→ ADVANCED ATMOSPHERIC TRAINING COURSE 2014

Greenhouse gas retrievals from satellite measurements: Why and how?

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Overview Talks 1 & 2

Greenhouse gas observations from space

1. Why and how ?

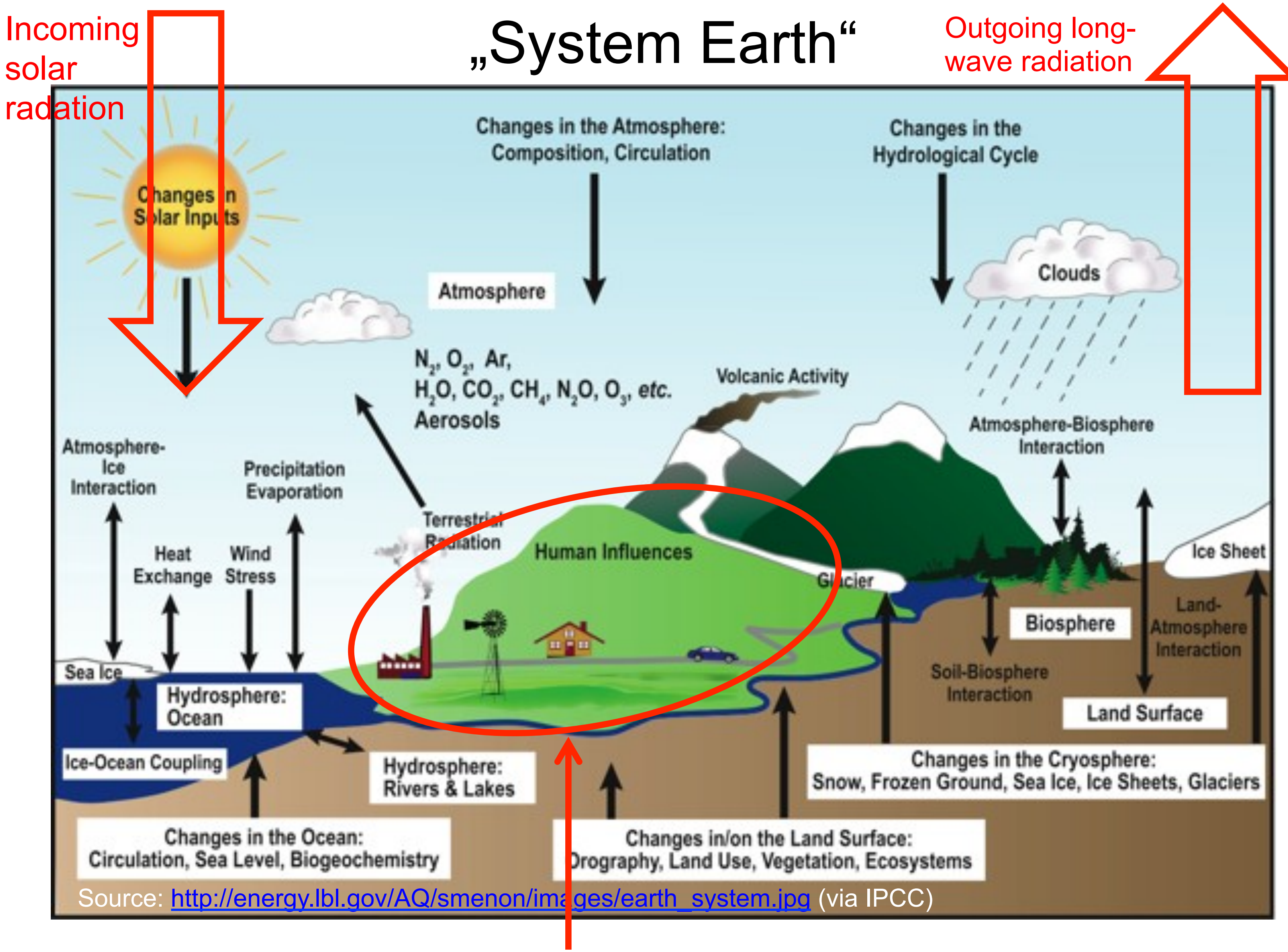
2. Key findings from 10 years of CO_2 and CH_4 satellite observations

Overview Talks 1

Greenhouse gas observations from space: Why and how?

- **Why ?**
  - … including at least a little bit of the most relevant background information …
- **How ?**
  - From satellite radiances -> atmospheric GHG concentrations -> GHG surface fluxes (sources & sinks)

„System Earth“



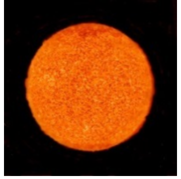
Source: http://energy.lbl.gov/AQ/smenon/images/earth_system.jpg (via IPCC)

A complex system with many positive and negative feedback cycles.

Large and increasing human influences

We are living in a new geological epoch (TBC), the

„Anthropocene“ (Crutzen, 2000)



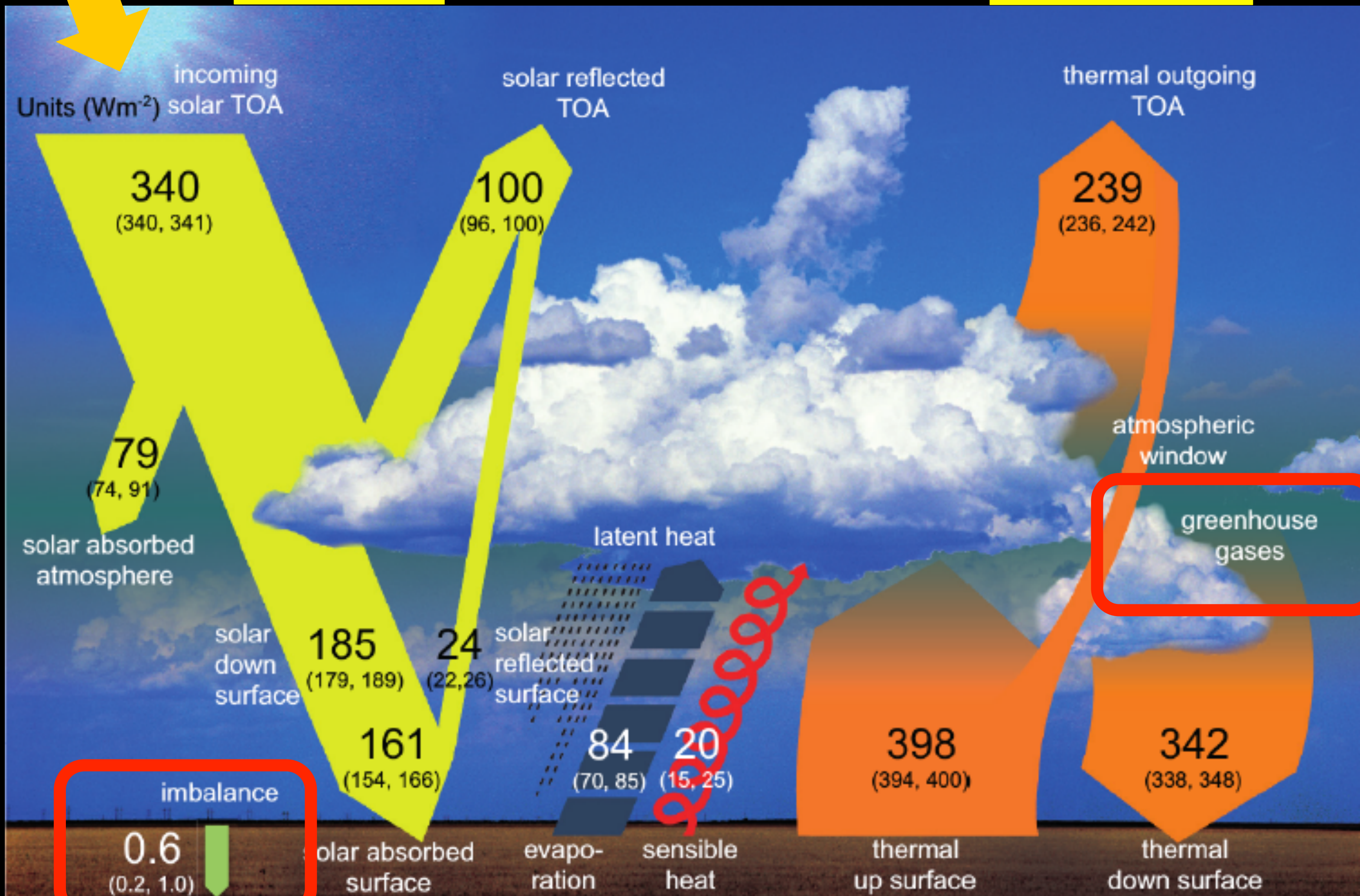
$1370\ W/m^2$

„Solar constant“

Energy fluxes & Greenhouse Effect

$240\ W/m^2$

$240\ W/m^2$?

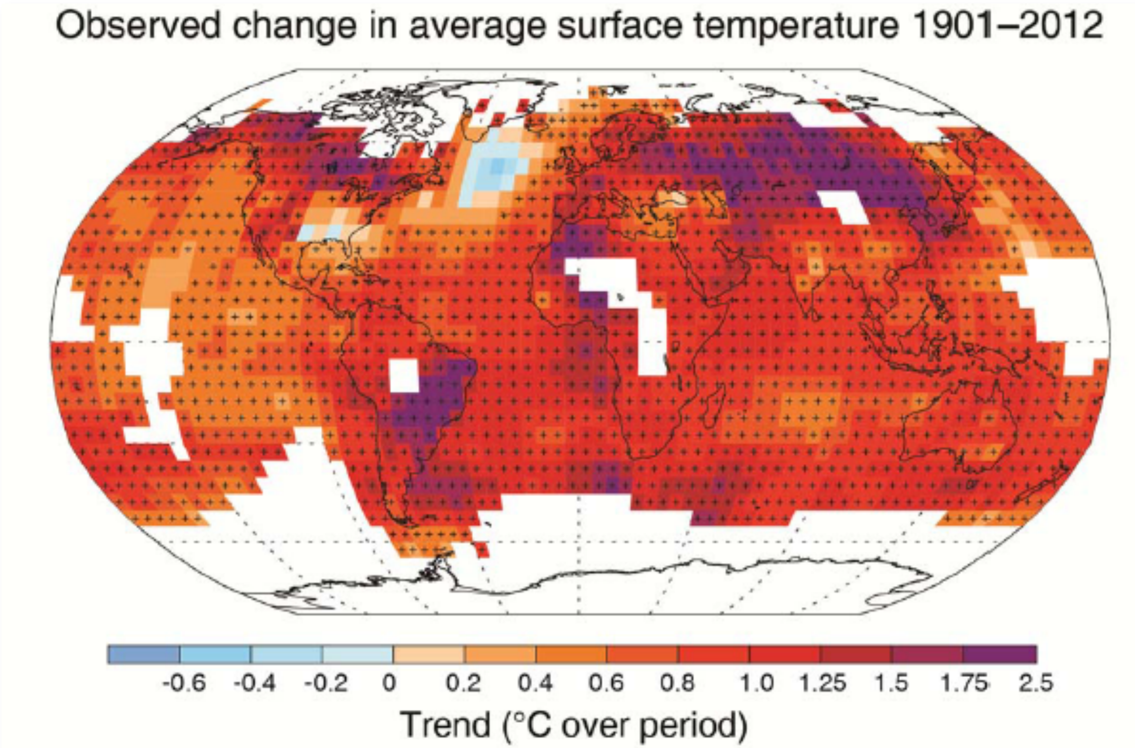


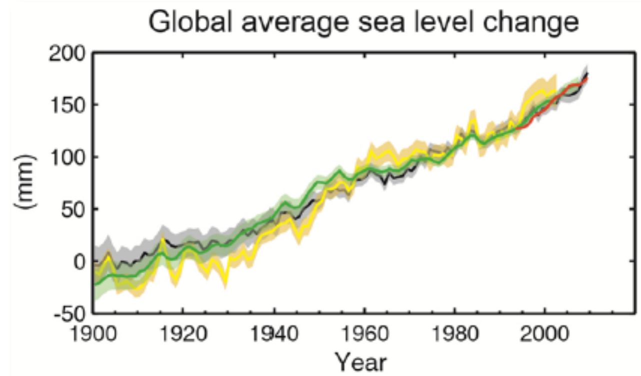
H_2O, CO_2, CH_4, …

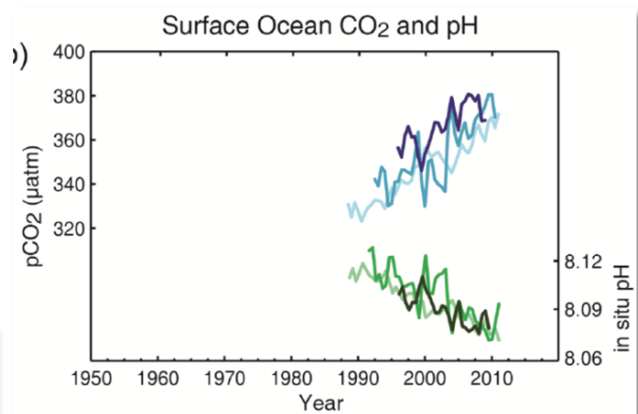
IPCC, AR5-WGI, 2013

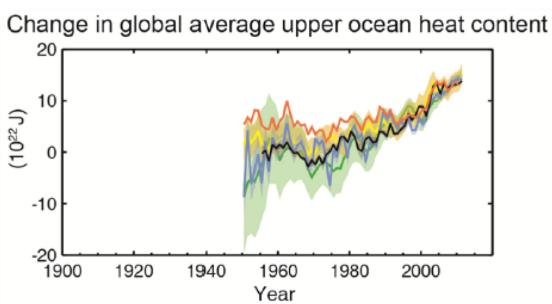
Climate Change: Observations

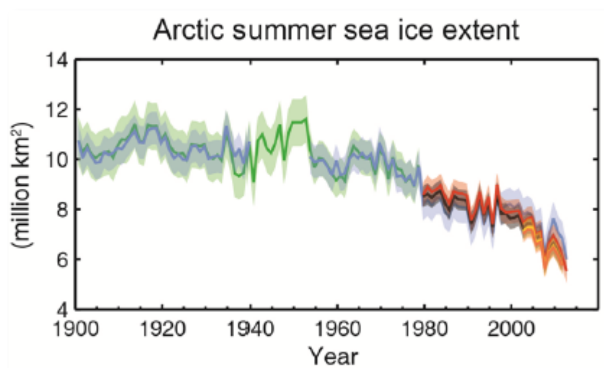
Mean temperature increase (1880-2012): +0.85 [0.65 - 1.06] °C







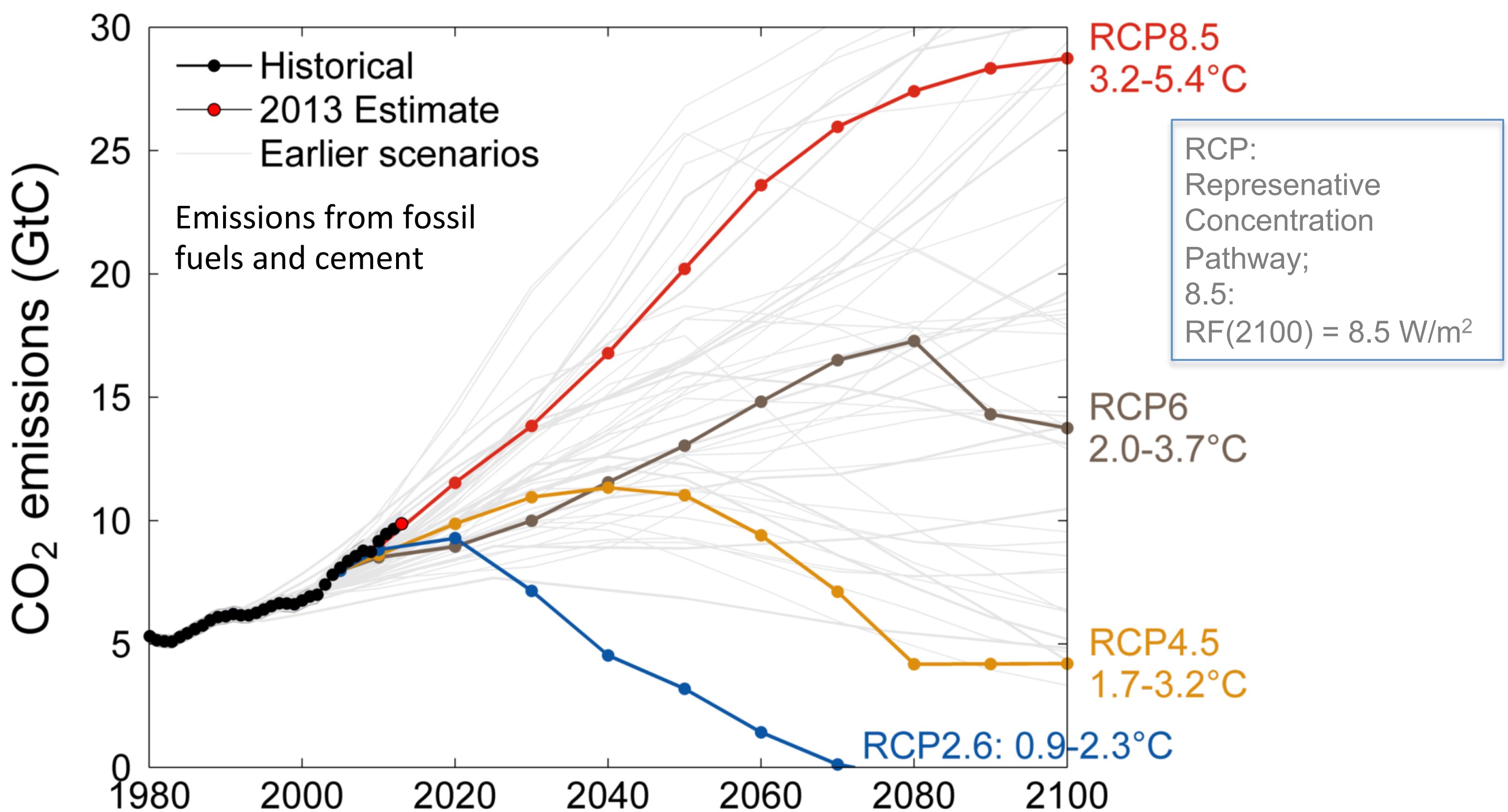




Source: IPCC 2013, AR5, Approved „Summary for Policy Makers“

Observed Emissions and Emissions Scenarios

Emissions are on track for 3.2–5.4ºC "likely" increase in temperature above pre-industrial
Large and sustained mitigation is required to keep below 2ºC

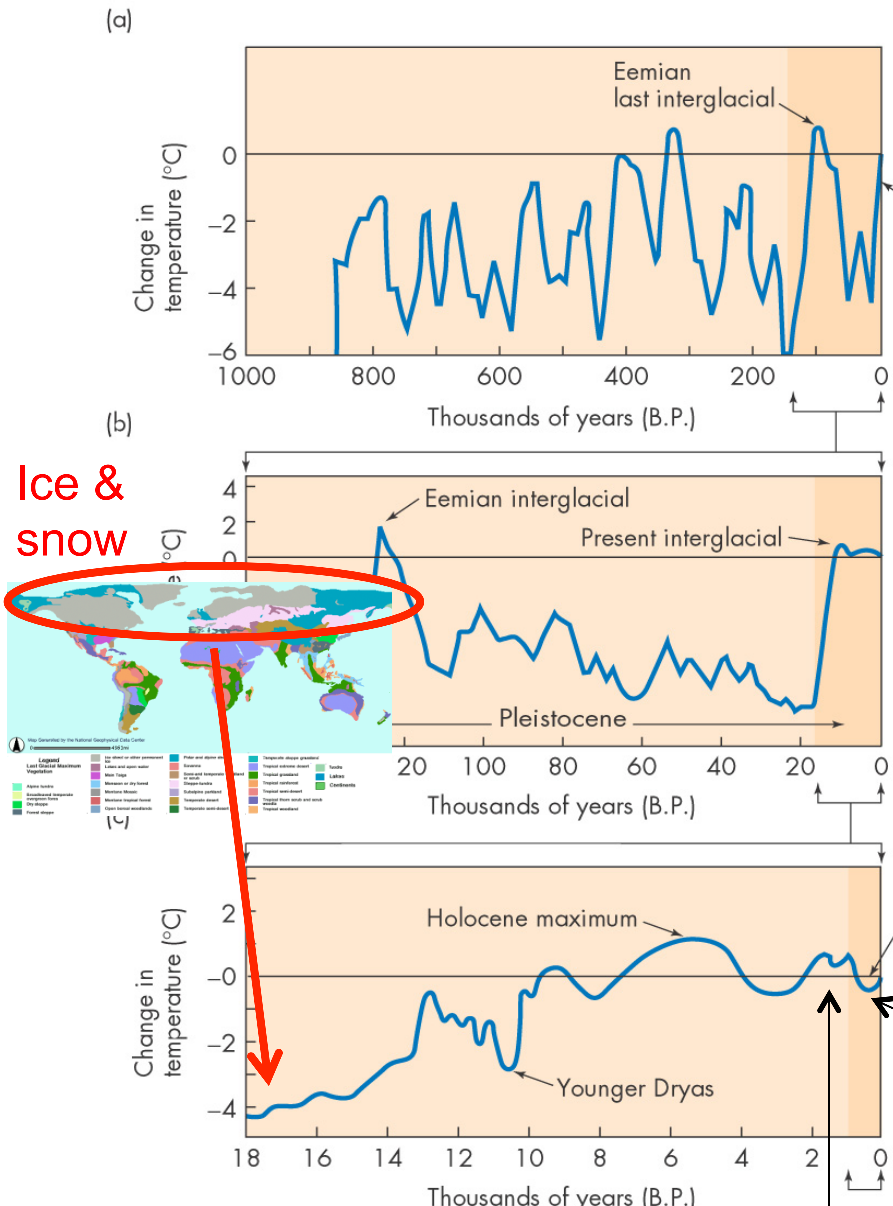


Linear interpolation is used between individual data points

Source: [Peters et al. 2012a](); [CDIAC Data](); [Global Carbon Project 2013]()

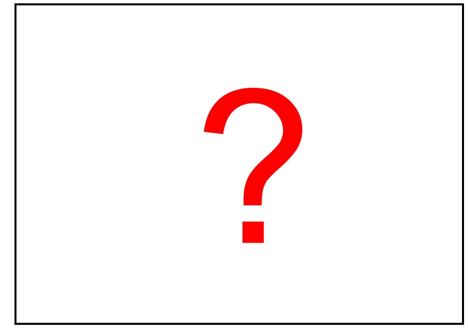
Why bother ? Just a few degrees more !

Ice &
snow



Major crop failures northern Europe, UK, …, „Great Famine“ ~1300

Medieval warm period (Vikings in Greenland with cattle & sheep, etc.)



