SO_2 and CO Retrievals from SCIAMACHY/GOME Measurements

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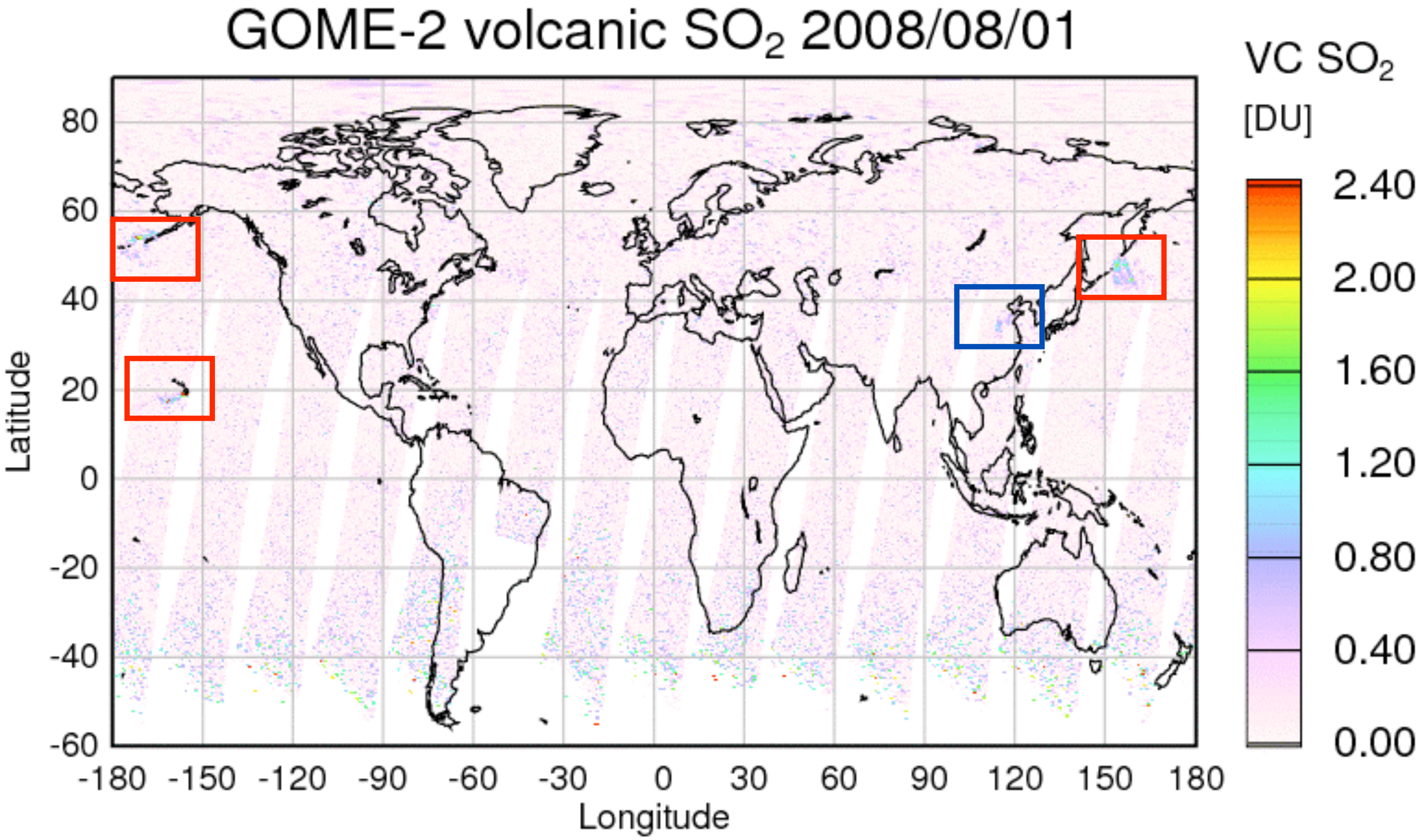
SCIAMACHY

SO_2: Example of IUP Bremen GOME-2



How is SO_2 observed with UV/vis Satellites?

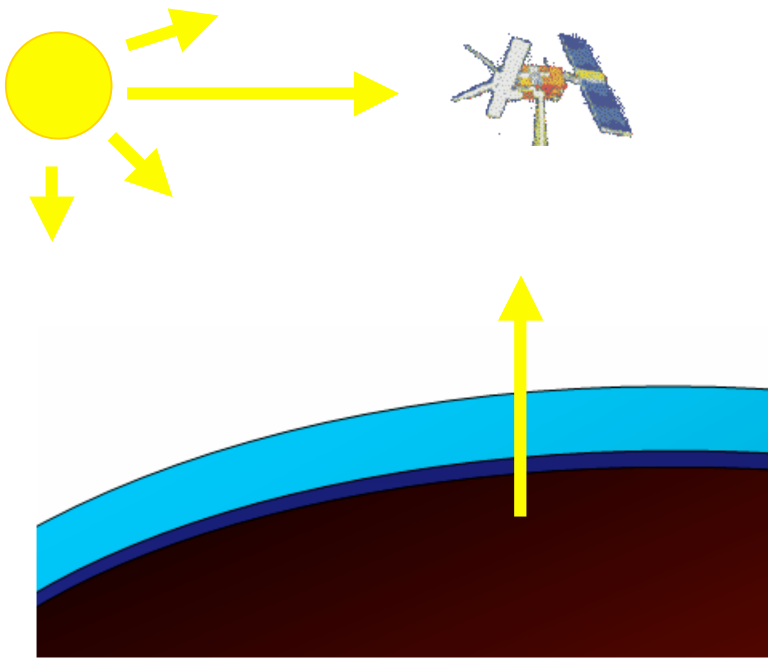
Basic Method:

- Absorption Spectroscopy
- Scattered / reflected sun light is light source
- UV-absorption bands of SO_2 (310 – 330 nm)
- Differential Optical Absorption Spectroscopy (DOAS) OR selected wavelengths to separate signatures of absorption and scattering

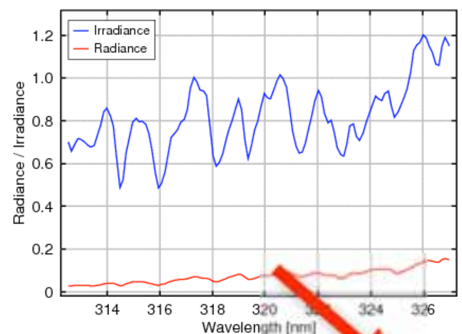
- Estimation of light path is key to accurate retrieval
- Sensitivity is often expressed as airmass factor

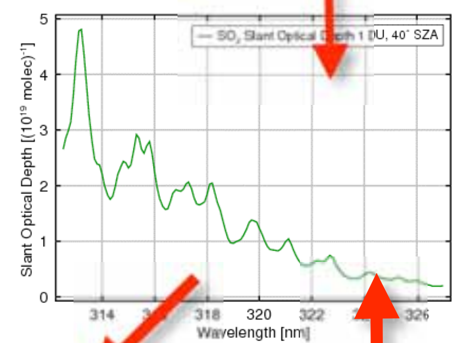
IUP Bremen SO_2 Retrieval Scheme

profile, albedo, aerosols, ...



SCIATRAN RTM (slant optical densities)





