Retrieval of atmospheric CO$_2$ from satellite near-infrared nadir spectra in a scattering atmosphere

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How to observe CO$_2$

Sparse but accurate network of ground based flask measurements:
NOAA Cooperative Air Sampling Network
www.esrl.noaa.gov/gmd/ccgg/flask.html
WFM-DOAS - The observed year-to-year increase

SCIAMACHY (Fit Windows)

Maximilian Reuter, Hamburg, 03.03.2009

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Retrieval of atmospheric CO$_2$ from satellite near-infrared nadir spectra in a scattering atmosphere

SCIAMACHY (Fit Windows)
Retrieval of atmospheric $\text{CO}_2$ from satellite near-infrared nadir spectra in a scattering atmosphere
Scattering
Retrieval of atmospheric CO$_2$ from satellite near-infrared nadir spectra in a scattering atmosphere

Scattering

- Thin cloud
- Aerosol
Weighting functions CO₂ (scattering)
Scattering

Retrieval of atmospheric CO$_2$ from satellite near-infrared nadir spectra in a scattering atmosphere.
Weighting functions $\text{O}_2$ (scattering)

weighting functions ($\text{O}_2$ fit window)

US–standard, SZA:40°, VZA:10°, albedo:0.2
CWP:10g/m², CGT:0.5km, $R_{\text{eff}}$:50μm, CP:ice(fractals)

- CTH:10km
- CTH:12km
- CTH:14km

cloud water path

cloud top height

aerosol profile scaling

surface pressure

$\frac{\Delta l}{\Delta \text{CWP}}$ [g/m²]

$\frac{\Delta l}{\Delta \text{CTH}}$ [km]

$\frac{\Delta l}{\Delta \text{APS}}$ [APS⁻¹]

$\frac{\Delta l}{\Delta \text{SP}}$ [hPa⁻¹]

wavelength [nm]
Merged fit windows and state vector

O₂ fit window
- Wavelength shift, FWHM
- Albedo (slope, offset)

CO₂ fit window
- Wavelength shift, FWHM
- Albedo (slope, offset)
- CO₂ Profile (10 layer)

- H₂O profile scaling
- Temperature profile shift
- Aerosol profile scaling
- Cloud water path
- Cloud top height
- Surface pressure
Results – Retrieval of state vector elements
Met. parameter plus 1σ

- retrieved parameters
  - a priori
  - first guess
  - a priori uncertainty
  - true
  - maximum a posteriori
  - a posteriori uncertainty

- fit windows
  - meas.
  - meas. err.
  - fit, residual
  - first guess

- CO₂ [ppm]
  - XCO₂: 394.9 (±1.9)
  - 395.6 (-0.7)
  - 376.8
  - 376.8 (±16.1)

- uncertainty reduction
  - XCO₂: 88%

- RMS of noise [%]
  - O₂: 0.040, CO₂: 0.049

- degree of freedom
  - surf.pres.: 0.99, CO₂ profile: 1.37

- RMS of residual [%]
  - O₂: 0.003, CO₂: 0.002
Results – Sensitivity to macro physical cloud parameters

Multi-layer clouds

retrieved parameters

- a priori
- first guess
- a priori uncertainty
- maximum a posteriori
- a posteriori uncertainty

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Uncertainty</th>
</tr>
</thead>
<tbody>
<tr>
<td>Surface pressure [hPa]</td>
<td>976.8</td>
<td>±3.2</td>
</tr>
<tr>
<td>981.0 (−4.3)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1013.0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1013.0 (±30.9)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cloud water path [g/m²]</td>
<td>12.8</td>
<td>±0.4</td>
</tr>
<tr>
<td>15.0 (−2.2)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>10.0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>5.0 (±10.0)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

$X_{CO_2}$ [ppm]
395.8 (±1.7)
395.6 (0.2)
376.8
376.8 (±16.1)

Uncertainty reduction
$X_{CO_2}$: 89%

Degree of freedom
surf.pres.: 0.99, CO$_2$ profile: 1.38

RMS of noise [%]
O$_2$: 0.043, CO$_2$: 0.049

RMS of residual [%]
O$_2$: 0.011, CO$_2$: 0.009
CALIPSO aerosol optical thickness

2007 Jan Feb Mar Apr May Jun Jul Aug Sep Oct Nov Dec

CALIPSO aerosol optical thickness (@532nm)
CALIPSO cloud top height (sub visible cirrus)
Retrieval of atmospheric CO\textsubscript{2} from satellite near-infrared nadir spectra in a scattering atmosphere

Thanks
Retrieval of atmospheric CO\textsubscript{2} from satellite near-infrared nadir spectra in a scattering atmosphere

Supplementary material
Can we retrieve the state vector elements?
CO₂ profile:
Weighting functions and layer correlations

CO₂ profile weighting functions
US-standard, SZA:40°, VZA:10°, albedo:0.2, SP:1013hPa
0-.1SP  .1-.2SP  .2-.3SP  .3-.4SP  .4-.5SP
.5-.6SP  .6-.7SP  .7-.8SP  .8-.9SP  .9-1SP

