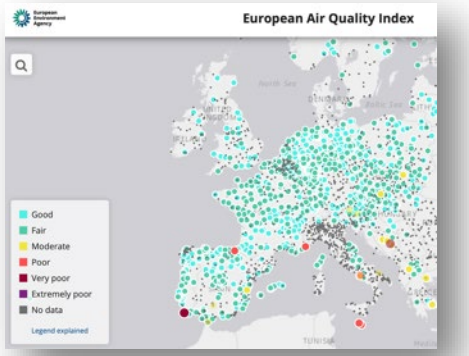


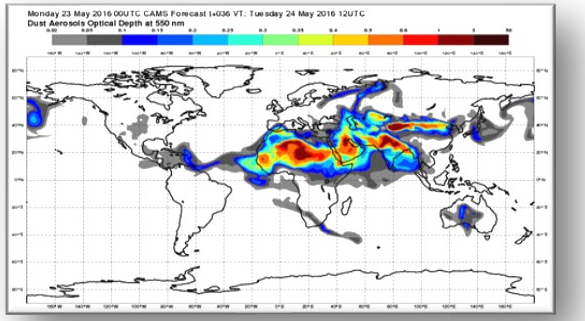
CAMS INFORMATION FLOW

Atmosphere Monitoring



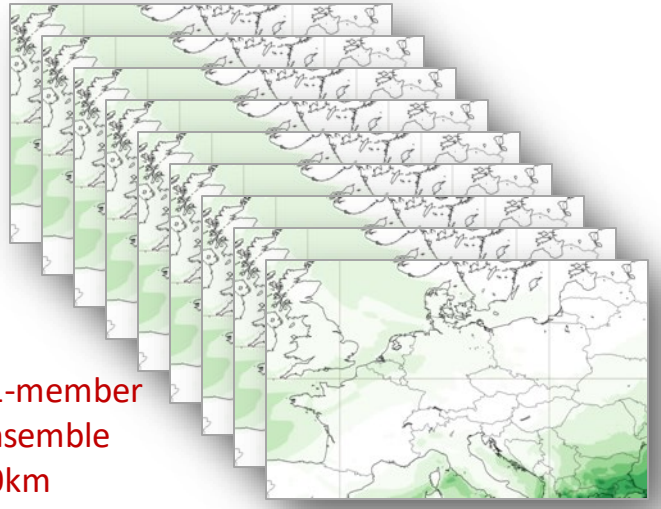
Earth Observation from satellite (>75 instruments) and in-situ (regulatory and research)



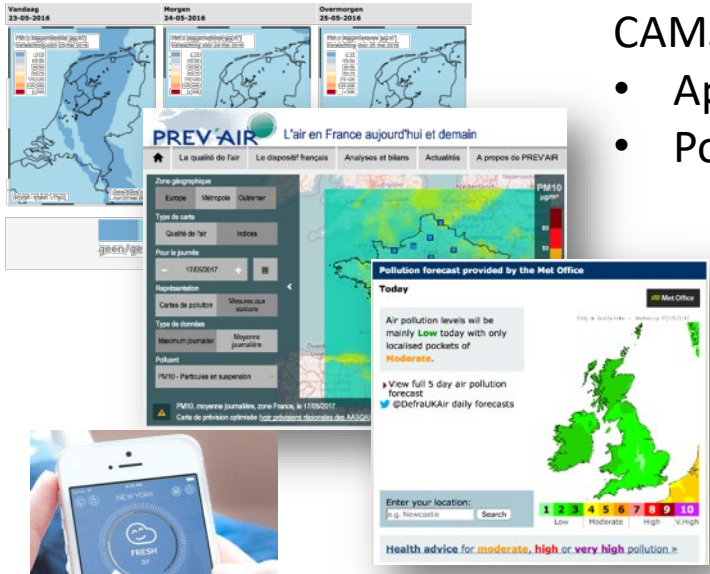


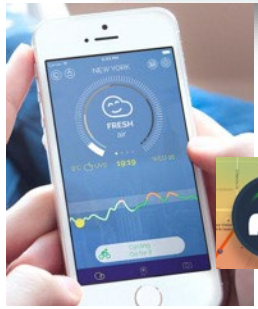
IFS 40km (oper) / 80km (rean) Globe

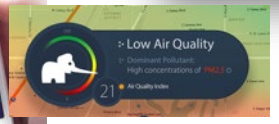
CAMS main operational data assimilation and modelling systems



11-member ensemble 10km Europe







CAMS users
- Applications
- Policy products

The Weather Channel

iOS

CNN

euronews.