DOAS analysis

Iterate for SO_2 column

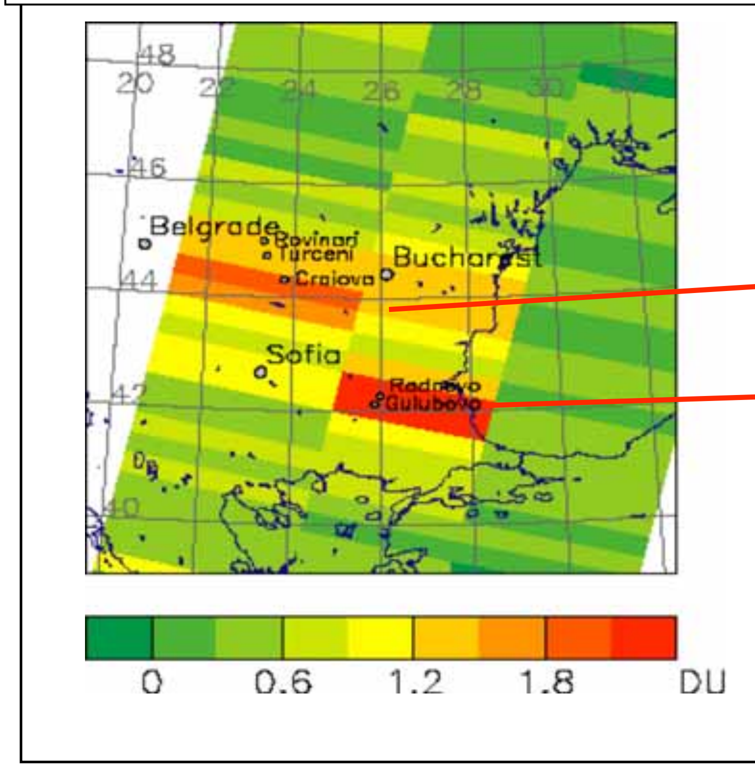
correction for latitude offsets

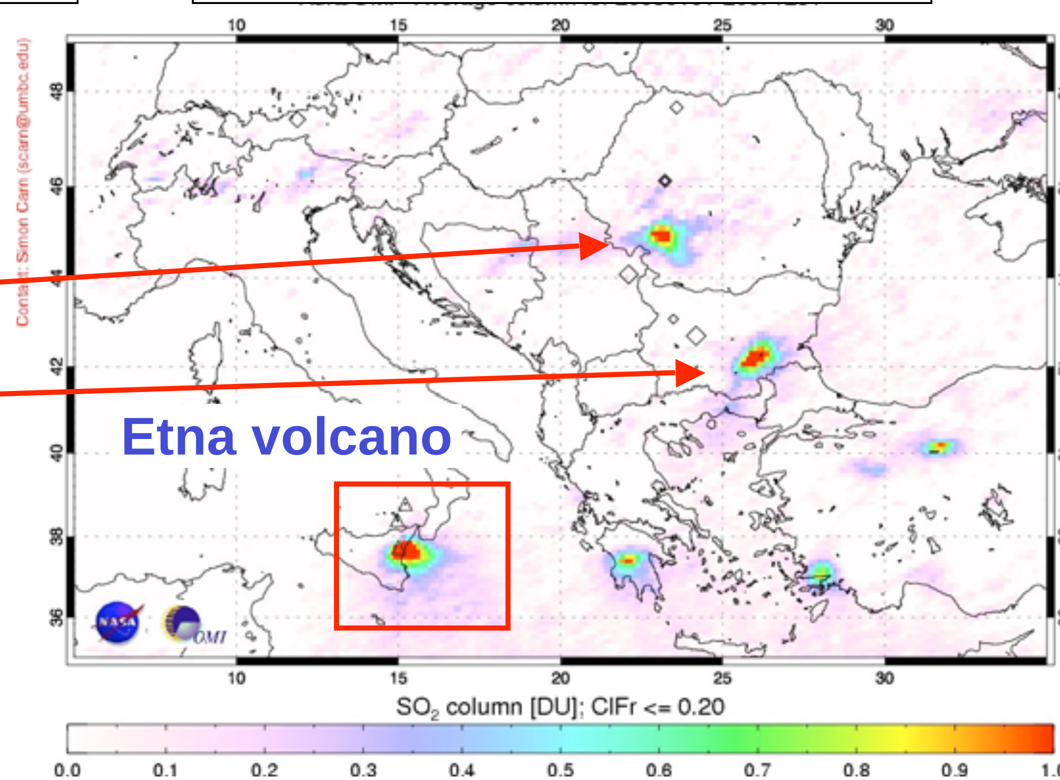
Tropospheric Vertical Column

Anthropogenic SO_2: power plants

GOME: 40km x 320km

OMI: 13km x 24km





SO_2 enhancements in the Balkan region first observed by GOME in Winter 1998 [Eisinger and Burrows, GRL 1998].

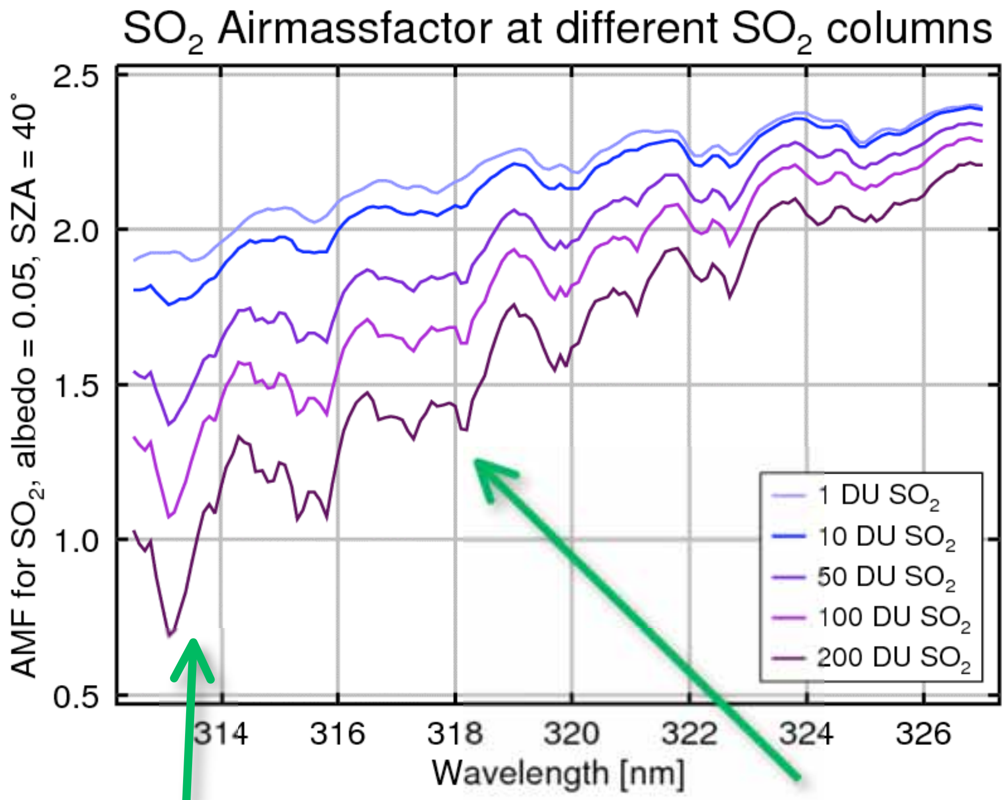
3 year average SO_2 enhancements detected by OMI over Eastern Europe and Turkey coincide with locations of power plants (Krotkov et al.)

What are the problems of SO_2 observations?

Challenges:

- Low signal for boundary layer applications
  => limited to high sun and large columns
- Spectral interference / offsets
  => spatial filtering <u>or</u> reference sector method applied
- Temperature dependence of SO_2 cross-section is significant but not well known
  => empirical corrections are applied to
- Uncertainty in vertical distribution leads to large uncertainties in columns retrieved
  => several scenarios evaluated and user chooses the most likely
- Aerosols and clouds have large and highly variable impact on light path
  => standard assumptions have to be made

Sensitivity: Dependence on SO_2 Column

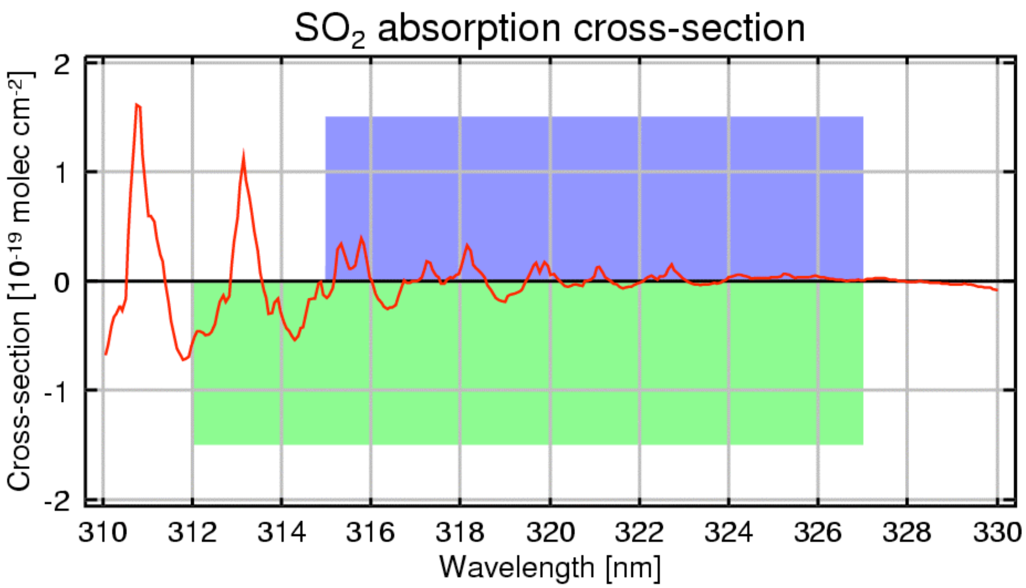


Small effect at longer wavelengths

Very large effect at short wavelengths

SO_2 absorption structures appear at large SO_2 column

SO_2 data analysis: Fit window selection



Fitting window Optimisation:

- as many lines as possible
- as large lines as possible
- as little interference as possible
- as much sensitivity to the lower troposphere as possible

UV bands seem attractive…

- More bands
- Larger depth

But

- O_3 interference
- loss of boundary layer sensitivity in the UV
- loss of intensity in the UV
- decreased sensitivity in UV

Current choice IUP:

