Observation of atmospheric composition from space

Nan Hao

Hamtetc/EUMETSAT

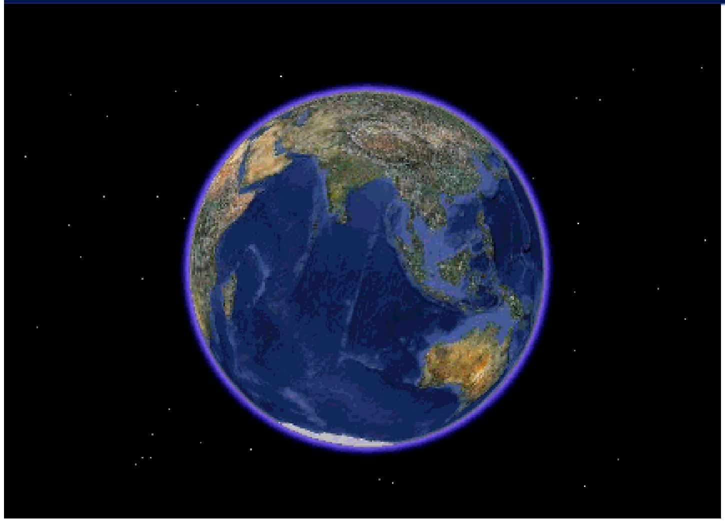
Outline

- Why observe atmosphere from space?
- Introduction of satellite observations
  - Satellite orbits
  - Different observation options
- Satellite instruments
  - History, Current and Future
- Algorithms and examples

Why observe atmosphere from Space ?

- Not all measurement locations are accessible
- Provide long time series trend analysis results and extended measurement areas
- Environmental/Climate Change requires Global Observations
- Automatic measurements and several parameters can be measured at the same time
- On a per measurement basis, satellite measurements usually are less expensive than in-situ measurements

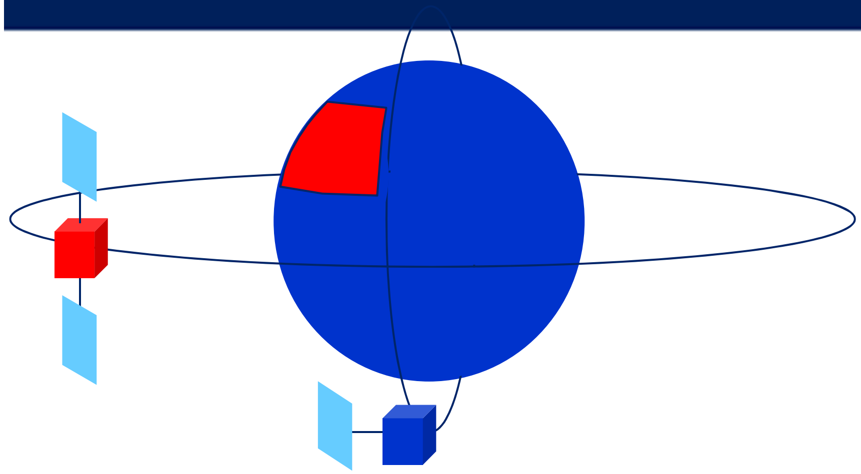
Satellite Orbits



Low Earth Orbit (LEO)

- orbits cross close to the pole
- Daily revisit time global coverage
- Climate, air quality, ozone & UV
- Tropospheric & stratospheric composition

Satellite Orbits



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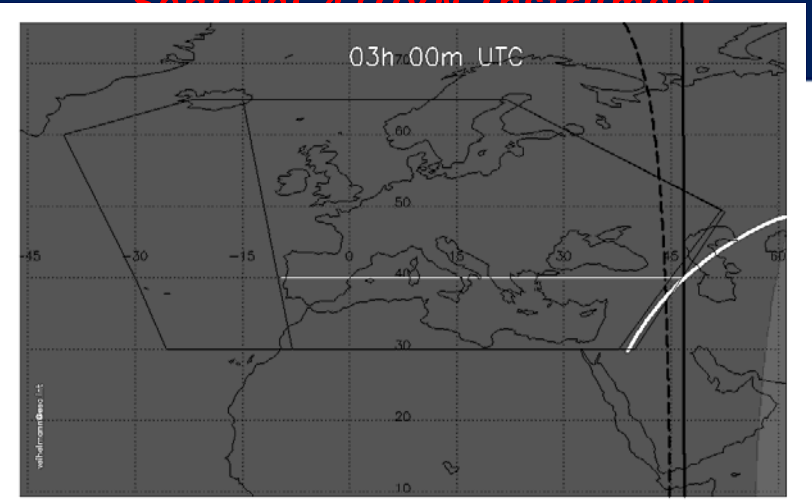


GEOstationary (GEO)

- satellite has fixed position relative to the Earth
- parallel measurements in a limited area from low to middle latitudes
- Mainly air quality
- Diurnal cycle of tropospheric composition

Comparison of different observation options

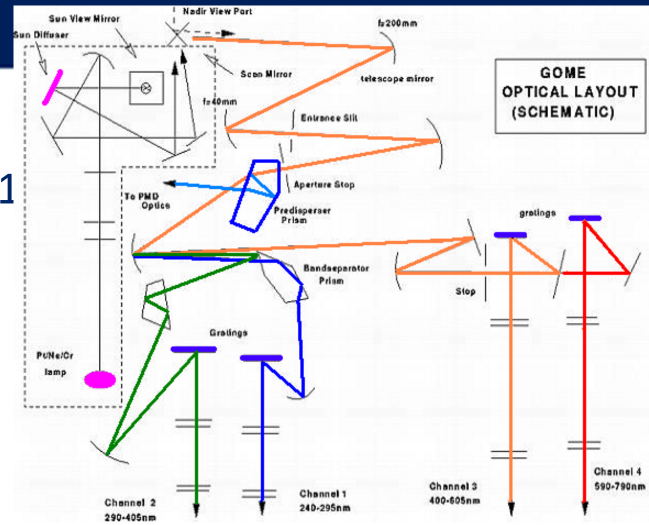
- **Nadir:**
  - view to the surface
  - good spatial resolution
  - little vertical resolution

- **Limb:**
  - good vertical resolution,
  - but only in the UT/LS region
  - large cloud probability

- **UV/vis/NIR:**
  - sensitivity down to surface
  - daytime only
  - no intrinsic vertical resolution in nadir
  - aerosols introduce uncertainties in light path

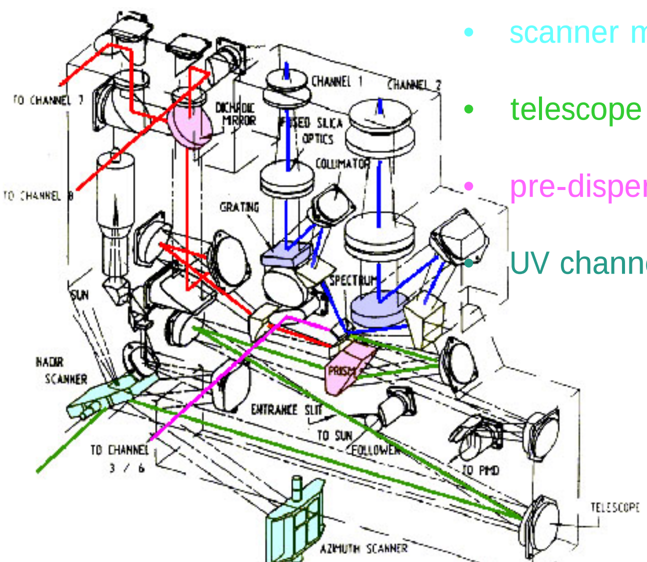
- **IR:**
  - large number of potential species
  - day and night measurements
  - some vertical resolution in nadir
  - weighted towards middle troposphere
  - problems with strong absorbers
  - problems with dark (solar IR) or cold (thermal IR) surfaces

History of LEO in Europe

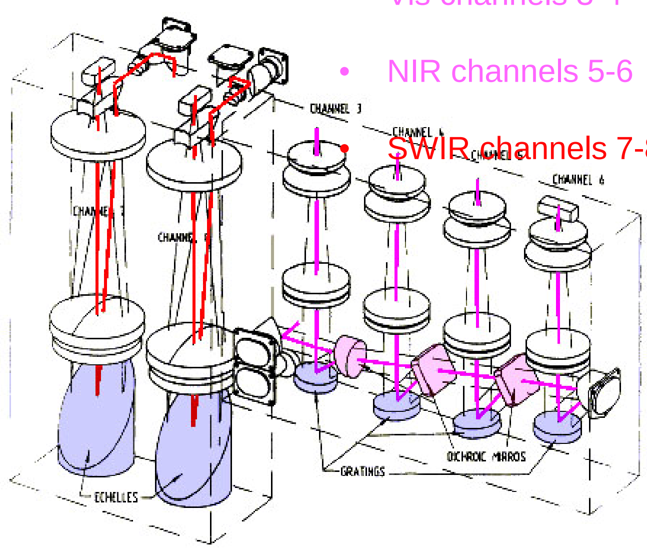


- 1995 Launch of **GOME** on ESA ERS-2 20th April
  Global 07 1995 - 06 2003 **Regional** 07 2003 - 07 2011
  Spatial resolution: 320 x 40 km^2
  Global coverage: 3 days
  10:30 am crossing time

- 2002 Launch of **SCIAMACHY** on ENVISAT
  Global **08 2002 - 04 2012**
  Spatial resolution: (30) 60 x 30 km^2
  Global coverage: 6 days
  10:00 am crossing time