Low sensitivity in the stratosphere
Highest sensitivity in the boundary layer
Large correlations in the free troposphere

Carbon Tracker XCO₂ correlation
Results – Dry run

<table>
<thead>
<tr>
<th>retrieved parameters</th>
<th>fit windows</th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="image" alt="Graph showing retrieved parameters and fit windows" /></td>
<td></td>
</tr>
</tbody>
</table>

- **CO₂ [ppm]**
  - XCO₂: 376.8 (±1.5)
  - 376.8 (0.0)
  - 376.8 ±15.6

- **Uncertainty reduction**
  - XCO₂: 90%

- **Degree of freedom**
  - surf.pres.: 0.99, CO₂ profile: 1.38

- **RMS of noise [%]**
  - O₂: 0.042, CO₂: 0.054

- **RMS of residual [%]**
  - O₂: 0.000, CO₂: 0.000
Results – No cloud

Retrieval of atmospheric CO$_2$ from satellite near-infrared nadir spectra in a scattering atmosphere

**retrieved parameters**

- a priori
- first guess
- a priori uncertainty
- maximum a posteriori
- a posteriori uncertainty

**fit windows**

- meas.
- meas. err.
- fit, residual
- first guess

**CO$_2$ [ppm]**
- $393.8$ (±$2.3$)
- $395.6$ (−$1.8$)
- $376.8$ ±$16.0$

**XCO$_2$ [ppm]**
- $393.8$ (±$2.3$)
- $395.6$ (−$1.8$)
- $376.8$ ±$16.0$

**uncertainty reduction**
- XCO$_2$: 86%

**degree of freedom**
- surf.pres.: 0.99, CO$_2$ profile: 1.44

**RMS of noise [%]**
- O$_2$: 0.056, CO$_2$: 0.043

**RMS of residual [%]**
- O$_2$: 0.006, CO$_2$: 0.003
Results – Retrieval of state vector elements

Met. parameter plus 1σ (with noise)

XCO₂ [ppm]
394.3 (±1.9)
395.6 (−1.3)
376.8
376.8 (±16.0)

uncertainty reduction
XCO₂: 88%

degree of freedom
surf.pres.: 0.99, CO₂ profile: 1.37

RMS of noise [%]
O₂: 0.040, CO₂: 0.049

RMS of residual [%]
O₂: 0.039, CO₂: 0.044
Results – Retrieval of state vector elements

CO$_2$ profile plus 5σ

![Graph showing retrieved parameters and fit windows with CO$_2$ and O$_2$ spectra.]

- **XCO$_2$ [ppm]**
  - 475.3 (±2.8)
  - 481.2 (-5.9)
  - 376.8
  - 376.8 (±15.8)

- **Uncertainty reduction**
  - XCO$_2$: 82%

- **Degree of freedom**
  - surf.pres.: 0.99, CO$_2$ profile: 1.32

- **RMS of noise [%]**
  - O$_2$: 0.042, CO$_2$: 0.054

- **RMS of residual [%]**
  - O$_2$: 0.005, CO$_2$: 0.008
Results – Retrieval of state vector elements

Artificial CO$_2$ profile

**retrieved parameters**

- **a priori**
- **first guess**
- **a priori uncertainty**
- **true**
- **maximum a posteriori**
- **a posteriori uncertainty**

**Fit windows**

- **meas.**
- **meas. err.**
- **fit, residual**
- **first guess**

**Surface pressure [hPa]**
- 1013.5 (±2.5)
- 1013.0 (0.5)
- 1013.0 (±31.9)

**Cloud water path [g/m²]**
- 0.0 (±0.4)
- 0.0 (0.0)
- 5.0 (±10.0)

**RMS of noise [%]**
- O$_2$: 0.051, CO$_2$: 0.050

**RMS of residual [%]**
- O$_2$: 0.001, CO$_2$: 0.001

**XCO$_2$ [ppm]**
- 386.2 (±1.8)
- 387.0 (−0.7)
- 376.8
- 376.8 (±15.6)

**Degree of freedom**
- surf.pres.: 0.99, CO$_2$ profile: 1.41

**XCO$_2$: 88%**

**Uncertainty reduction**
Sensitivity to macro physical cloud parameters not included
Results – Cloud geometrical thickness 2.5 km

XCO₂ [ppm]
394.7 (±2.0)
395.6 (-0.9)
376.8
376.8 (±16.1)

uncertainty reduction XCO₂: 88%

degree of freedom surf.pres.: 0.99, CO₂ profile: 1.38

RMS of noise [%]
O₂: 0.040, CO₂: 0.049

RMS of residual [%]
O₂: 0.008, CO₂: 0.003
Results – Cloud fractional coverage 50%

retrieved parameters

- a priori
- first guess
- a priori uncertainty
- maximum a posteriori
- a posteriori uncertainty