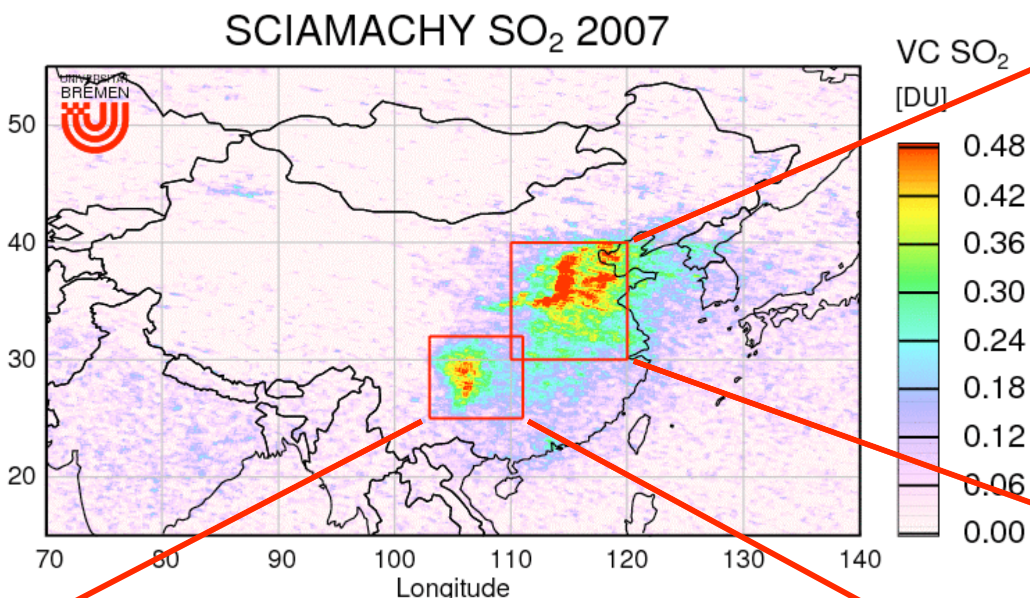
- volcanic SO_2: 312.5 – 327 nm

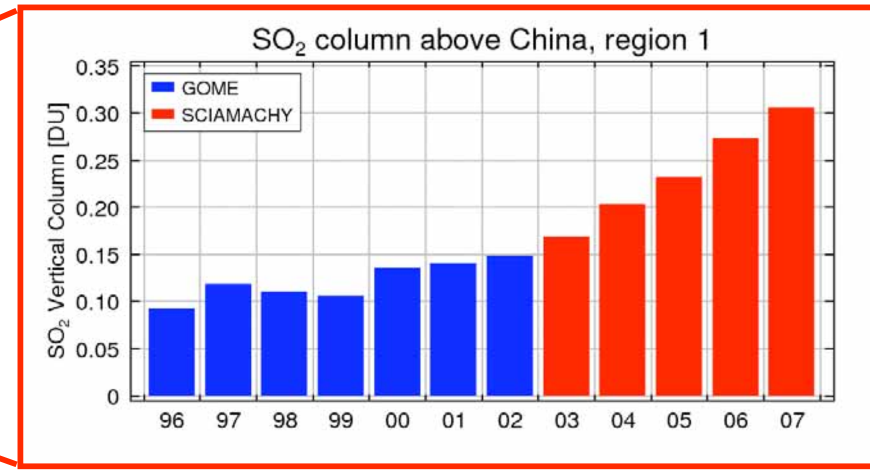
- BL SO_2: 315.0 – 327 nm

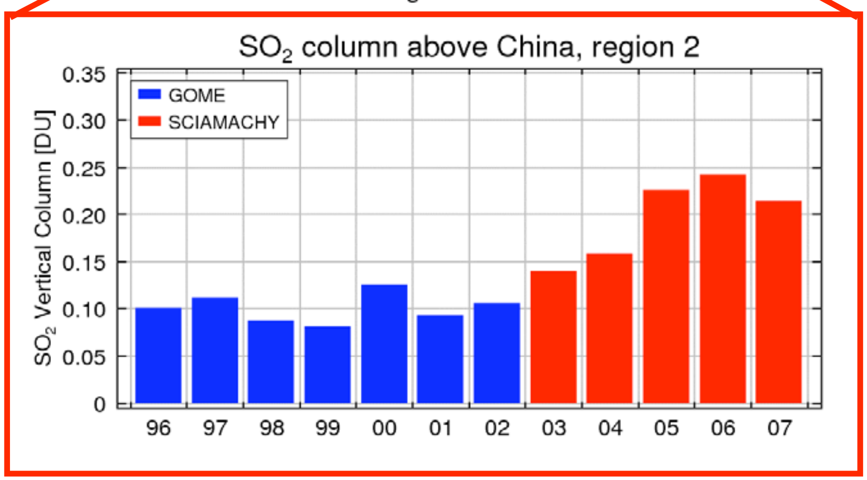
Rough SO_2 Error Budget

- Volcanic SO_2:
  - Noise for individual pixels: < 1 DU
  - Uncertainty from SO_2 profile: 20%
  - Uncertainty from saturation effects at large SO_2 column: 30%
  - Uncertainty from cloud effects: highly variable
- Pollution/BL SO_2:
  - Noise for individual pixels: < 4 DU
  - Uncertainty from SO_2 profile: 10 - 20%
  - Uncertainty from surface albedo/aerosol effects: 30%
  - Uncertainty from cloud effects: highly variable

SCIAMACHY measurements of SO_2 from Pollution



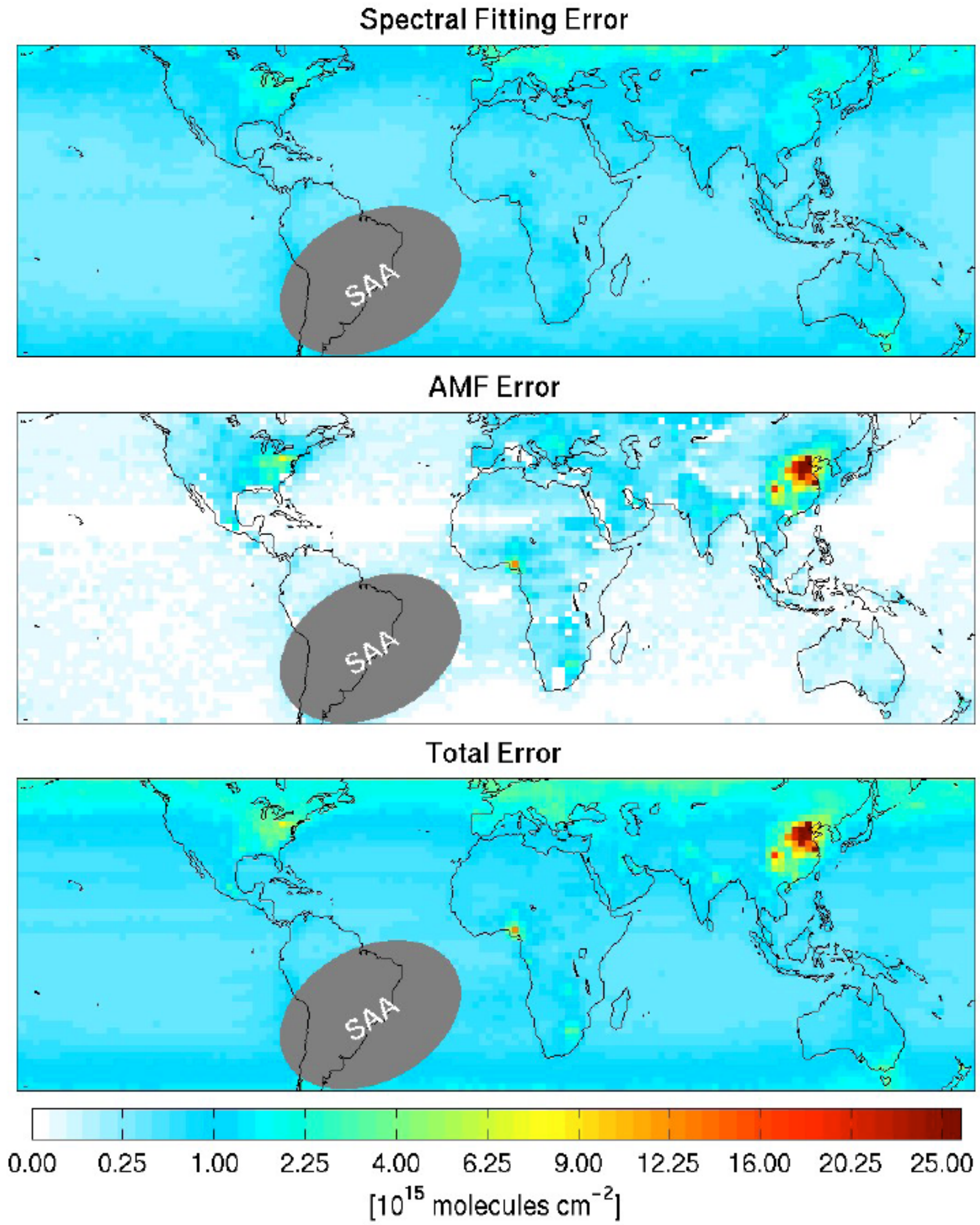




- Using a retrieval at longer wavelengths, tropospheric SO_2 pollution can be observed
- The largest signals are over China
- There is an increeasing trend over the last decase with hints of a turn around