- scanner modules
- telescope
- pre-disperser
- UV channels 1-2



- Vis channels 3-4
- NIR channels 5-6
- SWIR channels 7-8

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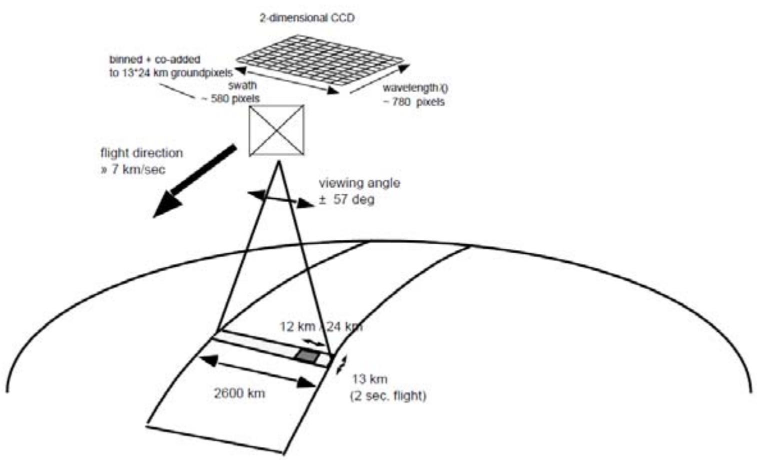
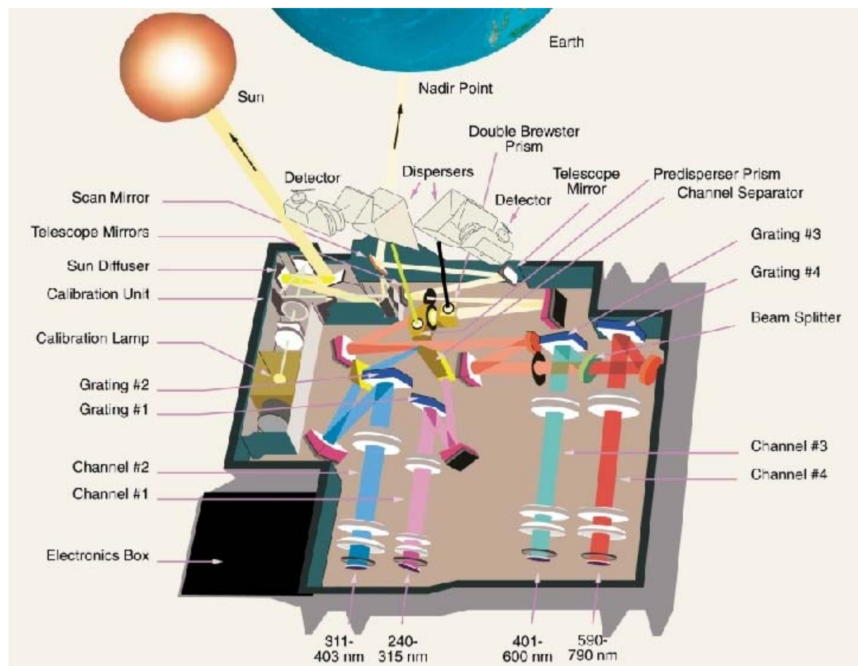
Current LEO

- 2004 Launch of **OMI** on Aura
  Global 10 2004 - present
  Spatial resolution: up to 13 x 24 km^2
- **Global coverage**: 1 day
  13:30 pm crossing time



- 2006 Launch of Metop A with **GOME-2** 19th October
  Global 02 2007 - present
- 2012 Launch of Metop B with **GOME-2** September
  Global 09 2012 - present
  Spatial resolution: 80 x 40 km^2
  Global coverage: 1.5 days
  09:30 am crossing time

GOME-2A change to 40 x 40 km^2 since July 2013



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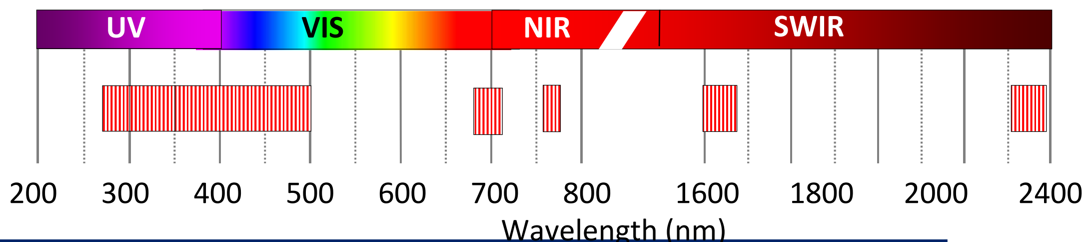
Future LEO and GEO in Europe

Sentinel-5p (TROPOMI)

- UV-VIS-NIR-SWIR nadir view grating spectrometer.
- Spectral range: 270-500, 675-775, 2305-2385 nm
- Spectral Resolution: 0.25-1.1 nm
- Spatial Resolution: 7x7km2
- Global daily coverage at 13:30 local solar time.

Sentinel-5

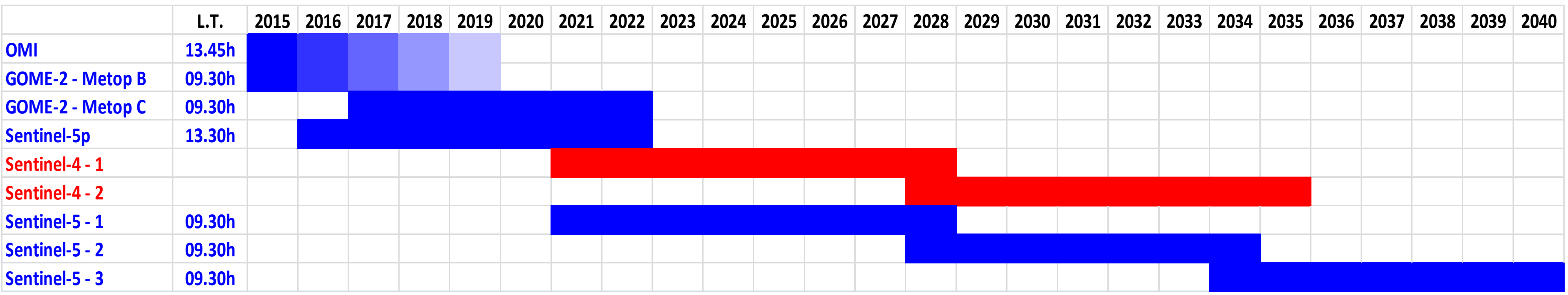
- Nadir-viewing push-broom UVNS spectrometer, 2 telescopes
- spectral ranges between 270 and 2385 nm
- spectral resolution 0.25 – 1.0 nm, oversampling factor 2.5 – 3
- daily coverage at latitudes > 12 deg
- spatial resolution 7.5 km @ nadir (45 km at λ < 300 nm)
- high signal/noise



Sentinel-4

Revisit time	1h
Geographic coverage	Europe + part of Atlantic + part of Sahara, FoV = 4° N/S, 11°-14° E/W
Spatial resolution	8.9 km N/S, 11.7 km E/W at 45°N
Spectral range	UV-VIS: 305-500 nm, NIR: 750-775 nm
Spectral resolution	UV-VIS ≤ 0.5 nm, NIR ≤ 0.12 nm

Future LEO and GEO



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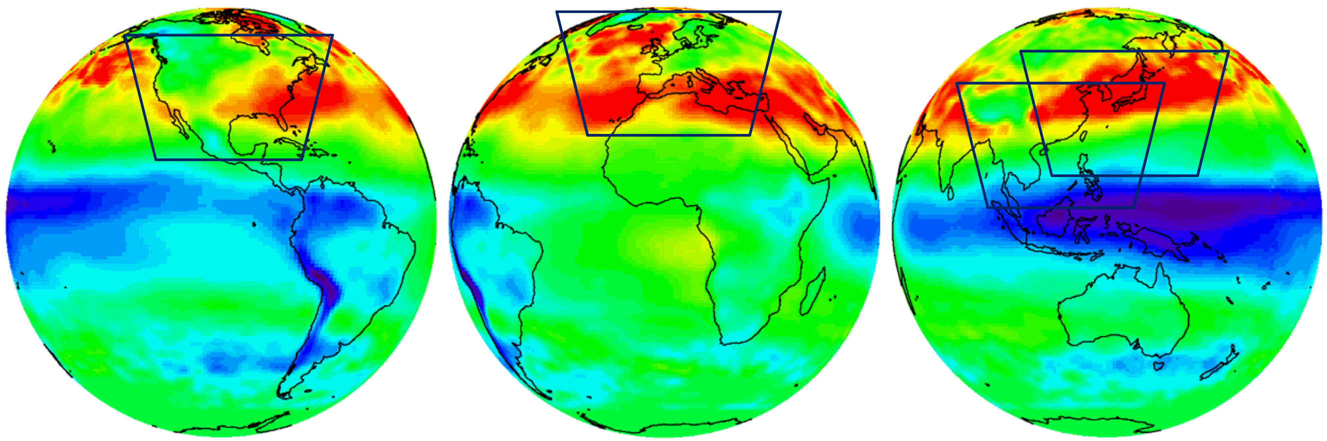
Future GEO



-NASA TEMPO

-ESA Sentinel-4

-KARI GEMS

JAXA GMAP-ASIA

- GEO dedicated air quality missions: GEMS, Sentinel-4, TEMPO, ...

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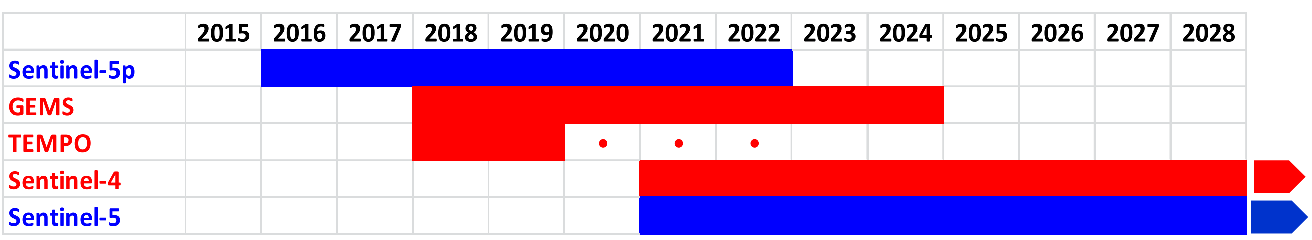
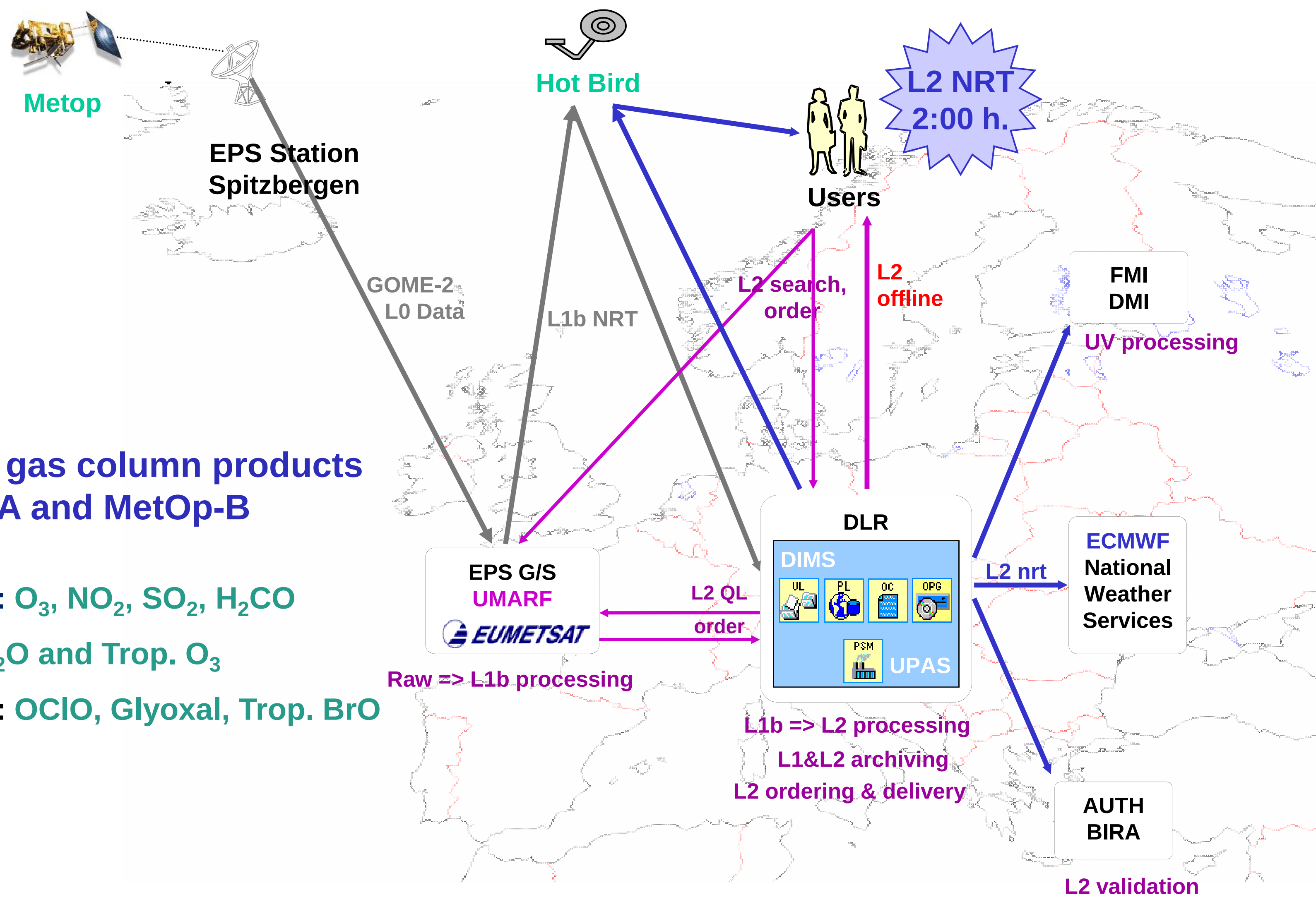