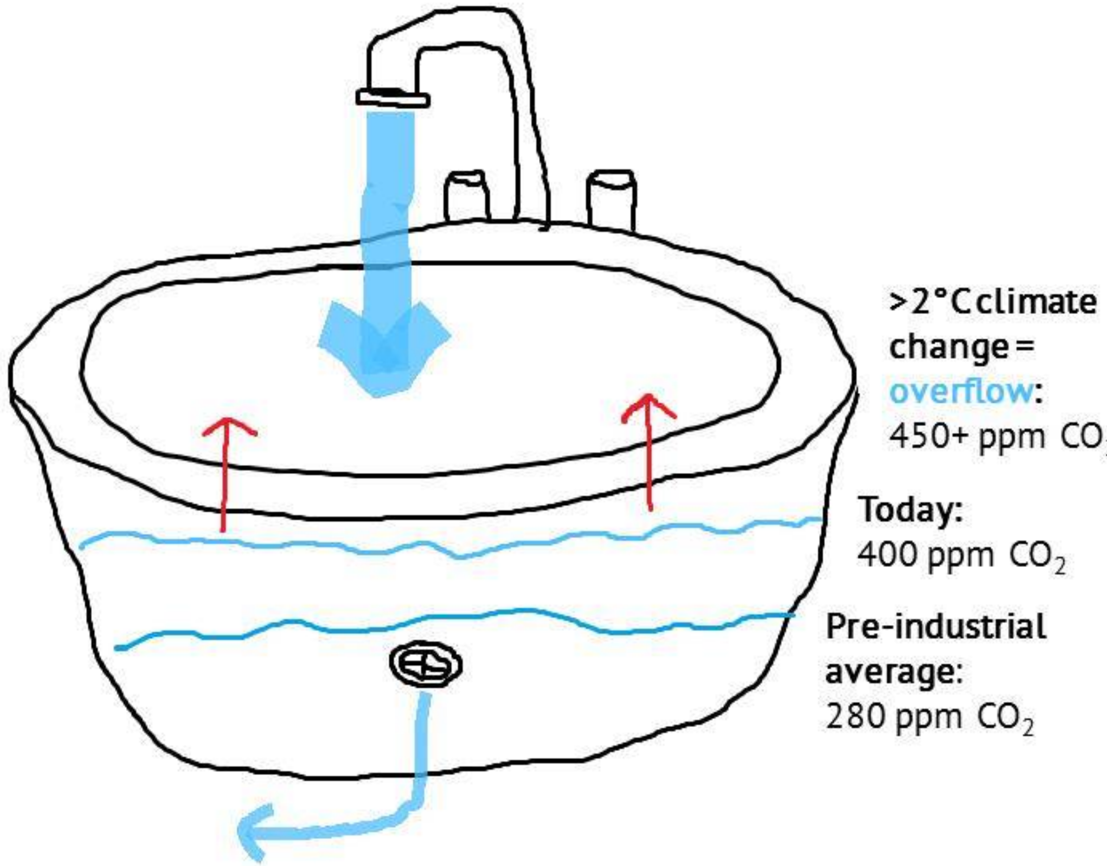
+4°C

-4°C

CO_2 emissions and carbon sinks

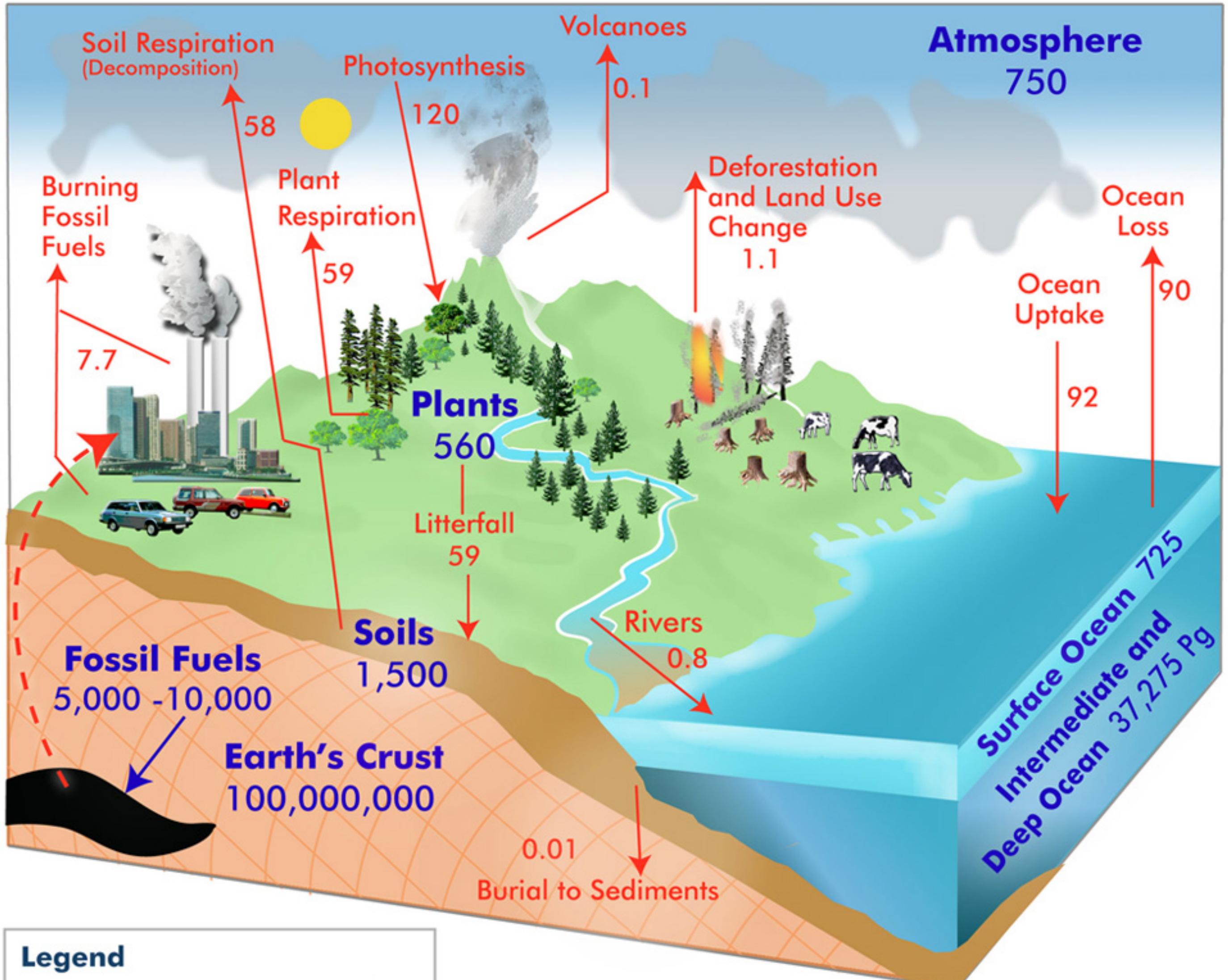
And risk overflowing "carbon sink" - i.e. causing dangerous climate change

If we don't start reducing carbon emissions significantly today, we will "overflow" the proverbial carbon sink, and our climate will change significantly



https://carbonremoval.files.wordpress.com/2014/09/cdr-infographic-3.jpg

Global Carbon Cycle



Legend

Units: Petagrams (Pg) = 10^15 gC

- Pools: Pg
- Fluxes: Pg/year

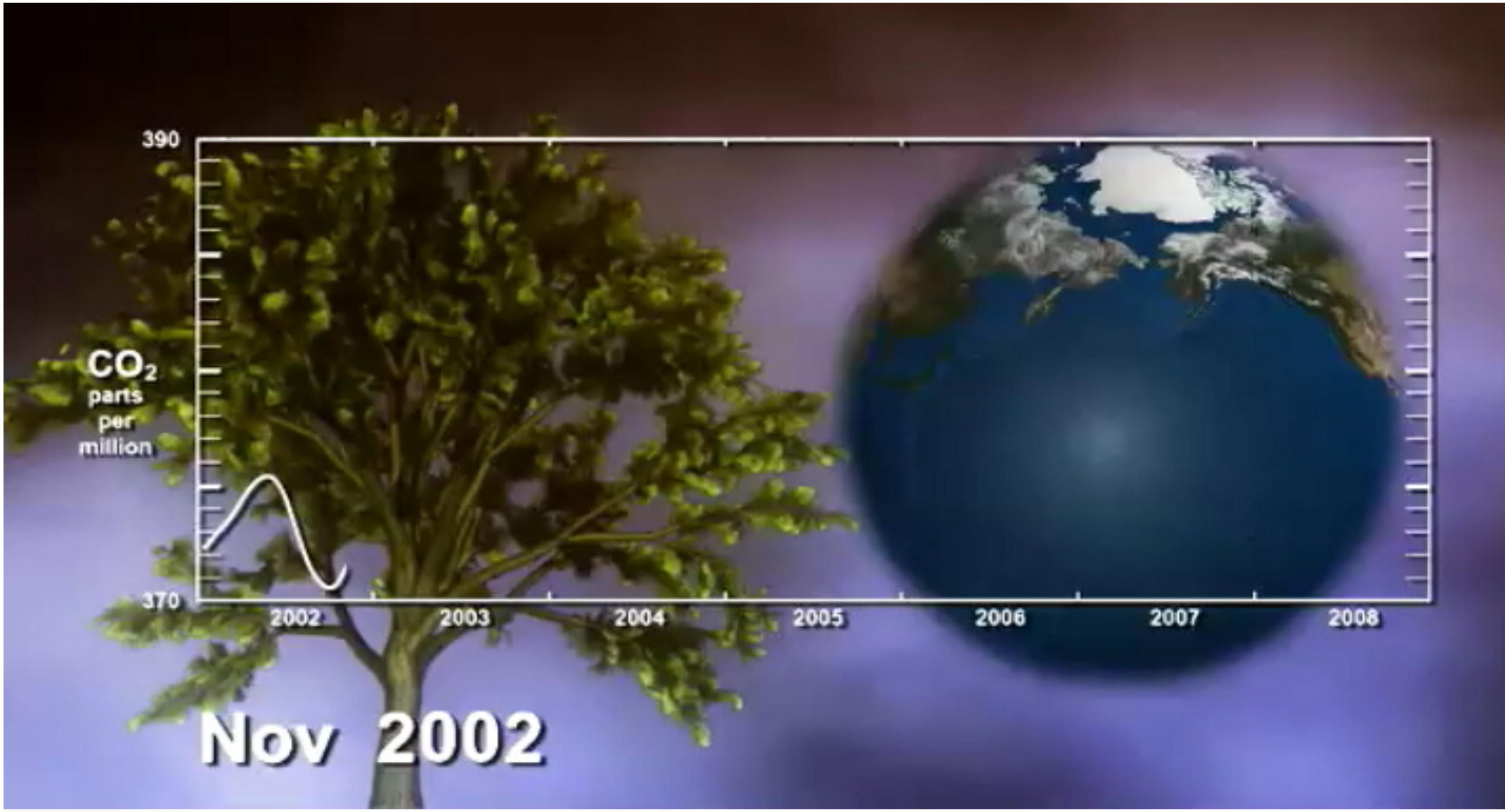
GtC

GtC/yr

Data Sources: Adapted from Houghton, R.A. Balancing the Global Carbon Budget. Annu. Rev. Earth Planet. Sci. 007.35:313-347, updated emissions values are from the Global Carbon Project: Carbon Budget 2009.

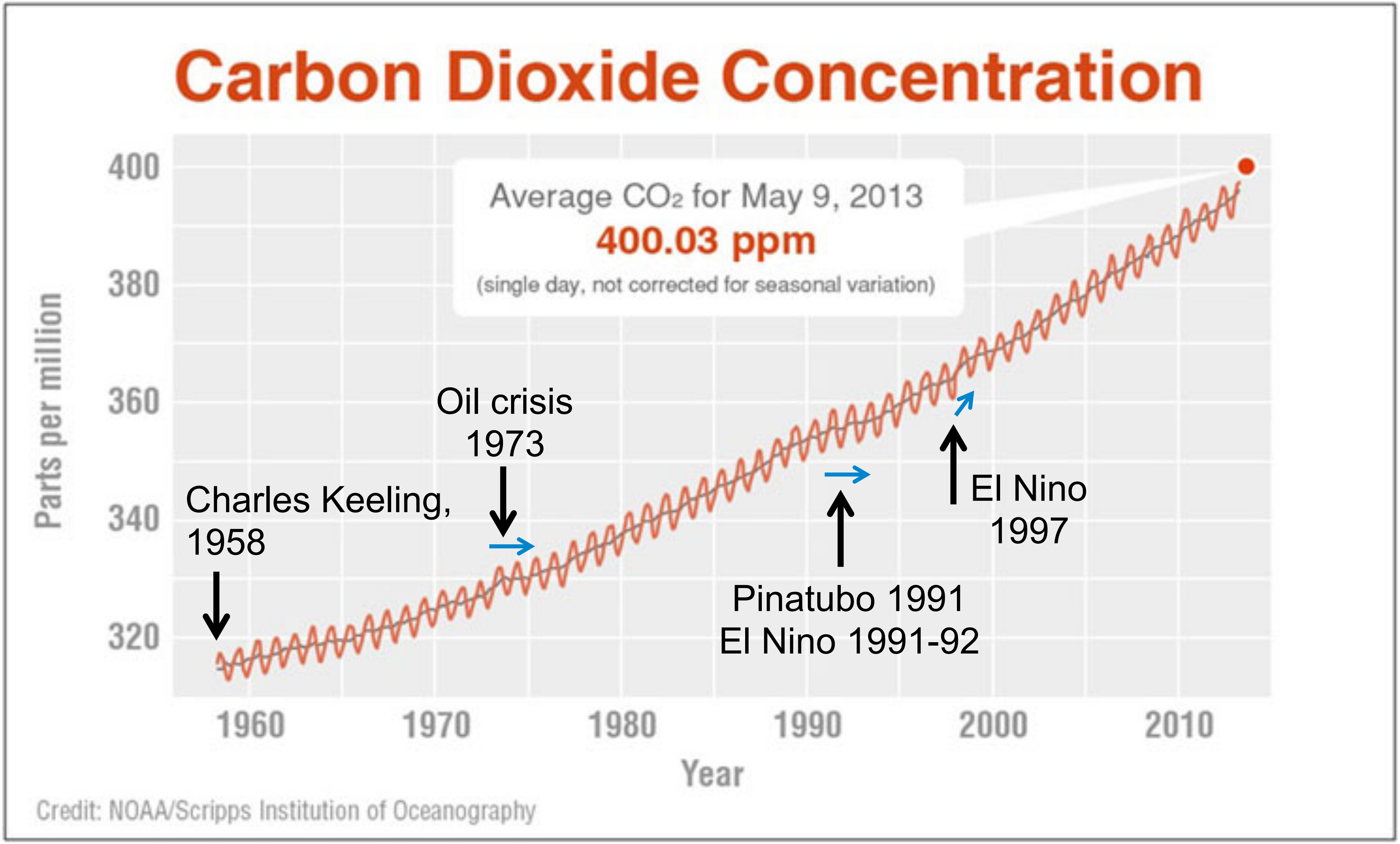
Earth's breathing

Atmospheric CO_2 2002 -2008



Courtesy: D. Crisp (NASA/JPL), GEO-X Meeting, Geneva, 13 Januar 2014

NOAA/Scripps CO_2 Time series



The more accurate and the longer the observational time series, the more we can learn from analyzing the observations …

Fate of Anthropogenic CO_2 Emissions (2004-2013 average)

32.4±1.6 $GtCO_2$/yr **91%**

3.3±1.8 $GtCO_2$/yr **9%**

+

15.8±0.4 $GtCO_2$/yr
44%

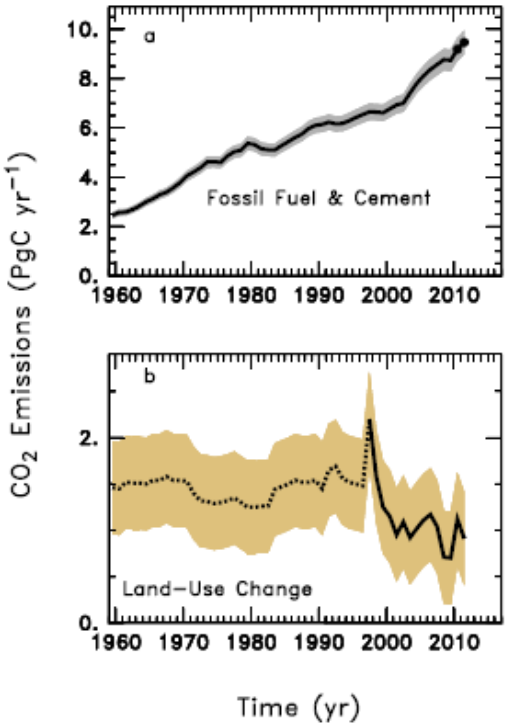
10.6±2.9 $GtCO_2$/yr
29%
Calculated as the residual
of all other flux components

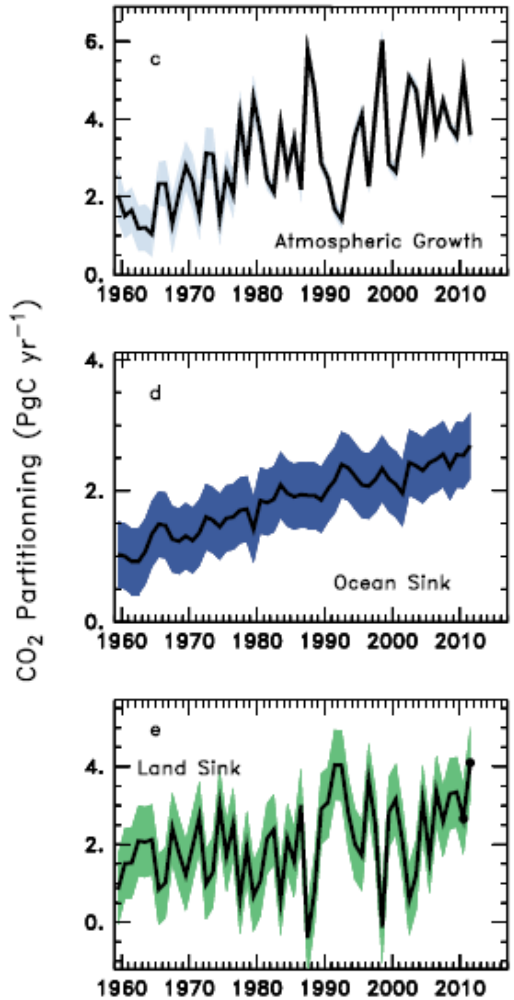
26%
9.4±1.8 $GtCO_2$/yr

Source: CDIAC; NOAA-ESRL; Houghton et al 2012; Giglio et al 2013; Le Quéré et al 2014; Global Carbon Budget 2014

Carbon cycle: Sources and sinks

Emissions





Atmospheric growth

Ocean sink

Land sink

Earth Syst. Sci. Data, 5, 165–185, 2013
www.earth-syst-sci-data.net/5/165/2013/
doi:10.5194/essd-5-165-2013

Global Carbon Project

Earth System Science Data

Le Quere et al., 2013

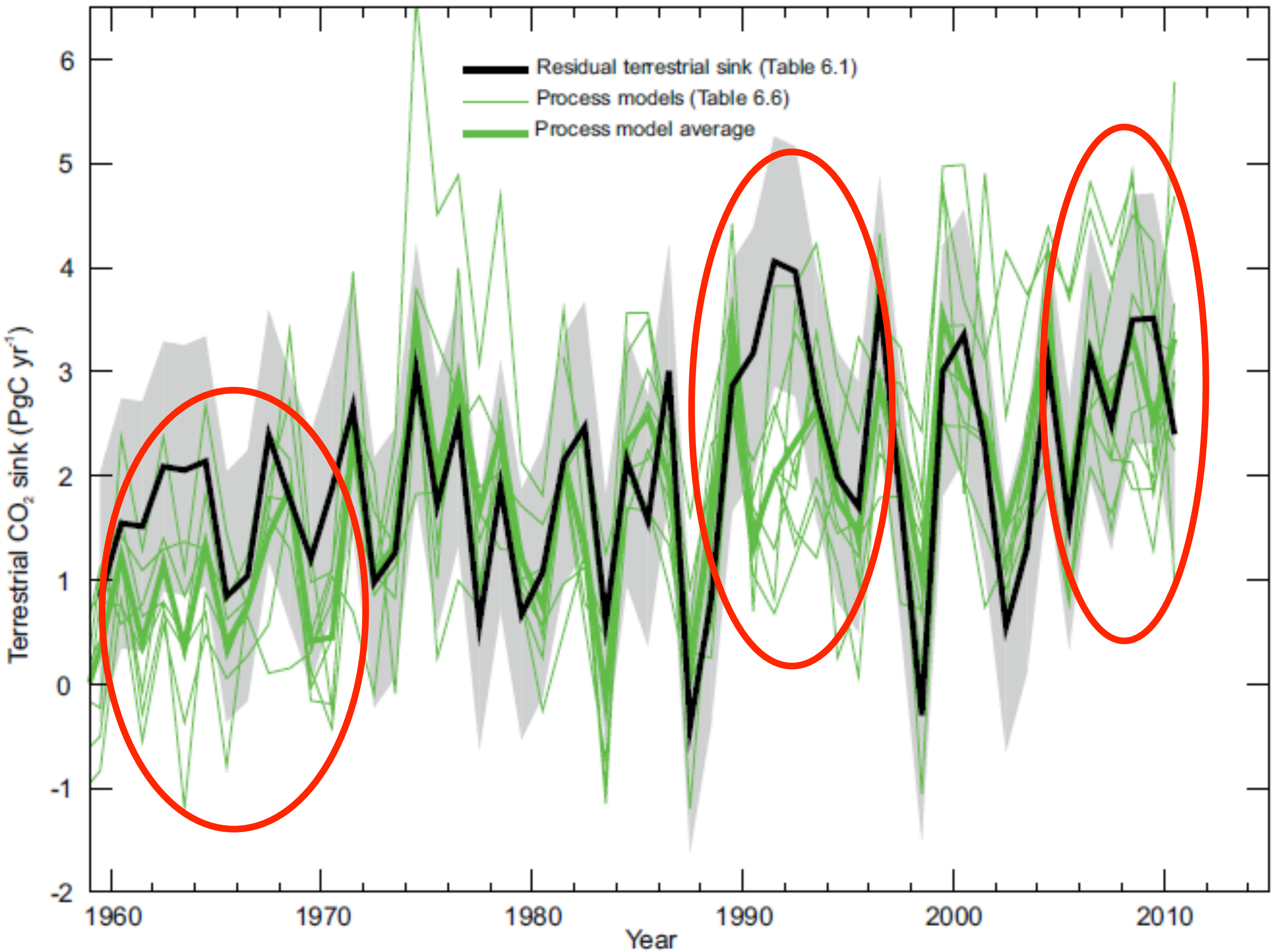
The global carbon budget 1959–2011

C. Le Quéré[1], R. J. Andres[2], T. Boden[2], T. Conway[3], R. A. Houghton[4], J. I. House[5], G. Marland[6], G. P. Peters[7], G. R. van der Werf[8], A. Ahlström[9], R. M. Andrew[7], L. Bopp[10], J. G. Canadell[11], P. Ciais[10], S. C. Doney[12], C. Enright[1], P. Friedlingstein[13], C. Huntingford[14], A. K. Jain[15], C. Jourdain[1,*], E. Kato[16], R. F. Keeling[17], K. Klein Goldewijk[18,19,20], S. Levis[21], P. Levy[14], M. Lomas[22], B. Poulter[10], M. R. Raupach[11], J. Schwinger[23,24], S. Sitch[25], B. D. Stocker[26,27], N. Viovy[10], S. Zaehle[28], and N. Zeng[29]

