Multispectral synergism for observing atmospheric ozone pollution

Juan CUESTA
Assoc. Professor of the University Paris Est Créteil
Laboratoire Interuniversitaire de Systèmes Atmosphériques
cuesta@lisa.ipsl.fr
Processes affecting tropospheric chemistry

- Scavenging processes
- Biomass burning emissions
- Biogenic emissions
- Fossil fuel emissions
- Megacities
- Aerosols
- Heterogeneous Chemistry
- Erosion
- Dry deposition
- Air-sea exchanges
- Long-range transport
- Deep convection
- Solar radiation
- Thermal radiation
- Stratosphere-Troposphere exchanges
- Gas phase chemistry
- Ozone layer
- Stratosphere
- Troposphere
- NO₂
- CO
- VOC
- CH₄
- SO₂
- OBSERVATION
- Deep convection
- Aqueous phase chemistry
- Scavenging processes
- Megacities
- Fossil fuel Emissions
- Biogenic emissions
- Biomass burning emissions
- Erosion
- Air-sea exchanges
Processes affecting tropospheric chemistry

A key air pollutant affecting public health and ecosystems:

Tropospheric Ozone
Major impact of air pollution on public health and ecosystems

Better knowledge of atmospheric chemistry and its environmental impacts

→ Only satellites can observe pollutants at the regional and global scales

How to observe air pollutants near the surface from space?

How to improve chemistry-transport models using satellite observations?
Ozone Pollution

- Severe impact on public health and ecosystems

Irritation of respiratory system

Limitation of photosynthesis

Necrosis on leaves
Remote sensing of the atmospheric composition

**PASSIVE spectrally-resolved measurements**

- Atmospheric spectrum
- Atmospheric radiative transfer calculation
- Spectroscopic databases

Retrieval approach: Iterative minimization of a cost function:

\[
\|y - F(x)\|_S + \|x - x_a\|_R
\]

- **Constrained fit** of calculated spectra with respect to atmospheric measurements
- Constraints \(R\): control of resemblance between \textit{a priori} knowledge of the atmosphere and the retrieved profiles
- Other approaches also exist (neural networks, look-up-tables, DOAS)
Minimization of the following function:

\[
\chi^2 = \| F(\hat{x}) - y \|_\varepsilon + \| \hat{x} - x_a \|_R
\]

- Radiative transfer model
- Satellite measurement
- Constraint matrix
- Climatological average a priori
- Variance-covariance matrix of radiometric noise
- Calculated spectrum
- \(O_3\) profile in the atmosphere
AVK \rightarrow \text{Averaging Kernels allow the evaluation of the sensitivity of the retrieved profile with respect to the real profile}

\rightarrow \text{Degree of freedom (DOF): } DOF = \text{Trace} (AVK)

\rightarrow \text{Number of independent points on the vertical (sensitivity to } O_3\text{)}

\rightarrow \text{Maximum sensitivity height (Hmax): Altitude of the maximum AVK value (i.e. the maximum sensitivity)}
Ozone remote sensing from space

UV reflectance

- Stratosphere
- Troposphere

Altitude (km)

Sensitivity to O$_3$
Nadir atmospheric spectrum at the UV/Visible

Spectra from GOME satellite radiometer:

1) Directly pointing the sun (Sun irradiance ➔ once a day)
2) Backscattered light from Earth (Earth radiance ➔ every pixel)

The ratio is reflectance
TOMS: Total Ozone Mapping Spectrometer

1978 –
Based on the UV backscattered radiations

Ozone total column

Antarctique

Arctique
GOME: Global Ozone Monitoring Experiment

Liu et al., 2005

derive ozone profiles and Tropospheric Column Ozone (TCO) from GOME sun-normalized ultraviolet radiances with the OE technique. We validate our retrievals against TOMS and Dobson/Brewer (DB) TO measurements, ozonesonde TCO and Stratospheric Aerosol and Gas Experiment II (SAGE-II) profiles. The paper is organized as follows. Section 2 describes the GOME data and the correlative data used for intercomparison. In section 3, we give a detailed description of the ozone profile retrieval algorithm, retrieval characterization, and error analysis. Section 4 shows examples of retrieved ozone profiles and global distribution of TCO. In section 5, we present the comparison with correlative measurements, which also serves to assess the accuracy of our retrievals. Section 6 summarizes this study.