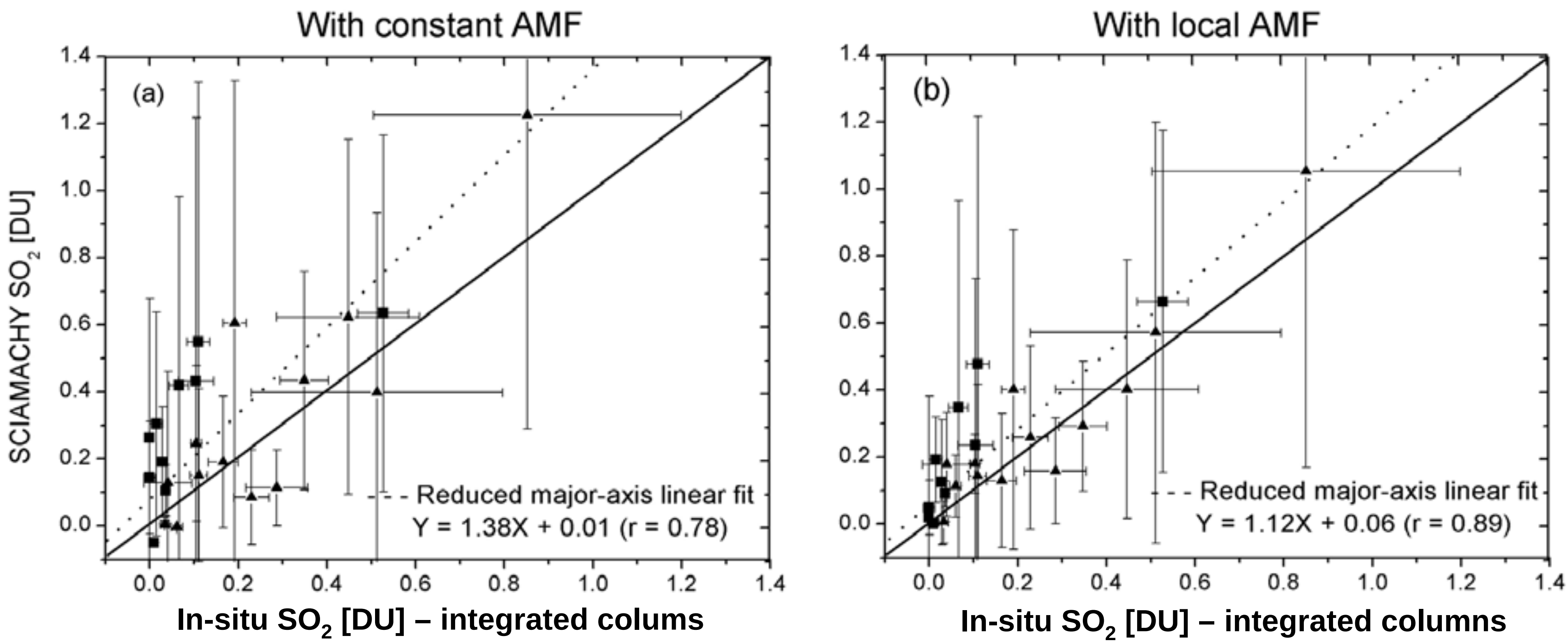
Details: SO_2 Error Budgets Pollution (Annual Mean)

- SC error:
  - Fitting:~2×10^{15} molec/ cm-2 over polluted areas
  - Offset: 0.4-1.2×10^{15} molecules cm-2
- AMF: 15 - 30% (clear sky)
  - Surface albedo: 10-20%
  - SO_2 profile: 10%
  - Aerosol: 10 – 20%
  - Clouds: 10 – 100%



Chulkuy Lee et al., JGR, 2009

Comparison with In-Situ SO_2 during INTEX-A/B (US)



- INTEX-A (triangles): North America and Atlantic, Summer 2004)
- INTEX-B (squares): US and Mexico, Spring 2006
- airborne in-situ data shows good correlation and quantitative agreement, especially when local AMF is taken into account

Chulkuy Lee et al., JGR, 2009

What is needed for better SO_2 observations?

- The increasing number of SO_2 measurements from space will help to better constrain SO_2 emissions from both volcanic but also anthropogenic sources
- Validation remains a challenge

SO_2 wish list:

- High UV throughput of instrument to reduce noise
- High spatial resolution of instrument to decrease impact of clouds and better resolve local hot-spots
- Colocated aerosol and cloud measurements, if possible with vertical resolution to correct for aerosol effects
- High temporal resolution surface spectral reflectance data at the spatial resolution of the SO_2 measurements to correct for albedo effects
- Combination of UV and IR measurements to assess the vertical distribution of SO_2

UV/vis Satellite Instruments for SO_2 retrieval

Instrument	Time	Spatial Resolution	Coverage
TOMS	1979 – 2006	39 x 39 km^2	1.5 days
GOME	07.1995 – 06.2003	40 x 320 km^2	3 days
SCIAMACHY	08.2002 – today	30 x 60 km^2	6 days
OMI	08.2004 – today	> 13 x 24 km^2	1 day
GOME-2 (+ 2 more)	01.2007 - today	40 x 80 km^2 40 x 40 km^2	1.5 days
OMPS NPP/NPOESS	*> 2010*	*40 x 40 km^2*	*1 day*
Sentinel 5 UVNS and 5Precursor	*> 2013/14*	*> 10 x 10 km^2*	*1 day*
Sentinel 4 UVN On MTG	*> 2017*	*< 8 km x 8 km*	*Europe, 1h*

SCIAMACHY Carbon Monoxide (CO)

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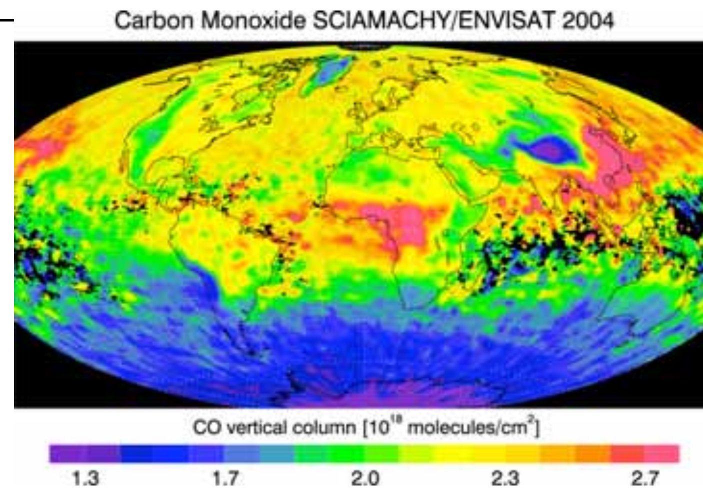
Overview CO

SCIAMACHY Carbon Monoxide:



- **SCIAMACHY nadir spectra contain CO total column information from weak CO overtone band around 2300 nm**

- **Horizontal resolution: 30 x 120 km²**

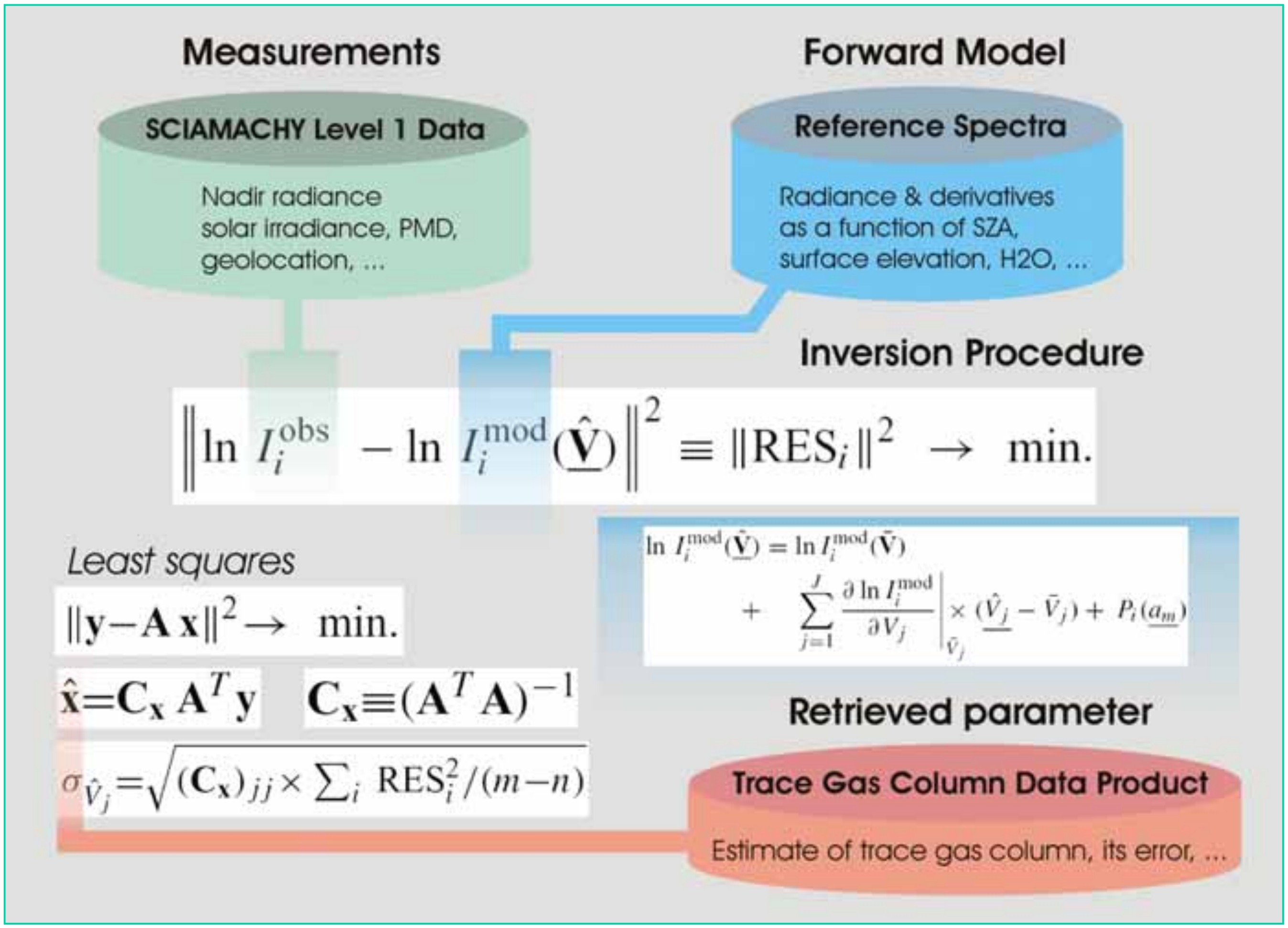
- **pre-launch precision estimate: 10% (depending on albedo)**

