Remote sensing of greenhouse gases (CO$_2$ and CH$_4$) using hyperspectral observations in the thermal infrared

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Introduction

• CO$_2$ is the main greenhouse gas influenced by human activities.
• CO$_2$ is absorbed and emitted by natural and anthropogenic sources and sinks.
• Understanding the future evolution of CO$_2$ atmospheric concentration, requires understanding it sources and sinks at the surface (location, amplitude, evolution).

Top-down approach

Atmospheric transport model  

Simulated CO$_2$  

Minimisation by optimizing sources and sinks  

CO$_2$ obs.

• Current surface observation of atmospheric CO$_2$ is limited, especially in the tropics.

Observation of CO$_2$ from space: global and continuous measurements.
Introduction

Current instruments

Global Operational Satellite Observation System

- FY-1/3 (China)
- METEOR 3M (Russian Federation)
- GOES-R (USA) 75W
- GOES-R (USA) 135W
- Terra NPP
- Jason-1
- Okean series
- GMS-5/MTSAT-1R (Japan) 140E
- COMS-1 (Rep of Korea) 120E
- FY-2/4 (China) 105E
- GPM ADEOS II
- GCOM
- Metop (EUMETSAT) 76E
- NPOESS (USA)
- Metop (EUMETSAT)
- Other R&D oceanographic, land use, atmospheric chemistry and hydrological missions
- ENVISAT/ERS-2
- METEOR 3M N1
- SPOT-5
- MSG (EUMETSAT) 0 Longitude
- METEOSAT (EUMETSAT) 63E
- GOMS (Russian Federation)
- INSATs (India) 83E
- GOSAT (JAXA/NIES)
- Aqua QuickScat TRMM
- Subsatellite Point

LMD/CI
Introduction

Current instruments

Global Operational Satellite Observation System

- FY-1/3 (China)
- GOES-R (USA) 75W
- METEOSAT 83E
- METEOR 3M (Russian Federation)
- 850 KM
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- GCOM
- Terra NPP
- Jason-1
- Okean series

Other R&D oceanographic land use atmospheric chemistry and hydrological missions

Aqua, TRMM, ENVISAT/ERS-2, METEOR-3M, SPOT-5
• Three types of observation:
  - Thermal Infrared @ nadir.
  - Thermal Infrared @ limb
  - Shortwave Infrared

• Active missions in preparation.

• Each technique has its own characteristics.
Greenhouse gases from infrared sounders

1. Different techniques to measure GHG from space.
2. How to retrieve GHG from IR sounders: example of IASI.
3. Retrieval of CH$_4$: seasonal cycle and comparison with TM5.
4. Retrieval of CO$_2$: seasonal cycle and diurnal cycle.
5. Coupling of CO$_2$ and CH$_4$ retrievals.
6. Conclusion and some perspectives.
Measuring greenhouse gases from space

The principle of the measurement is always the same:

1. A radiation goes through the atmosphere.

2. It is absorbed/re-emitted by the gas, the absorption being controlled by its atmospheric concentration.

3. The modified radiation measured above the atmosphere gives information on the gas.

To be absorbed, the radiation must have a wavelength located in the spectral absorption bands of the gas.

- The radiation is measured by various channels (and sometimes expressed in terms of brightness temperatures BT).
- Each channel is characterized by its central wavelength and its spectral resolution.
- The higher the resolution, the better we can isolate the absorption due to the gas.
Measuring greenhouse gases from space

Vertical sounding in the thermal Infrared

 radiation = Earth radiation in the thermal IR.

• First objective of thermal-IR sounders: to retrieve atmospheric T, H₂O, O₃

• Study of their ability to measure CO₂ in the mid-troposphere [Chédin et al. 2002, 2003]

• 1st generation TOVS on NOAA platforms since 1978 (20 channels)
  First retrieval of CO₂ from space [Chédin et al. 2003]
  Precision on CO₂: ~3.0 ppmv (1 month-15°x15°)

• AIRS-AMSU onboard NASA/Aqua since 2002 (2378 channels)
  Precision on CO₂: ~2.5 ppmv (1 month-15°x15°)
  CO₂: Crevoisier et al. 2004; Engelen et al. 2004, 2009; Chahine et al. 2005;
   Maddy et al. 2008; Strow and Hannon 2008
  CH₄: Xiong et al., 2008ab

• IASI-AMSU onboard MetOp-A since 2007 (8461 channels)
  Precision on CO₂: ~2.0 ppmv (1 month-5°x5°)
  CO₂: Crevoisier et al. 2009a
  CH₄: Crevoisier et al., 2009b, Razavi et al., 2010
Measuring greenhouse gases from space

Limb sounding in the thermal Infrared

**radiation** = atmospheric radiation in the thermal IR in solar occultation.

One instrument:

ACE-FTS onboard CSA/SciSat:
- First retrieval of CO$_2$ profiles:
  - from 8 to 25 km.
  - vertical precision: 2 km.
  - precision: 2 ppm.
  - highest coverage at high latitudes.