GOME-2 trace gas column products



GOME-2 trace gas column products MetOp-A and MetOp-B

Near-Real-Time: O_3, NO_2, SO_2, H_2CO

Off-line: BrO, H_2O and Trop. O_3

In development: OClO, Glyoxal, Trop. BrO

GOME-2 trace column algorithm

- GOME Data Processor (GDP) Version 4.8
  - Trace gas column retrieval using DOAS/AMF method

- Retrieval of slant column density (SCD) with DOAS algorithm:
  - O_3, SO_2, BrO and H_2CO in UV-wavelength region (315-360 nm)
  - NO_2 in VIS wavelength region (405 – 465 nm)
  - H_2O in NIR wavelength region (614 – 683 nm)

- AMF and vertical column calculation
  - AMF calculation with LIDORT radiative transfer model
  - Depends on forward model parameters:
    viewing geometry, surface albedo, trace gas profile, clouds, aerosols
  - Cloud correction (IPA) using GOME-2 cloud parameters

Total ozone column algorithm

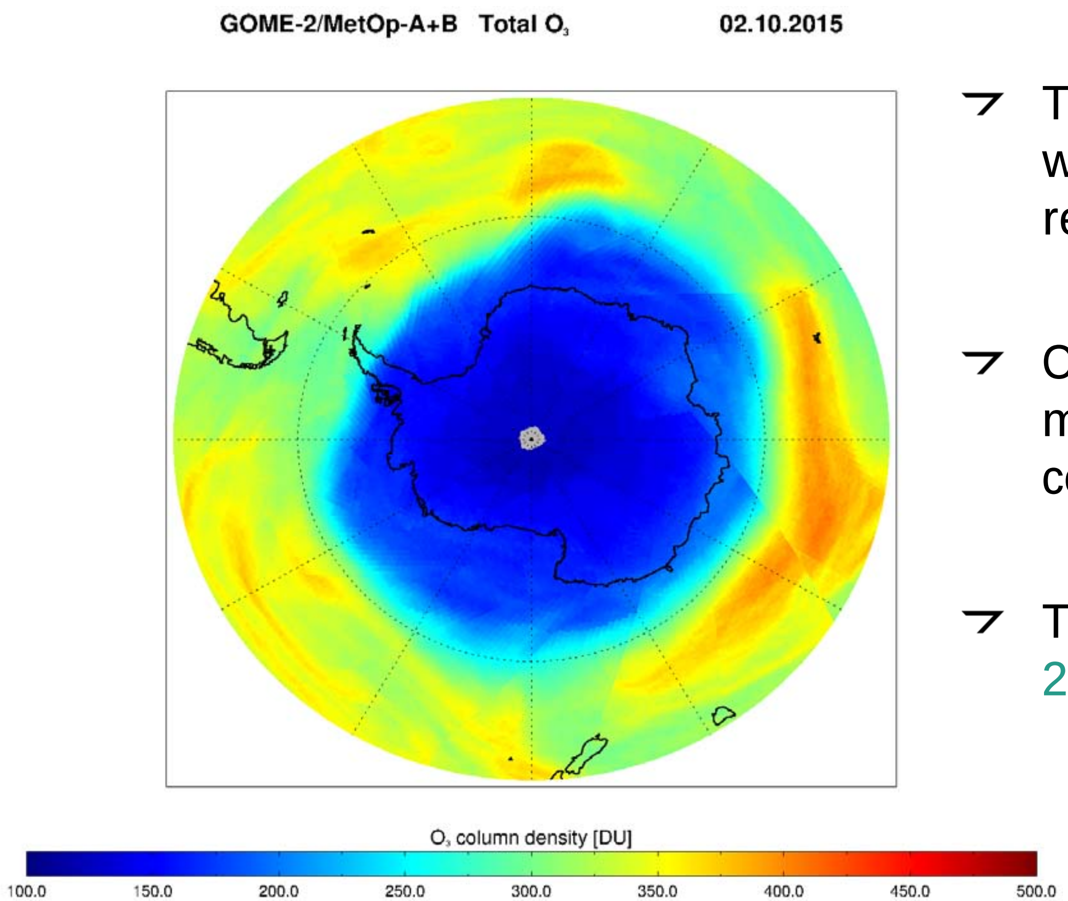
- Iterative two-step DOAS / AMF approach
  - DOAS fitting window: 325-335 nm
  - Brion/Dumont ozone cross-sections (2 Temp.)
  - molecular Ring correction
  - on-the-fly iterative AMF scheme using LIDORT V3.x

- Implemented algorithm improvements:
  - empirical correction for scan-angle dependence in total ozone (updated)
  - sun-glint correction