Land sink: Not directly observed:
-> „Residual land sink“:

$$S_{LAND} = E_{FF} + E_{LUC} - (G_{ATM} + S_{OCEAN})$$

Carbon cycle: Residual terrestrial sink

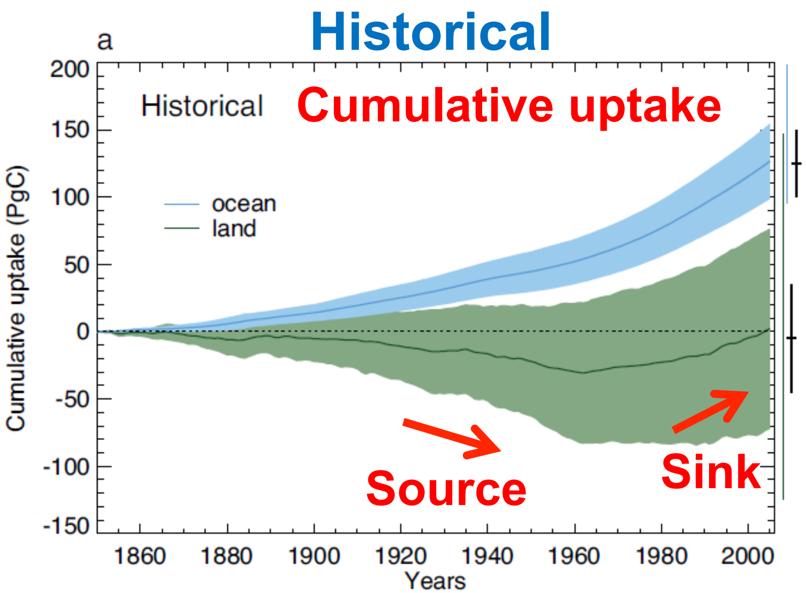


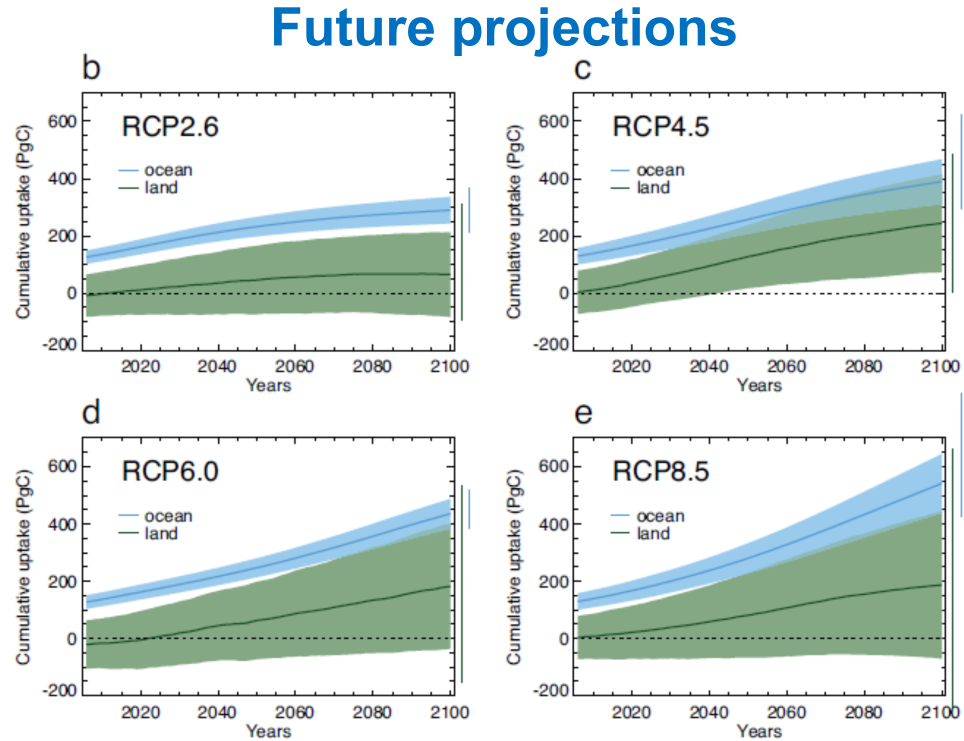
Large discrepancies !

IPCC 2013, WG1 **Carbon and Other Biogeochemical Cycles**

Carbon uptake: Historical & future projections

IPCC 2013, WG1
Carbon and Other Biogeochemical Cycles





IPCC: "The **future evolution of the land carbon uptake** is much more **uncertain** *[compared to ocean]*, with a majority of models projecting a continued net carbon uptake under all RCPs, but with some models simulating a net loss of carbon by the land due to the combined effect of climate change and land use change.

In view of the large spread of model results and incomplete process representation, there **is low confidence on the magnitude of modelled future land carbon changes**."

Carbon – climate feedback (“gamma”)

IPCC 2013, WG1

Carbon and Other Biogeochemical Cycles

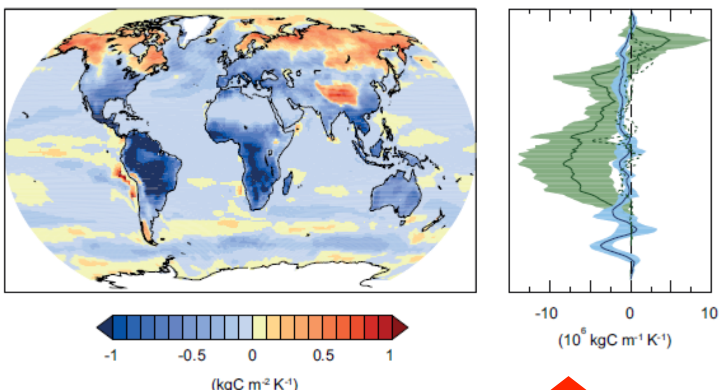
Regional carbon-climate feedback

gamma / γ

Land

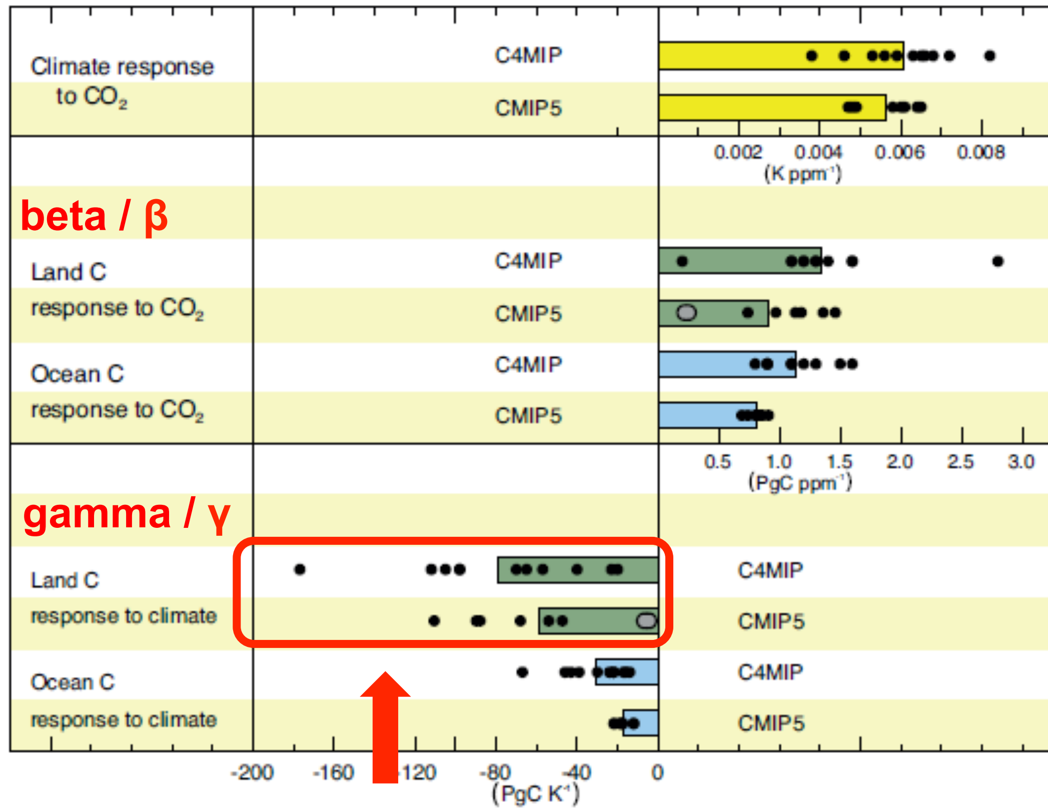
Ocean

b. Regional carbon-climate feedback



gamma
:= Δ C-reservoir / ΔT
where < 0:
Positive feedback !

Carbon cycle feedback metrics



Land carbon response to climate change:
Large uncertainties !

IPCC: **Positive carbon cycle feedback expected.**
Climate change will affect carbon cycle process in a way that will exacerbate the increase of CO_2 in the atmosphere (*high confidence*).
Sign is known but high uncertainty in the feedback magnitude.

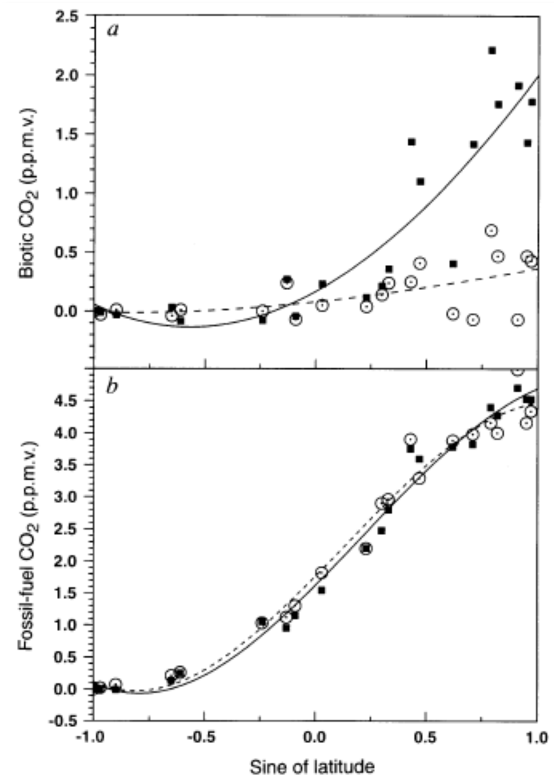
Carbon sources & sinks: Denning et al., Nature, 1995

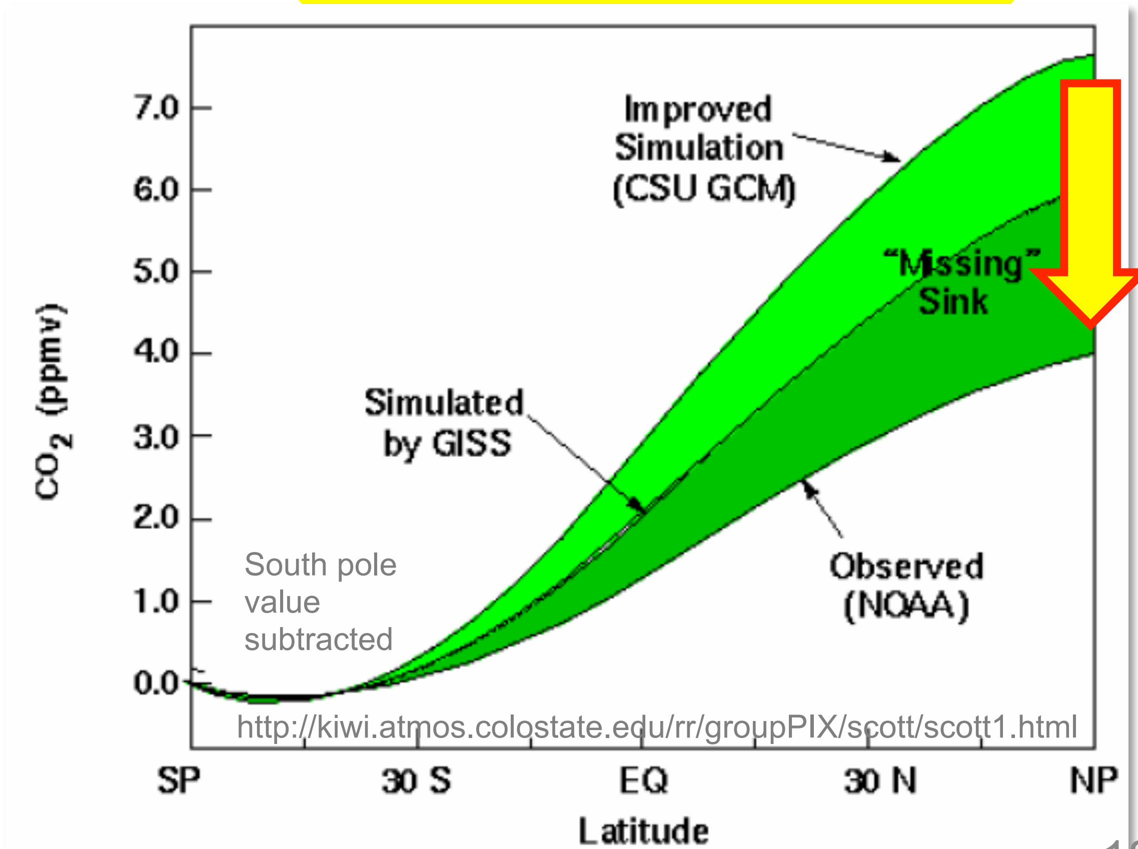
Latitudinal gradient of atmospheric CO_2 due to seasonal exchange with land biota

A. Scott Denning*, Inez Y. Fung† & David Randall*

„We find that the latitudinal (meridional) gradient imposed by the seasonal **terrestrial biota** is nearly half as strong as that imposed by fossil-fuel emissions. Such a contribution implies that the **sink of atmospheric CO_2 in the Northern Hemisphere** must be **stronger than previously suggested**."

Strong carbon land sink in northern hemisphere





Terrestrial carbon sinks: Status in 2002

Lowland rainforest, Borneo (F Lanting) © Minden Pictures/FLPA

Terrestrial carbon sinks – uncertain explanations

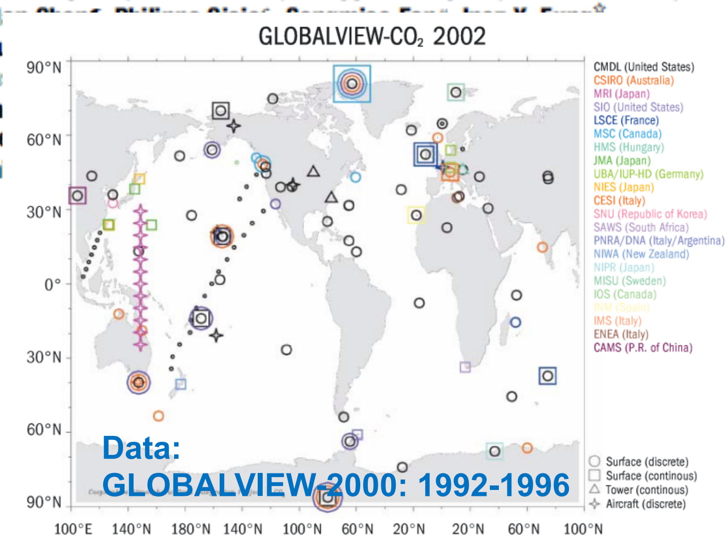
Houghton, Biologist, 2002:

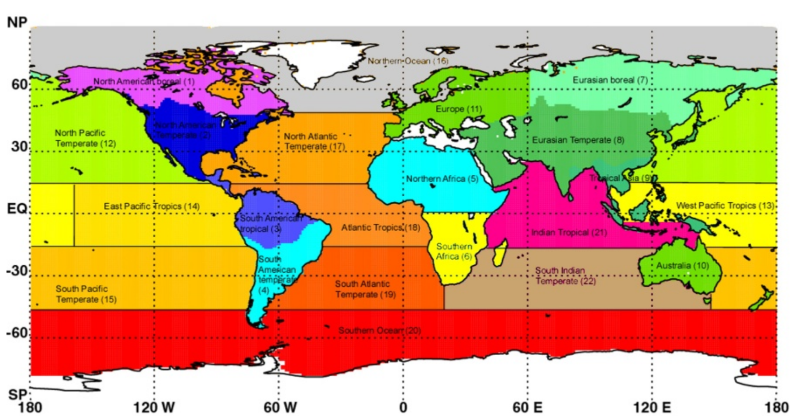
“Strangely, the difference between the net terrestrial sink and the emissions from land-use change **suggests that there is a residual terrestrial sink, not well understood, that locked away as much as 3.0 PgC/yr** **(3 GtC/yr)** **during the last two decades**. … **The exact magnitude, location and cause of this residual terrestrial sink are uncertain**, …”

Regional C sources and sinks: Gurney et al., Nature, 2002

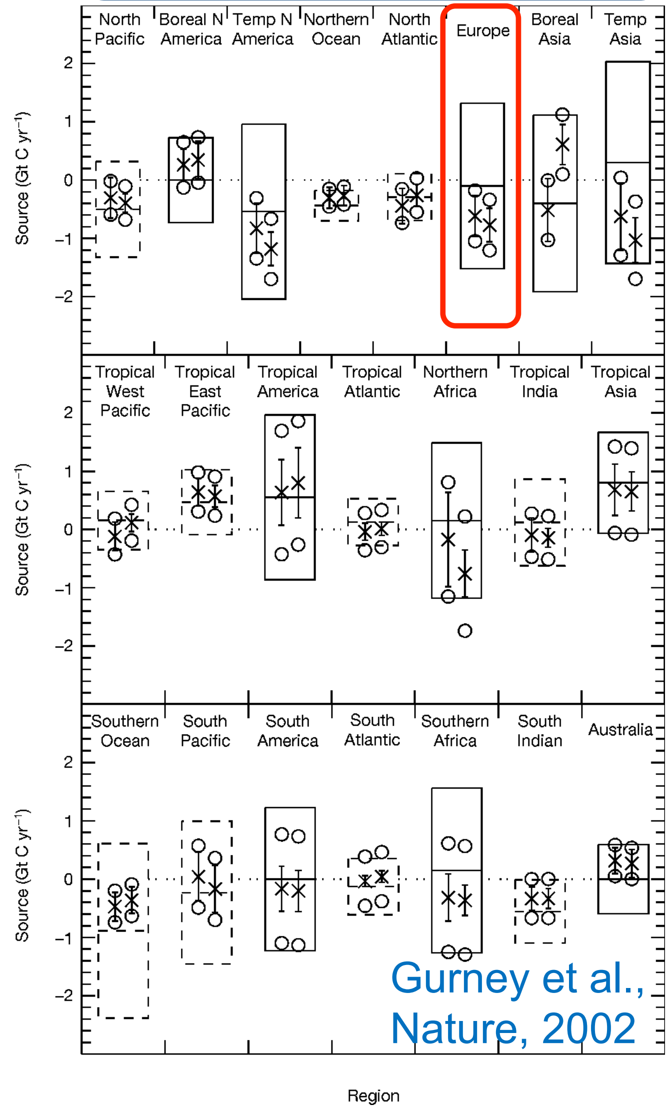
Towards robust regional estimates of CO_2 sources and sinks using atmospheric transport models

Kevin Robert Gurney*, Rachel M. Law†, A. Scott Denning*,
Peter J. Rayner†, David Baker‡, Philippe Bousquet§, Lori Bruhwiler‖,
Yu-H
Manu
Taka
Mich
Jorg
& Ch





TransCom 3 regional CO_2 flux inversions



Observartions: Very accurate but sparse

Information content sources & sinks (excluding fossil fuel fluxes):

Large regions only (continents, ocean basins)

Large uncertainties (often +/- 100%)

A priori land

Inversions:

X Mean flux

Within model uncertainty

Left / right: different inversions

Regional C sources and sinks: Stephens et al., Science, 2007

Adding aircraft CO_2 flask observations:

Stephens et al., Science , 2007

NEWS FEATURES

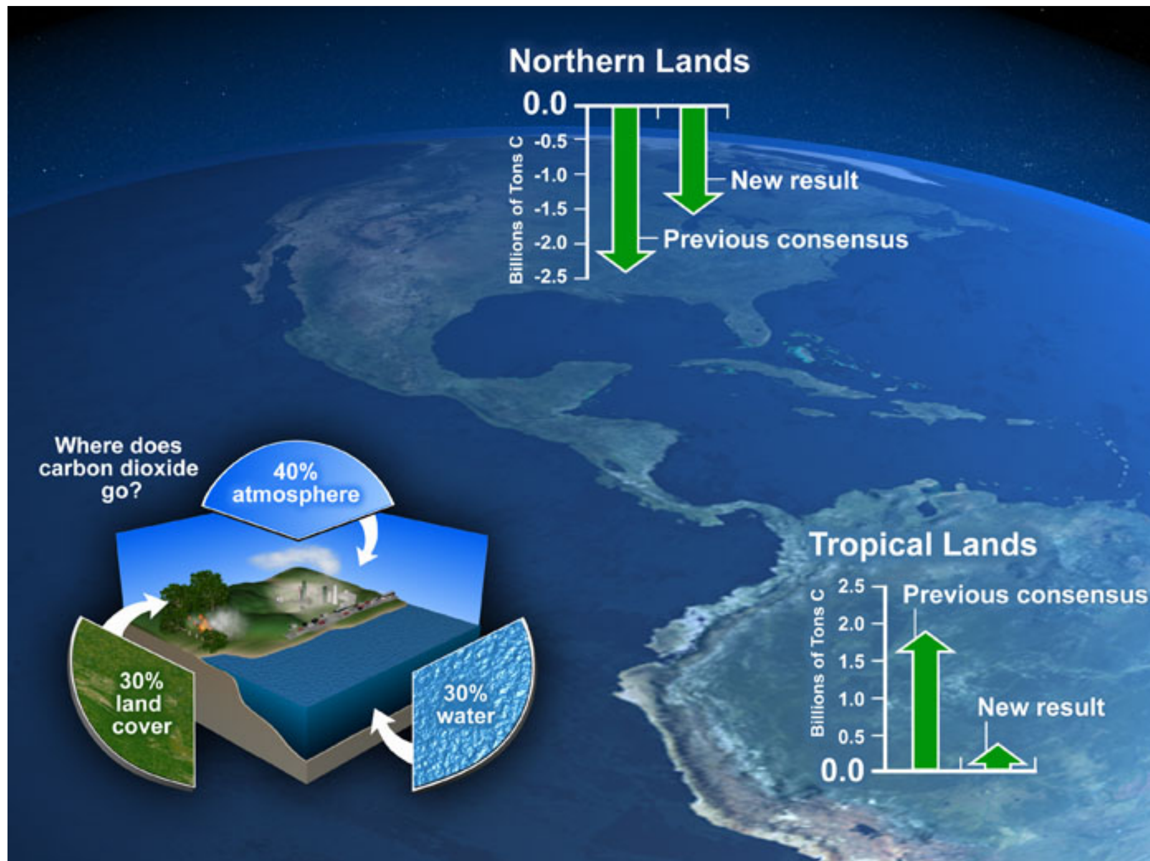
Missing carbon mystery: Case solved?