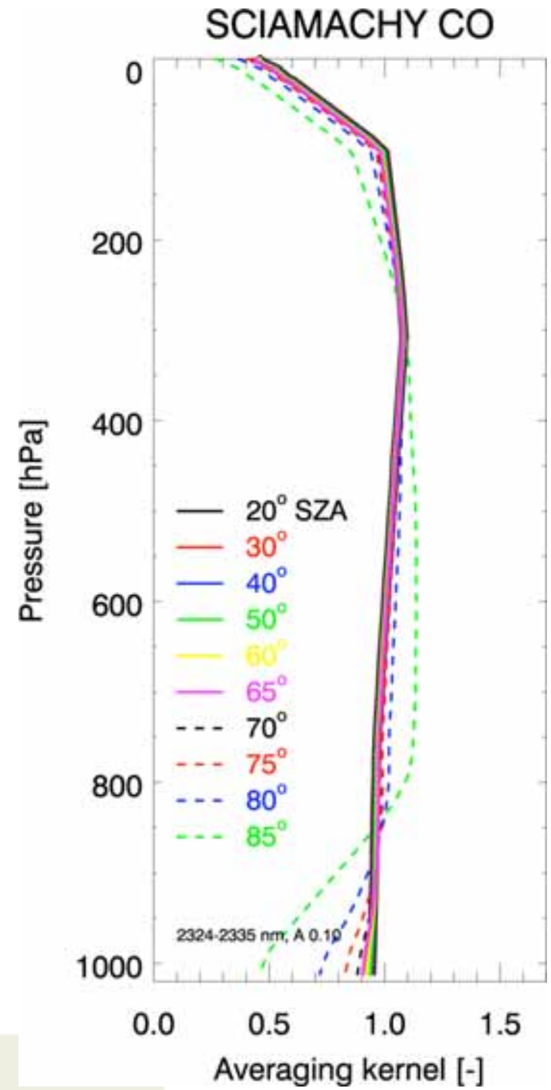
- **Several groups have developed somewhat different algorithms to retrieve this information, e.g.,**

  - **WFM-DOAS: Buchwitz et al., ACP, 2004, Buchwitz et al., ACP, 2007**
  - **IMAP-DOAS: Frankenberg et al., ACP, 2005**
  - **IMLM: Gloudemans et al., GRL, 2006, ACP 2009**
  - **BIRRA: Operational algorithm under development at DLR**

- **Examples are shown in the following for WFM-DOAS (version 0.6)**

WFM-DOAS retrieval algorithm





Buchwitz et al., JGR, 2000

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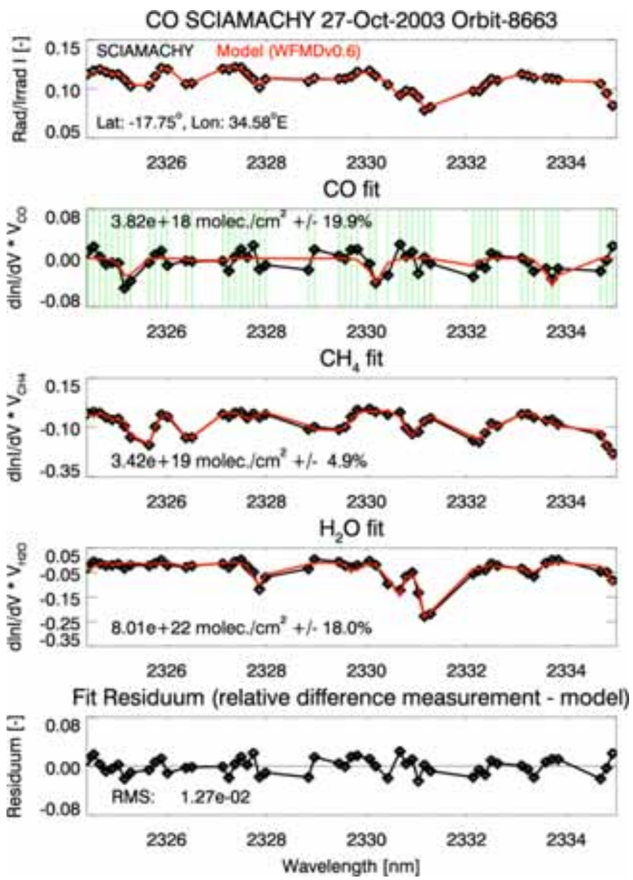
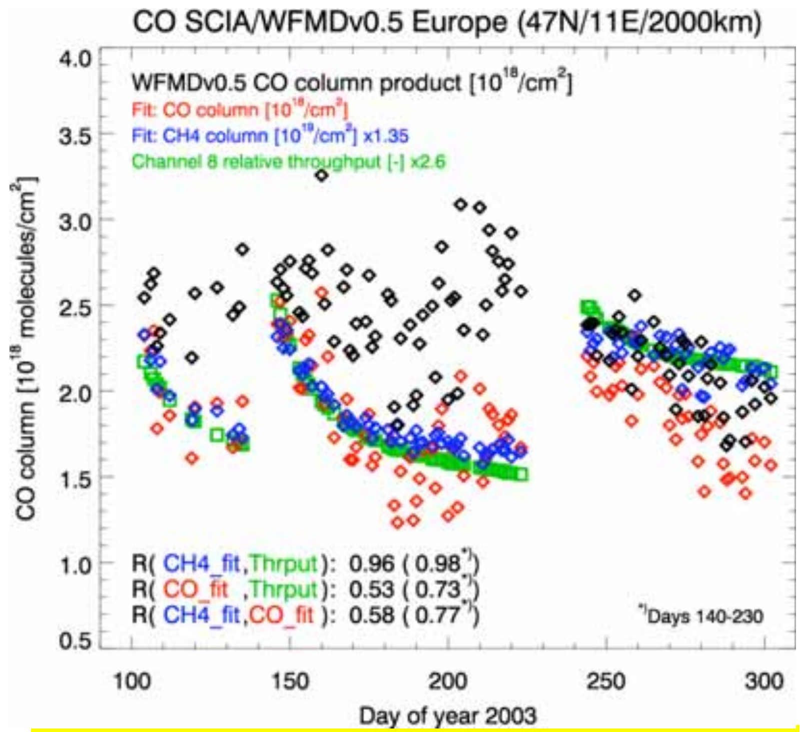
SCIAMACHY & CO: Challenges & „solutions“