2. Instruments and Data
2.1. GOME

ERS-2 is a near-polar sun-synchronous orbit satellite with a mean local equator crossing time of 10:30 am. GOME, on board ERS-2, is a nadir-viewing spectrometer that measures radiances in four continuous bands (i.e., 237–315 nm, 312–406 nm, 397–609 nm, and 576–794 nm). Under normal operation, the GOME instrument, scans across track from east (\(30^\circ\)C176\(30^\circ\)) to west (\(30^\circ\)C176\(30^\circ\)) and back with a swath of 960 km, so that global coverage is achieved in three days in the equator. One nominal scan cycle of GOME lasts 6 s, 4.5 s for the forward scan and 1.5 s for the back scan; the forward scan consists of three pixels each with an area of 320 km\(^2\) and the back scan consists of one pixel with an area of 960 km\(^2\). Because of the large dynamical range of the signal in band 1, it is divided into two sub-bands (i.e., bands 1a and 1b) at 307 nm before June 1998 and afterwards. The integration time for band 1a is 12 s, corresponding to 8 band-1b or band-2 pixels \([\text{ESA}, 1995]\). Because ozone profile retrieval uses measurements in both bands 1 and 2, 8 pixels of measurements in bands 1b and 2 are co-added to match the band 1a measurements. Therefore, the spatial resolution of our retrievals is normally 960 km\(^2\). In addition to radiance spectra, GOME measures direct solar irradiance via a Sun view mirror and diffuser plate on a daily basis \([\text{ESA}, 1995]\). The solar irradiance spectrum, measured on the same day, is used to normalize the measured earthshine radiance spectra.

2.2. Other Data

Ozonesonde data during 1996–1999 from 33 stations (Figure 1 and Table 1) are used to validate GOME TCO. For a global validation, we include stations from the far north (e.g., Resolute, 74.7\(^\circ\)N) to the far south (e.g., Neumayer, 70.7\(^\circ\)S) with at least one station in each 10\(^\circ\)-latitude band between 80\(^\circ\)N–80\(^\circ\)S. Data was primarily obtained from World Ozone and Ultraviolet Data Center (WOUDC, http://www.woudc.org). Some data unavailable or incomplete at WOUDC are directly obtained from the data originators (see Table 1). The measurements were made with three types of ozonesonde (Table 1). Ozonesonde techniques have different precisions, accuracies, and sources of errors. The Jülich Ozone Sonde Intercomparison Experiment (JOSIE) showed that measurements with different types of ozonesondes are typically within 10–20% with respect to the accurate UV photometer measurements and it was found that the precision of electrochemical concentration cell sondes is 5%, better than those of Brewer Mast and carbon iodine sondes (10–15%) \([\text{WMO}, 1998]\). The SHAZO measurement precision is also estimated to be ±5\% \([\text{Thompson et al.}\,\,2002]\).
Satellite remote sensing of Ozone

IR radiance

Altitude (km)

Sensitivity to O$_3$

Free Troposphere
Earth thermal infrared spectrum measured by IASI
Which information from the infrared spectrum?
Interferometric Monitor for Greenhouse gases

- Japanese mission ADEOS
- Launch in August 1996
- Michelson Interferometer
  - Spectral range 740-3030 cm\(^{-1}\)
  - Spectral Resolution 0.1 cm\(^{-1}\)
  - Spatial Resolution - 3 pixels of 8km*8km

Ozone vertical profile

Coheur et al., 2005
TES/Aura: Tropospheric Emission Spectrometer

Spectral Resolution at Nadir: 0.1 cm$^{-1}$
But no across-track scanning
In orbit since 2006 aboard MetOp-A and expected for at least 15 years with MetOp-B and MetOp-C

- Global coverage twice daily (morning ~ 9:30 LT, evening ~ 21:30 LT)

IASI (IR)

- Spatial resolution: 25 km (at nadir)
- Across track swath: ~ 2000 km
- Spectral resolution: 0.5 cm\(^{-1}\)

GOME-2 (UV-Vis)

- Spatial resolution: 40 x 80 km\(^2\)
- Across track swath: ~ 1920 km
- Spectral resolution: ~ 0.24 nm

And after 2020, A New Generation of satellites: EPS-SG with IASI-NG and UVNS
Sensitivity of IASI retrievals of ozone