Weak Northern and Strong Tropical Land Carbon Uptake from Vertical Profiles of Atmospheric CO_2

Britton B. Stephens,[1*] Kevin R. Gurney,[2] Pieter P. Tans,[3] Colm Sweeney,[3] Wouter Peters,[3] Lori Bruhwiler,[3] Philippe Ciais,[4] Michel Ramonet,[4] Philippe Bousquet,[4] Takakiyo Nakazawa,[5] Shuji Aoki,[5] Toshinobu Machida,[6] Gen Inoue,[7] Nikolay Vinnichenko,[8]† Jon Lloyd,[9] Armin Jordan,[10] Martin Heimann,[10] Olga Shibistova,[11] Ray L. Langenfelds,[12] L. Paul Steele,[12] Roger J. Francey,[12] A. Scott Denning[13]

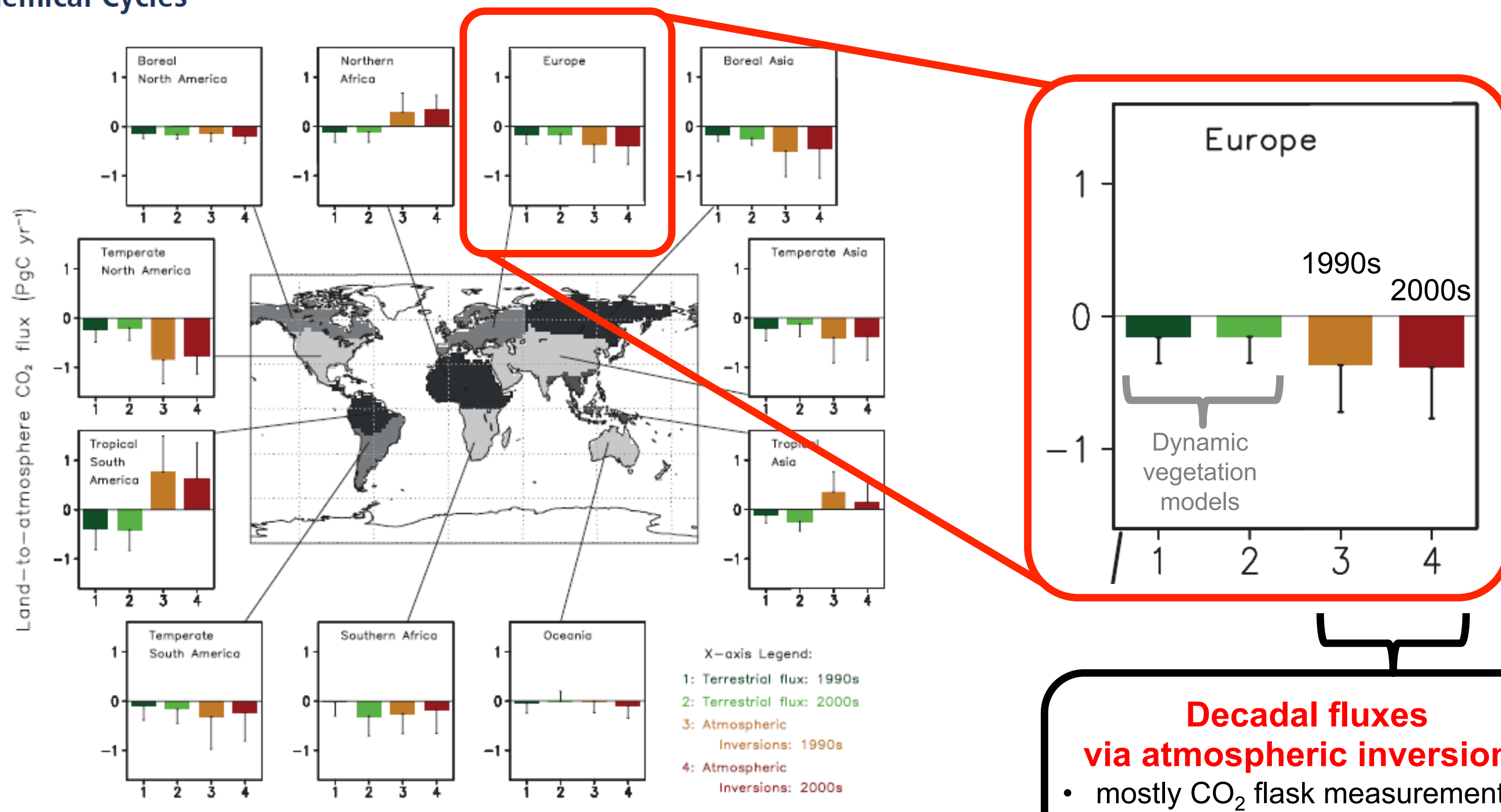
NH land:
Weaker sink?
(+1 GtC/yr)

Tropics:
Weaker source?
Net approx. zero ?
(-2 GtC/yr)



Regional terrestrial CO_2 fluxes

IPCC 2013, WG1
Carbon and Other Biogeochemical Cycles



Decadal fluxes via atmospheric inversions
- mostly CO_2 flask measurements (very accurate but sparse)
- without satellite CO_2

Large discrepancies models vs atmospheric inversions esp. in tropics and northern Africa & large uncertainties (~100%) !
Satellite CO_2 observations have potential to improve our knowledge

Uncertainty reduction using satellite data - I

Natural CO_2 fluxes from space?:

- **Yes ! If …**

Precision < 2.5 ppm for monthly 8°x10°

GEOPHYSICAL RESEARCH LETTERS, VOL. 28, NO. 1, PAGES 175-178, JANUARY

Rayner and O'Brien, 2001

The utility of remotely sensed CO_2 concentration data in surface source inversions

P. J. Rayner
Cooperative Research Centre for Southern Hemisphere Meteorology and CSIRO Atmospheric Research, Aspendale, Victoria, Australia

D. M. O'Brien
CSIRO Atmospheric Research, Aspendale, Victoria, Australia

Abstract. This paper aims to establish the required precision for column-integrated CO_2 concentration data to be useful in constraining surface sources. We use the method of synthesis inversion and compare the uncertainties in regional sources calculated from a moderate-sized surface network and either global or oceanic coverage of column-integrated pseudodata. With a simple measure of total uncertainty, we require precision of monthly averaged column data better than 2.5 ppmv on a 8° × 10° footprint for comparable performance with the existing surface network. If coverage is only oceanic we require 1.5 ppmv precision. We recommend more detailed studies on the feasibility of obtaining such observations from current and future satellite instruments.

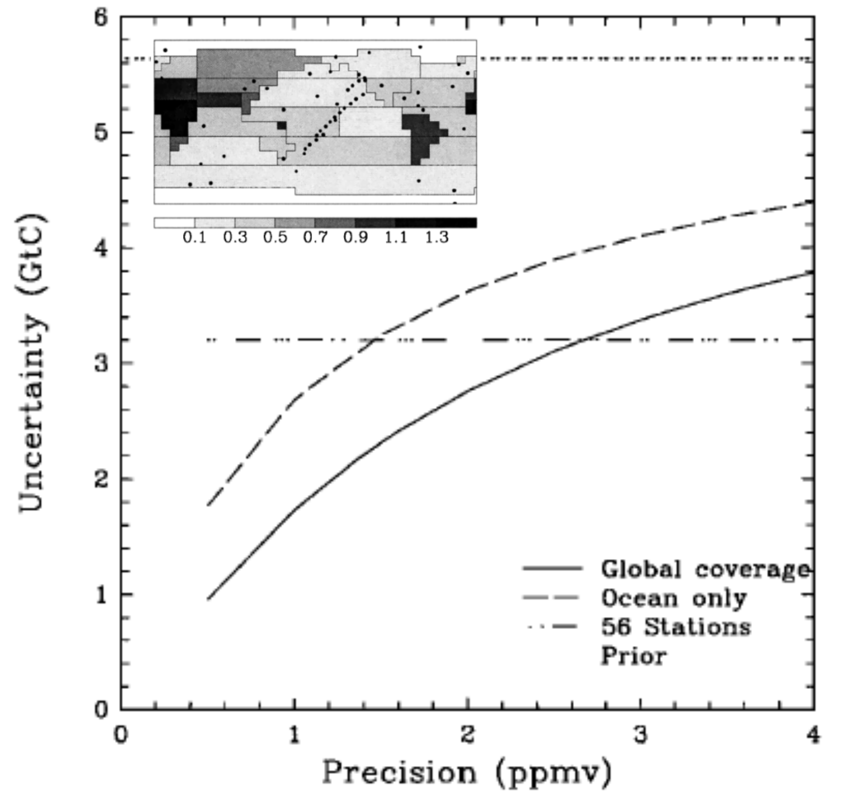


Figure 3. Plot of "total uncertainty" (see Eq. 1) in GtC yr^{-1} against the precision (ppmv) of column-integrated data. The dotted horizontal line shows the prior uncertainty while the dash-dot horizontal line shows the case for the surface network of Fig. 1.

Correction to "The utility of remotely sensed CO_2 concentration data in surface source inversions"

Uncertainty reduction using satellite data - II

Prior uncertainty

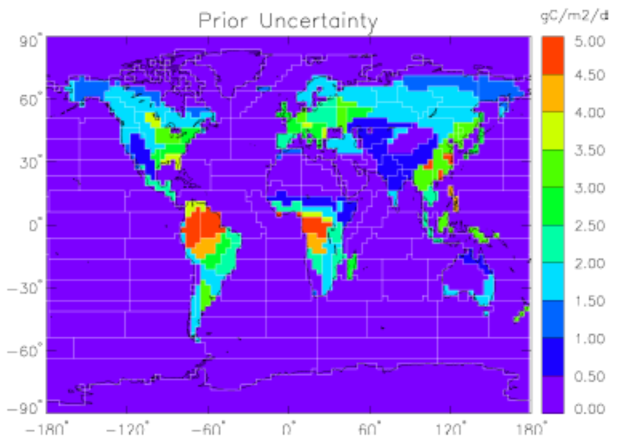
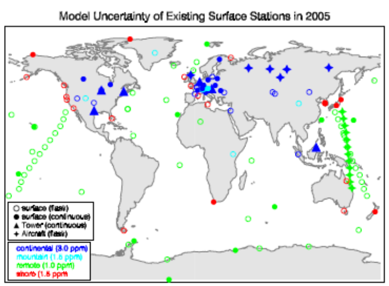
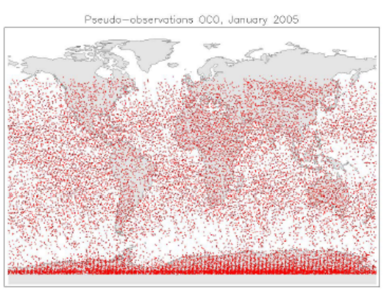


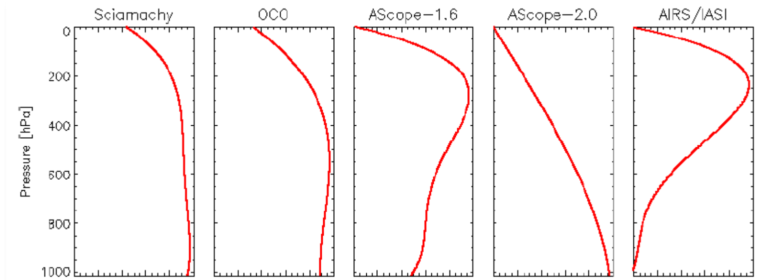
Fig. 1. Prior uncertainty of weekly fluxes in $\mathrm{g\,C\,m^{-2}\,d^{-1}}$. The white lines show the borders of the 200 regions for which the surface fluxes are retrieved.



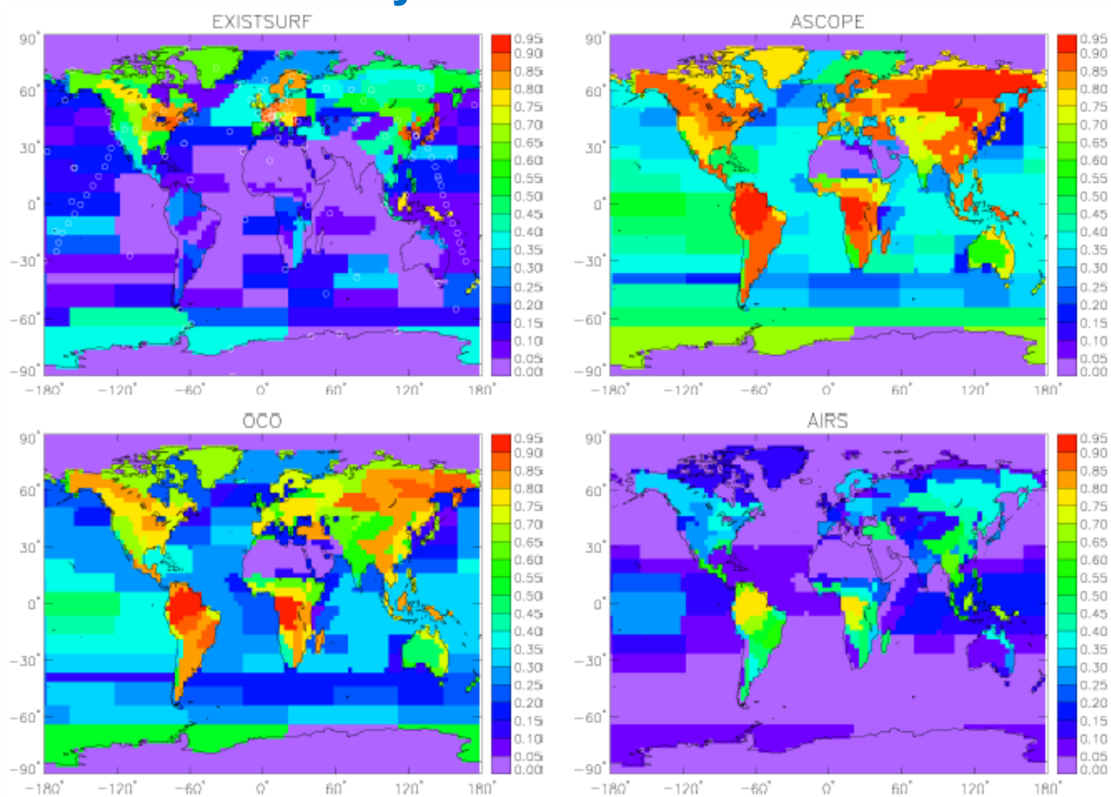


Hungershöfer et al., 2010

Altitude sensitivity



Weekly mean error reduction



Terrestrial C sources and sinks: Adding real satellite data ?

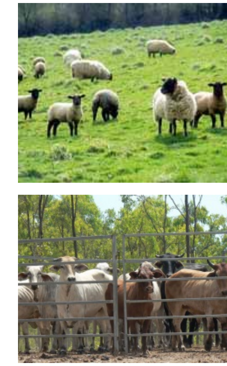
Methane

Natural gas

Coal mining

Wetlands

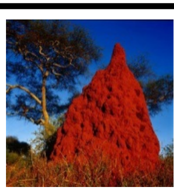
Rice



Ruminants

Wastewater

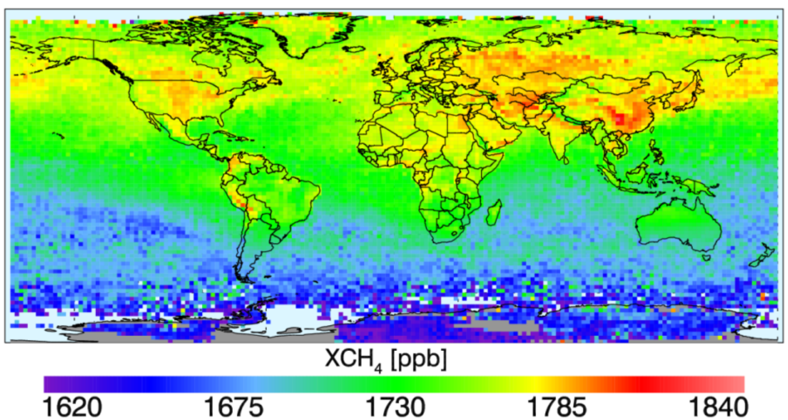
Landfills

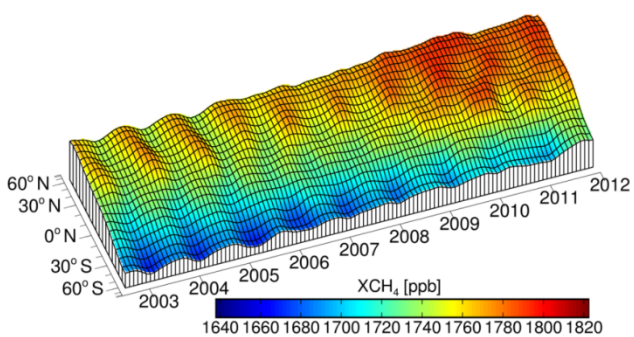


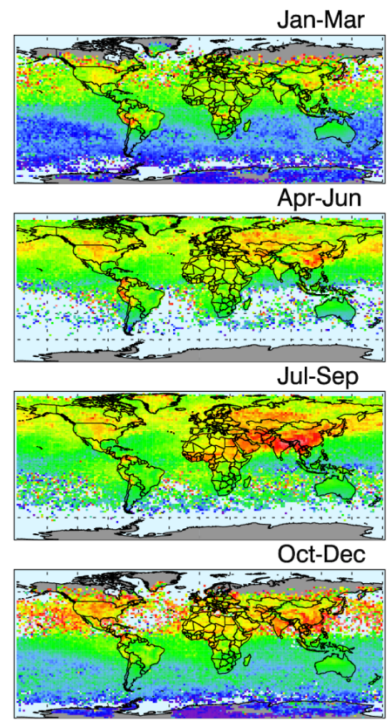
Termites

GHG-CCI 2002-2011

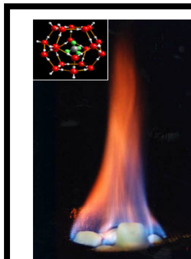
Methane SCIAMACHY/WFMD







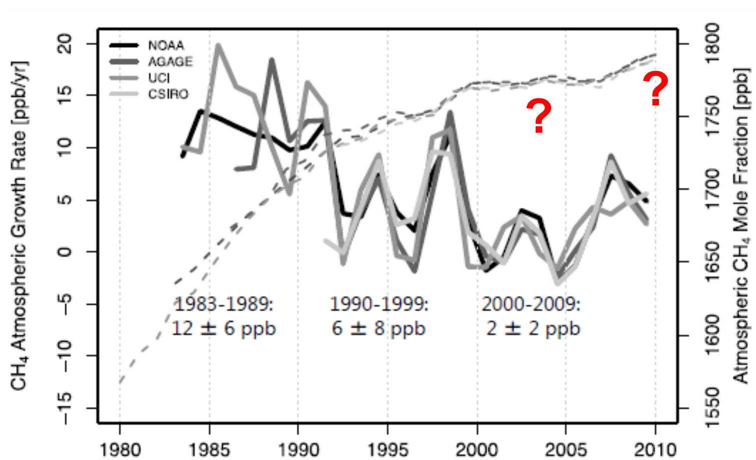
Energy



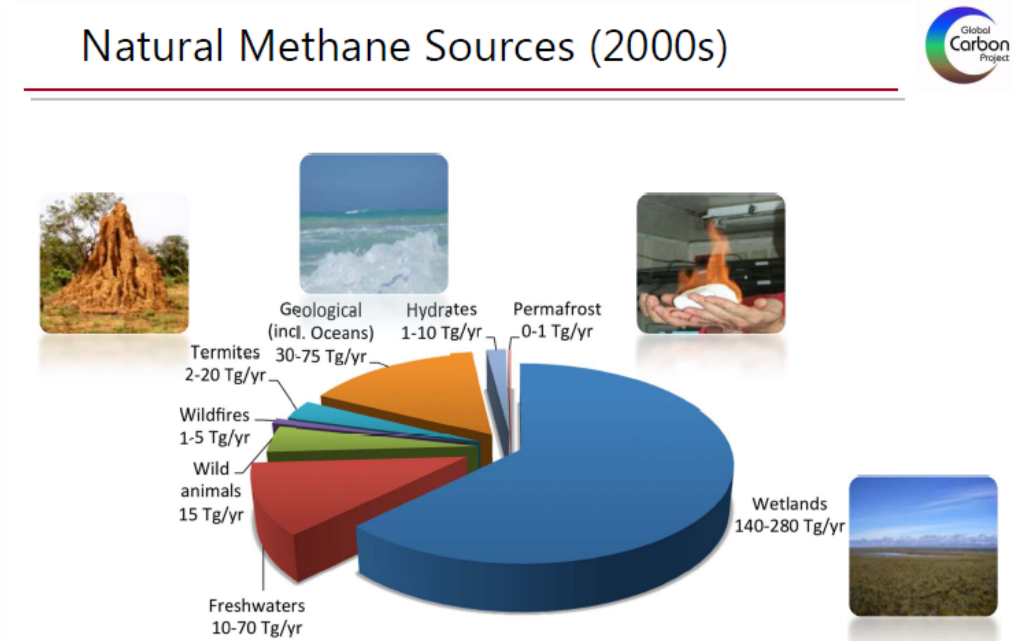
Hydrates

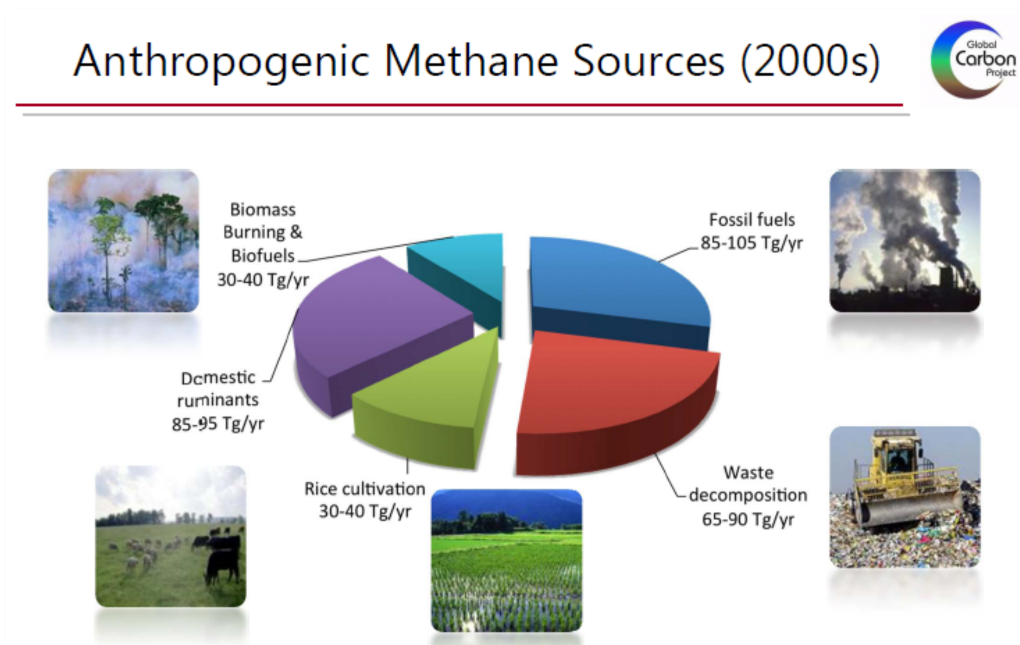
Methane

- Second most important anthropogenic GHG (directly after CO_2)
- Many anthropogenic and natural sources; **large uncertainties !**



Kirschke et al., 2013



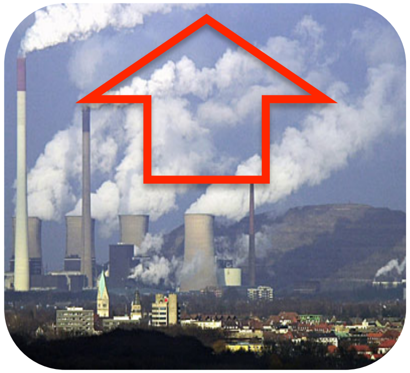


CO_2 and CH_4 sources and sinks: !! ??