- GDP v4 Cloud pre-processing
  - Cloud algorithms: OCRA & ROCINN

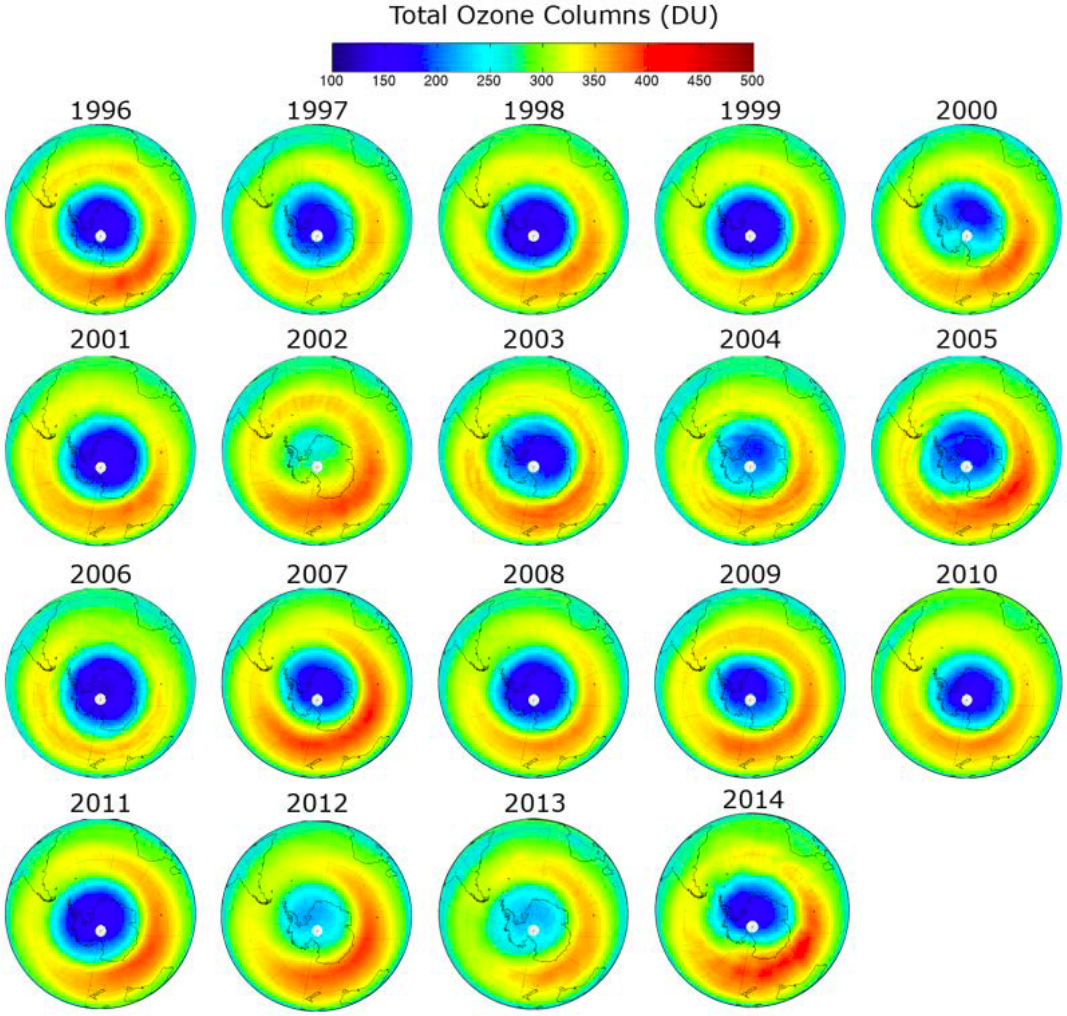
Hao et al., AMT, 2014

Antarctic ozone hole in 2015 as measured by GOME-2



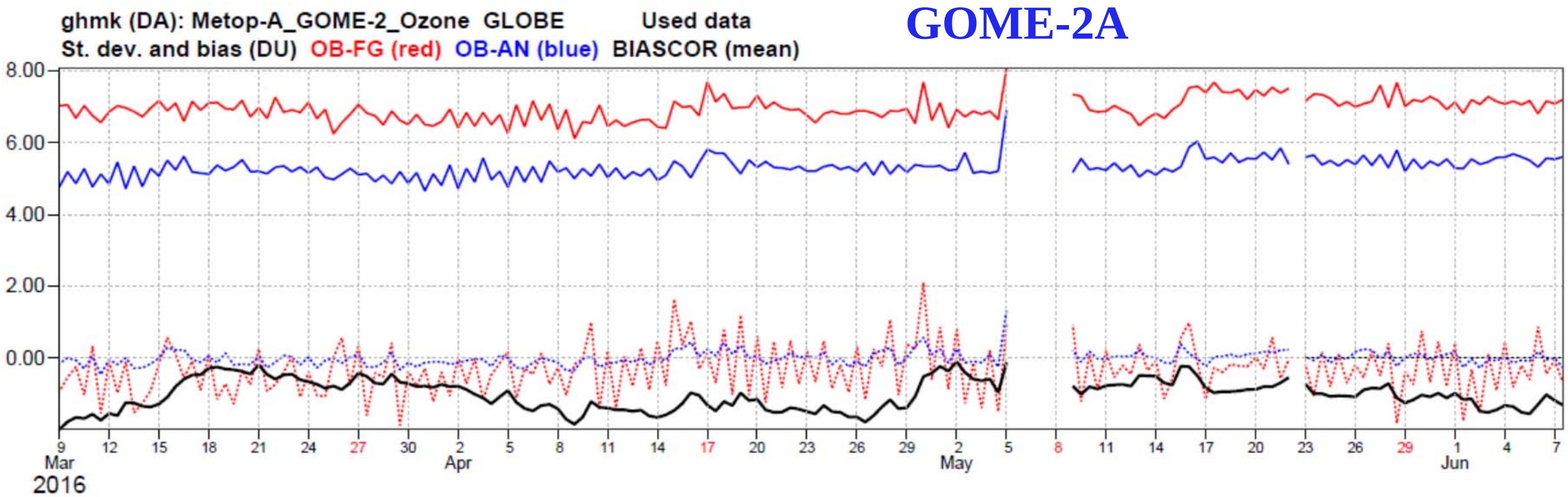
- The 2015 Antarctic ozone hole area was larger and formed later than in recent years
- On 2 Oct. 2015 GOME-2A&2B measured a minimum total ozone column of ~120 DU
- The ozone hole expanded to max. 28.2 million km^2

Long time ozone data records from GOME and GOME-2



GOME-2 total ozone: assimilation in CAMS system

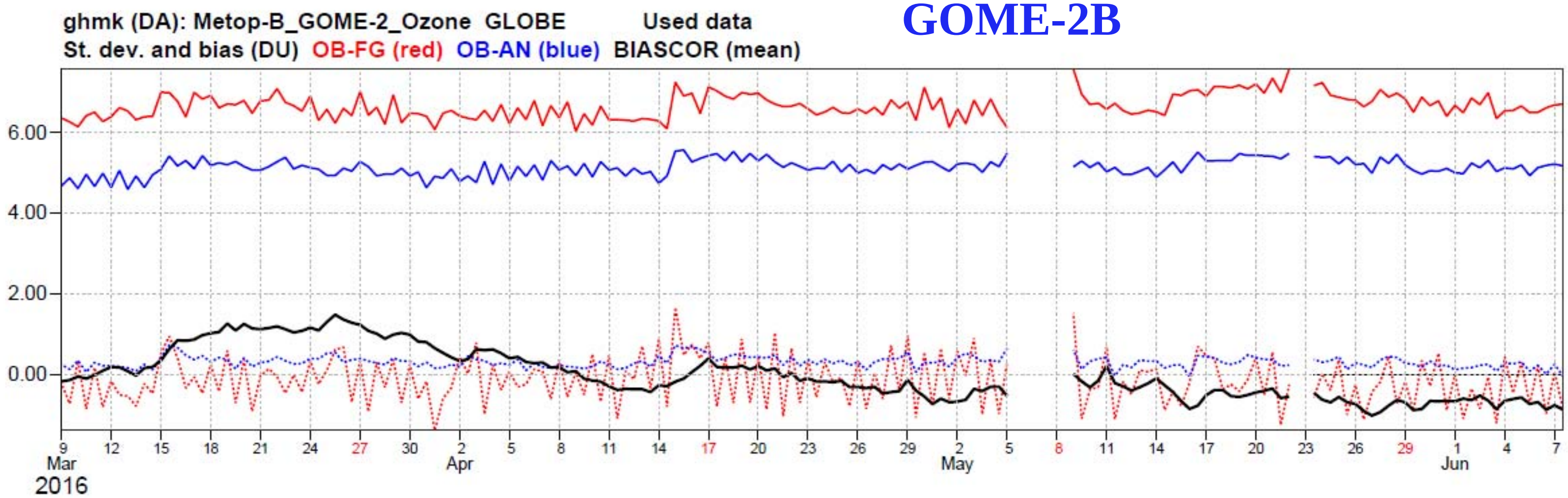
GOME-2A



Std. Dev.

Departures
Bias corr.

GOME-2B



Std. Dev.

Departures
Bias corr.

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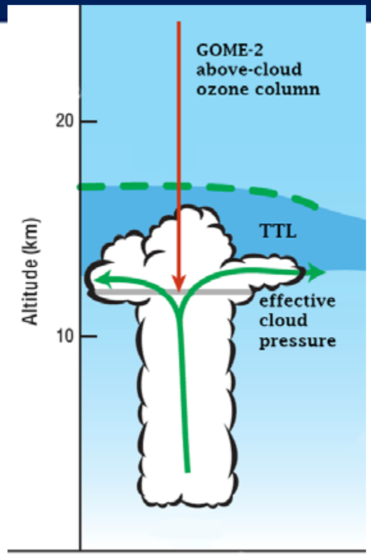
Tropical tropospheric ozone column

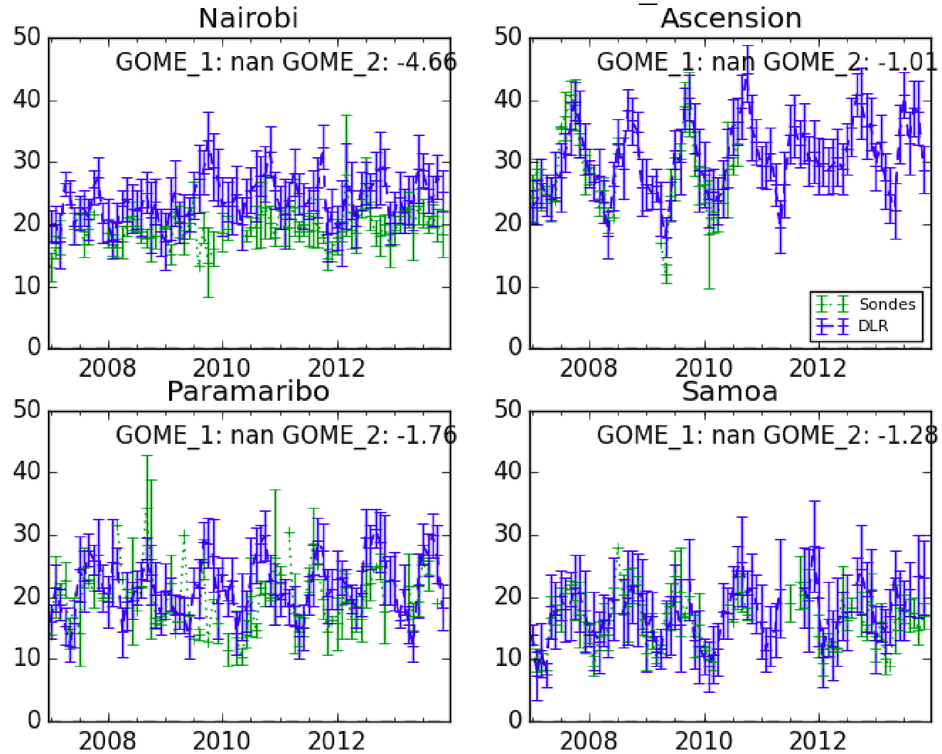
Convective-cloud-differential (CCD) method

- above cloud and clear-sky ozone column measurements
- Tropical tropospheric ozone columns (TTOC) below 200 hPa

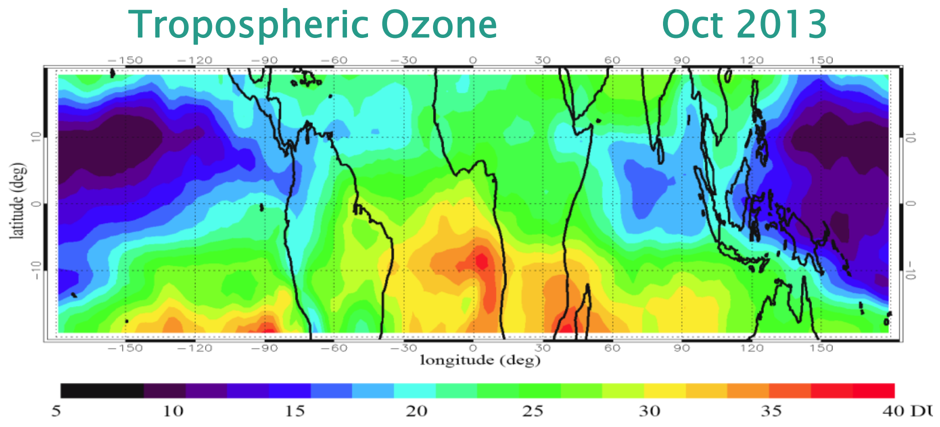
GOME-2 data required:

- Total ozone columns
- effective cloud fraction (OCRA), cloud pressure and albedo (ROCINN)





Valks et al., AMT, 2014



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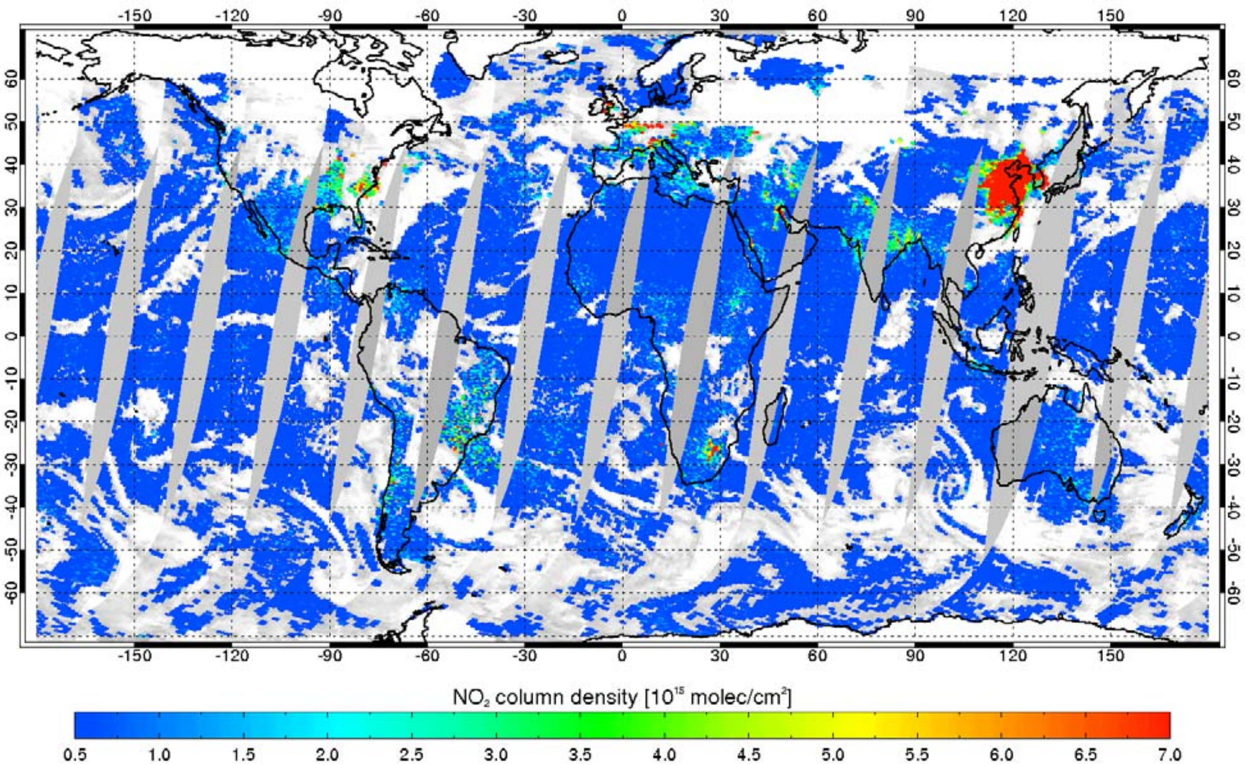
Tropospheric NO_2 column retrieval