dead&bad detector pixel



Approach: Carefully selected pixel mask & fitting window

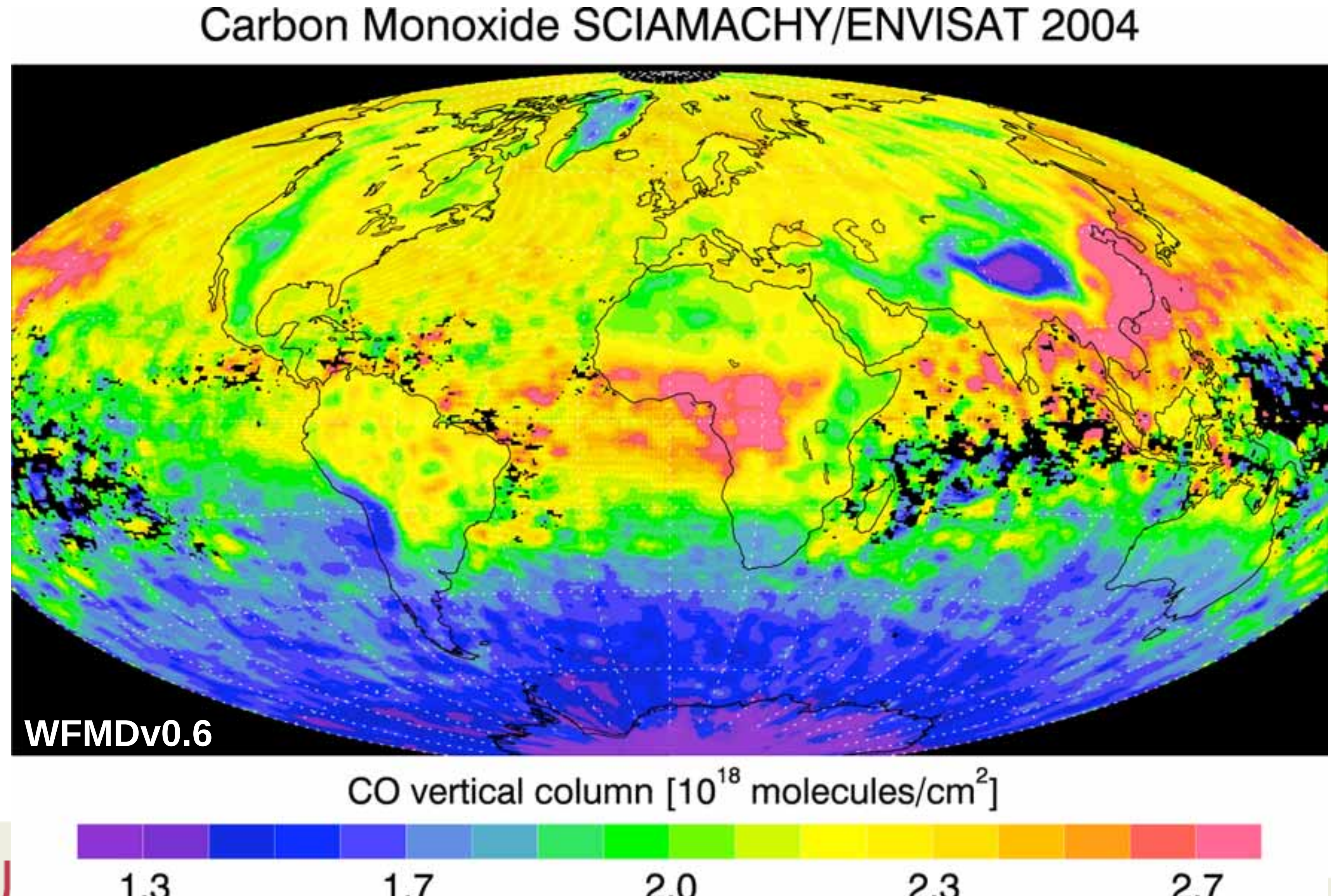
Variable ice-layer on cold detectors



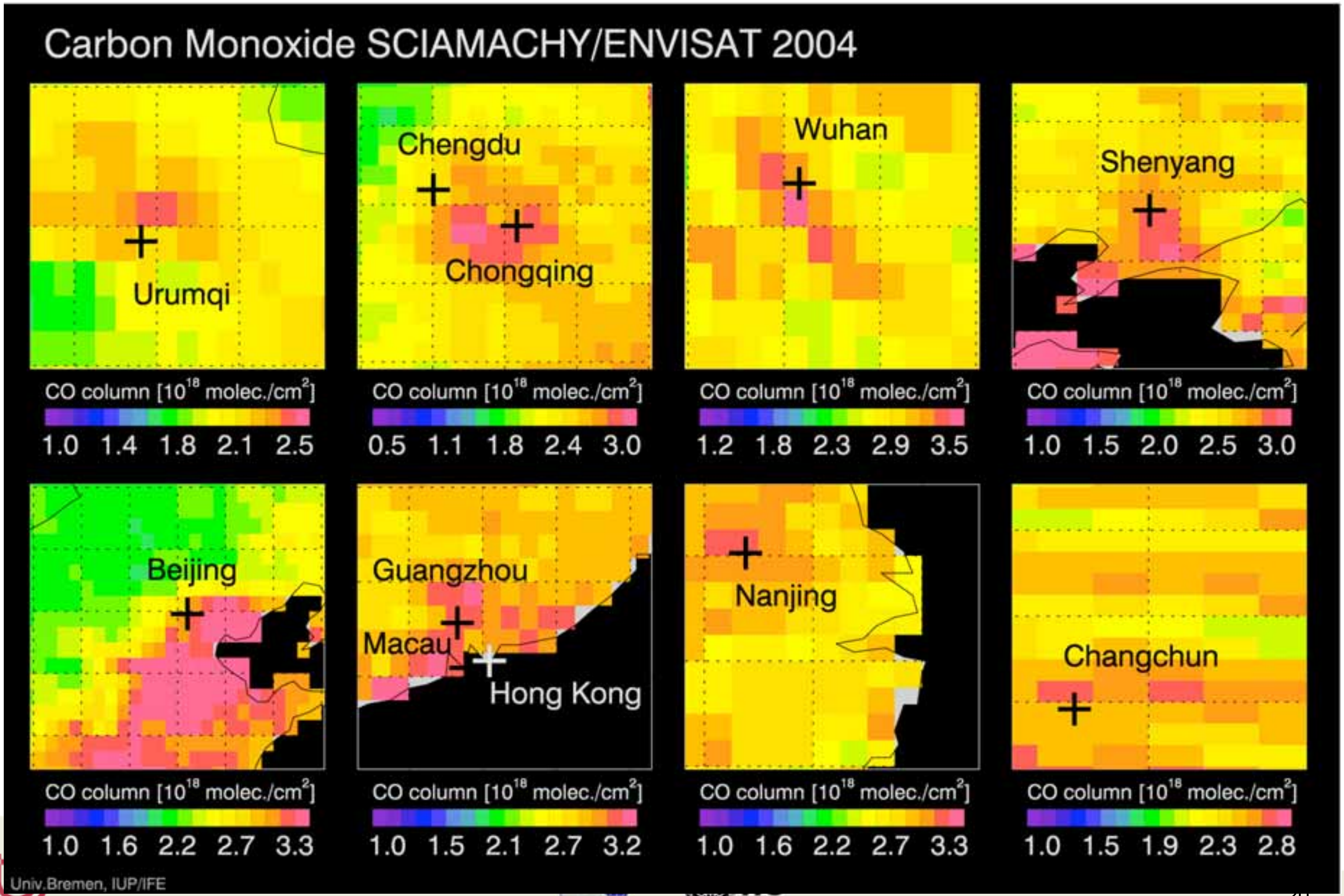
Approach: Ratio with CH4 from same fitting window (also used for residual cloud correction)

Buchwitz et al., ACP, 2006, 2007

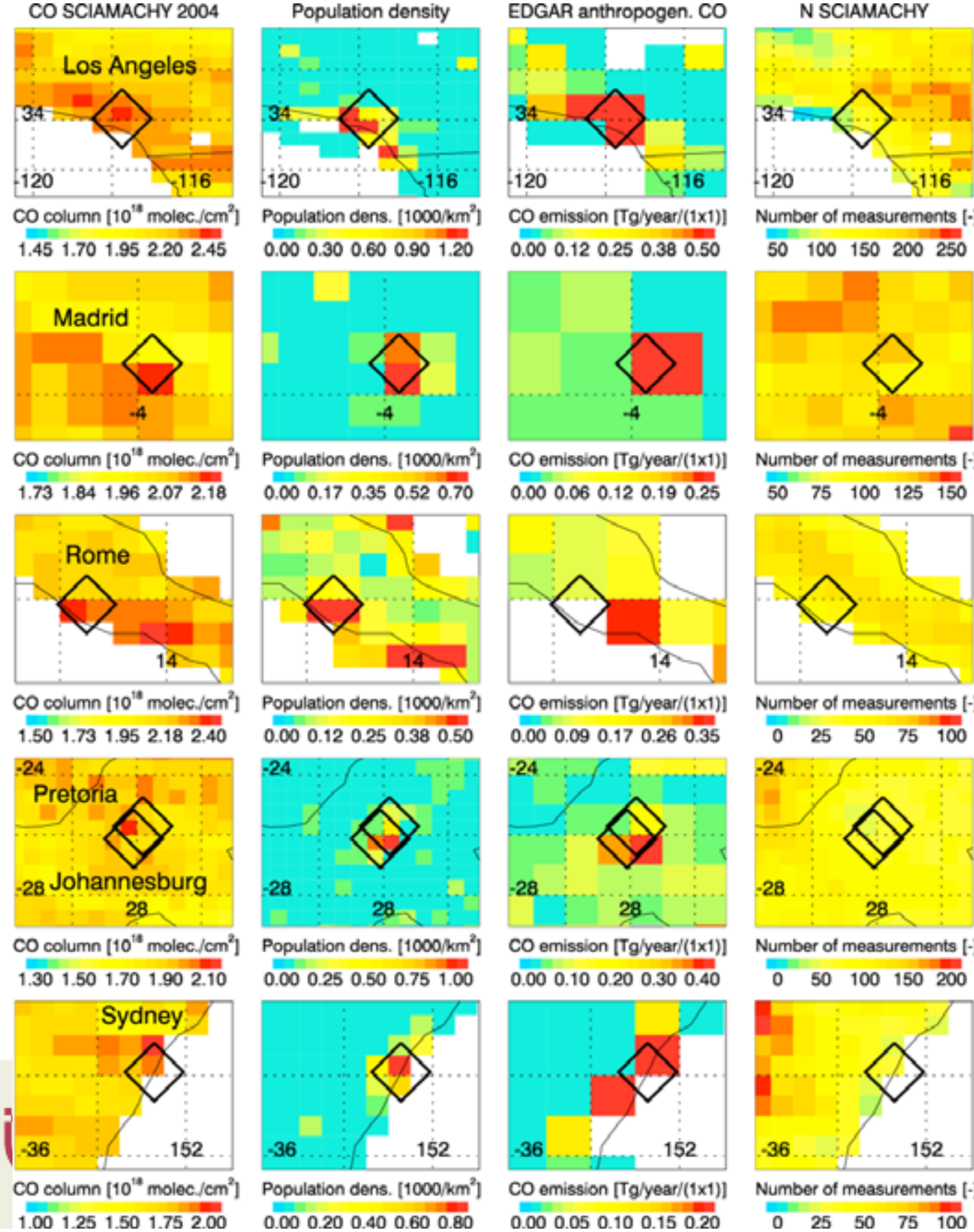
SCIAMACHY CO: Global year 2004 average



SCIAMACHY CO: Cities in China



SCIAMACHY CO: Cities (cont.)