[Foucher et al., ACP, 2009 and ACPD 2010]
Measuring greenhouse gases from space

Differential absorption in the SWIR

radiation = solar radiation reflected by the surface in a CO₂ absorption band.

Study of two measurements:
- One centered on the absorption line
- One centered on the edge.

• Two CO₂ lines are used: 1.6 and 2.0 μm
• Mainly sensitive to gas variations in the lower part of the atmosphere.
• Retrievals limited to daytime, mostly over land.

Instruments:

• SCIAMACHY (since 2002): CH₄ (and CO₂).
• GOSAT: launched by JAXA in Jan. 2009. → First instrument dedicated to the only CO₂.
• OCO-2 for CO₂ launch planned by NASA for 2013.

[Frankenberg et al., sub. 2010]
Measuring greenhouse gases from space

Active techniques (under development)

radiation emitted by a known source (LIDAR) and then backscattered to the satellite.

Same principle as absorption technique.

✓ two lines: 1.6 and 2.0 μm
✓ total column of CO₂.

Instruments:

• A-SCOPE for CO₂ (postponed by ESA until further technical developments).
• ASCENDS for CO₂ (considered by NASA for possible launch in 2020).
• MERLIN for CH₄ (CNES/DLR mission to be launched in 2014).
• Three types of observation available:
  - **Thermal Infrared @ limb:**
    vertical profile 8-25 km.
  - **Shortwave Infrared:**
    daytime only, mostly over land, not yet satisfactory for CO₂
  - **Thermal Infrared @ nadir:**
    day and night, land and sea, long time series for CO₂.
• Active missions in preparation.
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The IASI instrument

- IASI (Infrared Atmospheric Sounding Interferometer) is a Fourier Transform Spectrometer based on a Michelson Interferometer coupled to an integrated imaging system that measures infrared radiation emitted from the Earth.
- It has been developed by CNES, in collaboration with EUMETSAT.
- IASI provides
  - 8461 spectral channels between 645 and 2760 cm\(^{-1}\) (15.5 - 3.63 µm)
  - with a spectral resolution of 0.5 cm\(^{-1}\) after apodisation (“Level 1c” spectra)
  - the spectral sampling interval is 0.25 cm\(^{-1}\).
- FOV: 12 km at nadir.

Example of IASI spectrum in the tropics

![Graph showing example of IASI spectrum in the tropics.](Example of IASI spectrum in the tropics)
The IASI instrument

Study of IASI channel sensitivity to GHG through RT simulations

One atmosphere

\((T, H_2O, O_3, CO_2)\)

Radiative transfer

forward models

4A/STRANSAC

\(T_B(v)\)

8461 IASI channels

15 AMSU channels

+ \(T\)

+ Jacobians

spectroscopic database GEISA

• Use of the climatological database TIGR

2311 atmospheric situations described by their profiles of \(T, H_2O, O_3\).


Study of the variation of brightness temperatures due to the variation of several atmospheric and surface variables.
Sensitivity of IASI T_B to variations of atmospheric and surface variables (simulations with the 4A radiative transfert model)

Variation of brightness temp. (K) vs. Wave number (cm\(^{-1}\))

- \(\text{CO}_2 (1\%)\)
- \(\text{CH}_4 (20\%)\)
- \(T (1K)\)
- \(\text{H}_2\text{O} (20\%)\)
- \(\text{O}_3 (10\%)\)
- \(\text{CO} (40\%)\)
- \(\text{Tsurf} (1 \text{ K})\)

Jacquinet-Husson et al., 2008
http://ether.ipsl.jussieu.fr

Scott et Chédin, 1981
http://www.noveltis.fr/4AOP/
Sensitivity of IASI T<sub>B</sub> to variations of atmospheric and surface variables (simulations with the 4A radiative transfert model)

Variation of brightness temp. (K)

Wave number (cm<sup>-1</sup>)

CO<sub>2</sub> (1%)  CH<sub>4</sub> (20%)  T (1K)  H<sub>2</sub>O (20%)  O<sub>3</sub> (10%)  CO (40%)  Tsurf (1 K)