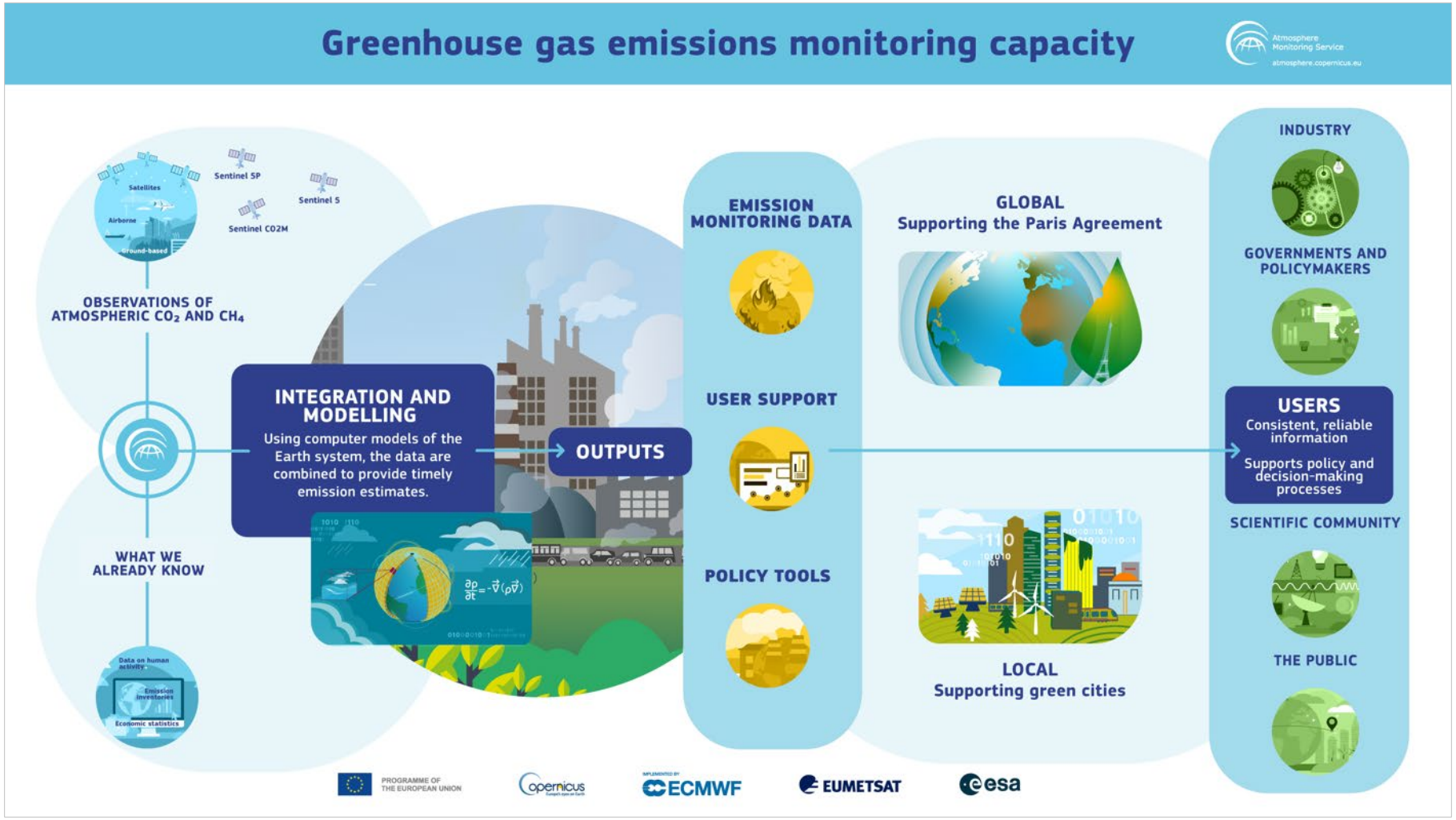
PROGRAMME OF THE EUROPEAN UNION

Copernicus Europe's eyes on Earth

IMPLEMENTED BY ECMWF

CAMS: GHG MONITORING CAPACITY

Atmosphere Monitoring



https://atmosphere.copernicus.eu/ghg-services

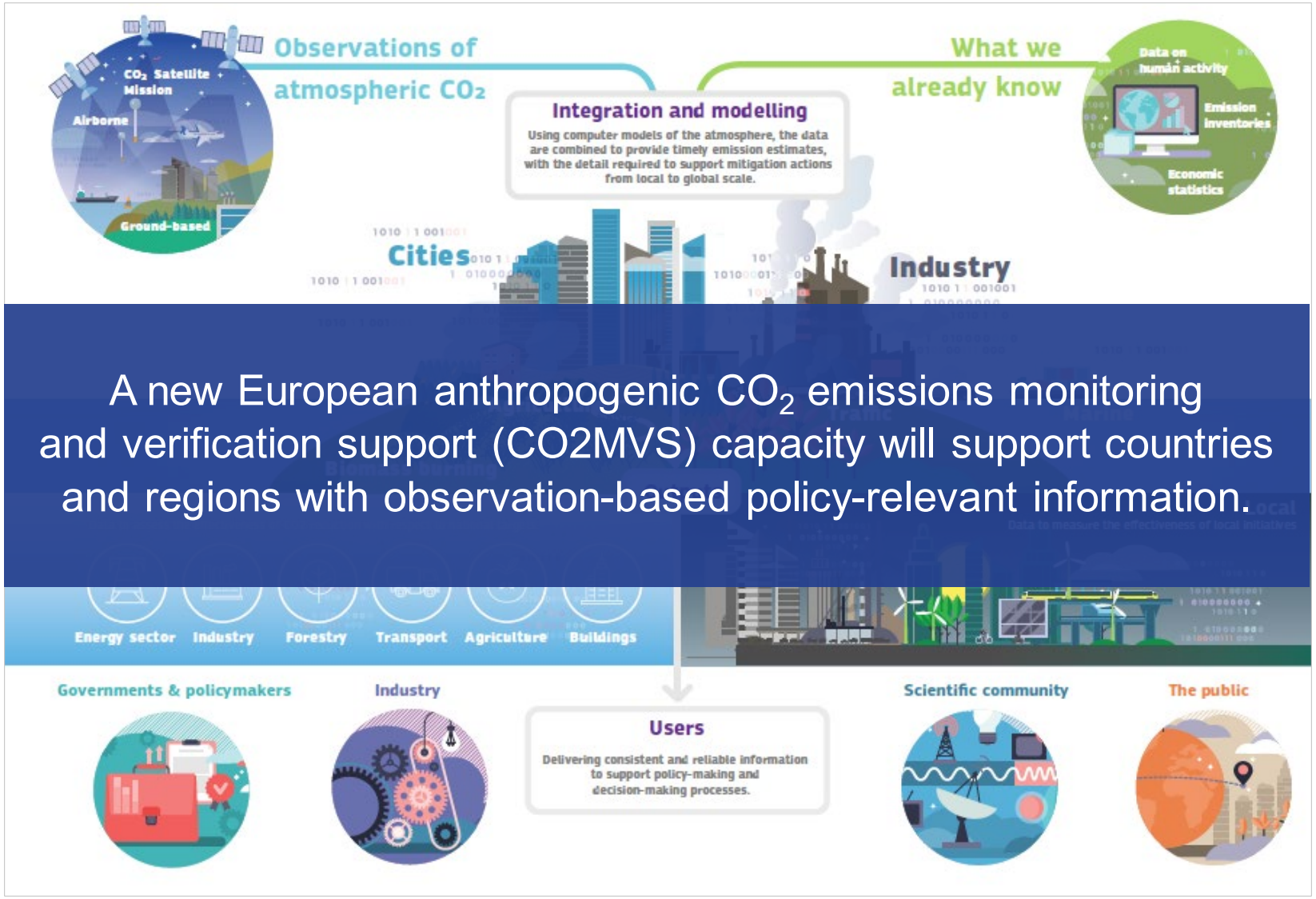
PROGRAMME OF THE EUROPEAN UNION

Copernicus Europe's eyes on Earth

IMPLEMENTED BY ECMWF

Atmosphere Monitoring

CAMS: CO2 MONITORING AND VERIFICATION SERVICE



PROGRAMME OF THE EUROPEAN UNION

Copernicus Europe's eyes on Earth

IMPLEMENTED BY ECMWF

TIMELINE OF COPERNICUS CO2MVS

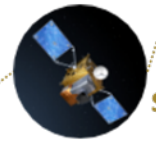
Atmosphere Monitoring

From expert groups through dedicated research funding, to operational services

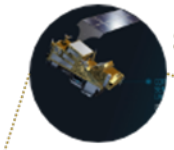
ECMWF esa EUMETSAT

Sentinel 5p

SATELLITE MISSIONS



Sentinel 4



Sentinel 5

CO_2 Mission

Air Quality emissions 2025

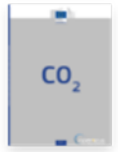
Operational ramp-up in CAMS

SERVICE COMPONENTS

2026

CO_2 Monitoring & Verification Support (CO_2MVS)