Findings consistent with expectations:

~100 retrievals have to be averaged to detect a regional enhancement of the column of a few percent

Validation by comparison with g/b FTS

SCIA_CO_WFMDv0.6 **SCIA_CO_WFMDv0.5** **FTS**

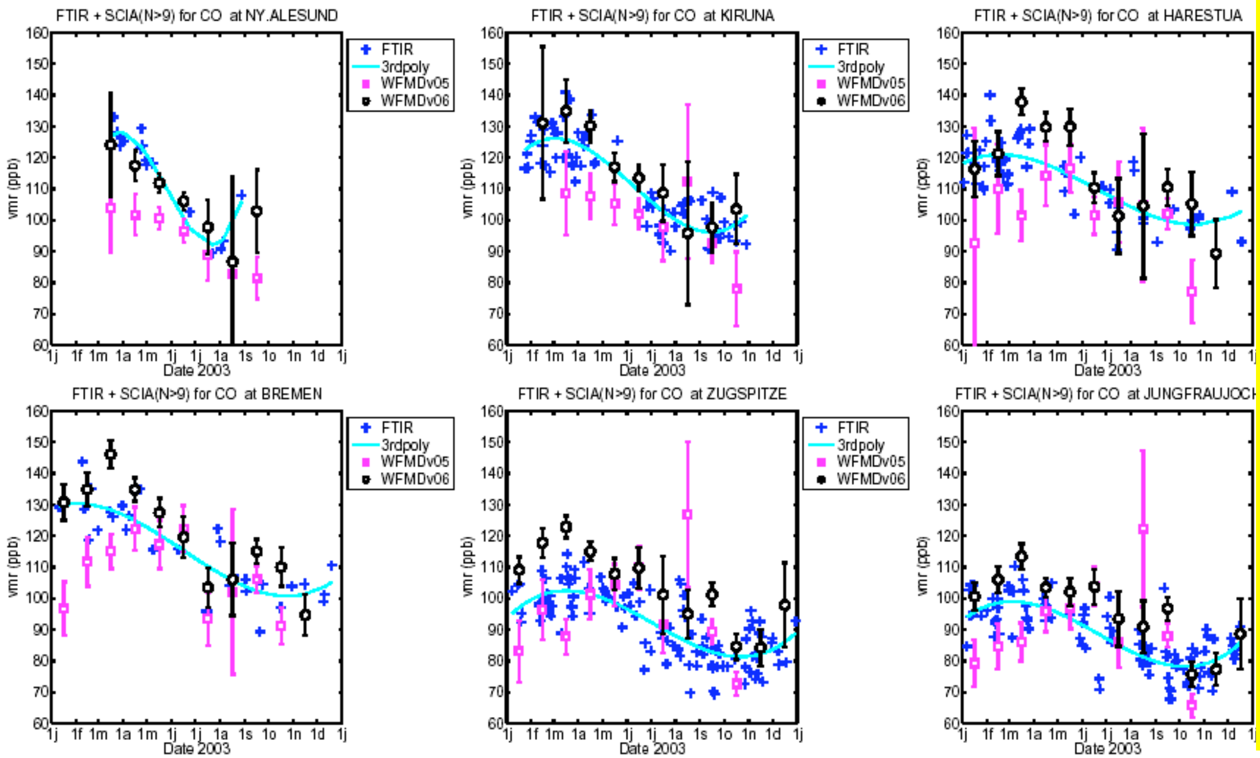


Table 1. Spatial coordinates of the ground-based FTIR stations.

Station	Lat N	Lon E	Altitude(m)
NY.ALESUND	78.91	11.88	20
KIRUNA	67.84	20.41	419
HARESTUA	60.22	10.75	580
BREMEN	53.11	8.85	27
ZUGSPITZE	47.42	10.98	2964
JUNGFRAUJOCH	46.55	7.98	3580
IZAÑA	28.30	-16.48	2367

CO	v0.6 yr 2003	v0.6 yr 2004
LG Bias	9.17 ± 0.58	0.49 ± 0.67
LG σscat	20.5	21.0
LG R	0.86	0.83
LG N	29553	20132
SG Bias	7.94 ± 0.88	0.24 ± 1.01
SG σscat	22.9	23.5
SG R	0.83	0.76
SG N	13639	9141

SCIA/WFMDv0.6 - FTS	2003	2004
Bias	+9.2%	+0.5%
Scatter	+/-20%	+/-20%

Dils et al., ACVE-3, 2006

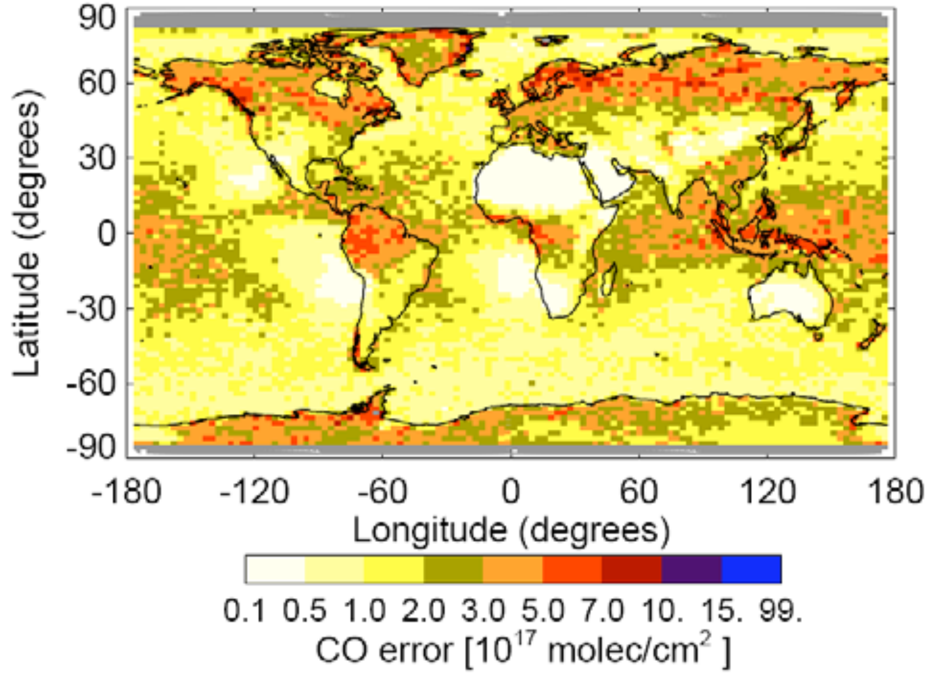
SCIAMACHY CO over low clouds over oceans

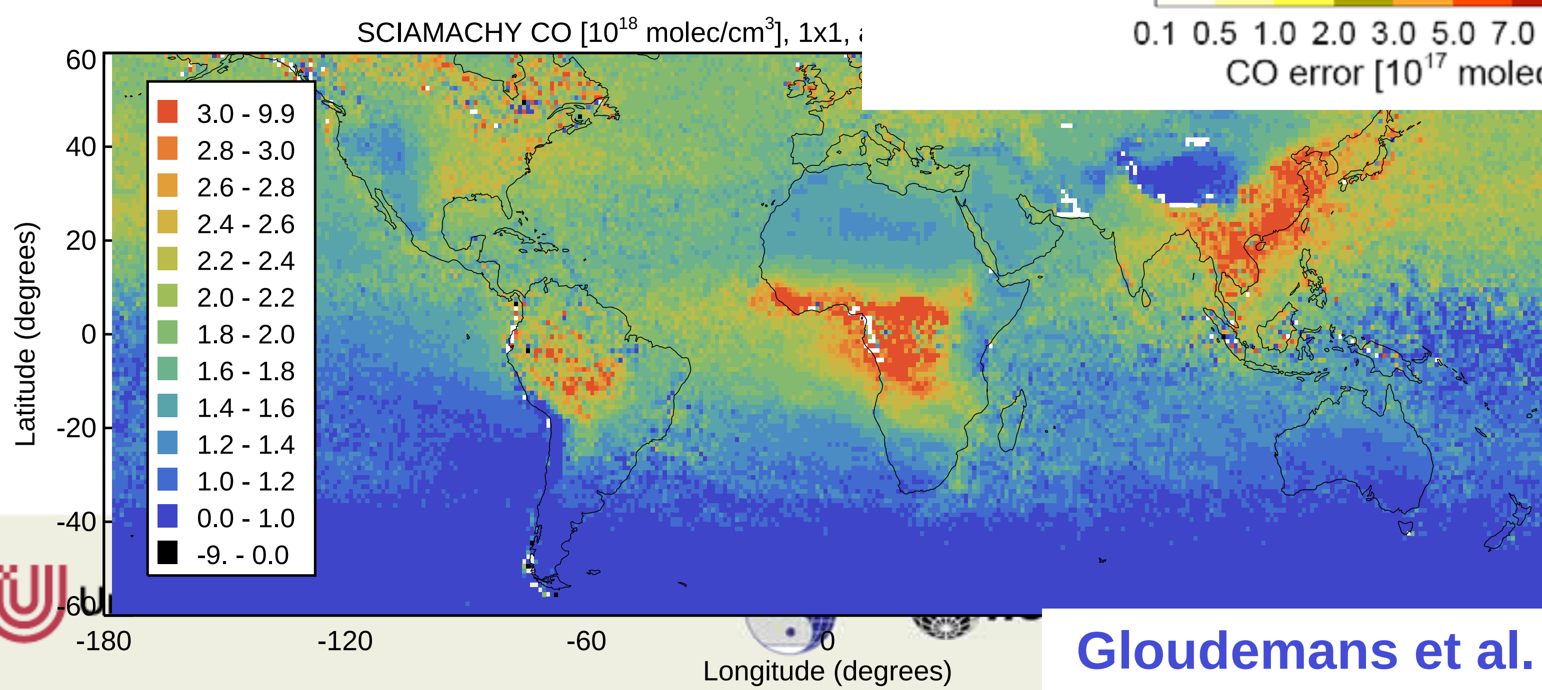
- mean SCIA CO columns above low clouds + TM4 below cloud = CO total column

-Clouds are bright ➔ sufficient signal to noise

- Simultaneously measured CH4 column: good proxy for cloud top height.