IASI → Lower tropospheric ozone

Possibility to discriminate between Lower Troposphere and Upper Troposphere when thermal conditions are favorable

LT sensitivity maximum around 3 km

Validation against ozonesondes:

Mid-latitudes bias : < 2.5%
Precision : ~15%

[IASI (IR)]

Averaging kernels

Over land DOFs up to 6 km : ~ 0.6
up to 12 km : ~ 1.2

[Dufour et al., 2012]
First observations of an ozone pollution event from space

[IASI retrieved]

[CHIMERE simulated]

July 17

July 18

[DU]

10 12 14 16 18 20 22 24 26 28 30 32 34

[Eremenko et al., 2008]
Monthly evolution of lower tropospheric ozone at East Asia – year 2008

January - winter
April
May
June
August
October - fall

Dufour et al. 2015
Monthly evolution for selected regions

Dufour et al.
Role of stratosphere-troposphere exchanges

Large ozone values observed in the north of East Asia are likely due to dynamical processes:
- large scale descending transport after cold fronts
- lower tropopause height after these fronts

Dufour et al. 2015
Multispectral synergism for retrieving Ozone

UV reflectance

IR radiance

Stratosphere

Troposphere

Free Troposphere

Altitude (km)

Sensitivity to $O_3$
Multispectral synergism for retrieving Ozone

UV reflectance

IR radiance

Stratosphere

Troposphere

Multispectral synergism

Lowermost troposphere

Free Troposphere
Multispectral approach IASI+GOME2

New approach of joint inversion of IR and UV co-localized spectra

Observed spectra
- GOME2 spectrum
- IASI spectrum

Simultaneous minimisation of UV and IR residuals

Adjustment of unique O$_3$ profile

Simulated spectra
- UV Reflectance
- IR Radiance

Radiative transfer models
- UV (VLIDORT)
- IR (KOPRA)

Atmospheric and surface conditions

Enhancement of sensitivity to lowermost tropospheric O$_3$

Multispectral retrieval for each satellite profile
Cuesta et al., 2013
Simultaneous fit of IR and UV spectra

Adjusting a unique Ozone profile and instrumental parameters

UV Reflectances

IR Radiances

~6.5%

~0.20%

~0.35%
Ozone spectroscopy coherence between UV and IR?

Similar results with UV cross sections -5% or HITRAN2010
Validation of IASI+GOME2 at the Global scale

IASI+GOME2 vs O3 sondes from 44 stations in 2009 and 2010

Lowermost tropospheric ozone: surface-3 km asl partial columns

Good agreement with sondes:

- Weak mean bias
- Good correlation
- Good variability
Sensitivity of the multispectral O3 retrieval: AVK

Two semi-independent tropospheric partial columns

Higher sensitivity for lower layers

IASI (IR)  GOME-2 (UV)  IASI+GOME-2
Sensitivity of the multispectral $O_3$ retrieval: Degrees of freedom in the Lowermost Troposphere (up to 3 km asl)

- **IASI (IR)**
  - 0.25 DOFs over land
  - 0.15 DOFs over ocean

- **GOME-2 (UV)**
  - $<0.10$ DOFs

- **IASI+GOME2**
  - 0.35 DOFs over land
  - 0.25 DOFs over ocean
  - $DOF_{\text{IASI}} + 40\%$
Sensitivity of the multispectral O$_3$ retrieval: Height of maximum sensitivity in the Lowermost Troposphere (up to 3 km asl)

IASI (IR)  GOME-2 (UV)  IASI+GOME2

3 km agl over land  2.2 km agl over land  3.5 km agl over ocean
4.3 km agl over ocean  3.7 km agl

$H_{\text{IASI}}$ - 800 m
A moderate O$_3$ pollution episode over Europe: 18 to 21 August 2009

20 August 2009 at 10 am: O$_3$ Surface – 6 km

- Western O$_3$ plumes → up to the lower free troposphere
- Eastern O$_3$ plumes → below 3 km (LMT)

Almost all O$_3$ plumes were photo-chemically produced with emissions from Europe

Cloud front

Anti-cyclonic conditions

Warm conveyor belt

CHIMERE Switching off O$_3$ precursor emissions since 01/08/2009

CHIMERE outputs

→ Almost all O$_3$ plumes were photo-chemically produced with emissions from Europe
Satellite observations of the \( \text{O}_3 \) pollution event: IASI+GOME2 vs. single-band approaches.