CO2 TASK FORCE GUIDANCE DOCUMENTS



2015

2017

2019

2017

CO_2 Human Emissions

2018

VERIFY

2021

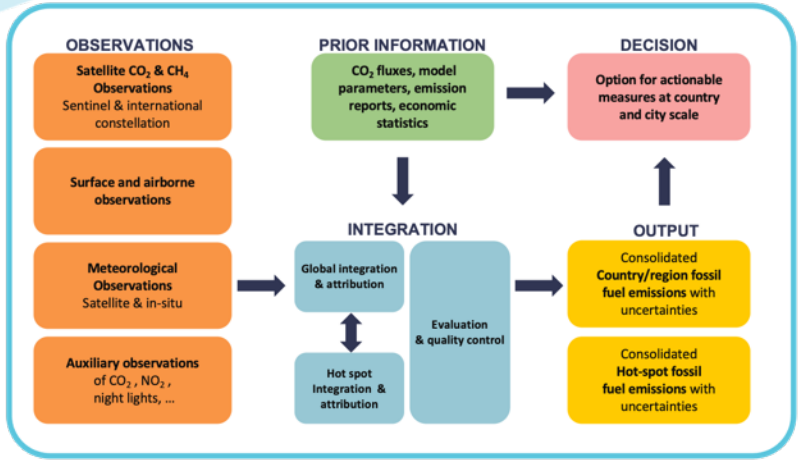
ICOS Cities

CoCO2 Prototype system for a Copernicus CO_2 service

2022

horizon europe

RESEARCH AND PREPARATORY PROJECTS



PROGRAMME OF THE EUROPEAN UNION

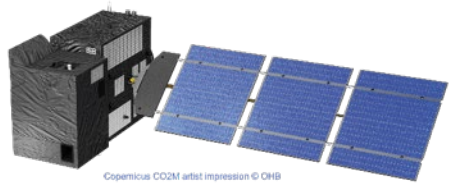
Copernicus Europe's eyes on Earth

IMPLEMENTED BY ECMWF

Atmosphere Monitoring

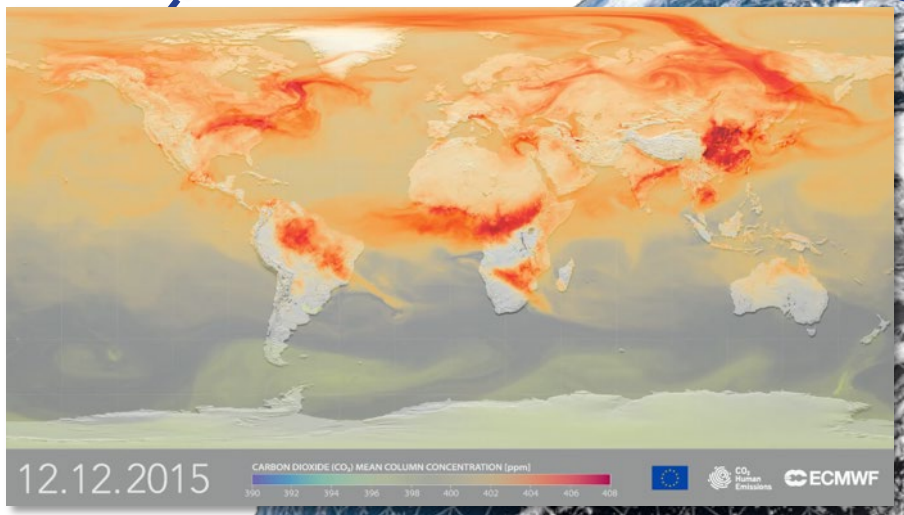
CHALLENGES OF OBSERVATION-BASED EMISSION MONITORING

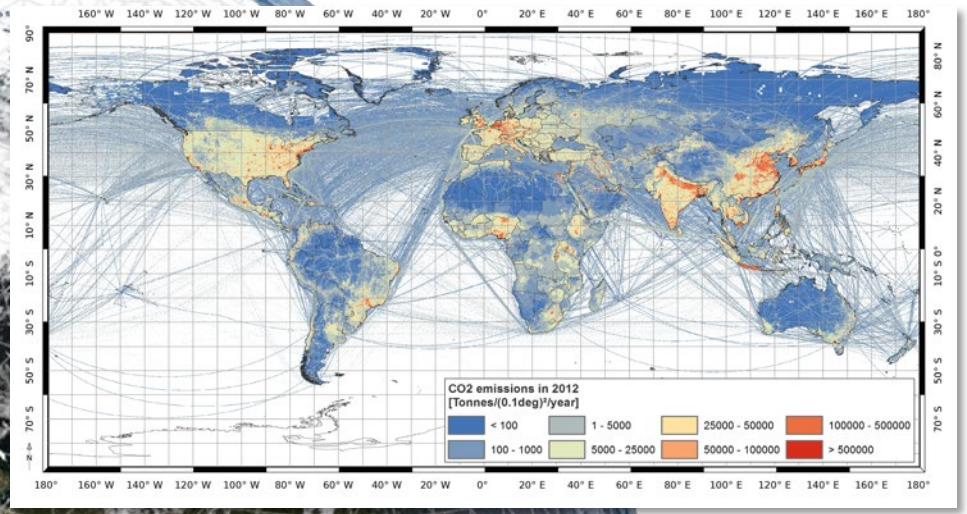
Satellites do not measure emissions directly; they measure the total impact of natural and anthropogenic emissions and removals on the atmosphere.



Earth System models are used to translate the **observations** into **emission estimates**.

Collaboration between space agencies, in-situ networks, and operational data assimilation centres.