How strong are the various sources and sinks ?

How much is emitted where, when and by what?

Are the reported emissions correct?



How much CO_2 is absorbed by land and oceans? Where and when?

How will today's CO_2 sinks behave in a changing climate?

How will today's CH_4 sources (e.g., wetlands) behave in a changing climate?

Will sinks turn into sources?

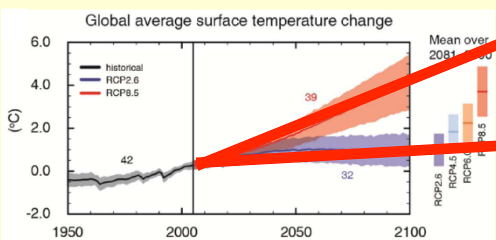
Will sources be amplified?

How will sources and sinks behave in a changing climate?

Essential Climate Variable "Greenhouse Gases" (CO_2 & CH_4)

CO_2 and CH_4 are the two most important anthropogenic greenhouse gases and increasing concentrations result in global warming.

Observed and predicted temperature change (AR5)



Future?

Ecomomy?

Population?

Technology?

GHG sources and sinks?

Reliable climate prediction requires a good understanding of the natural and anthropogenic (surface) **sources and sinks of CO_2 and CH_4**.

Important questions are, for example:

- Where are they ?
- How strong are they ?
- How do they respond to a changing climate ?

A better understanding requires appropriate global observations and (inverse) modelling.

ECV GHG (GCOS-154*)):

"Retrievals of greenhouse gases, such as CO_2 and CH_4, of sufficient quality to estimate <u>regional</u> sources and sinks."

*) „SYSTEMATIC OBSERVATION REQUIREMENTS FOR SATELLITE-BASED DATA PRODUCTS FOR CLIMATE"

Overview Talk 1

Greenhouse gas observations from space: Why and how?

- **Why ?**
  - … including at least a little bit of the most relevant background information …
- **How ?**
  - From satellite radiances -> atmospheric GHG concentrations -> GHG surface fluxes (sources & sinks)

Viewing Geometries

Satellite Observation Geometries

Nadir

SCIAMACHY, AIRS, IASI, TES, GOSAT, OCO-2, *CarbonSat, A-SCOPE, MERLIN, ASCENDS, …*

Most relevant for GHG source / sink application

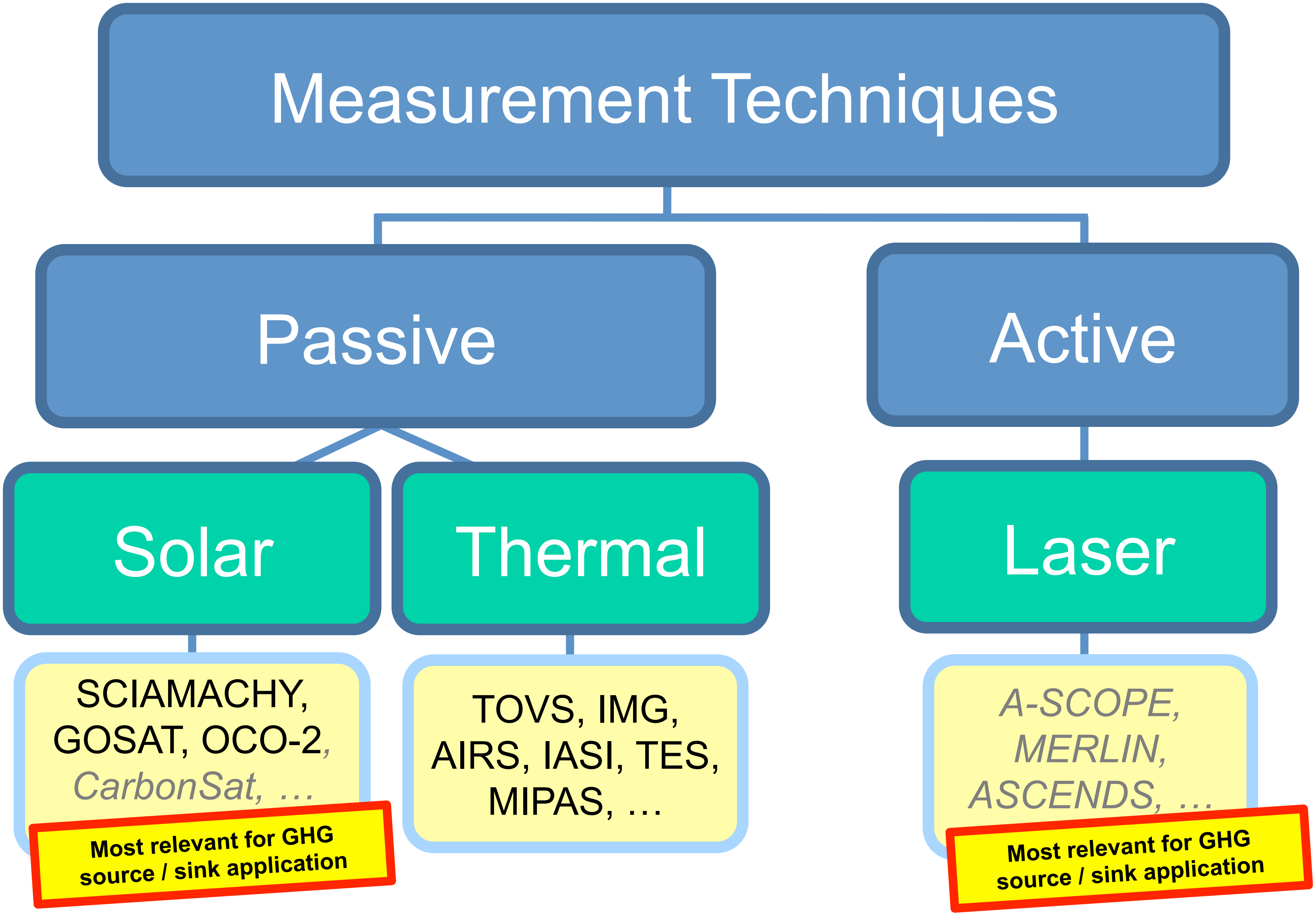
Limb

SCIAMACHY, MIPAS, …

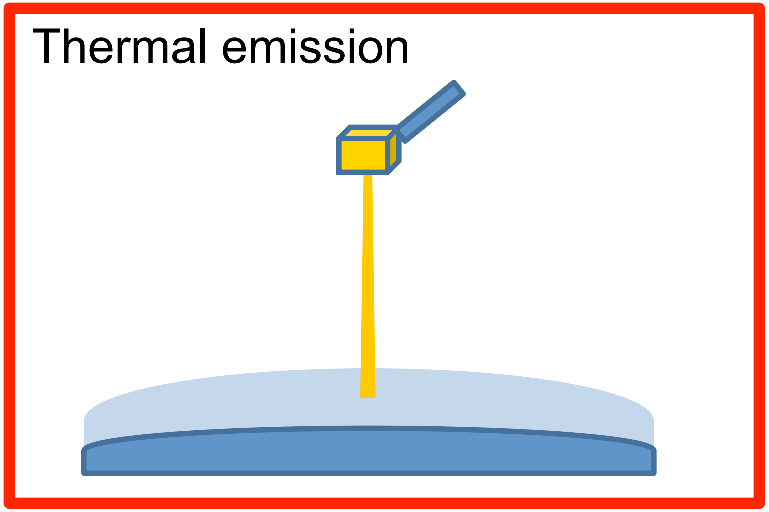
Occultation

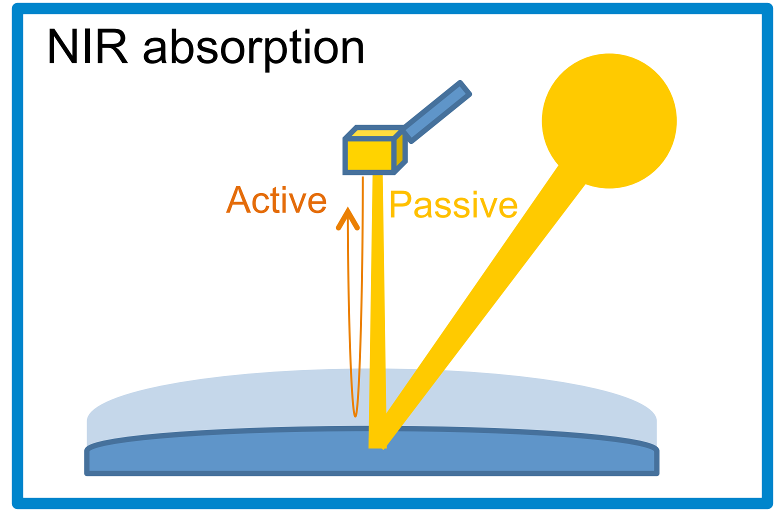
SCIAMACHY, ACE-FTS, …

Measurement Techniques



Reflected solar (NIR/SWIR) vs thermal (TIR)





Sensitive to mid/upper troposphere

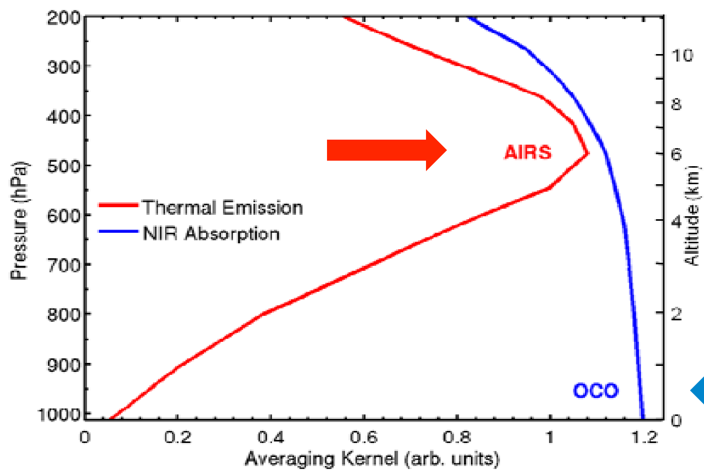


Figure 7. Representative vertical averaging kernels for column CO_2 soundings using NIR absorption of reflected sunlight in the 1.61 μm CO_2 band (blue)and thermal IR emission near 14.3 μm (red). TIR soundings are less sensitive to near-surface CO_2 because of the small surface–atmosphere temperature contrast (Crisp *et al.*, 2004; Chahine *et al.*, 2005).

Sensitive (also) to near-surface GHG concentration variations -> Important to get source/sink information

Note:

In the following I will focus on

- **nadir** observations in the
- **solar** spectral region using
- **passive** satellite observations

Existing missions:

- **SCIAMACHY** / ENVISAT (2002 – 2012)
- TANSO-FTS / **GOSAT** (2009 – now)
- OCO-2 (2014 – now)

Future missions:

- **CarbonSat** / Earth Explorer 8 candidate (2021 ?)
- other …

GHG-CCI project www.esa-ghg-cci.org

Global satellite observations

Global information on near-surface CO_2 & CH_4

SCIAMACHY/ENVISAT

TANSO/GOSAT

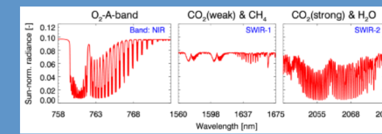
Preparing for: **OCO-2**

Upper layer CO_2 & CH_4

IASI, MIPAS, SCIA/occ, AIRS, ACE-FTS, …

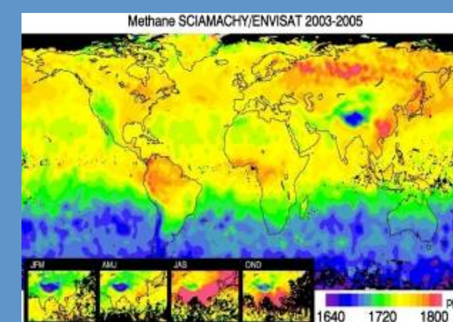
Calibration (L 0-1)

Calibrated radiances

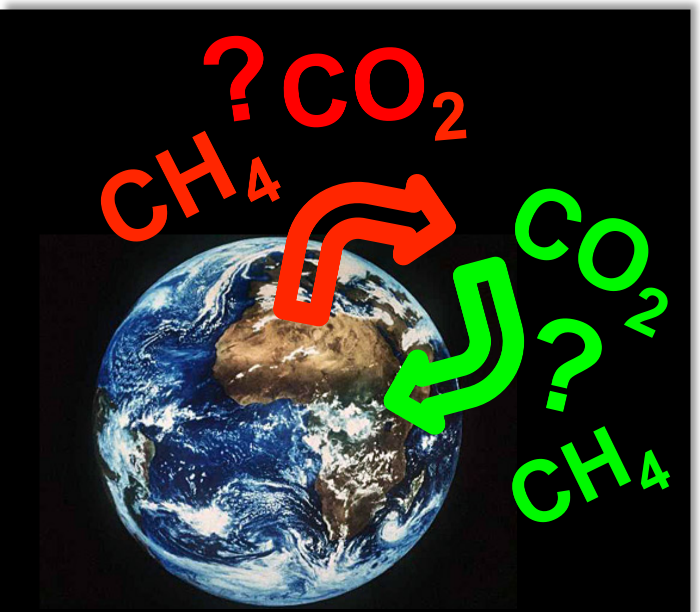


Retrieval (L 1-2)

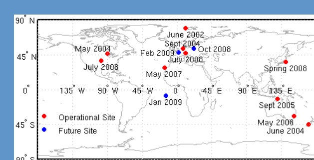
Atmospheric GHG distributions



Global observations

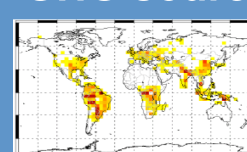


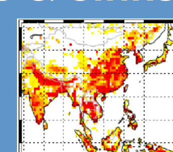
Reference observations



Validation

Improved information on GHG sources & sinks



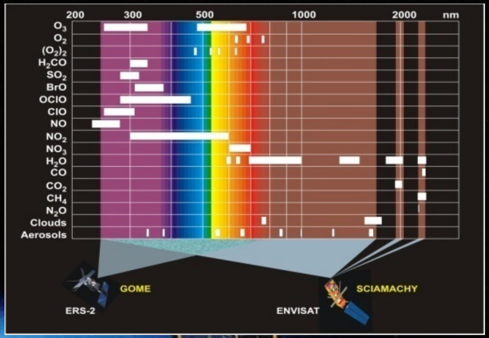


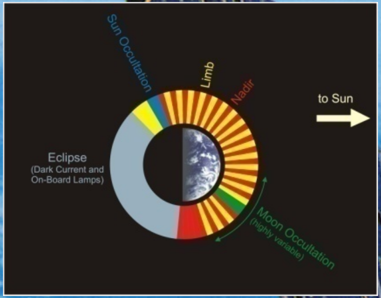
Inverse modelling (L 2-4)

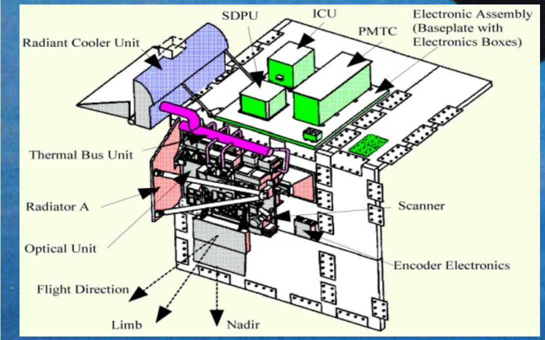
SCIAMACHY on ENVISAT

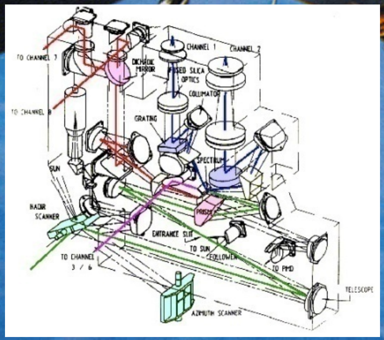
SCIAMACHY Scanning Imaging Absorption Spectrometer for Atmospheric CHartographY

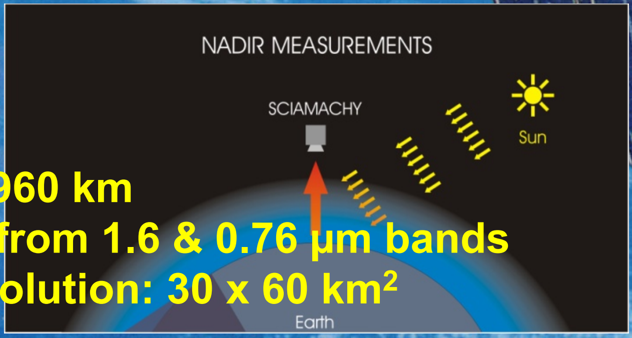
sciamachy /sʌɪ'aməki/ *n.* (also **skiamachy** /skʌɪ-/) *formal* **1** fighting with shadows. **2** imaginary or futile combat. [Greek *skiamakhia* (as SCIAGRAPHY, *-makhia* '-fighting')]











Nadir **mode:**

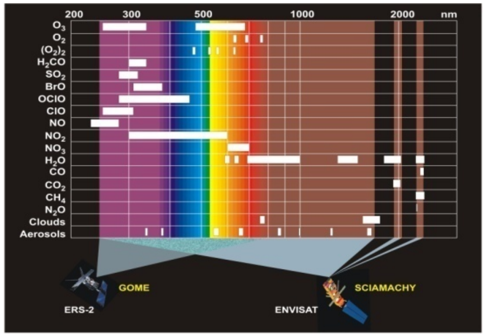
Swath width: 960 km

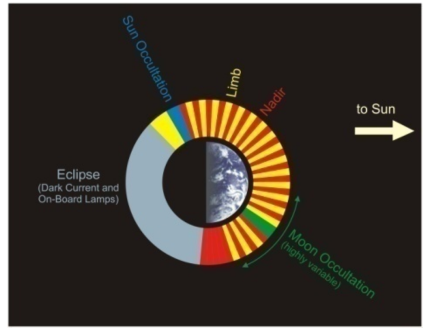
XCO_2 & XCH_4 from 1.6 & 0.76 µm bands

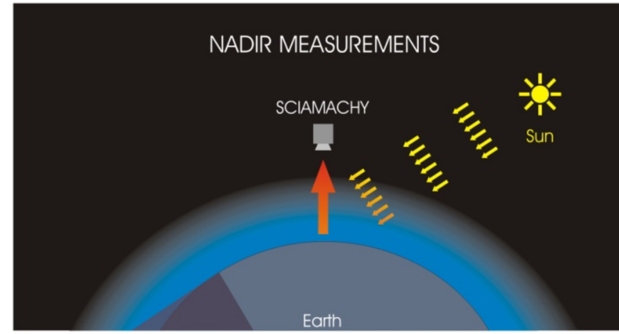
Horizontal resolution: 30 x 60 km^2

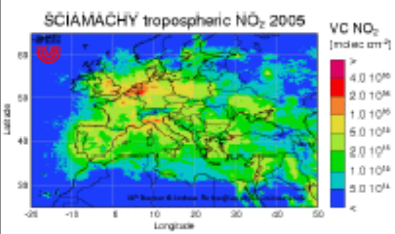
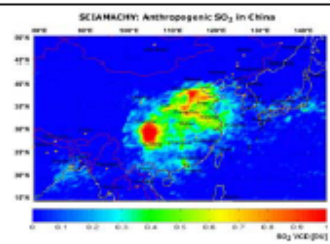
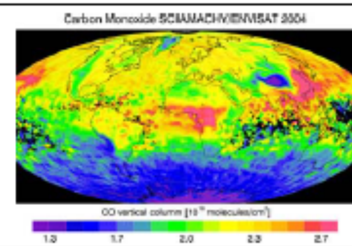
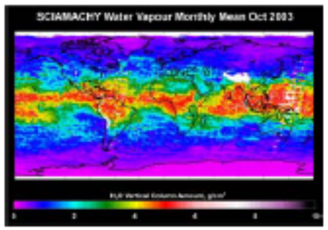
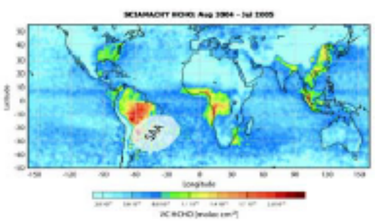
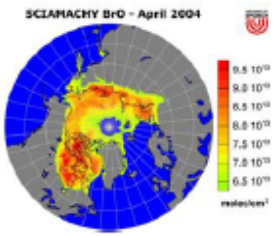
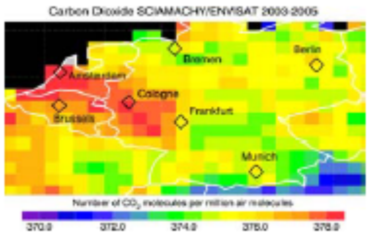
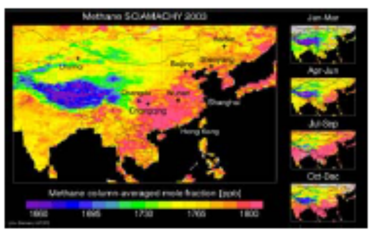
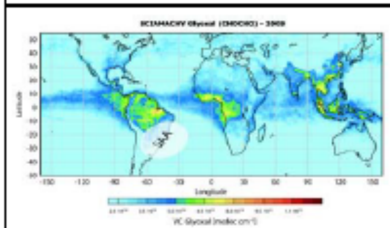
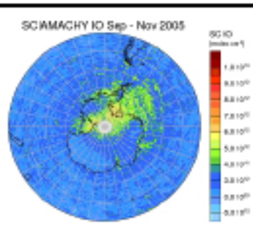
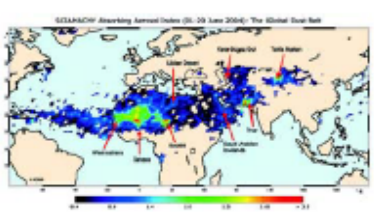
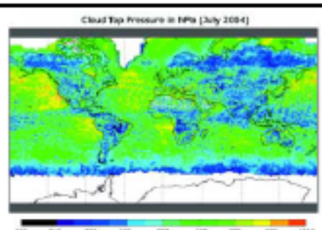
Tropospheric data products from SCIAMACHY/nadir