19 August 2009

**IASI (IR)**

**GOME-2 (UV)**

**IASI+GOME2**

Continental western \( \text{O}_3 \) plumes depicted by both IASI and IASI+GOME2 → up to 4-5 km asl

Eastern and over sea \( \text{O}_3 \) only observed by IASI+GOME2
Satellite observations of the O\textsubscript{3} pollution event: IASI+GOME2 vs. sing-band approaches

20 August 2009

Continental western O\textsubscript{3} plumes depicted by both IASI and IASI+GOME2 → up to 4-5 km asl

Eastern and over sea O\textsubscript{3} only observed by IASI+GOME2
IASI+GOME2 vs. CHIMERE: LMT and above

19 August 2009

Plumes below 3 km asl

Only seen by IASI+GOME2
IASI+GOME2 vs. CHIMERE: LMT and above

19 August 2009

- IASI+GOME2 LMT (<3 km)
- CHIMERE raw LMT
- CHIMERE raw 3–6 km asl

Plumes below 3 km asl
Only seen by IASI+GOME2

Also above
Also observed by IASI over land

O₃ LMT (DU)
IASI+GOME2 vs. MODELS at the LMT (<3 km):

19 August 2009

Good agreement with both models in the overall structure of O₃ plumes at the LMT.
IASI+GOME2 vs. MODELS at the LMT (<3 km):

19 August 2009

- Only modelled by CHIMERE & captured by IASI+GOME2
- Only modelled by MOCAGE & captured by IASI+GOME2
Assimilation of IASI+GOME2 LT observations into CHIMERE+EnK:

19 August 2009

IASI+GOME2
CHIMERE analysis*AVK

CHIMERE (analysis – forecast) at 10h00 am
Assimilation of IASI+GOME2 into CHIMERE:

19 August 2009

Assimilation of LT partial columns with CHIMERE+EnK

Corrections by IASI+GOME2 & also similar to MOCAGE
Comparison of IASI+GOME2 vs in situ measurements at the surface

2 pollution episodes: 4-9 April and 4-9 May 2009
Cases with gradient_{surface-2 km} < 20 ppb (according to CHASER)

✓ Good correlation: **Currently unique!!!**
✓ Weak mean bias
✓ Precision near expected IASI+GOME2 errors

Surface variability of O3 is not observed by IASI only approach
Ozone pollution over East Asia from IASI+GOME2

4 May 2009

IASI+GOME2 $\Rightarrow$ $O_3$ at 2 to 3 km

CO from IASI $\Rightarrow$ Anthropogenic tracer

$\Theta_{eq}$, geopotential and winds at 850 hPa

Potential vorticity at 300 hPa $\Rightarrow$ Stratosphere
Ozone pollution over East Asia from IASI+GOME2

5 May 2009

IASI+GOME2 $\Rightarrow$ O$_3$ at 2 to 3 km

CO from IASI $\Rightarrow$ Anthropogenic tracer

$\Theta_{eq}$, geopotential and winds at 850 hPa

Potential vorticity at 300 hPa $\Rightarrow$ Stratosphere
Ozone pollution over East Asia from IASI+GOME2

6 May 2009

IASI+GOME2 $\rightarrow$ O$_3$ at 2 to 3 km

CO from IASI $\rightarrow$ Anthropogenic tracer

$\Theta_{eq}$, geopotential and winds at 850 hPa

Potential vorticity at 300 hPa $\rightarrow$ Stratosphere
Ozone pollution over East Asia from IASI+GOME2

7 May 2009

IASI+GOME2 $\rightarrow$ O$_3$ at 2 to 3 km

CO from IASI $\rightarrow$ Anthropogenic tracer

$\Theta_{eq}$, geopotential and winds at 850 hPa

Potential vorticity at 300 hPa $\rightarrow$ Stratosphere
Ozone pollution over East Asia from IASI+GOME2

8 May 2009

IASI+GOME2 $\Rightarrow$ O$_3$ at 2 to 3 km

CO from IASI $\Rightarrow$ Anthropogenic tracer

$\Theta_{eq}$, geopotential and winds at 850 hPa

Potential vorticity at 300 hPa $\Rightarrow$ Stratosphere
$\Delta O_3 / \Delta CO$ is the relative increase of $O_3$, accounting for air masses dispersion and considering CO as a passive tracer.