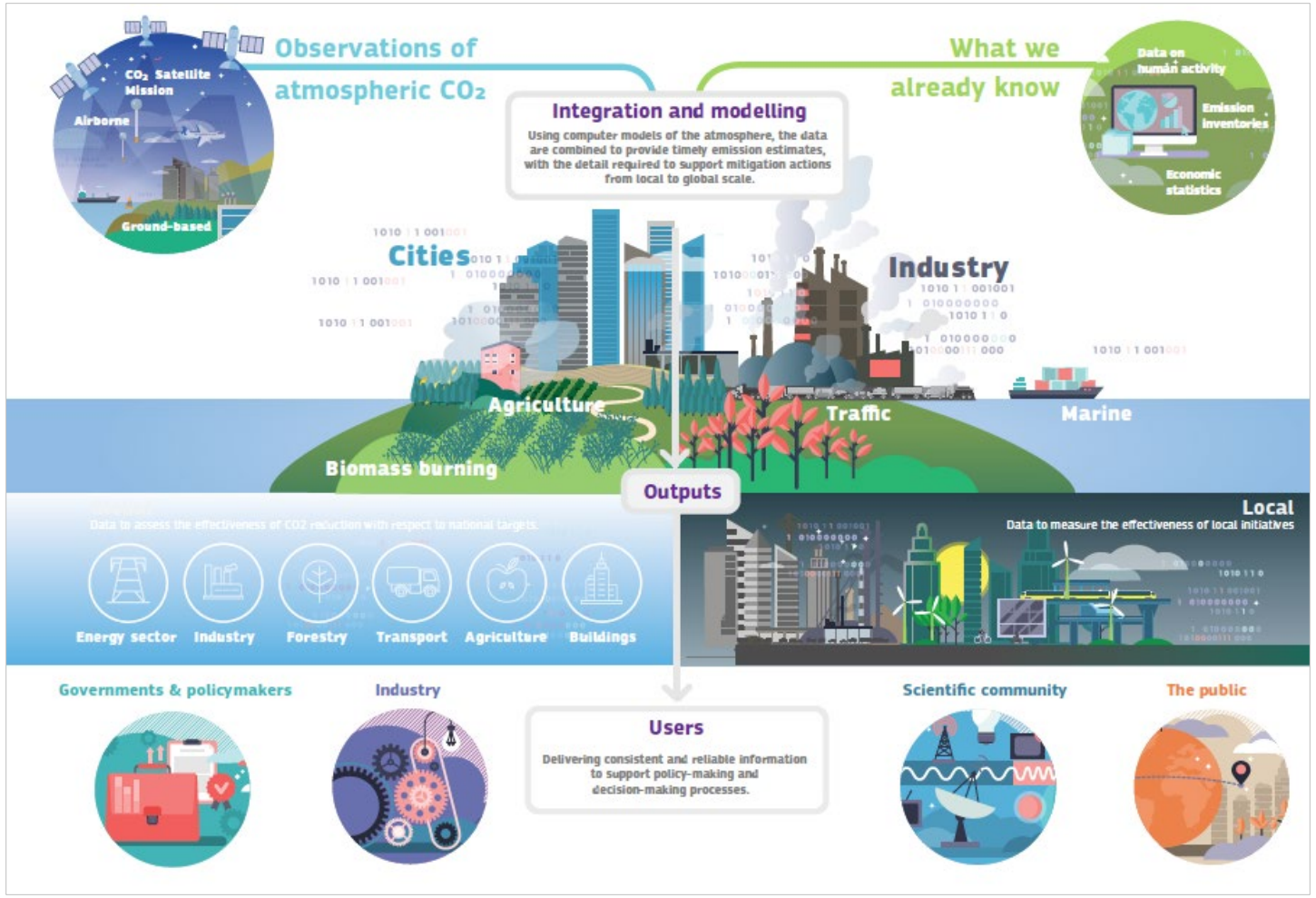


RAMPING-UP OF A NEW COPERNICUS CO_2 MONITORING SERVICE

Atmosphere Monitoring

Combining satellite and in-situ observations with Earth system models by expanding the existing CAMS operational infrastructure at ECMWF.

A European contribution to CEOS, GCOS, GEO, and WMO (IG3IS) efforts in support of the Paris Agreement.



PROGRAMME OF THE EUROPEAN UNION

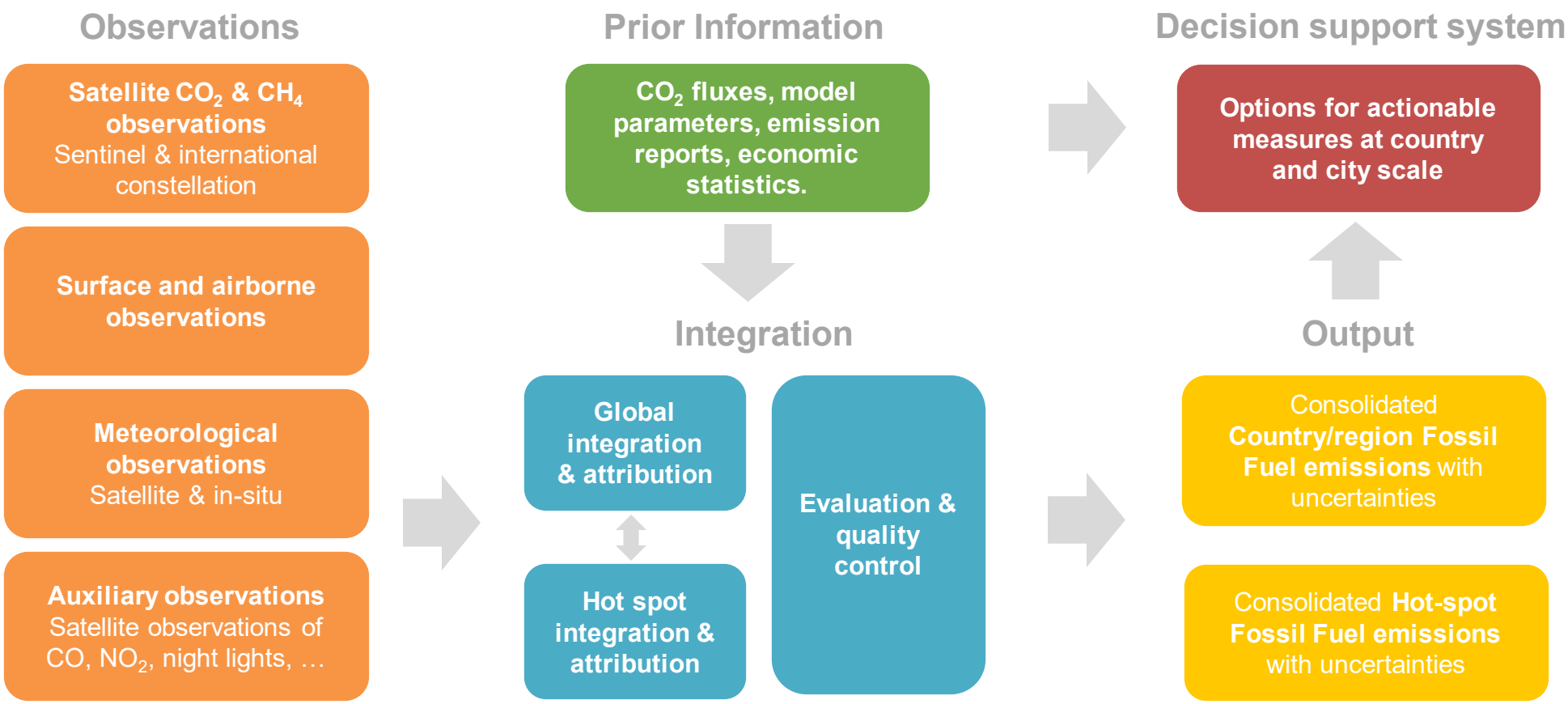
Copernicus Europe's eyes on Earth

IMPLEMENTED BY ECMWF

IMPLEMENTATION OF CAMS CO2MVS

Atmosphere Monitoring

Based on NWP and AQ frameworks with strong links to both.