Surface pressure [hPa]
- 978.1 ($\pm$3.6)
- 981.0 ($-3.0$)
- 1013.0
- 1013.0 ($\pm$30.9)

Cloud water path [g/m²]
- 8.7 ($\pm$0.3)
- 15.0 ($-6.3$)
- 10.0
- 5.0 ($\pm$10.0)

XCO₂ [ppm]
- 392.2 ($\pm$2.0)
- 395.6 ($-3.3$)
- 376.8
- 376.8 ($\pm$16.1)

Uncertainty reduction
XCO₂: 88%

Degree of freedom
surf.pres.: 0.99, CO₂ profile: 1.41

RMS of noise [%]
O₂: 0.045, CO₂: 0.046

RMS of residual [%]
O₂: 0.007, CO₂: 0.009
Sensitivity to micro physical cloud parameters not included
Volume scattering function of cloud particles

ice ($\lambda=750\text{nm}$, $\rho=1\text{g/m}^3$)  
ice ($\lambda=1600\text{nm}$, $\rho=1\text{g/m}^3$)  
water ($\lambda=750\text{nm}$, $\rho=1\text{g/m}^3$)  
water ($\lambda=1600\text{nm}$, $\rho=1\text{g/m}^3$)  

scattering angle [°]  

volume scattering function [sr$^{-1}$ m$^{-1}$]
Results – Ice particles (fractal, 300µm)

XCO₂ [ppm]
395.2 (±1.9)
395.6 (−0.4)
376.8
376.8 (±16.0)

uncertainty reduction
XCO₂: 88%
degree of freedom
surf.pres.: 0.99, CO₂ profile: 1.42

RMS of noise [%]
O₂: 0.051, CO₂: 0.046
RMS of residual [%]
O₂: 0.002, CO₂: 0.015

Retrieval of atmospheric CO₂ from satellite near-infrared nadir spectra in a scattering atmosphere
Results – Ice particles (fractal, 100µm)

Retrieval of atmospheric CO$_2$ from satellite near-infrared nadir spectra in a scattering atmosphere

XCO$_2$ [ppm]  
396.0 (±1.9)  
395.6 (0.4)  
376.8 (±16.0)

uncertainty reduction  
XCO$_2$: 88%

degree of freedom  
surf.pres.: 0.99, CO$_2$ profile: 1.39

RMS of noise [%]  
O$_2$: 0.045, CO$_2$: 0.048

RMS of residual [%]  
O$_2$: 0.003, CO$_2$: 0.009
Results – Sensitivity to micro physical cloud parameters
Ice particles (hexagonal, 25µm)

XCO\textsubscript{2} [ppm]
397.8 (±2.0)
395.6 (2.2)
376.8
376.8 (±16.1)

uncertainty reduction
XCO\textsubscript{2}: 88%

degree of freedom
surf.pres.: 0.99, CO\textsubscript{2} profile: 1.40

RMS of noise [%]
O\textsubscript{2}: 0.041, CO\textsubscript{2}: 0.046

RMS of residual [%]
O\textsubscript{2}: 0.006, CO\textsubscript{2}: 0.005
Results – Water droplets (18μm)

XCO₂ [ppm]
394.9 (±2.2)
395.6 (-0.7)
376.8
376.8 (±16.1)

Uncertainty reduction
XCO₂: 86%

Degree of freedom
surf.pres.: 0.99, CO₂ profile: 1.45

RMS of noise [%]
O₂: 0.054, CO₂: 0.042

RMS of residual [%]
O₂: 0.024, CO₂: 0.005
Results – Water droplets (12µm)

retrieved parameters

- a priori
- first guess
- a posteriori uncertainty
- maximum a posteriori

Pressure [hPa]
- 984.8 ± 3.3
- 981.0 (3.8)
- 1013.0
- 1013.0 (±30.9)

Surface pressure [hPa]
- 984.8 ± 3.3
- 981.0 (3.8)
- 1013.0
- 1013.0 (±30.9)

Cloud water path [g/m²]
- 1.0 ± 0.7
- 3.0 (-2.0)
- 10.0
- 5.0 (±10.0)

CO₂ [ppm]
- XCO₂: 86%
- XCO₂ [ppm]:
  - 393.6 ± 2.2
  - 395.6 (-2.0)
  - 376.8
  - 376.8 (±16.0)

Degree of freedom
- surf.pres.: 0.99, CO₂ profile: 1.45

RMS of noise [%]
- O₂: 0.054, CO₂: 0.042

RMS of residual [%]
- O₂: 0.031, CO₂: 0.005
Results – Sensitivity to micro physical cloud parameters

Water droplets (6µm)

XCO₂ [ppm]
- 397.4 (±2.3)
- 395.6 (1.8)
- 376.8
- 376.8 (±16.2)

uncertainty reduction
XCO₂: 86%

degree of freedom
surf.pres.: 0.99, CO₂ profile: 1.46

RMS of noise [%]
O₂: 0.050, CO₂: 0.041

RMS of residual [%]
O₂: 0.019, CO₂: 0.012