- Retrieval of trop. NO_2 column requires three algorithm steps
  - Retrieval of total NO_2 slant column using DOAS method (405 – 465 nm)
  - Stratosphere-Troposphere Separation (STS) algorithm
  - Tropospheric AMF and NO_2 column calculation
    - NO_2 profile shape information from global CTM



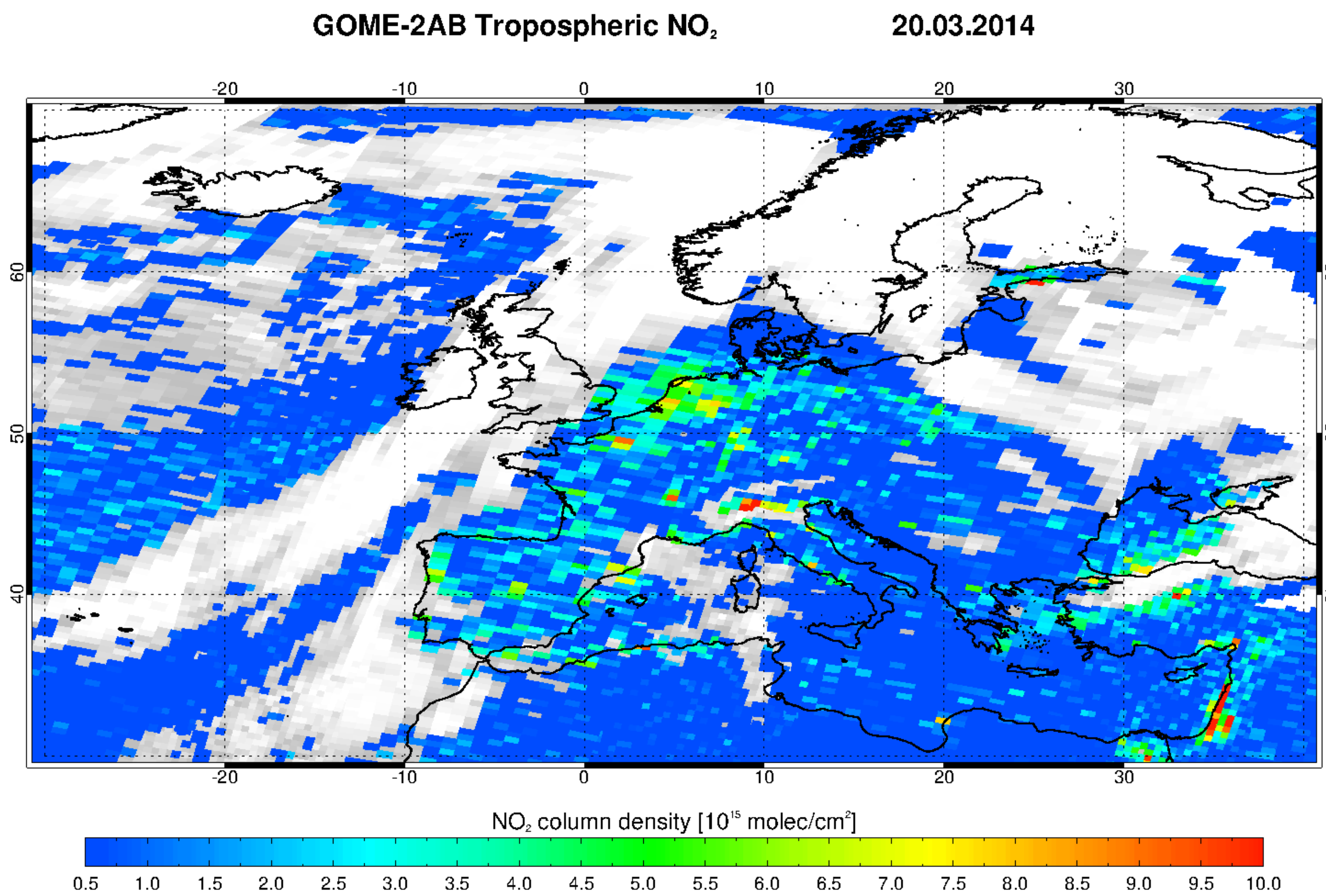
GOME-2/MetOp-B

3 March 2013

Trop. NO_2 column

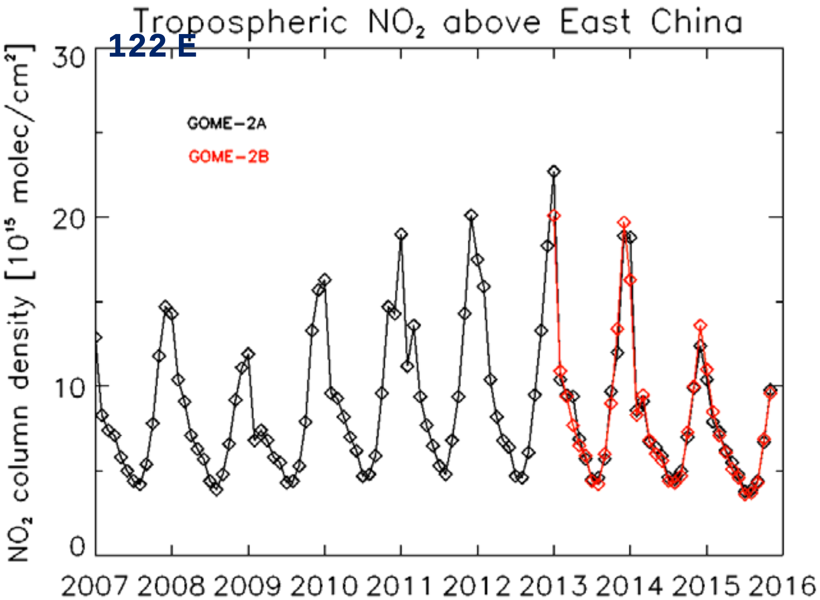
Valks et al., AMT, 2011

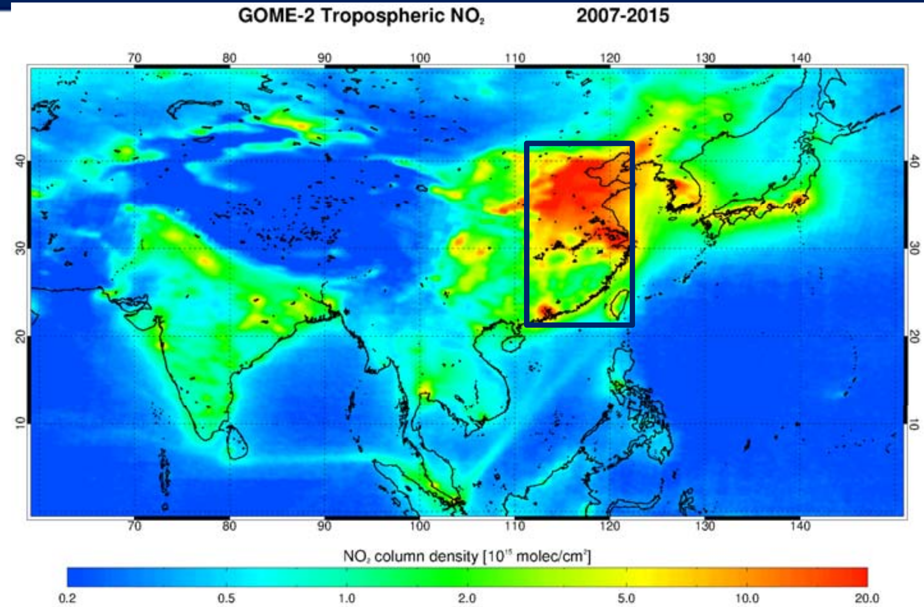
Air pollution event over Europe in March and April 2014



Tropospheric NO_2 trends over East China

-Latitude: 21.5-41 N, Longitude: 112-122 E



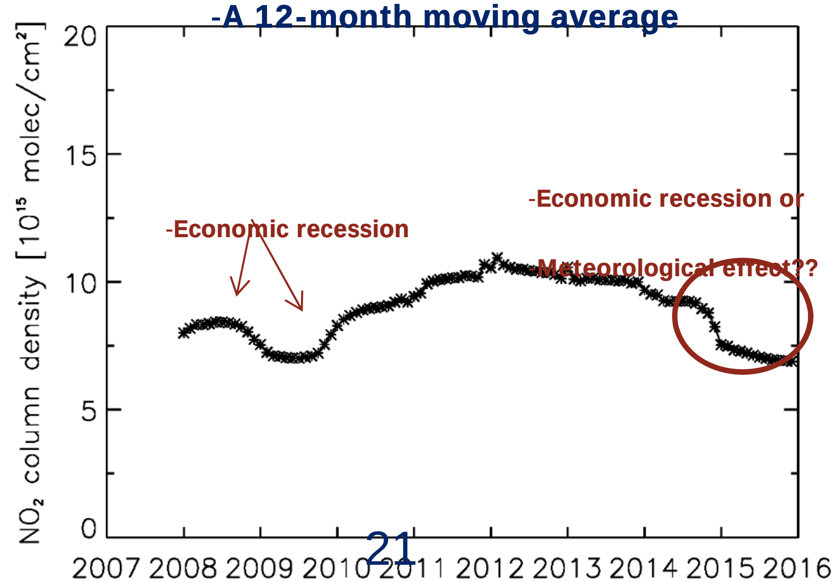


A **significant increase** of NO_2 over China from 1994 to 2006 observed by GOME and SCIAMACHY

Richter A, et al., Nature 2005;