SCIAMACHY



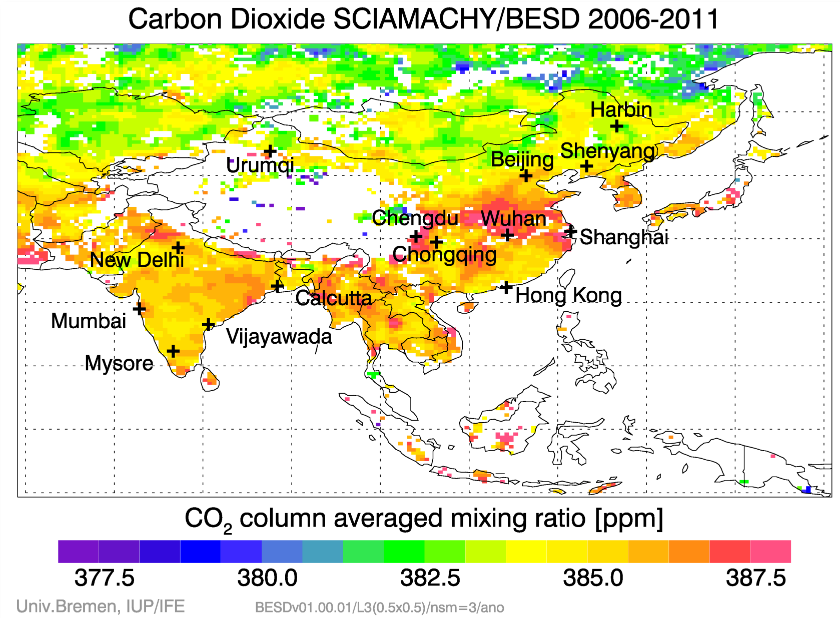


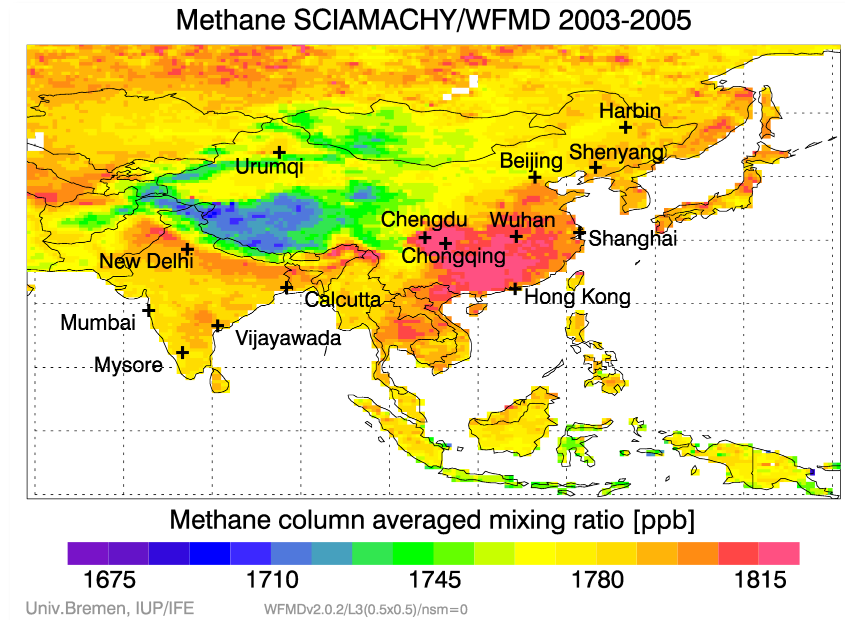


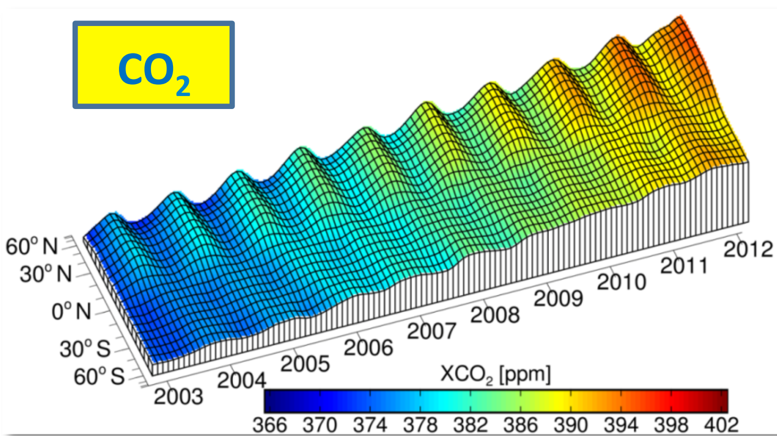
NO2	SO2	CO	H2O
			
HCHO	**BrO**	**CO2**	**CH4**
			
CHOCHO	**IO**	**Aerosols**	**Clouds**
			

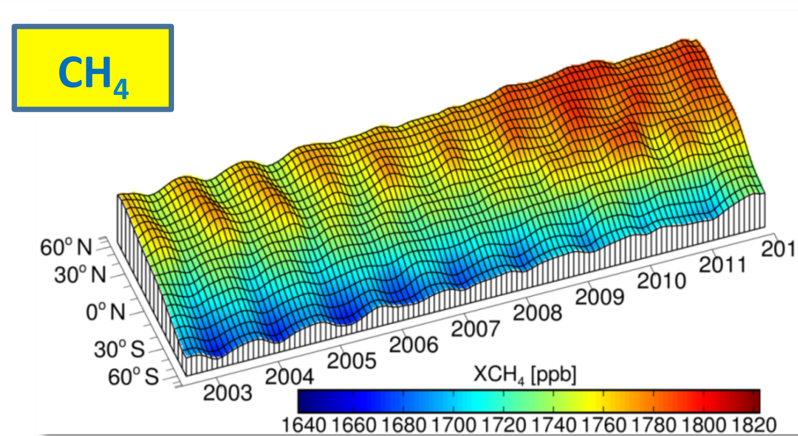
... and more.

Greenhouse gases from SCIAMACHY/ENVISAT









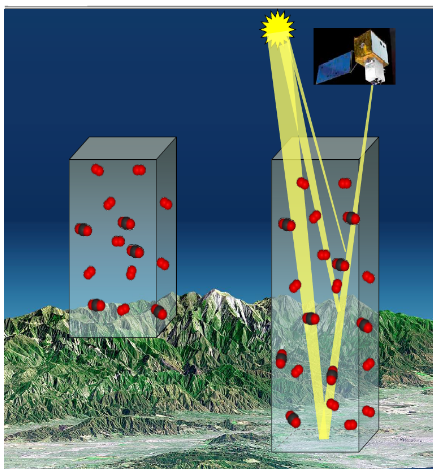
Universität Bremen

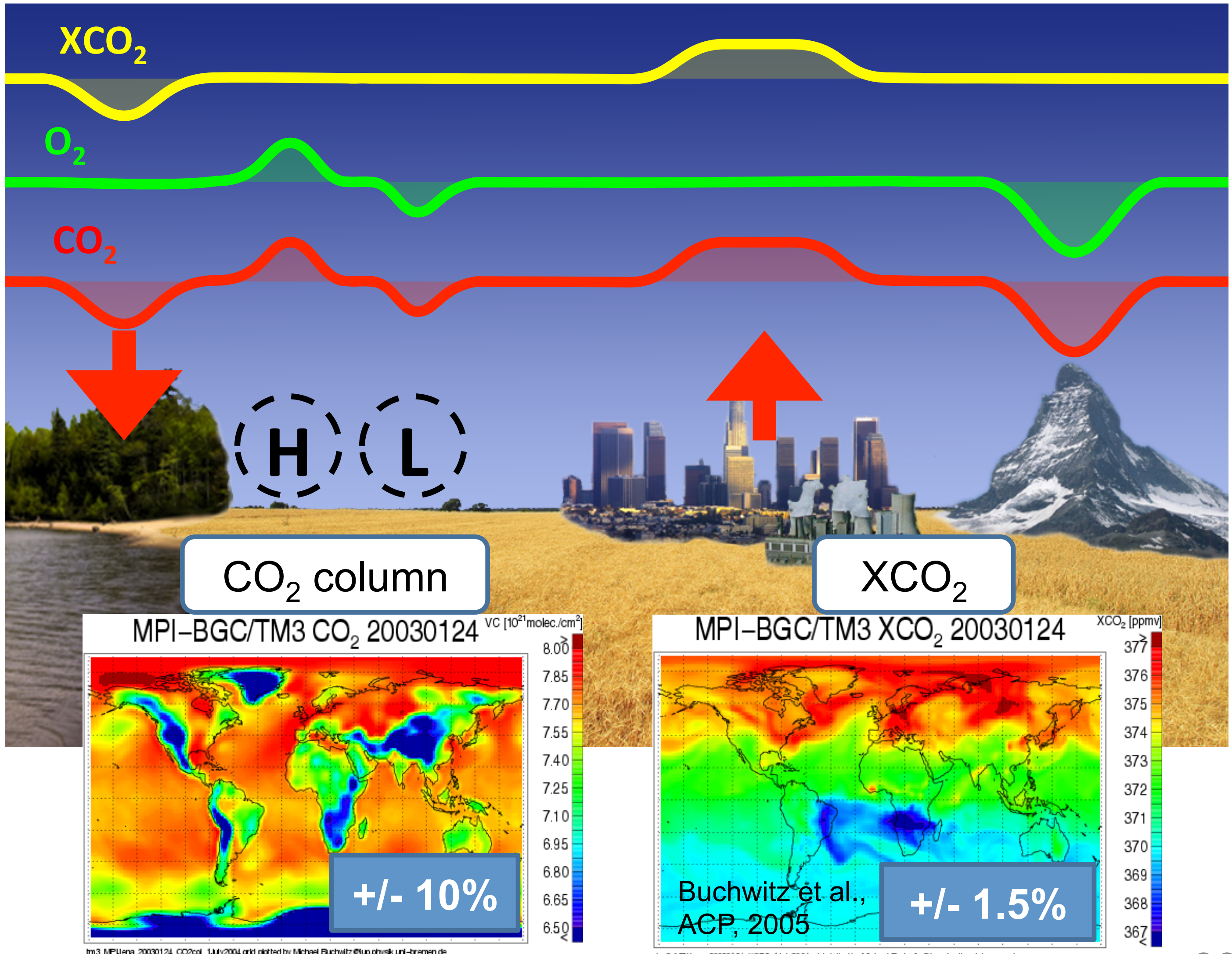
SCIAMACHY

XCO_2 = CO_2 column / Air column

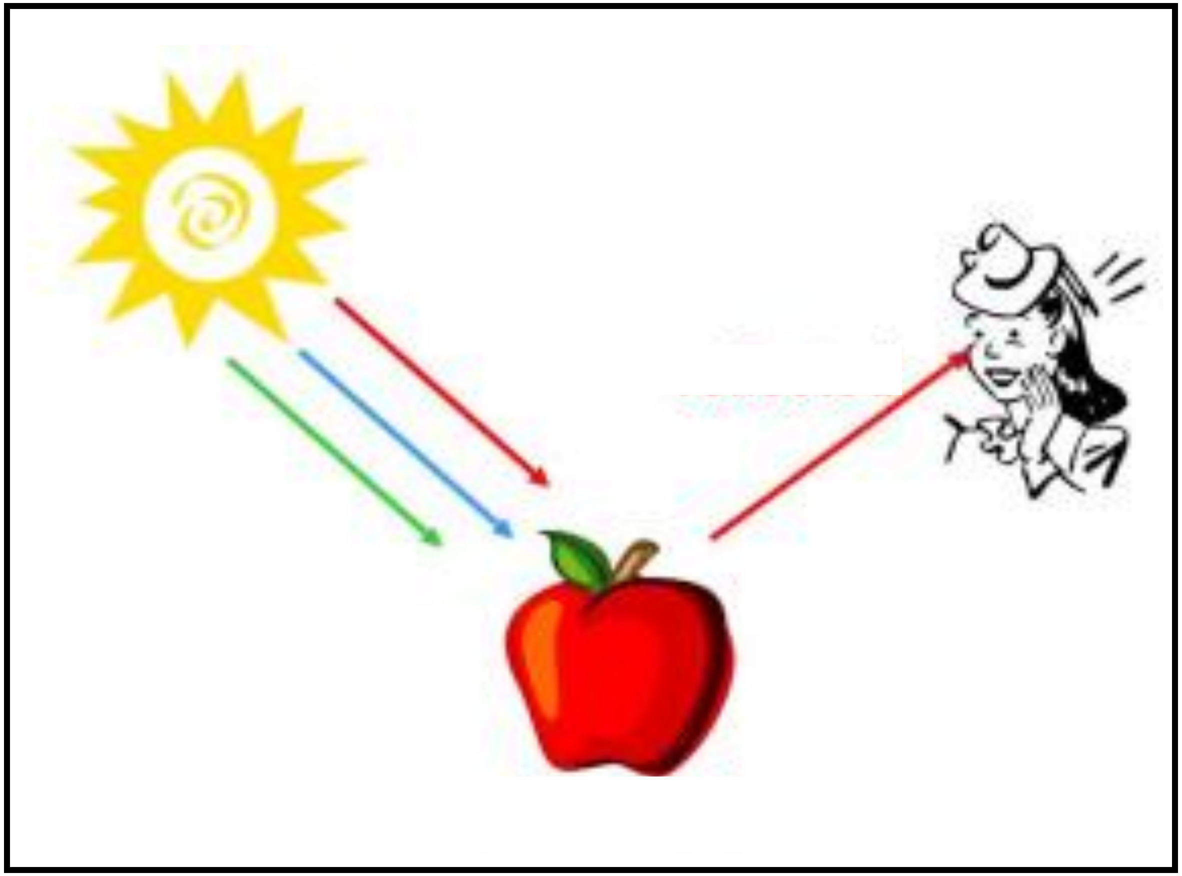
XCO_2 := CO_2 column-averaged dry air mixing ratio (mole fraction)

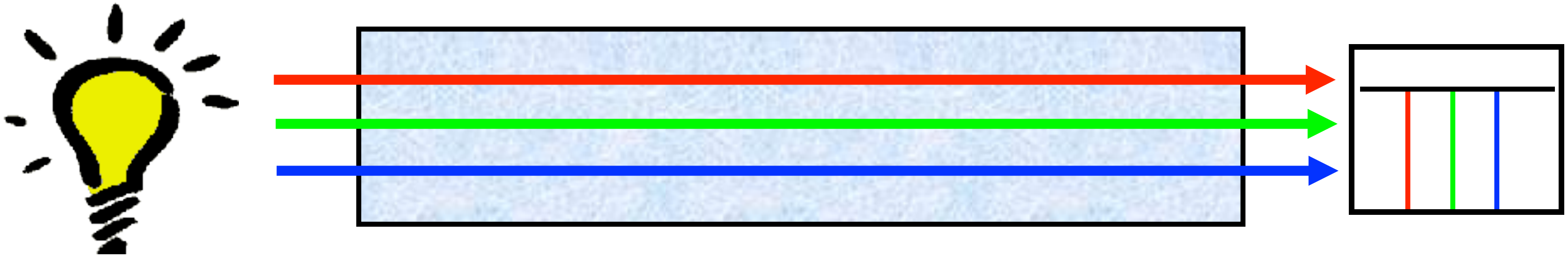
Vertical columns
[number of molecules / area]



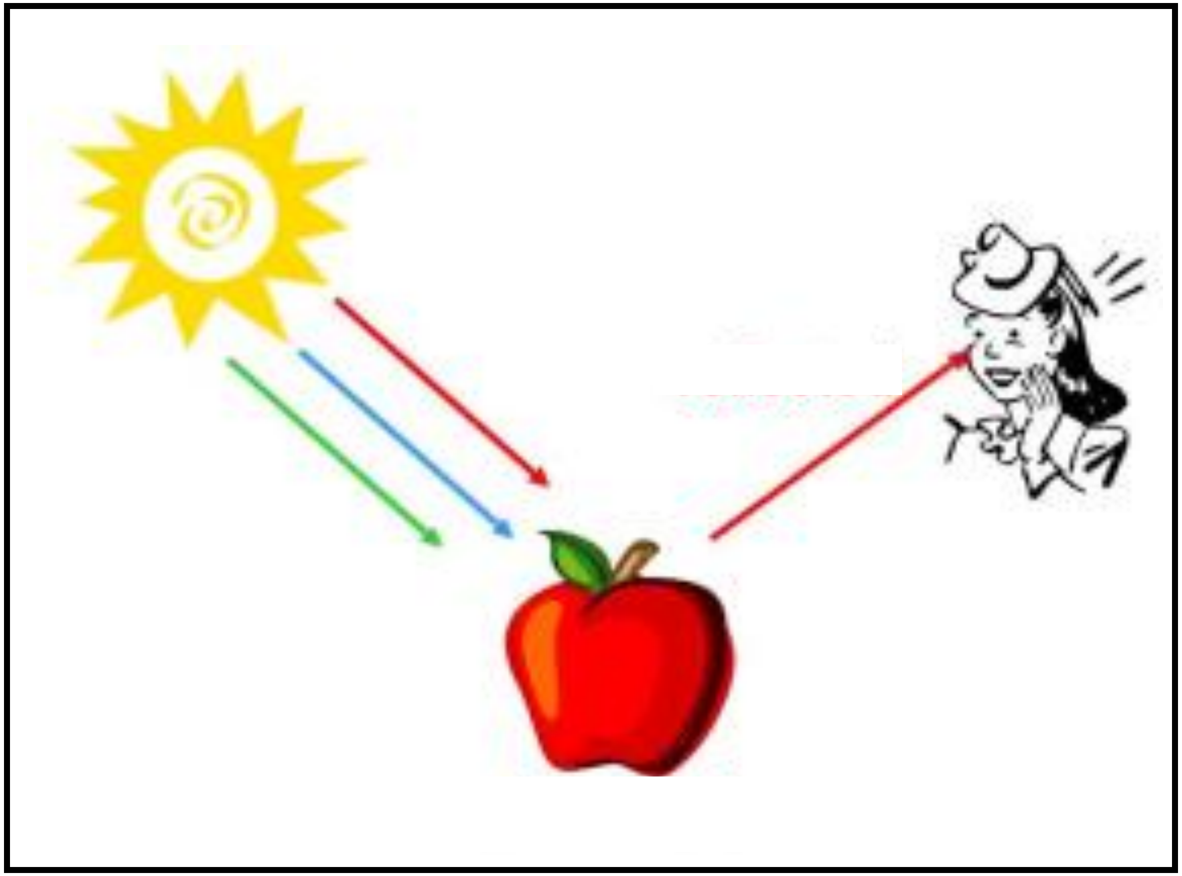


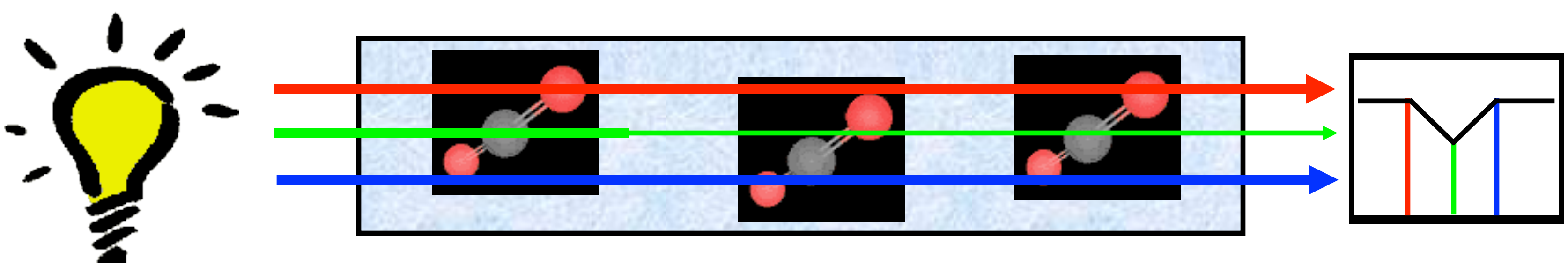
Counting molecules ?: Measurement principle - I