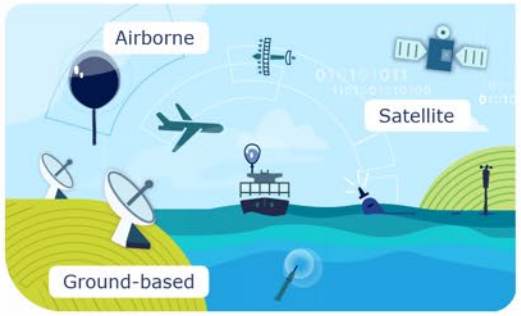


COPERNICUS ATMOSPHERE MONITORING SERVICE

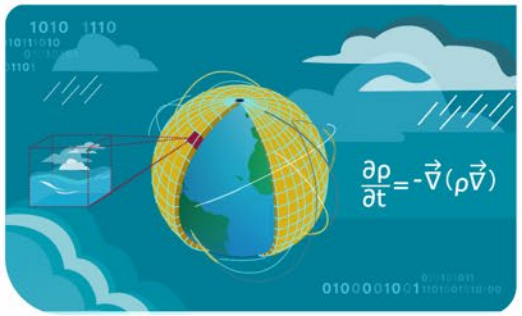
Atmosphere Monitoring

CAMS provides consistent and quality-controlled information related to air pollution and health, solar energy, greenhouse gases and climate forcing, everywhere in the world.

AIR QUALITY OBSERVATIONS



MODELLING



OUTPUTS

1. Monitoring the current situation

- Air quality
- Solar radiation
- Greenhouse gases
- Fire emissions

2. Forecasts for the next few days

- Global
- Europe

3. Tools to explore further

- Emissions and impact of reductions
- Origins of pollution
- Annual air quality assessments

USERS

- Industry
- Businesses
- Government and policymakers
- Scientific community
- The public

PROGRAMME OF THE EUROPEAN UNION

Copernicus Europe's eyes on Earth

IMPLEMENTED BY ECMWF

Atmosphere Monitoring

CAMS' THEMATIC AREAS

CAMS delivers consistent and quality-controlled information related to air pollution and health, solar energy, greenhouse gases and climate forcing, everywhere in the world.

Air quality

Policy tools

Solar energy

Ozone layer and UV radiation

Emissions and surface Fluxes

Climate forcing

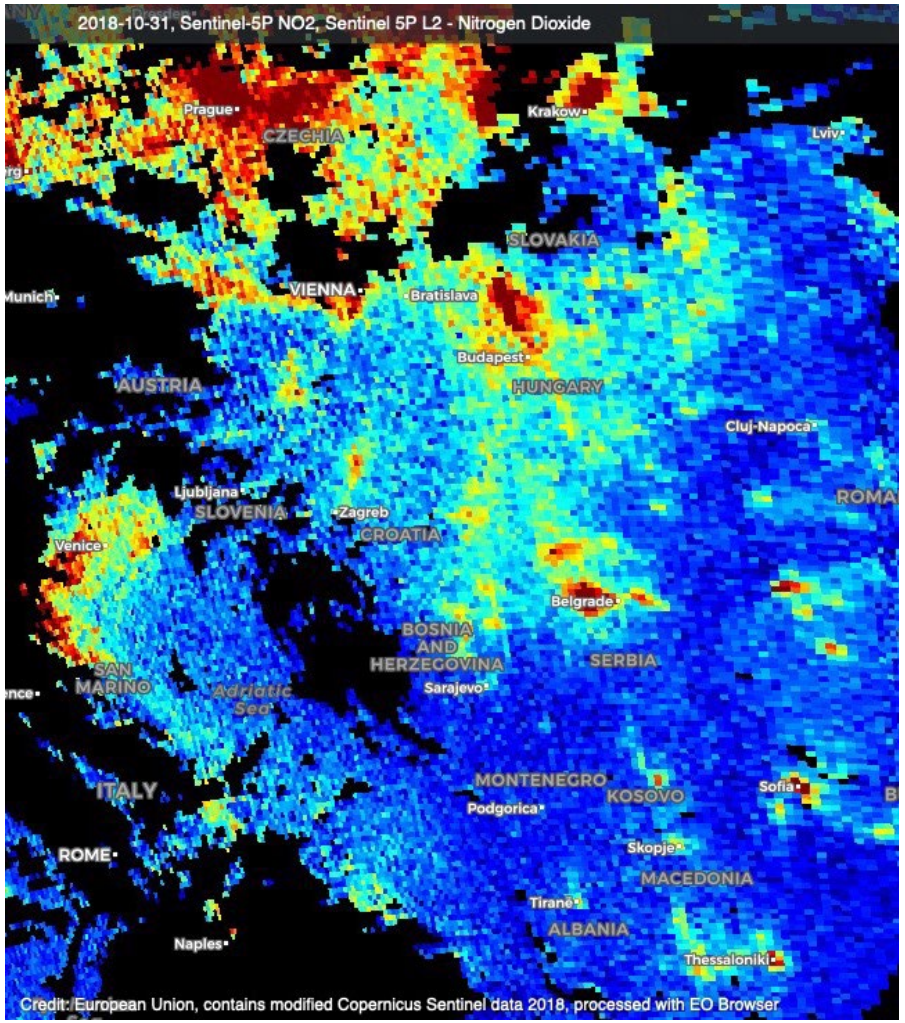
PROGRAMME OF THE EUROPEAN UNION

Copernicus Europe's eyes on Earth

IMPLEMENTED BY ECMWF

Atmosphere Monitoring

WHY IS CAMS NEEDED?



Example: NO_2 tropospheric column from Copernicus Sentinel-5P (31/10/2018)

Observations are essential, but **direct use** is generally **limited**:

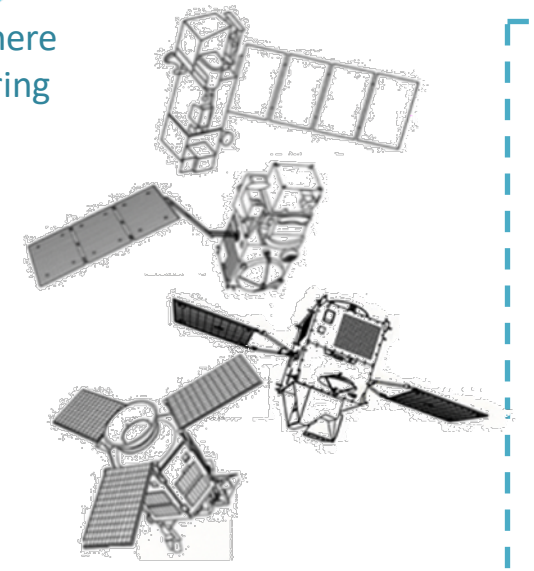
- gaps in space and time
- observed quantities may not be directly relevant (vertical column vs surface concentration)
- can be complex and numerous