Van der A et al., J. Geophys. Res., 2006

-A 12-month moving average



Hao N et al., 2012

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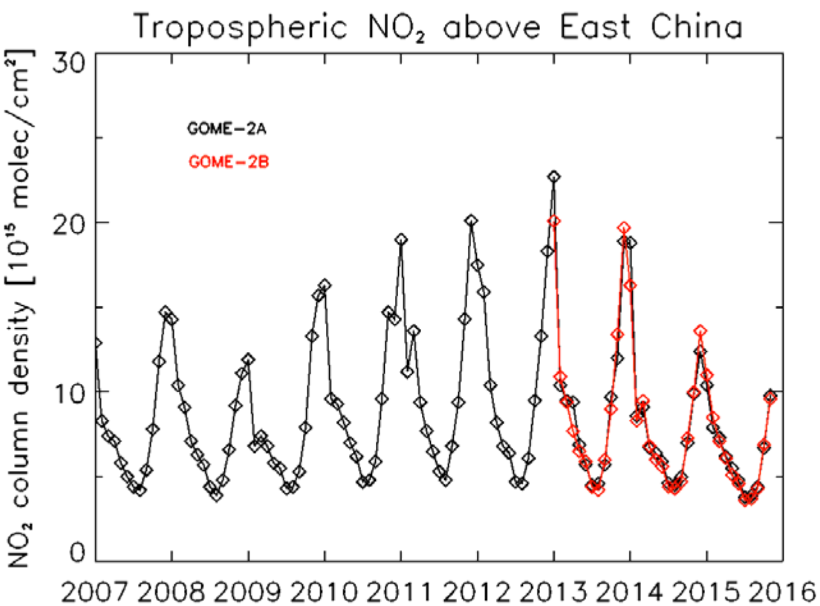

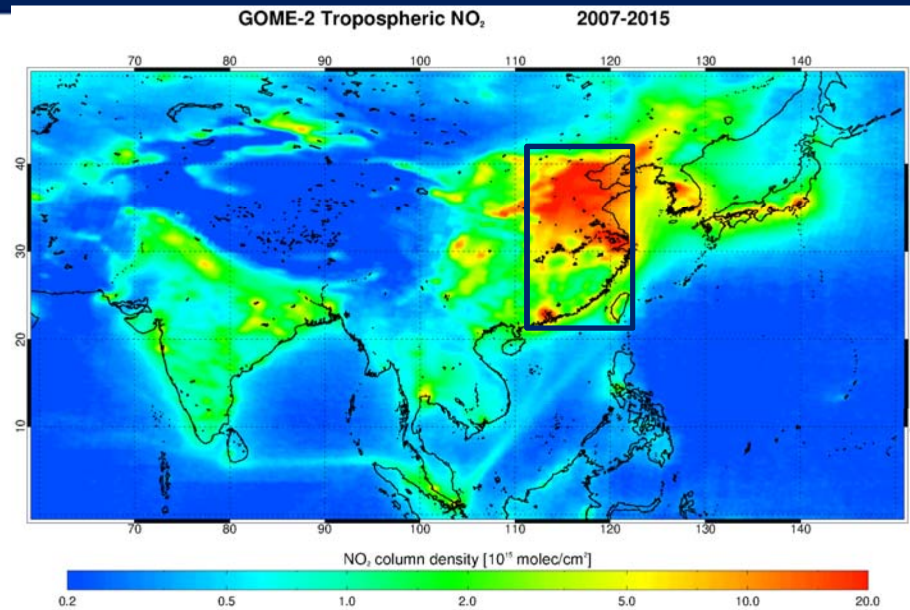

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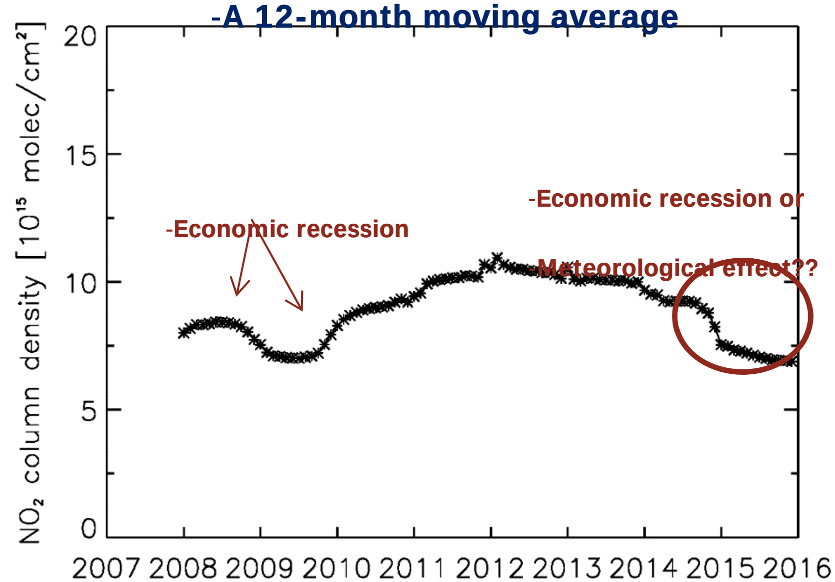
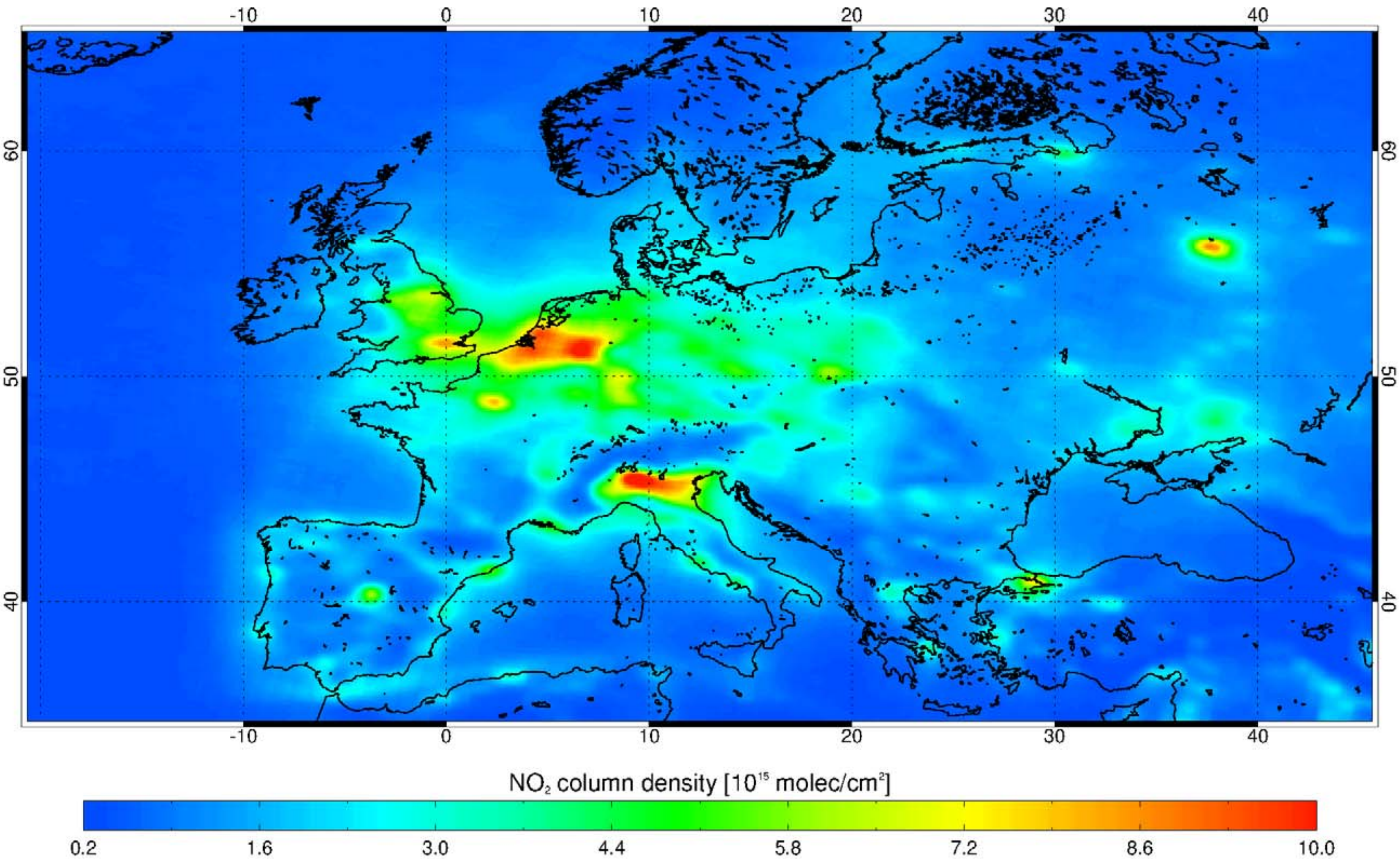


Hao N et al., 2012

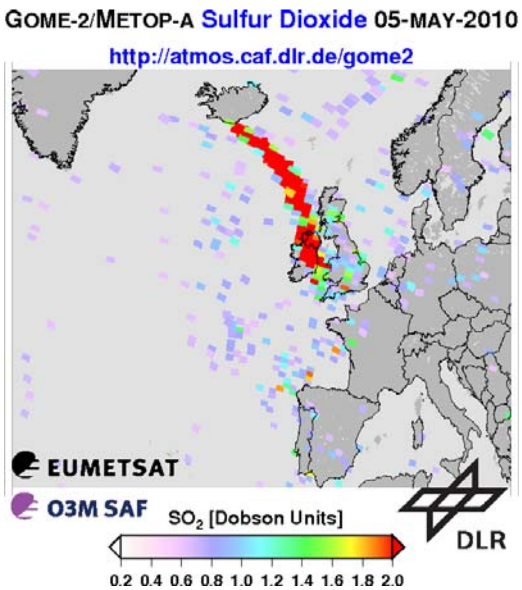
GOME-2 tropospheric NO_2 over Europe 2007-2013



SO_2 Column Algorithm for GOME-2/S5P

- 3-steps DOAS algorithm - Spectral fitting in multiple windows to avoid saturation 312-326 nm (pollution, volcanic degassing) 325-335 nm (moderate eruptions) 360-390 nm (extreme eruptions)
- Background Corrections
- Computation of VCD with using modeled (anthropogenic SO2) and predefined profiles (volcanic SO2)