- only use low clouds





Gloudemans et al. ACP, 2009

Assimilation of SCIAMACHY total column CO observations: Global and regional analysis of data impact

Andrew Tangborn,[1,2] Ivanka Stajner,[1,3] Michael Buchwitz,[4] Iryna Khlystova,[4] Steven Pawson,[1] John Burrows,[4,5] Rynda Hudman,[6,7] and Philippe Nedelec[8]

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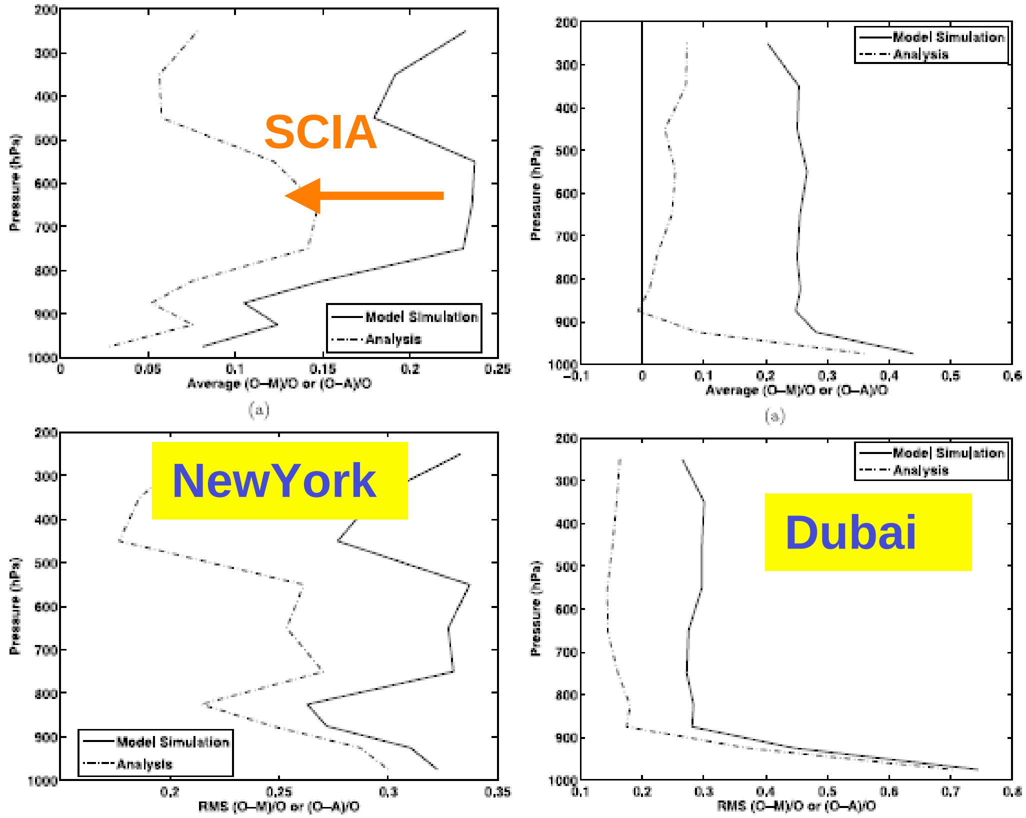
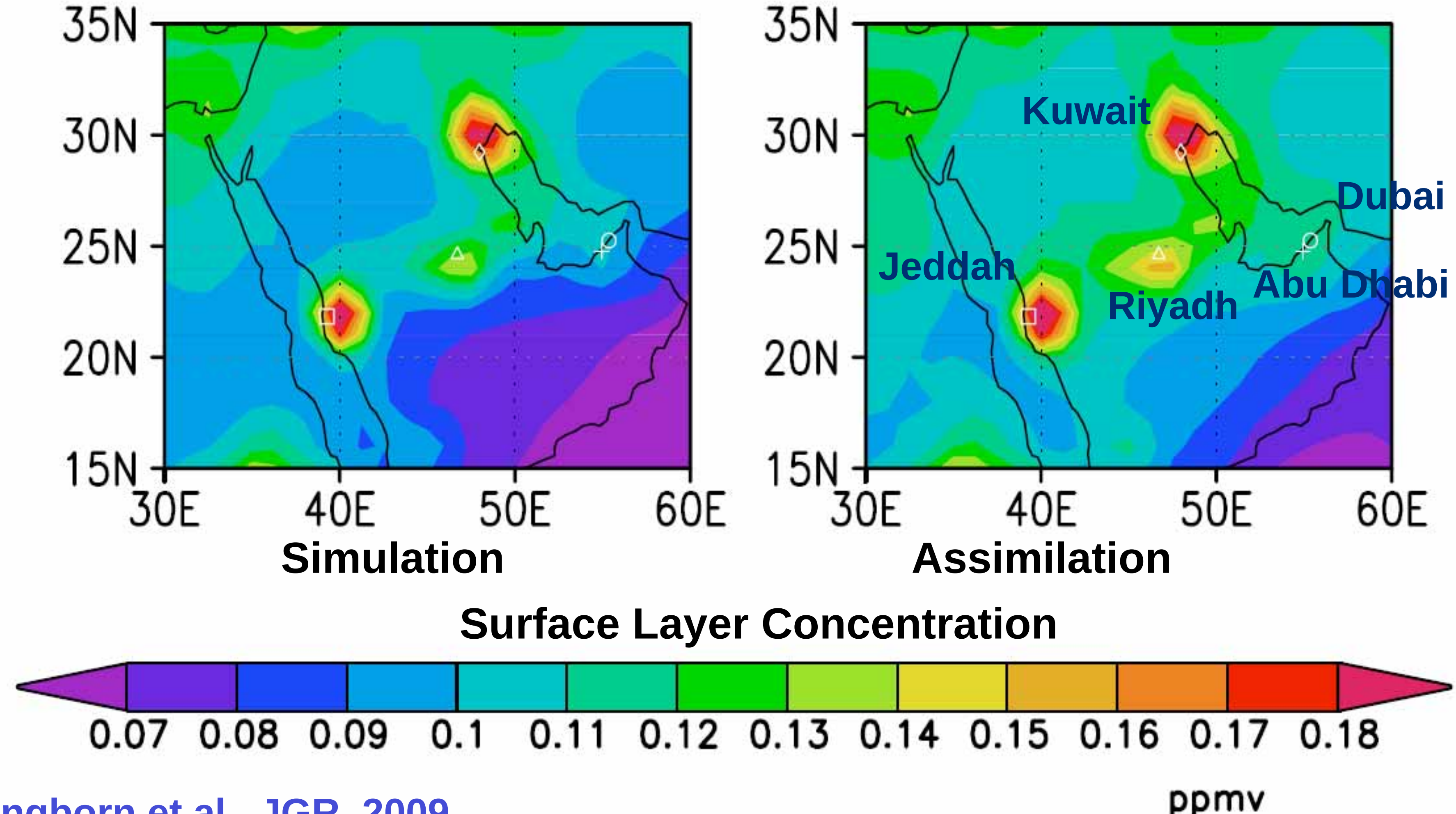
NASA-GSFC-GMAO model with (A) & without (M) SCIA CO versus MOZAIC CO (O)



Tangborn et al., JGR, 2009

First assimilation of SCIAMACHY CO

- Usage of SCIAMACHY CO data for september and October 2004 improves quantification of sources in Near East significantly
- Factor 2 increase in CO in Dubai from 1998 (inventory) to 2004 (assim.)



Tangborn et al., JGR, 2009

SCIAMACHY CO: Summary

- **SCIAMACHY has demonstrated for the first time CO column retrieval from space using reflected solar radiation at 2.3 µm**
    - Interhemispheric gradient, seasonal cycle, elevated CO over major (eg biomass burning) and minor (eg cities) source regions, source inversion ...
- **Precision: ~ 20% (albedo dependent)**
- **Accuracy: Regionally averaged columns at approx. monthly resolution show biases of approx. 10% relative to g/b FTS and MOPITT**
- **Operational CO product from SCIAMACHY expected in summer/autum 2009 (ESA)**
- **Data set can continued after ENVISAT with Sentinel 5P (2013/14-) & 5 (2020-)**
    - Smaller ground pixels (less cloud issues, more data), better detectors (higher S/N, less dead pixel), hopefully no ice layer issues, ...