What CAMS does:

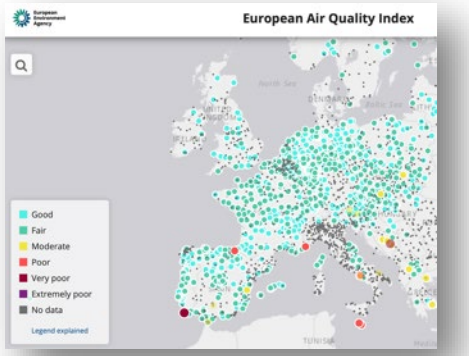
- blend observations (satellite and non satellite) with model to provide a consistent 3D state
- forecasts, a few days ahead
- reanalyses over past years or decades

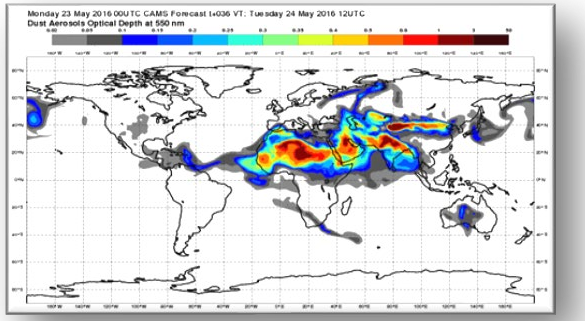
CAMS INFORMATION FLOW

Atmosphere Monitoring



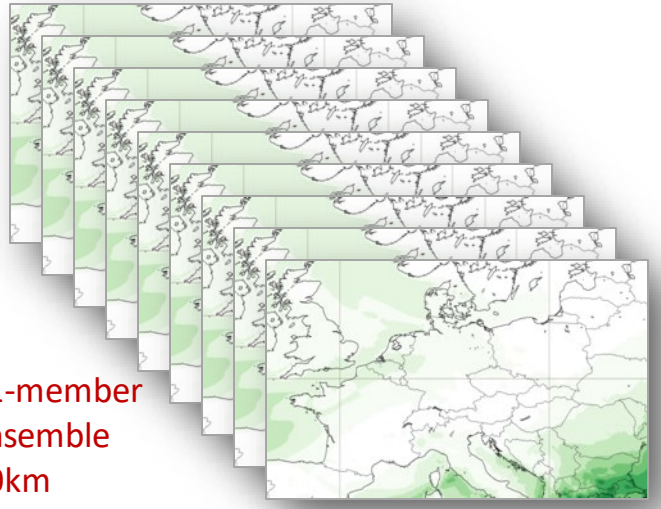
Earth Observation from satellite (>75 instruments) and in-situ (regulatory and research)



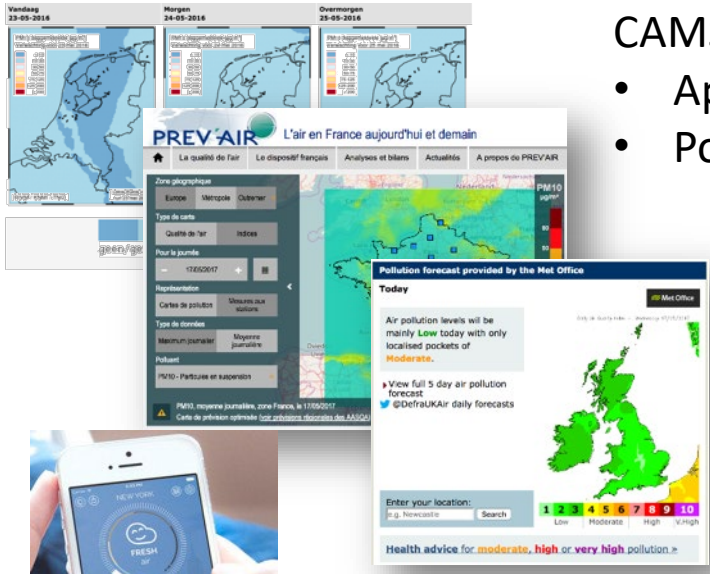


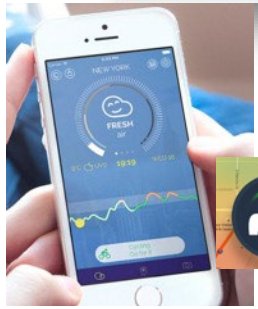
IFS 40km (oper) / 80km (rean) Globe

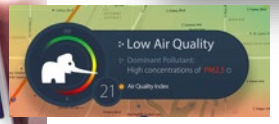
CAMS main operational data assimilation and modelling systems



11-member ensemble 10km Europe







CAMS users
- Applications
- Policy products

The Weather Channel

iOS

CNN

euronews.