Photo-chemical production of $O_3$ during transport

Production of $O_3$ limited by NOx concentration

Cuesta et al.
O₃ pollution over Europe during the COVID-19 lockdown of springtime 2020

- Quantify the impact of the COV-19 lockdown on ozone pollution over Europe
- Analyze the link with photochemical regimes: NOx-limited & VOC-limited

Which approach?

- Synergism of satellite observations, in-situ data and a chemistry-transport model

The new multispectral satellite data “IASI+GOME2”

- Enhanced sensitivity to near-surface O₃
Approach to study the impact of COVID19 lockdown on ozone pollution

**Observations**

- Satellite
- In-situ

**Chemistry-transport model**

- 2020 vs 2019
  - Ambiguity on differences in meteorological conditions
- 2020 (with reduced emissions COVID) vs 2020 (standard emissions)
  - Ambiguity on emissions during COVID lockdown

**Complexity**

- Secondary pollutant with non-linear effects according to NOx-limited and VOC-limited regimes
CHIMERE v2017 (Menut et al., 2020)
20 x 20 km$^2$ - 9 vertical levels
Anthropogenic emissions from HTAP v2.2
Meteorological fields from the BOLAM model
MEGAN biological emissions
COVID run:
↓ road traffic, ↓ industry, ↓ airplane & ship traffic (% from CAMS covid inventory)

April 2020 (COVID emissions), April 2020 (reference emissions) & April 2019

Model-derived COVID lockdown effect

Δ Meteorology correction for observations
Satellite IASI+GOME2 vs Surface In situ

$O_3 (2020) - O_3 (2019) \Rightarrow$ Lockdown effect + $\Delta$Meteorology

**IASI+GOME2 satellite observation**

1-15 April

**In situ measurements at the surface**

Agreement with regimes from Beekmann and Vautard, 2010

Good satellite/in situ agreement on spatial distribution and concentrations in absolute value!
Satellite IASI+GOME2 vs Surface In situ

$O_3$ (2020) – $O_3$ (2019) $\rightarrow$ Lockdown effect + $\Delta$Meteorology

Clear signatures from VOC-limited & NOx-limited regimes from Beekmann and Vautard, 2010
Satellite IASI+GOME2 vs CHIMERE model

$O_3$ (2020) – $O_3$ (2019) $\Rightarrow$ Lockdown effect + $\Delta$Meteorology

IASI+GOME2 satellite observation

1-15 April

Not very clear signatures from VOC-limited & NOx-limited regimes
Estimation of the impact of the COVID-19 lockdown from models and observations

From the CHIMERE model

$$\Delta O_{3_{mod}}^{covid} = O_{3_{modCOVID}}^{2020} - O_{3_{modSTD}}^{2020}$$

From surface & satellite observations

$$\Delta O_{3_{obs}}^{covid} \approx O_{3_{obs}}^{2020} - O_{3_{obs}}^{2019} - \left( O_{3_{modSTD}}^{2020} - O_{3_{modSTD}}^{2019} \right)$$

➤ Adjustment for changes in meteorological conditions between 2020 and 2019 using model simulations
2015 to 2019. In addition to the meteorological drivers mentioned in the predictors on the predictand and their non-linear relationships. This tool is commonly used to quantify the influence of meteorology on surface ozone observations in Europe (Hersbach et al., 2020). We have built the models using March and April data from NCEP/NCAR meteorological data at 0.75° horizontal resolution, for the period in 2015–2019. As expected, the emission reductions yielded decreases in the NO\textsubscript{2} emission changes and meteorology on O\textsubscript{3} concentrations and meteorological variables extracted the following variables. We have applied this statistical technique, provided by the pyGAM Python module (Barmpadimos et al., 2016). The resulting deviance explained by the GAMs for March–April, we have also included the occurrence of working vs. non-working days in the models as it is known to affect the day-to-day evolution. The numbers below the panels respectively indicate the 10th, 25th, 50th, 75th and 90th percentiles of the NO\textsubscript{2} concentrations for each site. O3 conc. reanalyses (in % and g/m\textsuperscript{3}) can be found in Fig. S3. While the model uses spline functions to estimate the pollutant response to continuous variables, the categorical variables are treated both the weekends and Easter holidays as non-working days. The left panels of Figs. 1–3 illustrate the concentration anomalies of NO\textsubscript{2} and O\textsubscript{3} during early March and late April 2020 with respect to the same periods in 2015–2019. From Ordoñez et al., 2020, the in situ surface & statistical predictive model evidencing the consistency of the model (not shown).
COVID-19 lockdown impact on O$_3$ pollution

Satellite IASI+GOME2
Meteo-adjusted

In situ surface
Meteo-adjusted

1-15 April

Large-scale reduction seen by ozone sondes & lidars in the free troposphere (Steinbrech et al., 2021)
Agreement over France, Benelux and Italy.