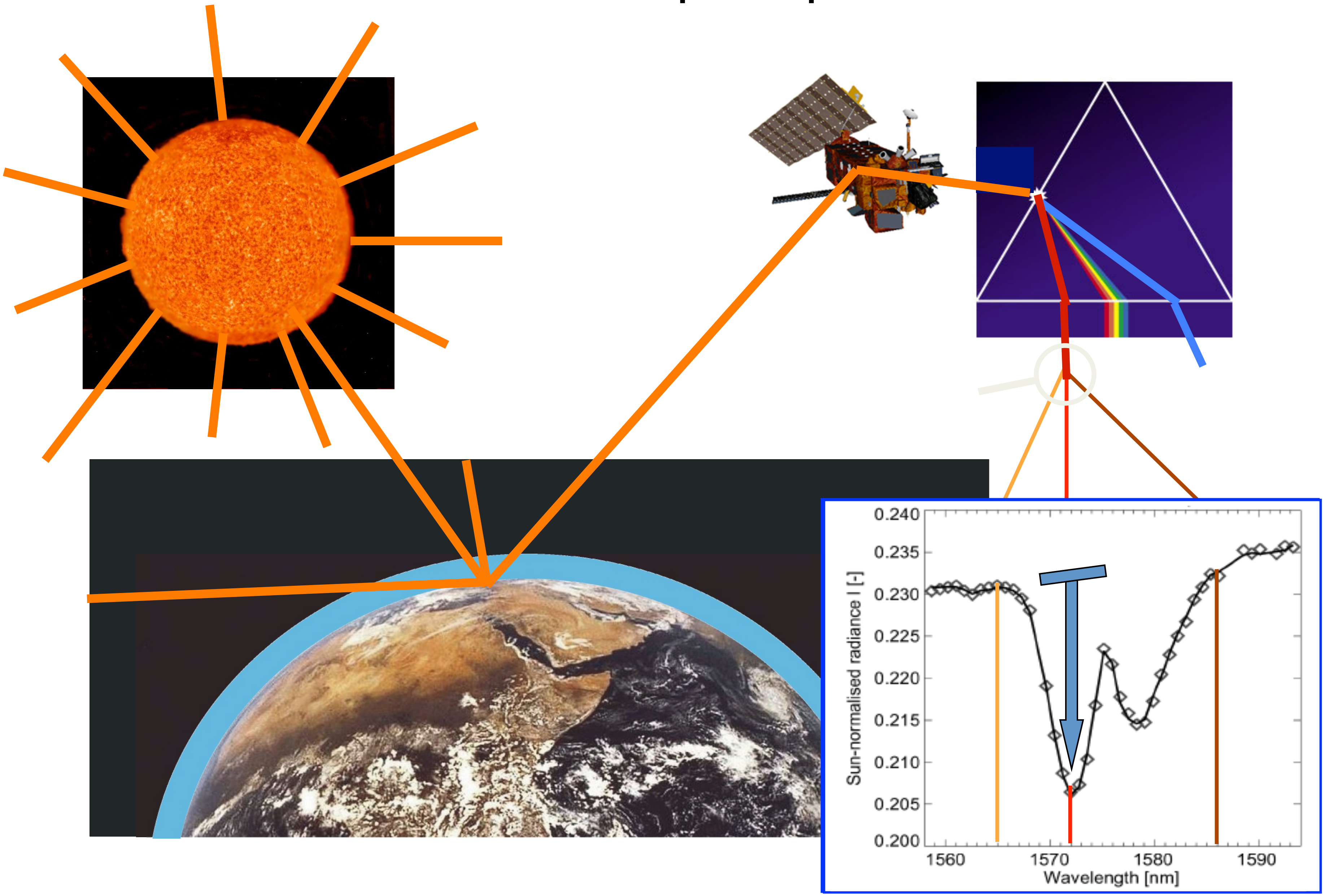


Measurement principle - II

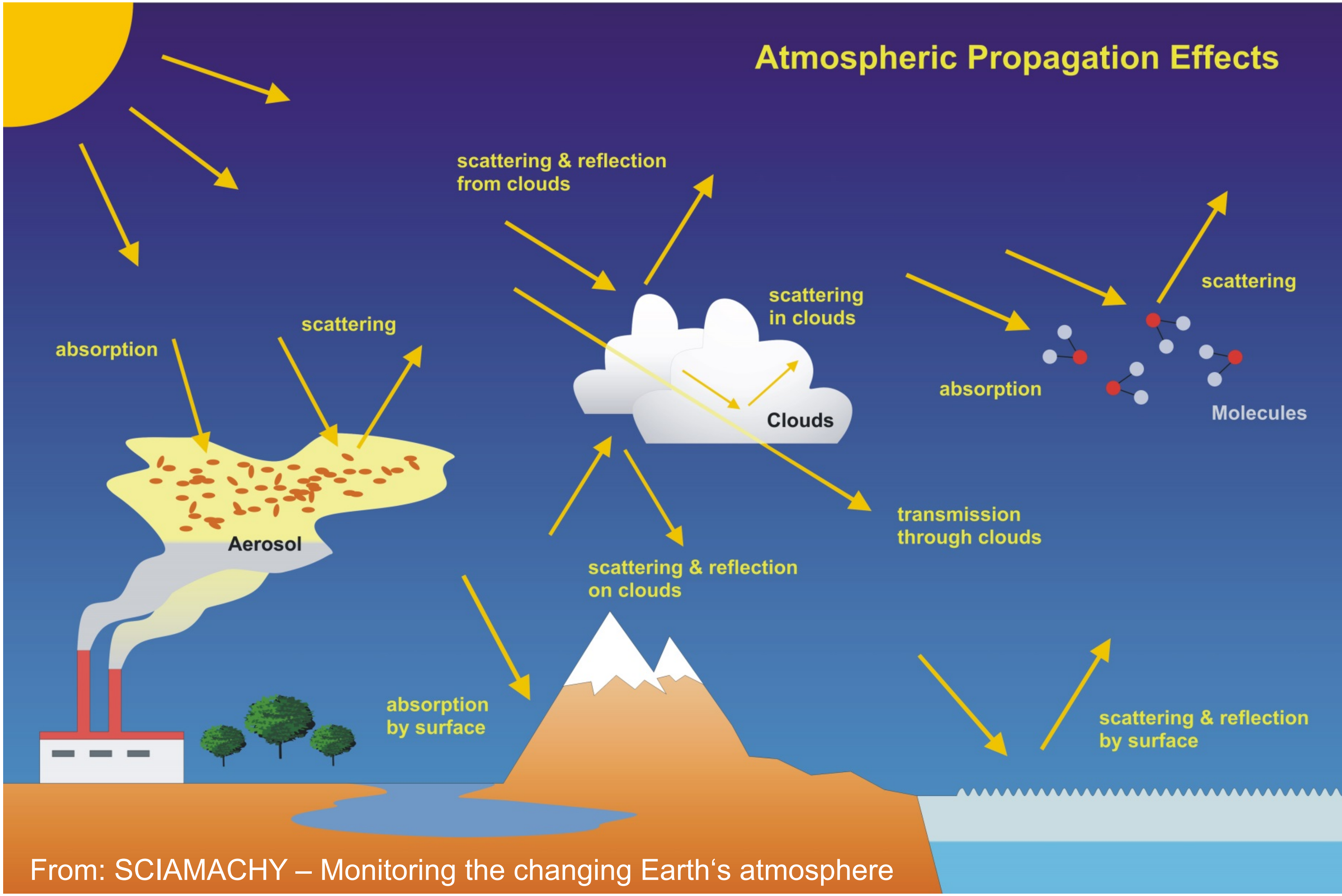




Measurement principle - III

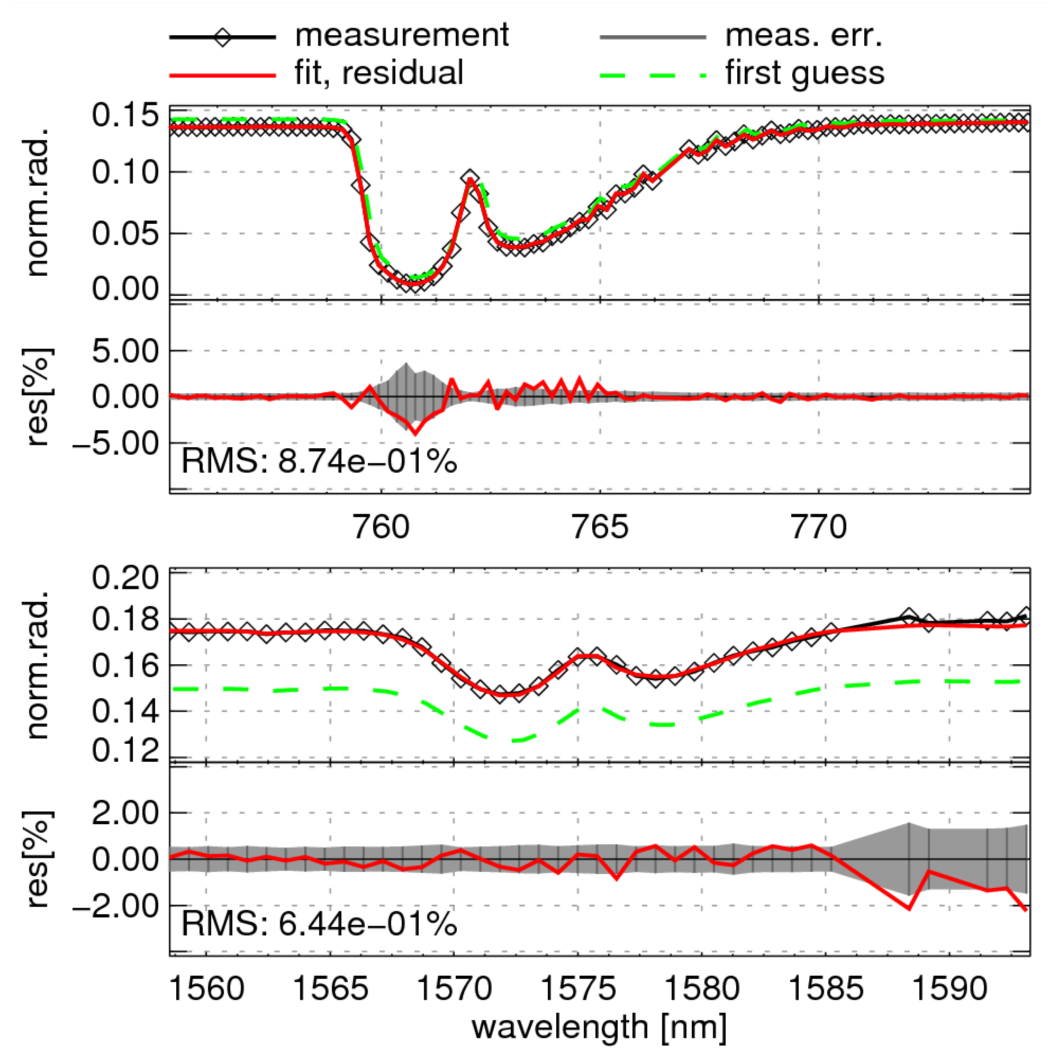


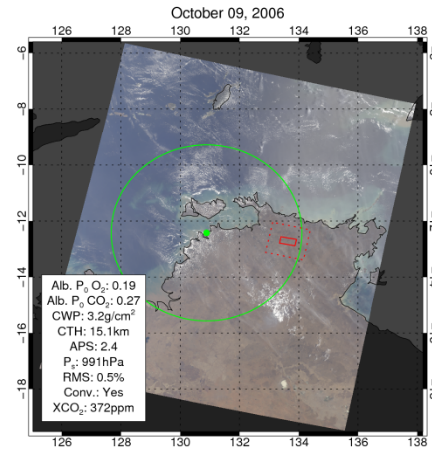
Light path issues

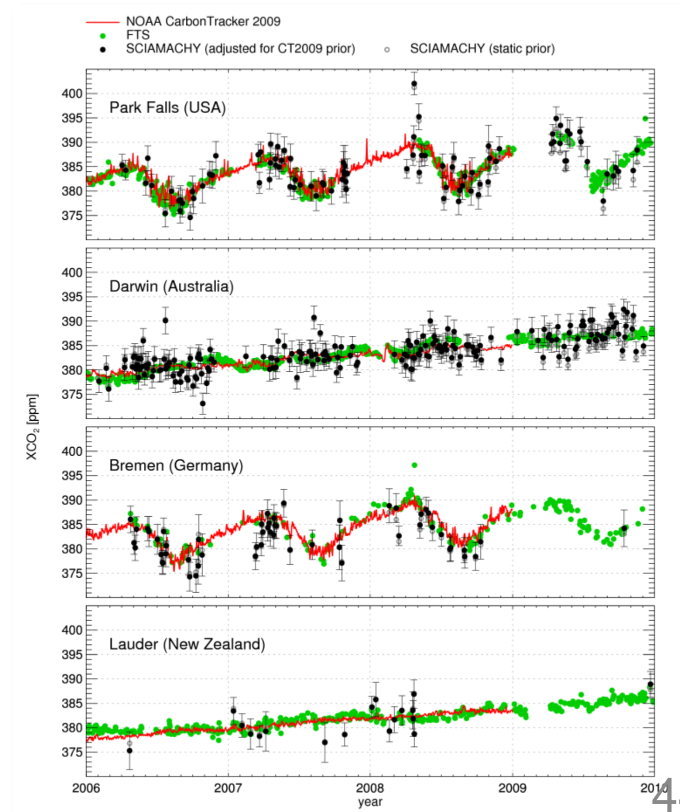


From: SCIAMACHY – Monitoring the changing Earth‘s atmosphere

SCIAMACHY / BESD: Example fit





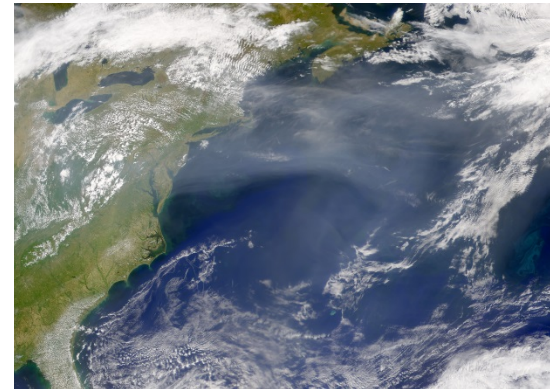


Reuter et al., JGR 2011

Radiative Transfer

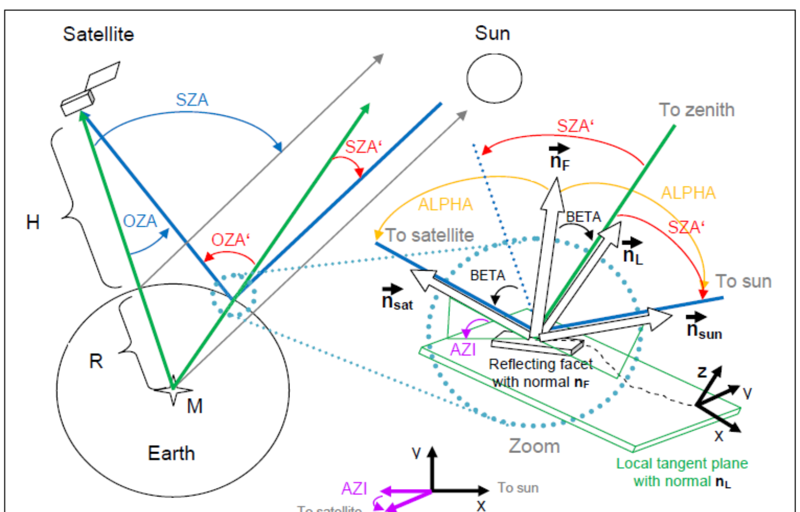
$$\frac{dI}{ds} = \varepsilon(S - I)$$

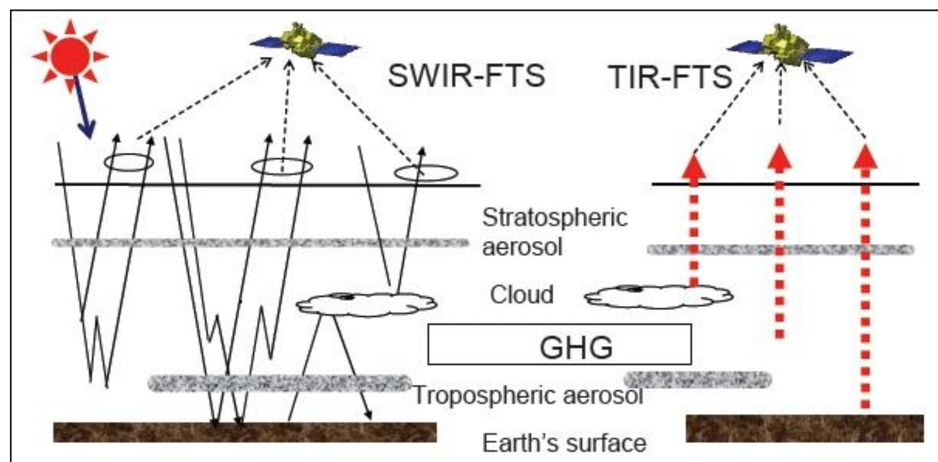
Change of radiance *I, dI,* along path *ds* due to sources (+εS) and/or losses (-εI).



e.g., plane-parallel RTE

$$\mu\frac{dI(z,\mu,\phi)}{dz} = -\varepsilon(z)\, I(z,\mu,\phi) + \frac{\beta(z)}{4\pi}\int_{0}^{2\pi} d\phi' \int_{-1}^{1} p(z,\mu,\mu',\phi,\phi')\, I(z,\mu',\phi')\, d\mu'.$$





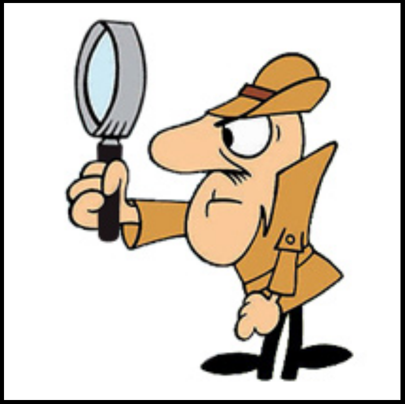
SCIA: IUP-UB retrieval algorithms

WFM-DOAS (WFMD)

- XCO_2 & XCH_4
- Focus on speed and data volume
- Tabulated RT
- Least squares fitting
- References:
  - Buchwitz et al., 2000, 2005
  - Heymann et al., 2012
  - Schneising et al., 2011, 2012, 2013

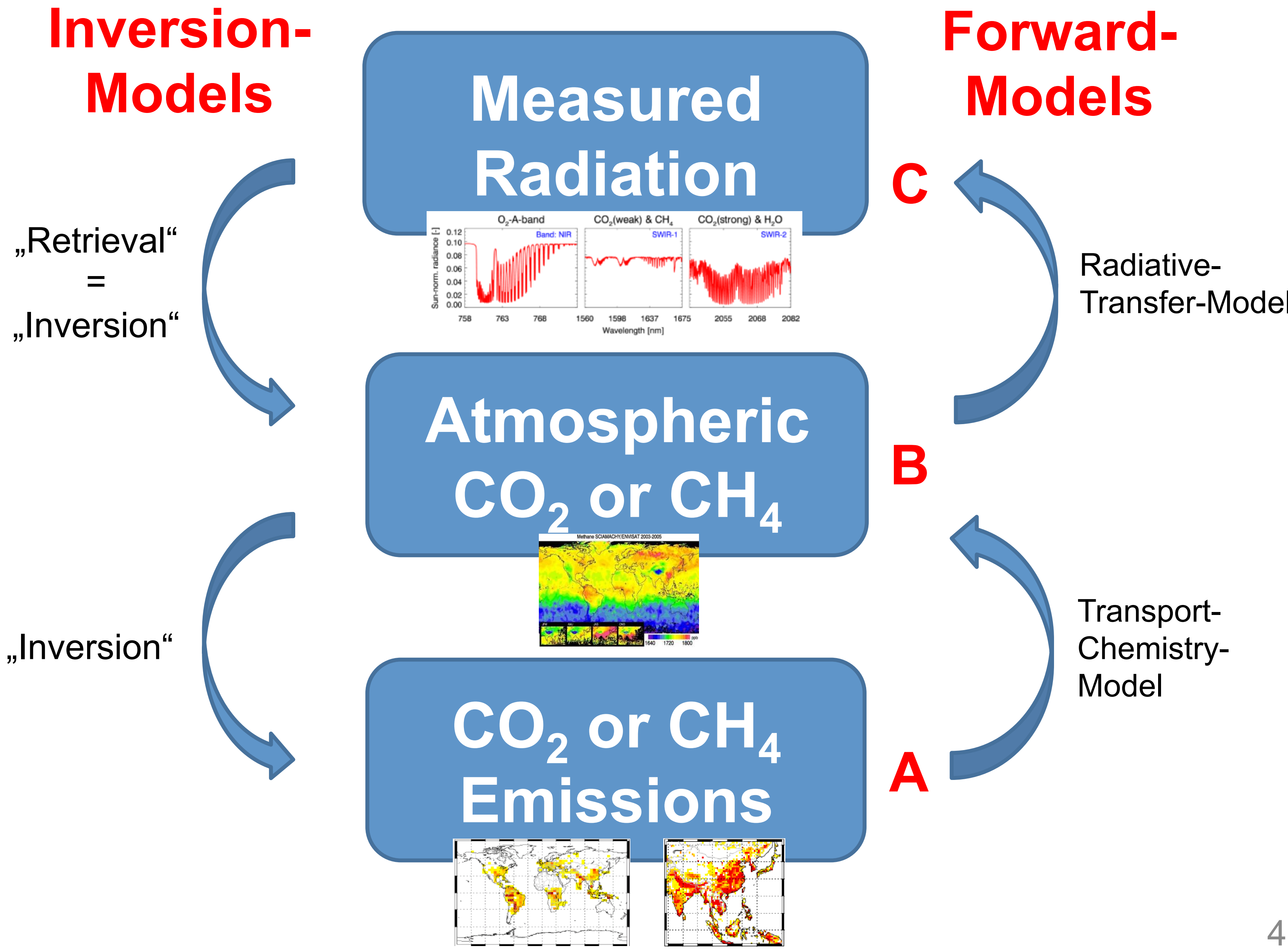
BESD

- XCO_2
- Focus on accuracy and precision
- Online RT
- Optimal estimation
- References:
  - Reuter et al., 2010, 2011



Details see ATBDs at http://www.esa-ghg-cci.org/

Measured radiation -> CO_2 emissions



Inversion ?

- Different methods
  - (Nearly all are) Based on „adjusting“ model parameters until model data „optimally“ agree with the observations
  - Requires sufficiently accurate and fast forward models
  - Often based on „Bayesian Inference“ or „Optimal Estimation“

Thomas Bayes [beɪz] (~1701 - 1761).
- English statistician, philosopher and Presbyterian minister.
- **Bayes‘ Theorem**: he suggested using this theorem to update beliefs considering new knowledge.

Thomas Bayes (wohl nicht authentisch)

http://en.wikipedia.org/

Bayes‘ Theorem

$$P(X|Y) = \frac{P(Y|X)P(X)}{P(Y)}$$

P(X = atmos.CO_2 | Y = radiation)
P(X = CO_2 emission | Y = atmos.CO_2)

+ Gaussian statistics

To be minimized cost function (Optimal Estimation (Rodgers, 2000)):

$$C(\boldsymbol{x}) = (\boldsymbol{y}^o - \boldsymbol{y}^m(\boldsymbol{x}))^T S_y^{-1} (\boldsymbol{y}^o - \boldsymbol{y}^m(\boldsymbol{x})) + (\boldsymbol{x} - \boldsymbol{x}_a)^T S_{xa}^{-1} (\boldsymbol{x} - \boldsymbol{x}_a)$$

Does God exist ?