Eyjafjallajökull eruption, April – May 2010

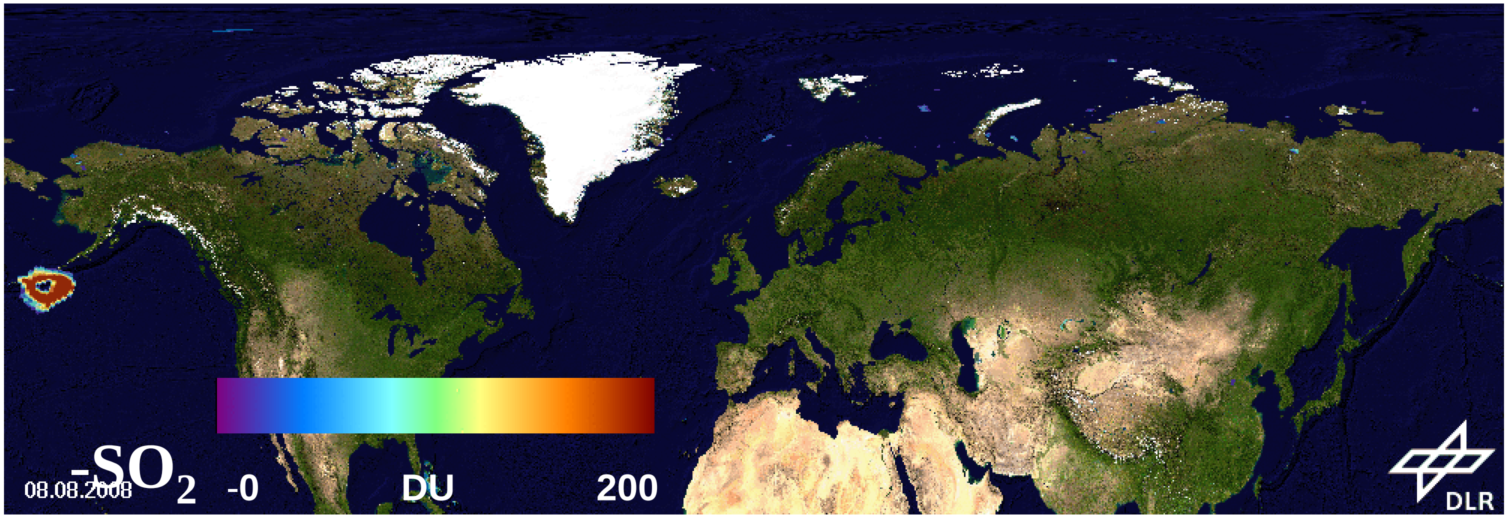


-Over **95,000** flights had been cancelled all across Europe during the six-day travel ban

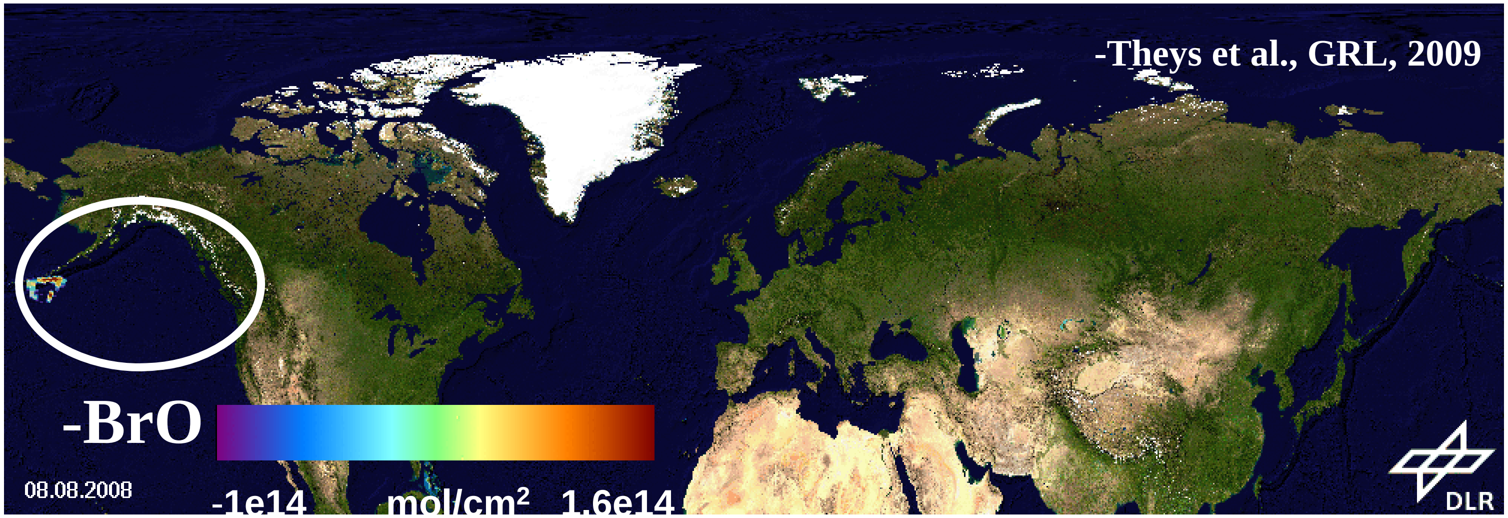
-The total loss for the airline industry was around €1.3 billion

-SO_2 information is valuable for aviation safety and for early warning of volcanic activity

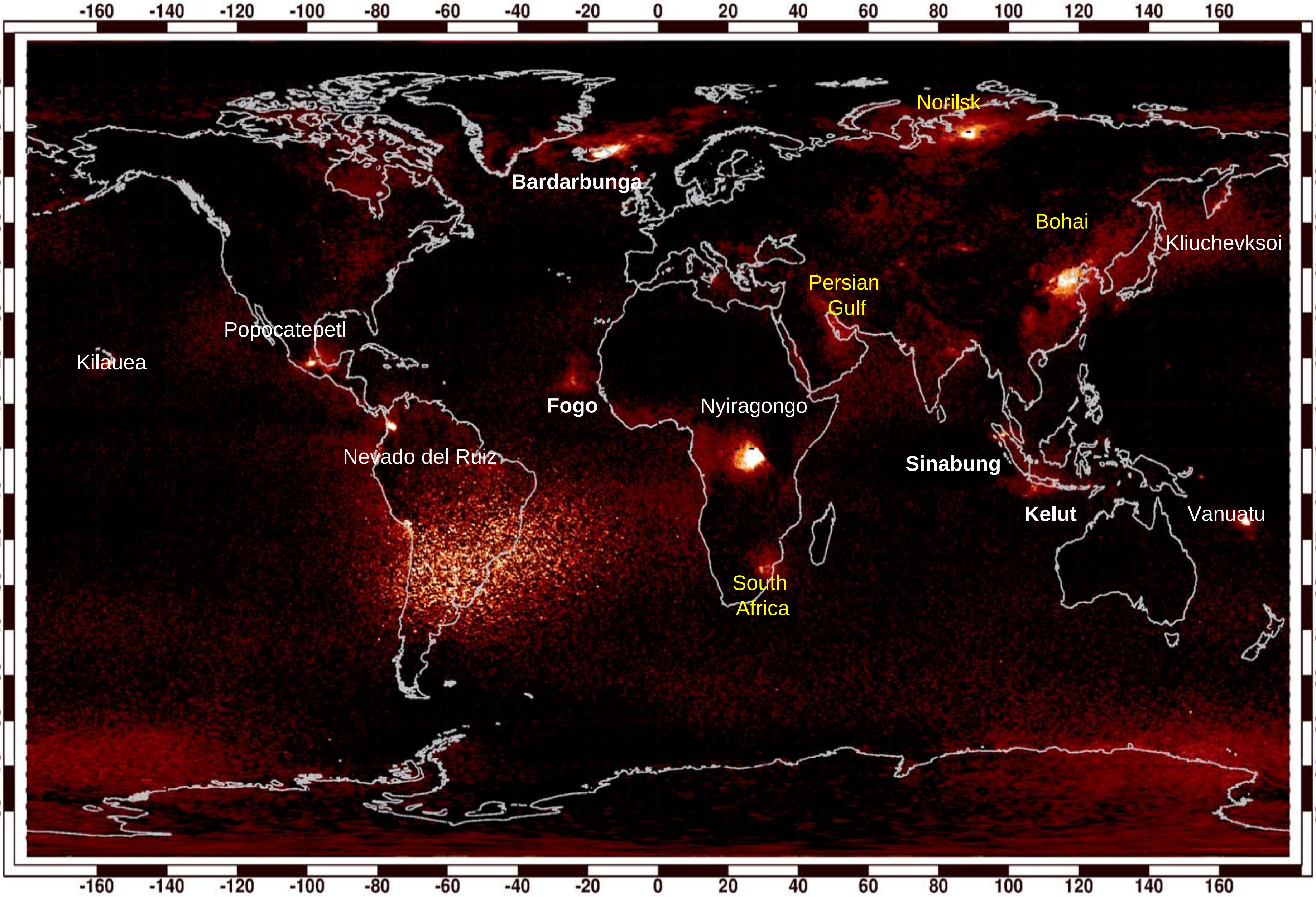
GOME-2 – Kasatochi Eruption (8-31 August 2008)