PROGRAMME OF THE EUROPEAN UNION

Copernicus Europe's eyes on Earth

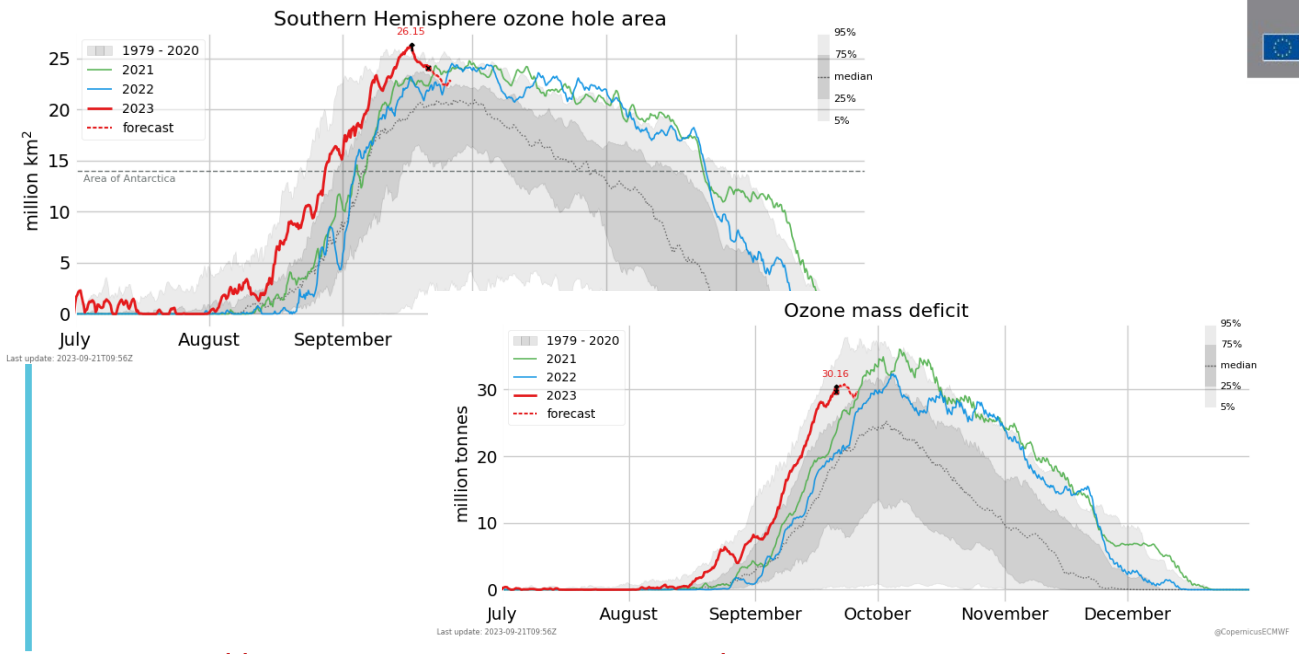
IMPLEMENTED BY ECMWF

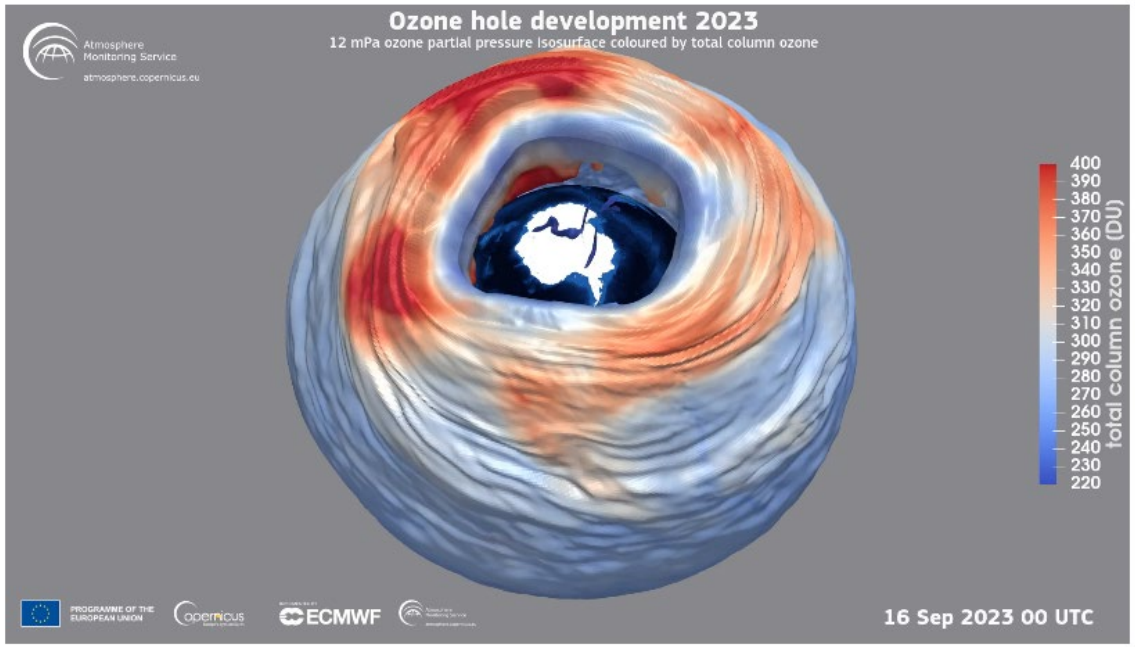
MONITORING OZONE

Atmosphere Monitoring

The ozone layer protects us from potentially harmful ultraviolet (UV) radiation.

CAMS monitors ozone throughout the atmosphere, including the Antarctic ozone hole, and provides forecasts of associated ground-level ultraviolet radiation.





CAMS provides NRT monitoring of the evolution of the Antarctic ozone hole between August and December.

Context provided cf 40+ year dataset combining ERA-5 and CAMS reanalysis products.