Jacquet-Husson et al., 2008
http://ether.ipsl.jussieu.fr

Scott et Chédin, 1981
http://www.noveltis.fr/4AOP/
Retrieval of greenhouse gases from IR sounders

Sensitivity of IASI $T_B$ to variations of atmospheric and surface variables

- Channels are selected to minimize interferences from other species.
- Channels are first and most sensitive to temperature.

\[
\begin{align*}
\text{CO}_2 & : 1\% \rightarrow 0.1 \text{ K} \\
T & : 1 \text{ K} \rightarrow 1 \text{ K} \\
\text{Radiometric noise} & \sim 0.2 \text{ K}
\end{align*}
\]

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\begin{align*}
\text{CO}_2 & : 1\% \rightarrow 0.2 \text{ K} \\
T & : 1 \text{ K} \rightarrow 1 \text{ K} \\
\text{Radiometric noise} & \sim 2 \text{ K}!
\end{align*}
\]

4.3 $\mu$m band not used with IASI but it can be used with AIRS.
Retrieval of greenhouse gases from IR sounders

Sensitivity of IASI $T_B$ to variations of atmospheric and surface variables

- Channels are selected to minimize interferences from other species.
- Channels are first and most sensitive to temperature.

- $\text{CO}_2$: $1\% \rightarrow 0.1\ K$
- $T$: $1\ K \rightarrow 1\ K$
- Radiometric noise $\sim 0.2\ K$

- $\text{CO}_2$: $1\% \rightarrow 0.2\ K$
- $T$: $1\ K \rightarrow 1\ K$
- Radiometric noise $\sim 2\ K$

4.3 $\mu m$ band not used with IASI but it can be used with AIRS
Retrieval of greenhouse gases from IR sounders

Sensitivity of IASI $T_B$ to variations of atmospheric and surface variables

CO$_2$ Jacobians (simulated by 4A)
Retrieval of greenhouse gases from IR sounders

Sensitivity of IASI $T_B$ to variations of atmospheric and surface variables

$T_B$, ref. ($K$)

Channel in 4.3 $\mu$m see lower than channels at 15 $\mu$m.
Summary: IASI channel selection for retrieval of CO₂

- Channels are selected to minimize interferences from other species.
- Channels are first and most sensitive to temperature.
- Channels only cover the mid-to-upper troposphere.

\[
\begin{align*}
\text{CO}_2: & \quad 1\% \rightarrow 0.1 \text{ K} \\
T: & \quad 1 \text{ K} \rightarrow 1 \text{ K} \\
\text{Radiometric noise:} & \quad \sim 0.2 \text{ K}
\end{align*}
\]

Very low signal/noise ratio!
Methodology: non-linear inference scheme

• We use a non-linear inference scheme based on neural networks. [Chédin et al. 2003, Crevoisier et al. 2004, Crevoisier et al. 2009]

• Need to decorrelate T/gas

  → Use of independent info on T: we use synchronized microwave observations from AMSU flying onboard both Aqua and MetOp-A.
Characteristics of the retrievals

• The decorrelation between T/GHG is easier to do in the tropics. ⇒ a better precision is expected there.

• Need to average the retrievals: here, 1 month, 5°x5°.

• Retrievals in clear sky only (no clouds, no aerosols).

• Retrievals in day and night, over land and over sea.

• We retrieve a mid-tropospheric content:
  ~“one degree of freedom”.
  ~boundary layer not measured.
CO$_2$ and CH$_4$ retrieved from AIRS and IASI

We have now 7 years of monthly averaged mid-to-upper tropospheric CO$_2$ integrated content from AIRS and IASI and ~3 years of IASI CH$_4$.

Averaged seasonal cycle of CO$_2$ over [0-20N]

Averaged seasonal cycle of CH$_4$ over [0-20N]
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Results: \( \text{CH}_4 \) seasonal cycle

Since July 2007, monthly means of mid-tropospheric contents of \( \text{CH}_4 \) have been retrieved from IASI in the tropical band [Crevoisier et al. ACP 2009b].

IASI \( \text{CH}_4 \) monthly zonal variation over [20S-20N]
Results: \( \text{CH}_4 \) seasonal cycle

Validation of the retrievals?

- **Problem**: we lack validation data in the mid-troposphere.
- **One aircraft campaign** (flying at \(~10\) km) over 7 months in 1993 [Matsueda and Inoue, 1996].

N-S gradient of \(~30\) ppb @ 11 km vs. 50 ppb at the surface.
Results: CH₄ seasonal cycle

Trend of methane

• Since the end of 2006/beginning of 2007, an increase of CH₄ has been seen at the surface after a decade of near stability.
• No mechanism clearly identified.