The model: ➔ underestimates the accumulation of O₃ over the Po Valley
➔ overestimates that over Germany and Poland
➔ Misses the large-scale reduction
Global production and distribution of IASI+GOME2 multispectral satellite observations starting in 2017
http://www.aeris-data.fr
Multi-annual evolution of $O_3$ pollution at global scale

5 years of global IASI+GOME2 data at AERIS

IASI+GOME2 Ozone from surface to 3 km a.s.l. (2017-2021)

Global decreasing trend, especially at middle latitude in Northern Hemisphere

Trend of Zonal Mean Ozone

-0.69 ppb/yr (p>0.01)
-0.49 ppb/yr (p>0.01)
-0.11 ppb/yr (p>0.01)
-0.40 ppb/yr (p>0.01)

Currently in production at TGCC/CEA
Chemical reanalysis

- CAMSRA (Innes et al., 2019)
- TCR-2 (Miyazaki et al., 2020)

Global distribution is roughly similar but we can see some large standard deviation regions.

S.D. is calculated from the seasonal values of the three datasets.
The future

- Upcoming satellite missions with better performances ➔ ESP-SG & MTG

- Improvement on pollution forecast
  - 3 EU controlled pollutants (CO, O₃ and NH₃)

- Better tracking of long range pollution (e.g., fire emissions)

- Essential Climate Variables monitoring and understanding
  - Clouds, GHG, aerosols

- Atmospheric profiling

- For T, WV, O₃, CO, CO₂, etc: more information on the vertical.
- For weak absorbers: improved detection limit + more species measured instead of detected

- Improved volcano alerts
  - Early alerts possible + SO₂ and ash tracking
→ For quantifying the added values of future satellite observations

Pseudo-observation simulator

MOCAGE model analysis

KOPRA

Forward calculation

IR radiance spectrum

Inversion

VLIDORT

UV/VIS reflectance spectrum

Comparison

Pseudo-reality

Pseudo-observations

« Observed » Ozone
Sensitivity enhancement with IASI-NG+UVNS

IASI-NG ➔ ½ radiometric noise and ½ spectral resolution wrt IASI
UVNS ➔ 1/3 radiometric noise and 2 x spectral resolution wrt GOME-2

IASI+GOME2
IASI-NG+UVNS

Degrees of freedom
DOF (surf.-2 km)

Max. Sensitivity height
$H_{max}$ (surf.-2 km)

$H_{max}^{\text{land}} = 1.25 \text{ km agl}$ ➔ Air Quality !!

Max. Sensitivity height
$H_{max}^{\text{land}} = 1.25 \pm 0.48$; SEA: $2.00 \pm 0.67$

-1.2 km

Max. Sensitivity height
$H_{max}^{\text{land}} = 0.49 \pm 0.17$; SEA: $0.40 \pm 0.15$

x3

Max. Sensitivity height
$H_{max}^{\text{land}} = 0.16 \pm 0.05$; SEA: $0.10 \pm 0.03$

Image 71x-19 to 598x437
Observation of O3 pollution with IASI-NG+UVNS

- O3 plumes below 2 km of altitude
- Better vertical resolution
Some conclusions

- Spectrally-resolved satellite observation are widely used to study atmospheric chemistry and air pollution.

- Retrieval approaches are designed for extracting the information on the 3D distribution of atmospheric constituents from spectra measured in the UV, Visible, IR and Microwaves.

- The performance for deriving the atmospheric composition relies on:
  - The quality of the atmospheric measurements (calibration, resolution, knowledge of errors, etc.)
  - The quality of the “direct” model (spectroscopy databases, physical representation of the atmosphere and surface) → particularly for multispectral approaches
  - Appropriate constraints of the retrievals

- **Multispectral approaches** are promising tools for observing air pollution (sensitivity for lowest layers, 3D distributions, etc.)
Acknowledgements