https://atmosphere.copernicus.eu/monitoring-ozone-layer

PROGRAMME OF THE EUROPEAN UNION

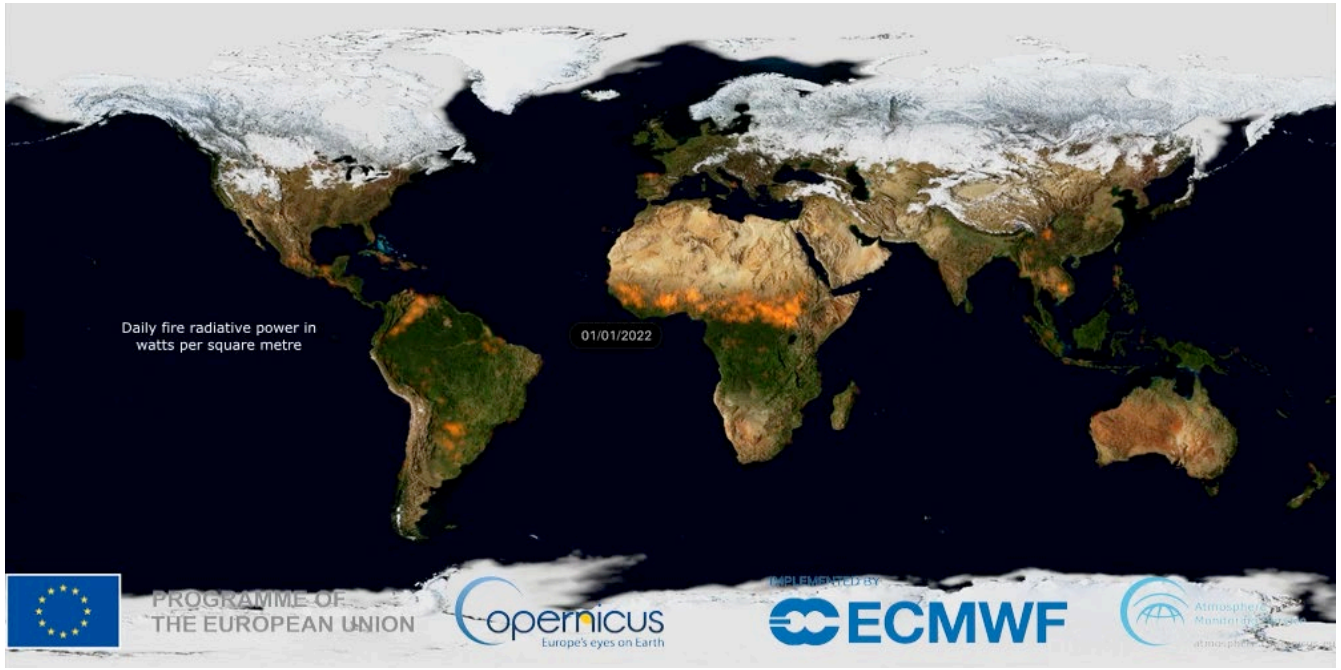
Copernicus Europe's eyes on Earth

IMPLEMENTED BY ECMWF

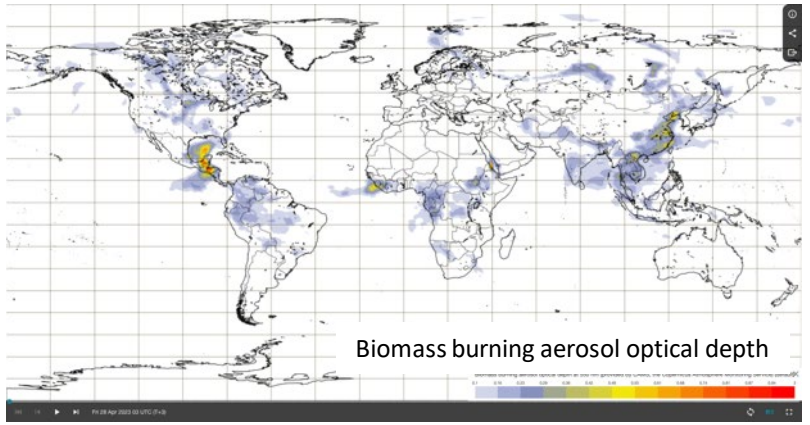
MONITORING WILDFIRE EMISSIONS

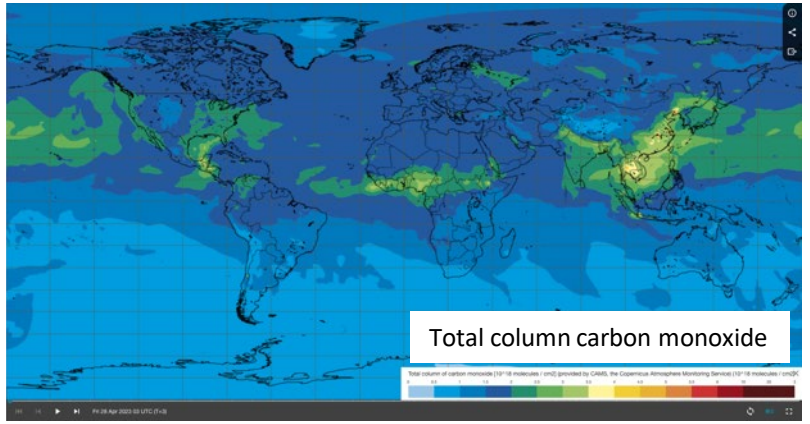
Atmosphere Monitoring

Wildfires are a significant source of atmospheric pollution, including carbon gases, volatile organic compounds and particulate matter, influencing global atmospheric composition and chemistry.



Daily total Fire Radiative Power 1 Jan-31 Dec 2022





Example CAMS forecasts initialized 28 April 00 UTC valid for 03 UTC

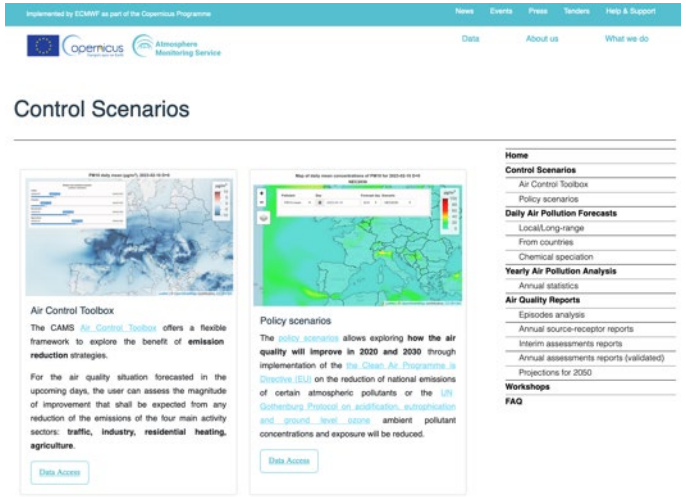
https://atmosphere.copernicus.eu/global-fire-monitoring

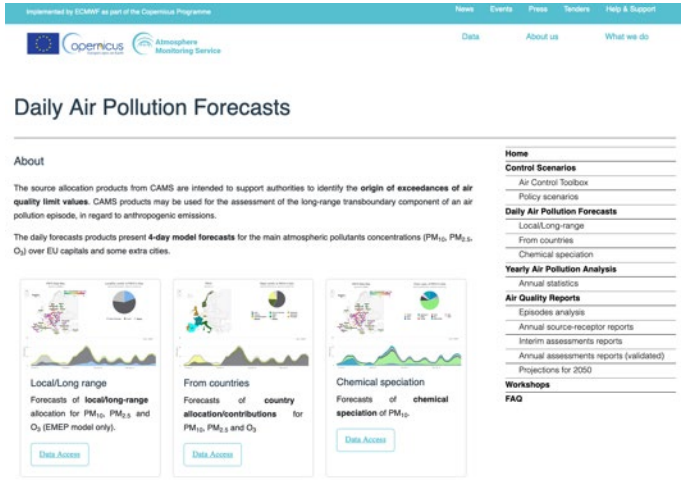
PROGRAMME OF THE EUROPEAN UNION
opernicus
Europe's eyes on Earth
IMPLEMENTED BY
ECMWF

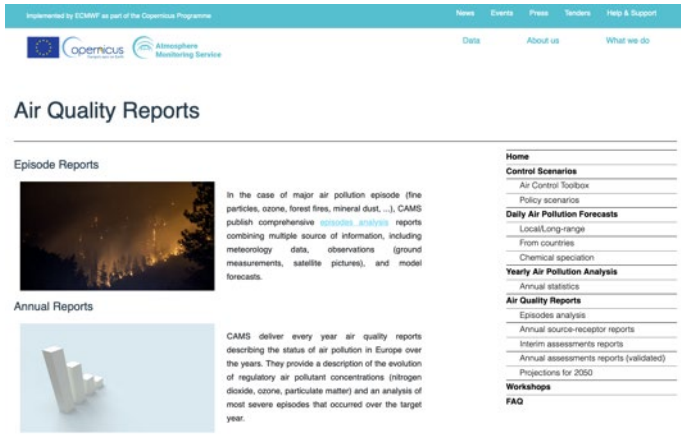
KEY POLICY TOOLS

Atmosphere Monitoring

- Daily air quality forecasts are provided for Europe and the rest of the world.
- Green Scenario policy tool simulates emission reductions by sector.
- Air Control Toolbox helps users explore the benefits of emission reduction strategies.







https://policy.atmosphere.copernicus.eu/

PROGRAMME OF THE EUROPEAN UNION

Copernicus Europe's eyes on Earth

IMPLEMENTED BY ECMWF