-<u>First satellite</u> detection of volcanic BrO emission



GOME-2 SO_2 [MetOp A&B] 2014



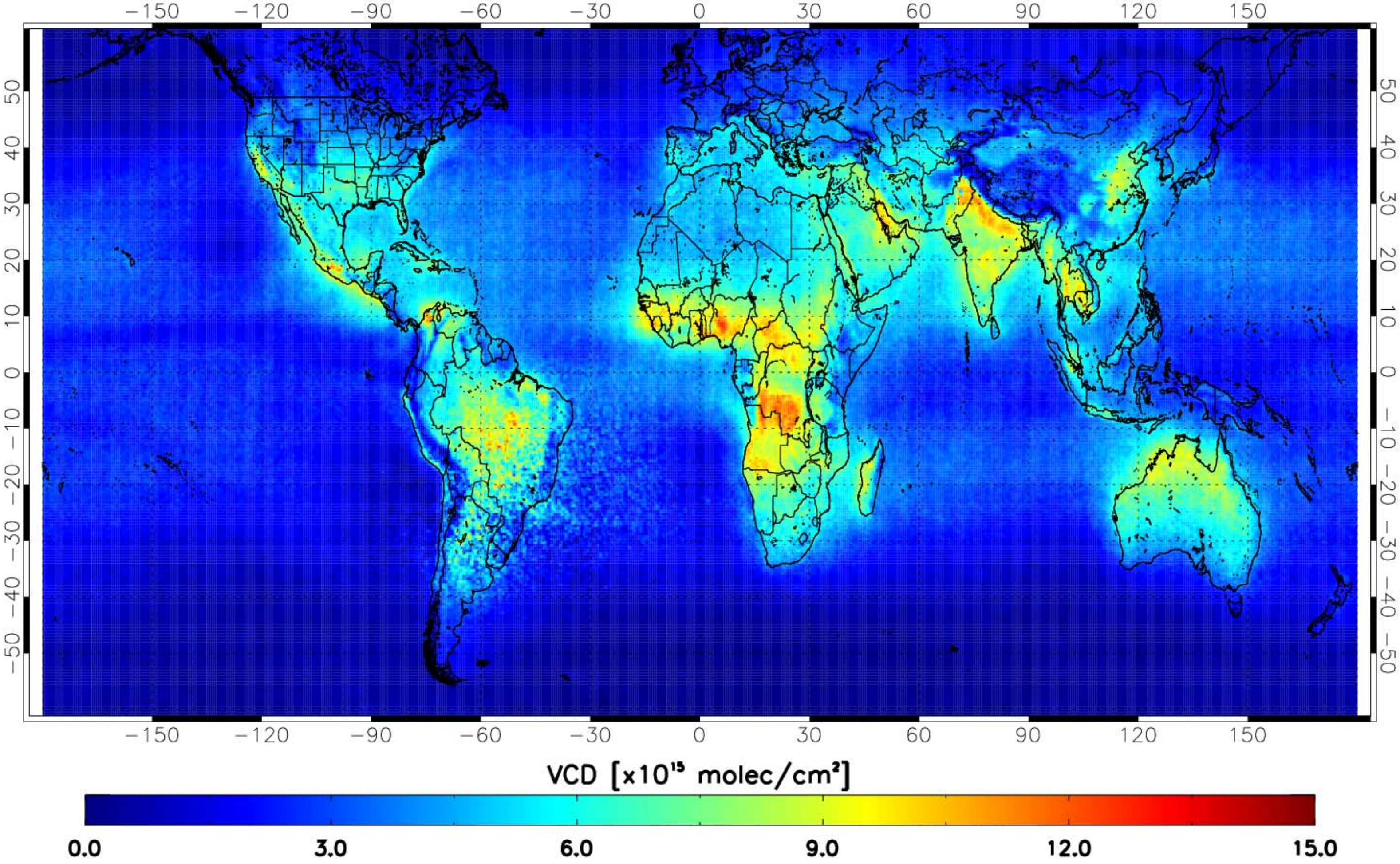
Formaldehyde column algorithm

De Smedt et al., AMT, 2012

- New DOAS slant column fitting algorithm
  - 2 inter-linked fitting intervals:
    332-359 nm for BrO, 328.5-346 nm for H_2CO
  - Reduced spectral interference between BrO and H_2CO
  - Significantly reduced noise in retrieved H_2CO columns
- Reference Sector correction
  - Latitude dependent reference sector: Pacific Ocean (160º-240ºE)
- AMF determination
  - LUT of scattering weights calculated with LIDORT V3.x.
  - A-priori profile shape from IMAGESv2 model (Muller and Stavrakou, 2005)
  - Correction for clouds (IPA)
- Averaging Kernel information

GOME-2/MetOp-B Formaldehyde column 2013

GDP 4.8



High H_2CO regions related the release of hydrocarbons from forests, biomass burning, traffic and industrial emissions.

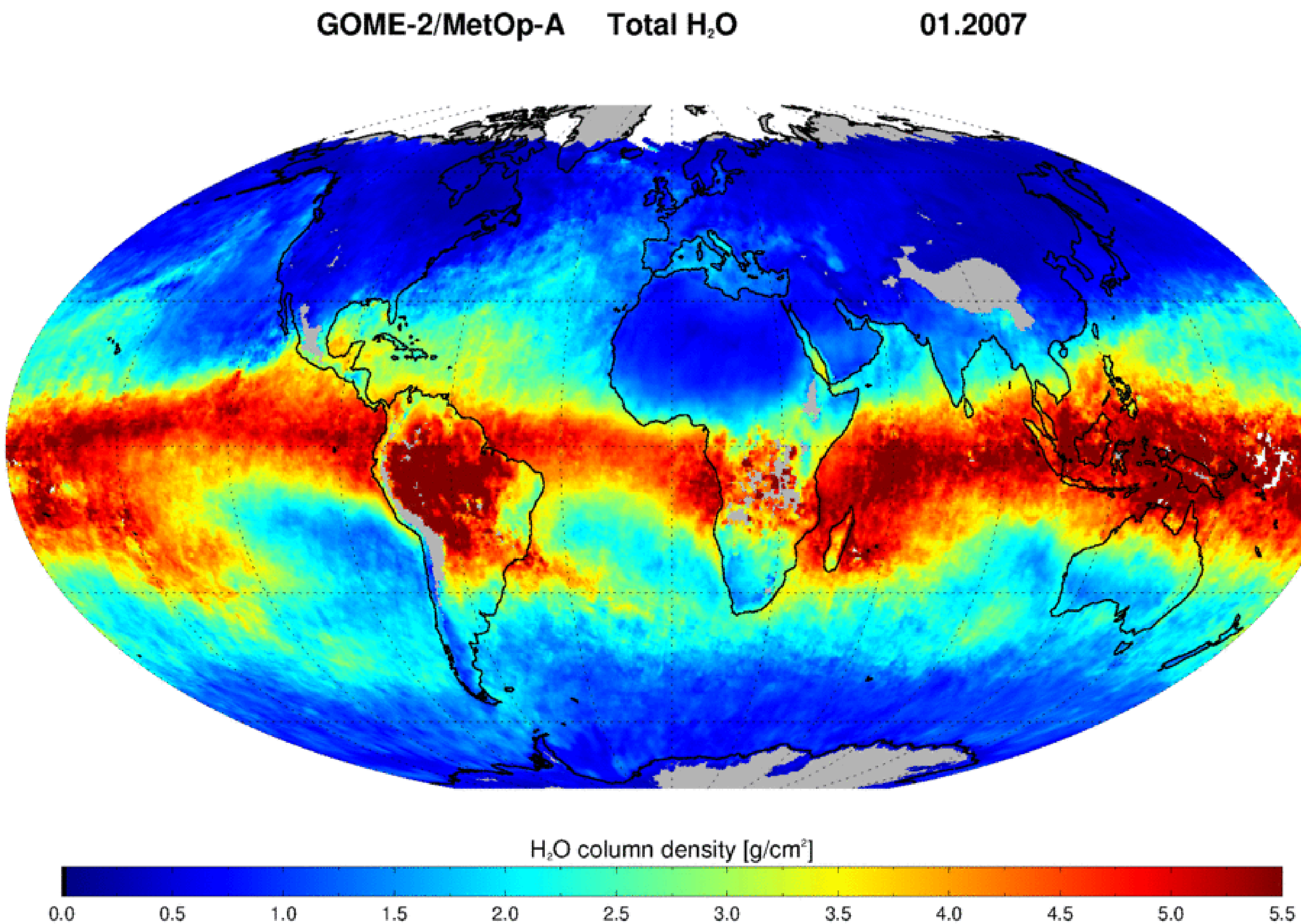
GOME-2 Water vapour column

Classical DOAS algorithm (Uni Heidelberg/MPI Mainz; Wagner et al. 2003)

- DOAS slant column algorithm
  - Fitting window 614-683 nm (below vegetation peak, “weak” O_2, H_2O)
  - Includes O_2, O_2 -O_2 , 3 vegetation types, Ring, straylight offset
- Saturation correction
- AMF computation based on “measured” AMF of O_2
  - VCD of O_2 is known, $AMF_{meas}(O_2) = SCD_{meas}(O_2) / VCD_{known}(O_2)$
  - $VCD(H_2O) = SCD_{meas}(H_2O) / AMF_{meas}(O_2)$ x *correction_factor*
- Empirical correction for scan angle dependency

Grossi et al., AMT, 2014

GOME-2 Water vapour 2007-2013



Application of satellite measurements

-Environmental Themes

-air quality

-climate

-stratospheric ozone and surface UV

-Missions and Services

-regional AQ at 1h temporal res.

- emission and abundance monitoring
- forecast

-global AQ at 1d temporal res.

- emission and abundance monitoring
- forecast

climate

- GHG emissionmonitoring
- aerosol

-ozone total column

- long term total O_3 evolution
- surface UV (health)

- GEO (Sentinel-4, TEMPO, GEMS)

- diurnal variation, e.g. NO_2, aerosol
- part of CEOS virtual constellation

LEO (GOME-2, OMI, Sentinel-5p, Sentinel-5)

-Sentinel-5P

bridging between OMI and S-5

- CO and CH_4
- x6 step in 2-D spatial resolution vs. OMI
- some diurnal information (with GOME-2)

Sentinel-5

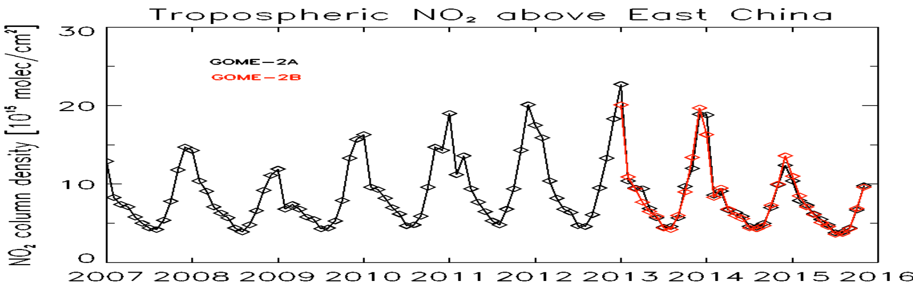
- continuity and long-term datasets
- CH_4 from 2 bands
- Some CO_2 (quality not sufficient for operational monitoring)

Application of satellite measurements-NO2

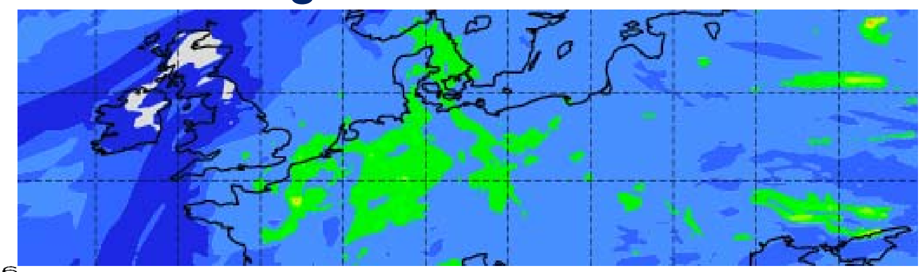
NOx emission estimates

Surface pollution

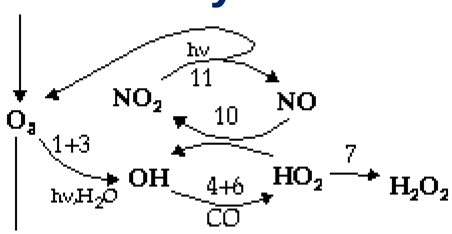
Trend studies



Forecasting



NOx chemistry



Chemical regimes

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What is problematic about satellite measurements?

- Always **indirect measurements**
- Usually, additional **assumptions and models** are needed for the interpretation of the measurements
- **Spatial** resolution and **temporal** resolution too large
- **Validation** of remote sensing measurements is a major task
  - Comparison of satellite retrievals with other measurements are only meaningful if the **averaging kernels** are accounted for
- estimation of the **errors** often is difficult

Summary and Conclusions

- Satellite observations of tropospheric composition in the UV/vis, NIR and thermal IR provide consistent global datasets for many species including major air pollutants such as O3, CO, NO2, and HCHO
- The measurements are averaged horizontally and vertically which makes them difficult to compare to point measurements
- Remote sensing in an indirect method that necessitates use of a priori information in the data retrieval which has an impact on the results
- In spite of the relative large uncertainties involved in satellite remote sensing , they provide a unique source of information on the composition of the troposphere