<table>
<thead>
<tr>
<th>Year</th>
<th>NH</th>
<th>SH</th>
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<tbody>
<tr>
<td>2007</td>
<td>7.3 ± 1.3</td>
<td>9.2 ± 0.3</td>
</tr>
<tr>
<td>2008</td>
<td>8.1 ± 1.6</td>
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</table>

From Dlugokencky et al., 2009

What can IASI tell us about this trend?
Results: CH$_4$ seasonal cycle

We fit the IASI seasonal cycle with:

$$f(t) = \alpha_1 + \alpha_2 t + \alpha_3 t^2 + \sum_{i=1}^{4} (\alpha_{2i+2} \sin(2\pi t) + \alpha_{2i+3} \cos(2\pi t))$$

...from which we derive the annual trend:

<table>
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<tbody>
<tr>
<td>2007</td>
<td>9.5 ± 2.8</td>
<td>8.2 ± 1.8</td>
<td>10.7 ± 2.5</td>
<td>7.3 ± 1.3</td>
<td>9.2 ± 0.3</td>
</tr>
<tr>
<td>2008</td>
<td>6.3 ± 1.7</td>
<td>5.6 ± 1.0</td>
<td>7.0 ± 1.4</td>
<td>8.1 ± 1.6*</td>
<td></td>
</tr>
<tr>
<td>2009</td>
<td>3.2 ± 2.1</td>
<td>3.0 ± 1.6</td>
<td>3.3 ± 1.8</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2010</td>
<td>0.0 ± 3.1</td>
<td>0.5 ± 2.3</td>
<td>-0.4 ± 2.8</td>
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</tbody>
</table>

NB: There are only three years of IASI (July 2007-Sept. 2010): The trend is an estimation based on the extrapolation of the fit for 2007 and 2010.

We find a trend of +10 ppb.yr$^{-1}$ in 2007, +6 ppbv.yr$^{-1}$ in 2008, which then decreases to a near zero increase in 2010.

→ Increase due to wetland emissions due to increase precipitation is one of the major drivers.

[Crevoisier et al. submitted to GRL]
Results: CH$_4$ geographic distribution

3-month average of IASI CH$_4$ 5°x5°
Precision for 1 month: ~16ppbv

- Year-long minimum over the Pacific.
- Outgoing CH$_4$ from Africa (Central in DJF, East in JJA) associated to wetlands emissions.
- Plume of elevated CH$_4$ over Asia (rice + deep monsoon CNV) moving southward.
Results: $CH_4$ geographic distribution

SON 2007

DJF 2007-2008

MAM 2008

JJA 2008

SON 2008

DJF 2008-2009

MAM 2009

JJA 2009
• TM5: with surface sources constrained by NOAA surface stations (4Dvar), sampled at the spatio-temporal resolution of IASI and with CH$_4$ weighting function applied to the profiles (courtesy of P. Bergamaschi).
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Results: $CO_2$ seasonal cycle

Detrended $CO_2$ seasonal cycle in the northern tropics

AIRS 5-15 km (max ~10 km); mean over 2003-2007
Results: \( CO_2 \) seasonal cycle

Detrended \( CO_2 \) seasonal cycle in the northern tropics

\[
\text{AIRS} \quad 5-15 \text{ km (max } \sim 10 \text{ km); mean over 2003-2007}
\]

\[
\text{CONTRAIL} \quad \text{JAL aircrafts } \sim 10 \text{ km}; \text{ mean over 2003-2007 [Matsueda et al. 2008; Machida et al. 2008]}
\]
Results: CO$_2$ seasonal cycle

Detrended CO$_2$ seasonal cycle in the northern tropics

**AIRS**  5-15 km (max $\sim$10 km); mean over 2003-2007

**CONTRAIL**  JAL aircrafts $\sim$10 km; mean over 2003-2007 \cite{Matsueda2008, Machida2008}

**IASI**  9-15 km (max $\sim$13 km); mean over 2007-2009
Results: \( CO_2 \) seasonal cycle

Detrended \( CO_2 \) seasonal cycle in the northern tropics

Time-lag of \( CO_2 \) while transported from the surface to the upper troposphere

- **MLO**: 4 km; mean over 2003-2007 [GLOBALVIEW-2008]
- **AIRS**: 5-15 km (max ~10 km); mean over 2003-2007
- **CONTRAIL**: JAL aircrafts ~10 km; mean over 2003-2007 [Matsueda et al. 2008; Machida et al. 2008]
- **IASI**: 9-15 km (max ~13 km); mean over 2007-2009
- **16 km**: entering point of stratospheric air [adapted from Strahan et al. 1998]
Results: CO$_2$ seasonal cycle

• Comparison with CO$_2$ seasonal cycle simulated by Carbon Tracker [Peters et al., 2007] at various pressure levels.
• CT simulations have been colocated in time and space with IASI orbits.

Detrended CO$_2$ seasonal cycle in the northern tropics
**Results: CO₂ seasonal cycle**

- Comparison with CO₂ seasonal cycle simulated by Carbon Tracker [Peters et al., 2007] at various pressure levels.
- CT simulations have been colocated in time and space with IASI orbits.

Detrended CO₂ seasonal cycle in the northern tropics

One month lag between AIRS and IASI and no shift in fall/winter well simulated by CT.
Results: \( \text{CO}_2 \) diurnal cycle from TOVS

Two TOVS measurements per day: one in the morning (7.30am), one in the evening (7.30pm). The difference between the two gives the DTE (Diurnal Tropospheric Excess) of \( \text{CO}_2 \) [Chédin et al., 2005, 2008]
Results: $CO_2$ diurnal cycle from TOVS

Comparison between DTE and fire emission estimates

$CO_2$ fire emissions (g/m$^2$/month) from GFEDv2 averaged over 1997-2002 [Van der Werf et al., 2003]

Seasonal average of TOVS DTE over 1987-1991
Results: $CO_2$ diurnal cycle from TOVS

Comparison between DTE and fire emission estimates

GFED: mean over 1997-2004
DTE: mean over 1987-1990

Linear relationship between $CO_2$ DTE and GFED emissions!

⇒ DTE as a proxy for $CO_2$ fire emissions (25-year archive from TOVS)
Results: $\text{CO}_2$ diurnal cycle from TOVS

Possible explanation of the DTE

The DTE signal could result from the “convolution” of:

- the **diurnal cycle** of fire emissions [Giglio et al., 2008].

- **transport**: a fire-enhanced convective uplift of $\text{CO}_2$ plumes to the middle-upper troposphere between late morning and afternoon, detected by the satellite at 19h30, (mechanism suggested by Andreae et al., 2004, Freitas et al., 2006) followed by a dilution of the emission-laden air in altitude by the prevailing UT flow during the night, before the next satellite pass at 7h30 [Krishnamurti et al. 1996, Freitas et al. 2004]

![](image1.png)

**Diurnal cycle at the surface**

![Diagram showing diurnal cycle at the surface in Southern Africa with labeled hours 7h30 and 19h30.]

**CO plume rise** from the new cloud-resolving model at INPE Brazil

![Diagram showing CO plume rise over South America and Africa with a height scale in meters.]

[Freitas et al., 2006]
Results: $CO_2$ diurnal cycle from TOVS

Simulation of DTE using LMDz with new thermal-plume injection scheme

• Use of the LMDz transport model with a new thermal-plume injection scheme [Rio et al., 2009].
• Simulation of integrated $CO_2$ concentration and DTE.

Importance of getting the transport right! [Rio et al., 2009]
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An interesting perspective: Correlation between GHG

The simultaneous retrieval of CO$_2$ and CH$_4$ from IASI gives us the opportunity to study the correlation between both gases.

CH$_4$ vs. CO$_2$ measured at 11 km during two CARIBIC flights [Schuck et al., 2009]

August 2007
February 2008
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Conclusions and perspectives

• Infrared sounders give access to many information on greenhouse gases: trend, seasonality, strong emissions uplifted to the mid-troposphere (e.g. fires), atmospheric transport.

• Coupling with various instruments:
  - **SWIR** (eg GOSAT) to combine observations sensitive to PBL+tropo with observations sensitive to tropo-only.
  - **limb sounding**: first retrieval of profiles of CO$_2$ from ACE-FTS [Foucher et al. ACP 2009, 2010 in prep.]

• Three successive IASI: Metop-B in 2013 and Metop-C in 2016.

• The successor of IASI is currently designed by CNES: IASI-NG will fly on the EUMETSAT EPS-SG missions planned for 2018, with an improvement by a factor of 2 on the spectral resolution and the radiometric characteristics: getting two points on the vertical will then be achievable.

• Improvement of radiometric noise and synchronization between infrared and microwave observations are essential.

• Data needed to validate and analyze results (regular measurements of CO$_2$/CH$_4$ in the mid- and upper-troposphere)
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• Foucher P.-Y. et al., Technical Note : Feasibility of CO₂ profile retrieval from limb viewing solar occultation made by the ACE-FTS instrument, ACP, 9, 2873–2890, 2009.

For more information, data and references ➔ please visit http://ara.lmd.polytechnique.fr/