GOD AND REV. BAYES

Bayes' theorem (Thomas Bayes, d. 1761) provides a means for directly calculating the probability for a statement being true based on the available evidence. In a 2003 book *The Probability of God* (New York: Three Rivers Press), Stephen Unwin attempted to calculate the probability that God exists. Unwin's result: 67 %. Physicist Larry Ford (private communication) has examined Unwin's calculation and made his own estimate using the same formula. Ford's result: 10^{-17}. In what follows I present Ford's nicely concise analysis, slightly modified.

http://www.colorado.edu/philosophy/vstenger/Briefs/Bayes.pdf

Retrieval: Optimal Estimation (Rodgers, 2000)

High-resolution radiance

$$I_\lambda^{mono}(x) \stackrel{\text{def}}{=} \pi L_\lambda(x)/F_\lambda$$

Radiance @ instrument resolution

$$< I_\lambda^{mono}(x) >_\lambda \stackrel{\text{def}}{=} I(x) \stackrel{\text{def}}{=} \pi < L_\lambda(x) > / < F_\lambda >$$

Linearized model:

$$ln(I(x)) \approx ln(I(x_a)) + \frac{\partial}{\partial x} ln(I(x))|_{x=x_a} (x - x_a)$$

$$\boldsymbol{y}^{mod}(\boldsymbol{x}) = \boldsymbol{y}_a + \boldsymbol{K}(\boldsymbol{x} - \boldsymbol{x}_a)$$

$$y_a \stackrel{\text{def}}{=} \boldsymbol{y}^{mod}(\boldsymbol{x}_a)$$

Jacobian matrix K:

rel./abs.

$$K_{ij} \stackrel{\text{def}}{=} \frac{\partial y_i}{\partial x_j} = \frac{\partial \ln(I(x_j))}{\partial x_j} \approx \frac{{}^{\Delta I}/_{I}}{\Delta x_j} \quad \rightarrow \quad \Delta\hat{x}_j = x_j - x_{aj}$$

rel./rel.

$$K_{ij} \stackrel{\text{def}}{=} \frac{\partial y_i}{\partial x_j} = \frac{\partial \ln(I(x_j))}{\partial \ln(x_j)} \approx \frac{{}^{\Delta I}/_{I}}{{}^{\Delta x_j}/_{x_j}} \quad \rightarrow \quad \Delta\hat{x}_j = (x_j - x_{aj})/\, x_{aj}$$

Cost function:

$$C(\boldsymbol{x}) = (\boldsymbol{y} - \boldsymbol{y}^{mod}(\boldsymbol{x}))^T S_y^{-1}(\boldsymbol{y} - \boldsymbol{y}^{mod}(\boldsymbol{x})) + (\boldsymbol{x} - \boldsymbol{x}_a)^T S_{xa}^{-1}(\boldsymbol{x} - \boldsymbol{x}_a)$$

Solution: Linear problem

$$\hat{\boldsymbol{x}} = \boldsymbol{x}_a + \boldsymbol{G}_y(\boldsymbol{y} - \boldsymbol{y}_a)$$

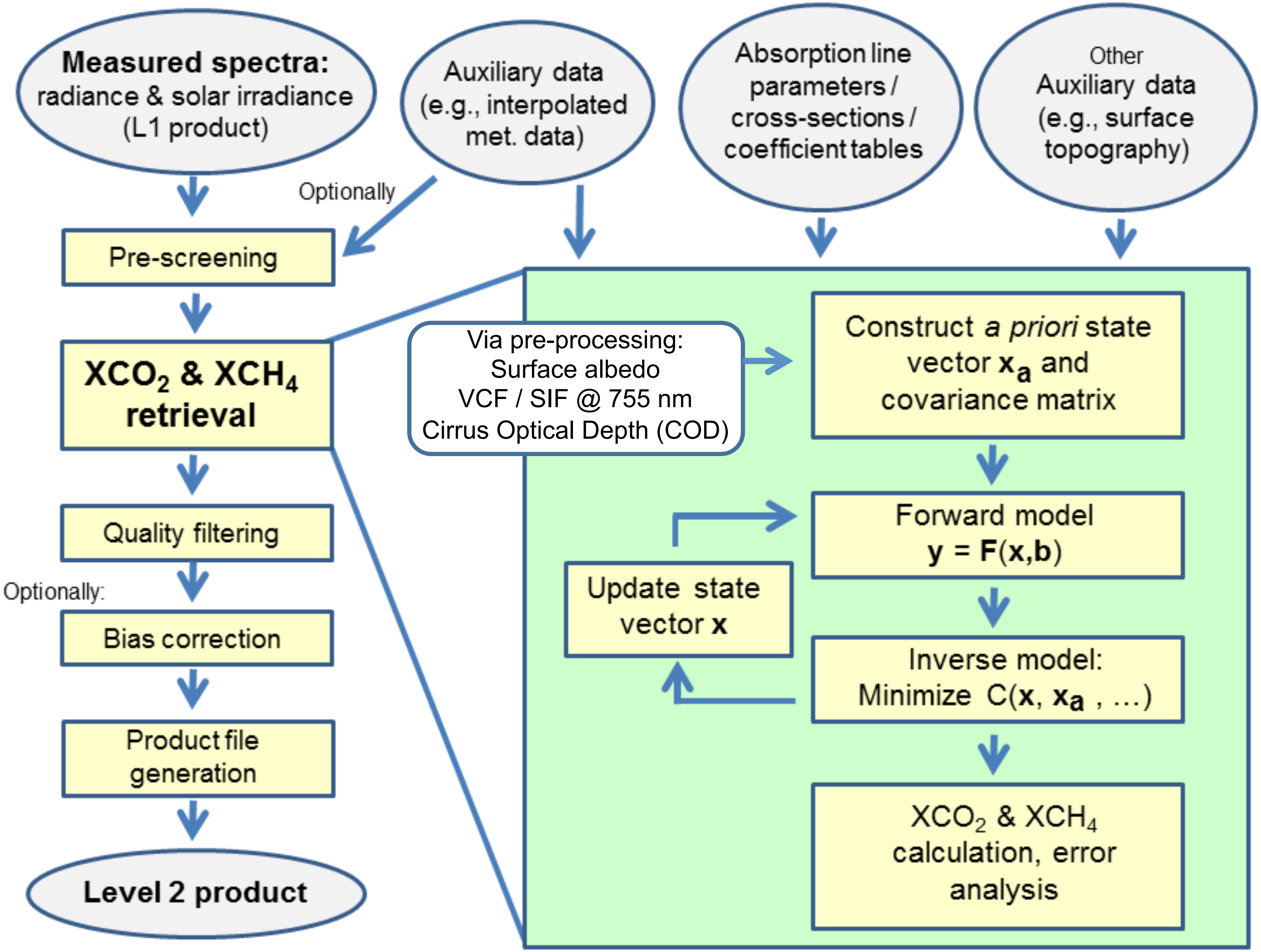
Non-linear problem

$$\boldsymbol{x}_{i+1} = \boldsymbol{x}_i + \hat{\boldsymbol{S}}_{x_i}\,[\boldsymbol{K}_i^T \boldsymbol{S}_y^{-1}\left(\boldsymbol{y} - \boldsymbol{y}^{mod}(\boldsymbol{x}_i)\right) - \boldsymbol{S}_{xa}^{-1}(\boldsymbol{x}_i - \boldsymbol{x}_a)]$$

$$\boldsymbol{G}_y = \frac{d\hat{x}}{dy} = \hat{\boldsymbol{S}}_x \boldsymbol{K}^T \boldsymbol{S}_y^{-1}$$

$$\hat{\boldsymbol{S}}_x = \frac{d\hat{x}}{dy} = (\boldsymbol{K}^T \boldsymbol{S}_y^{-1} \boldsymbol{K} + \boldsymbol{S}_{xa}^{-1})^{-1}$$

CarbonSat: BESD/C algorithm



BESD/C error anal.: Aerosols & clouds: Previous

Previous: COD a priori = 0.05, …

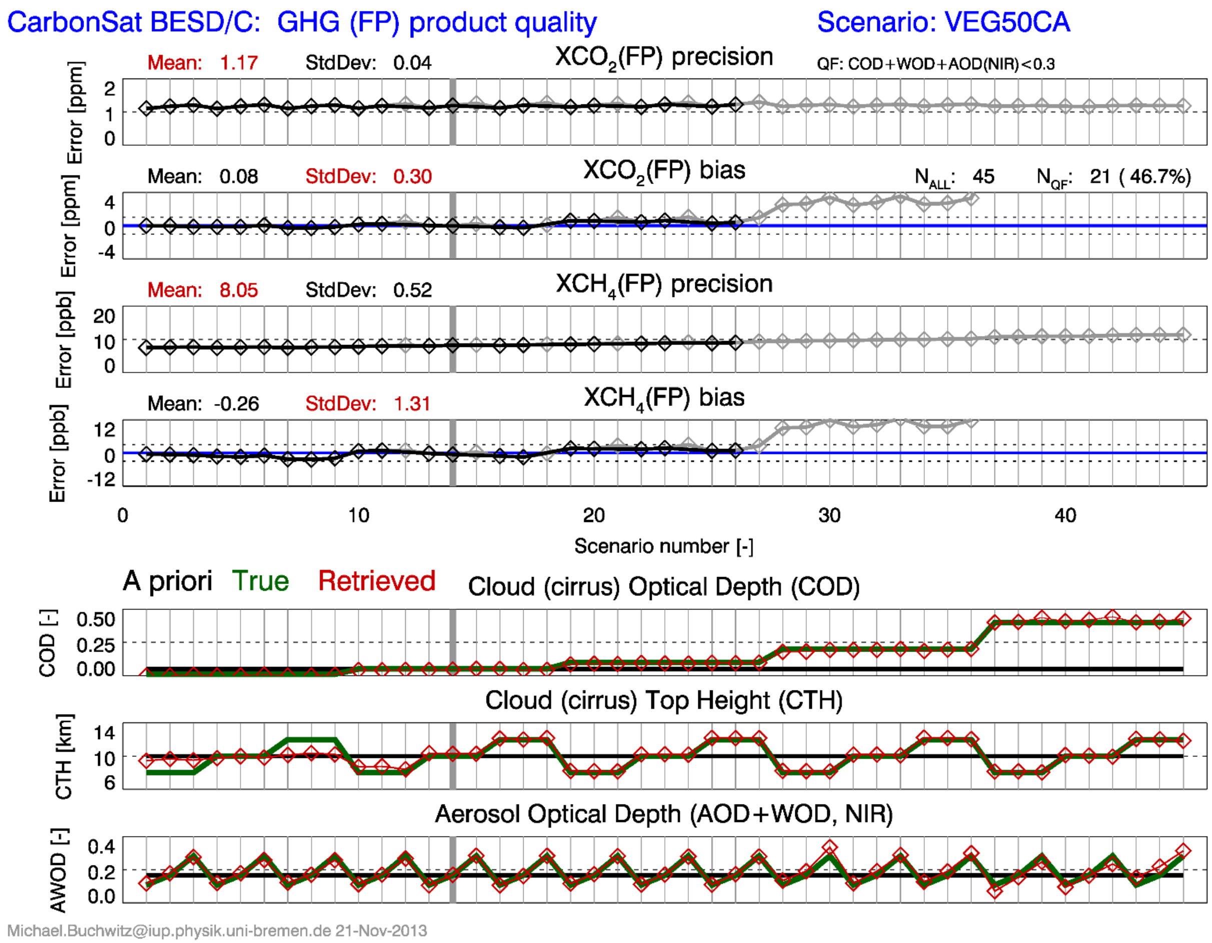
Aerosol type: Continental Average (CA70) SZA: 50, Albedo: Vegetation

Small particles: α ~2.3

Bias XCO_2:
+0.08+/-0.30 ppm

Bias XCH_4:
-0.26+/-1.31 ppb

QF: SOD<0.3
Ngood: 21 (47%)
Nall: 45



BESD/C error anal.: Aerosols & clouds: Latest

Latest: COD a priori via 1939 nm, …

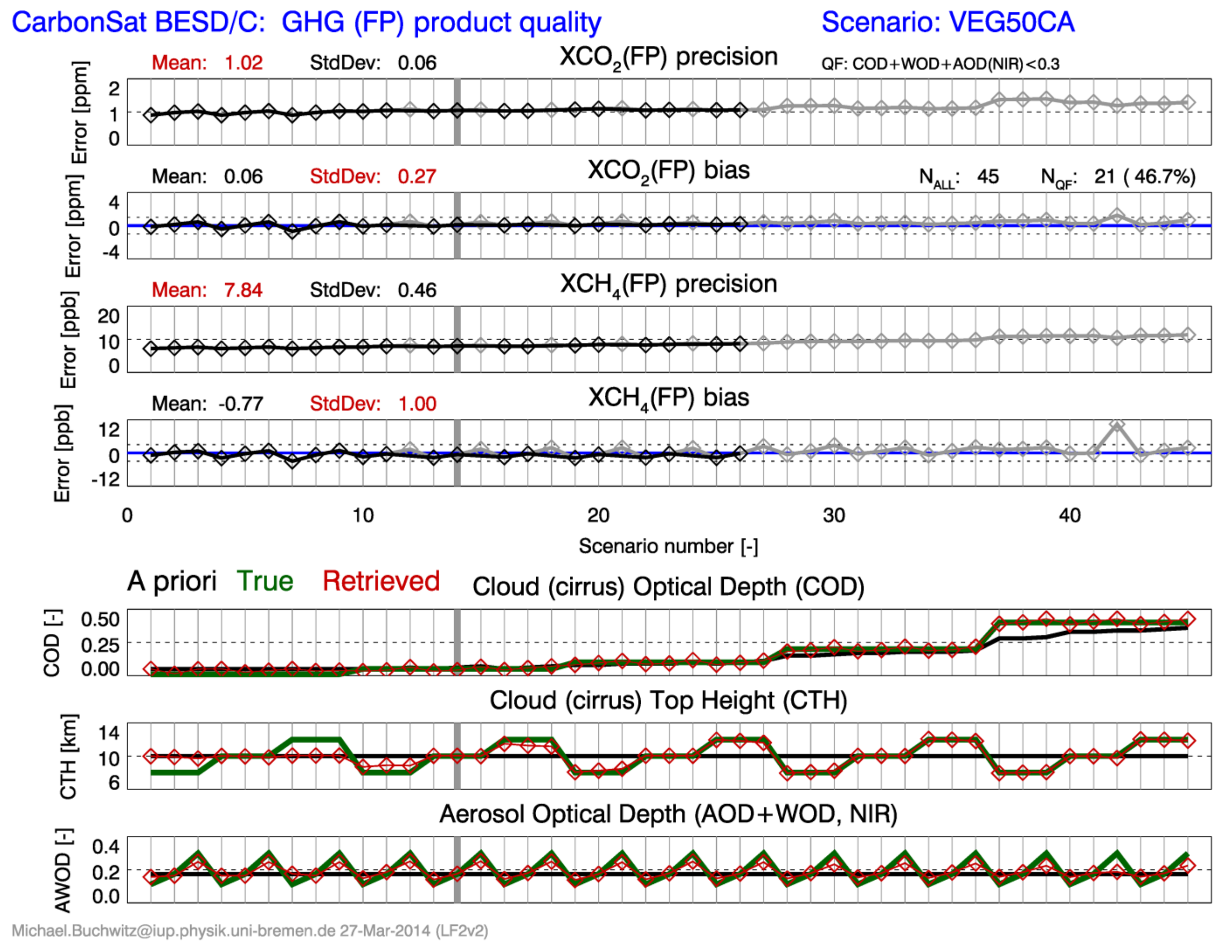
Aerosol type: Continental Average (CA70) SZA: 50, Albedo: Vegetation

Small particles: α ~2.3

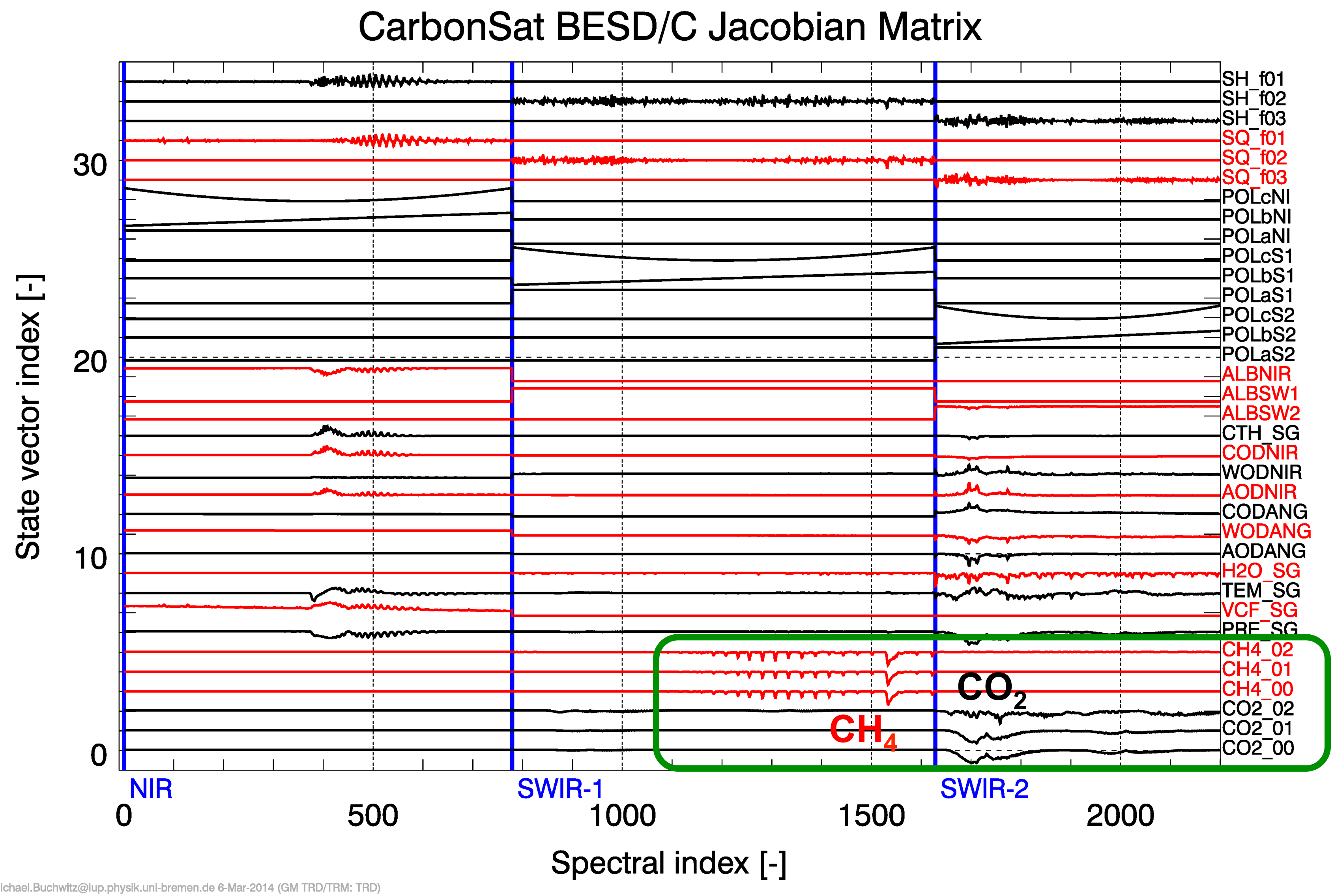
Bias XCO_2:
+0.06+/-0.27 ppm

Bias XCH_4:
-0.77+/-1.00 ppb

QF: SOD<0.3
Ngood: 21 (47%)
Nall: 45



Jacobian matrix (K): Example

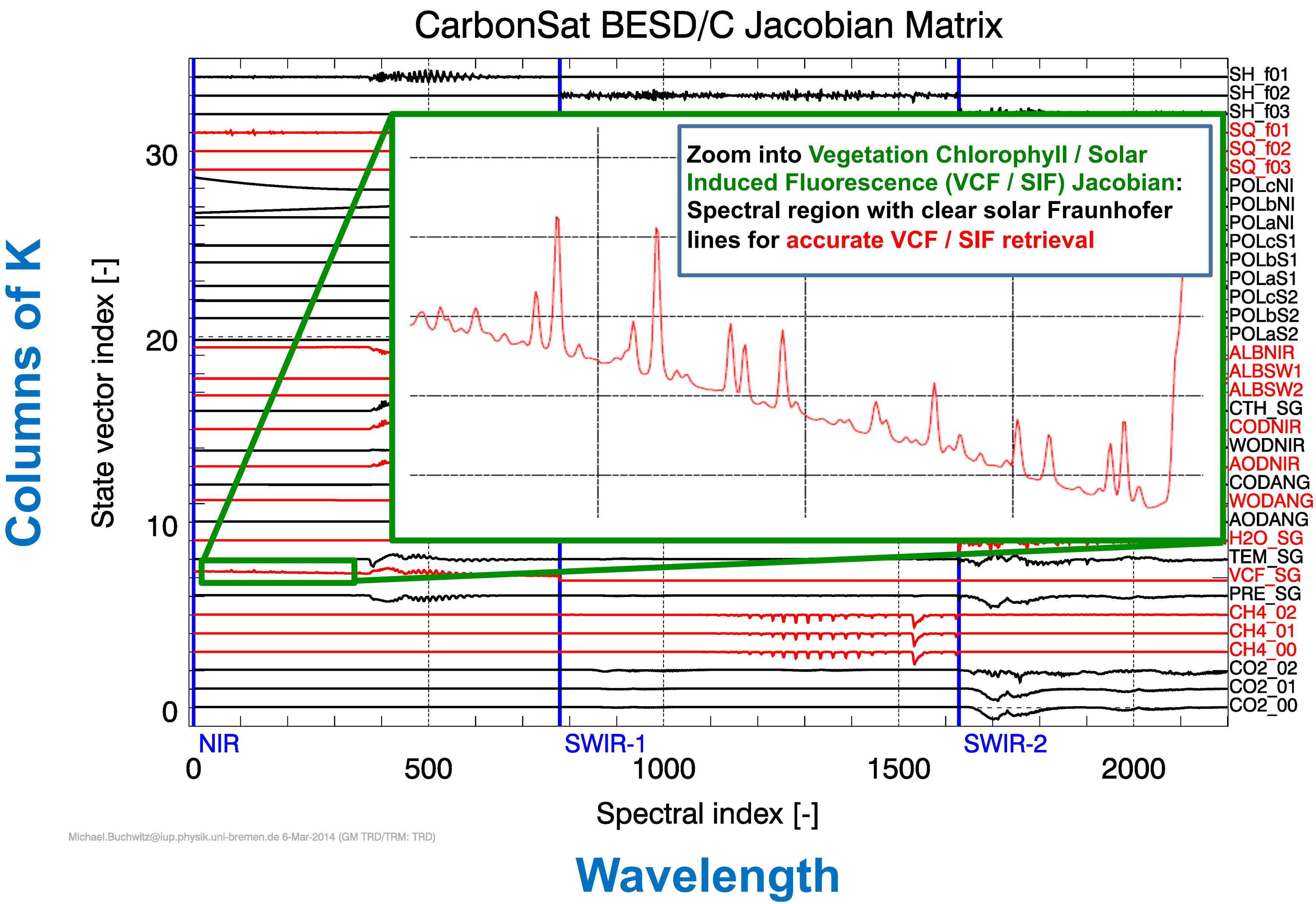


Columns of K

Wavelength

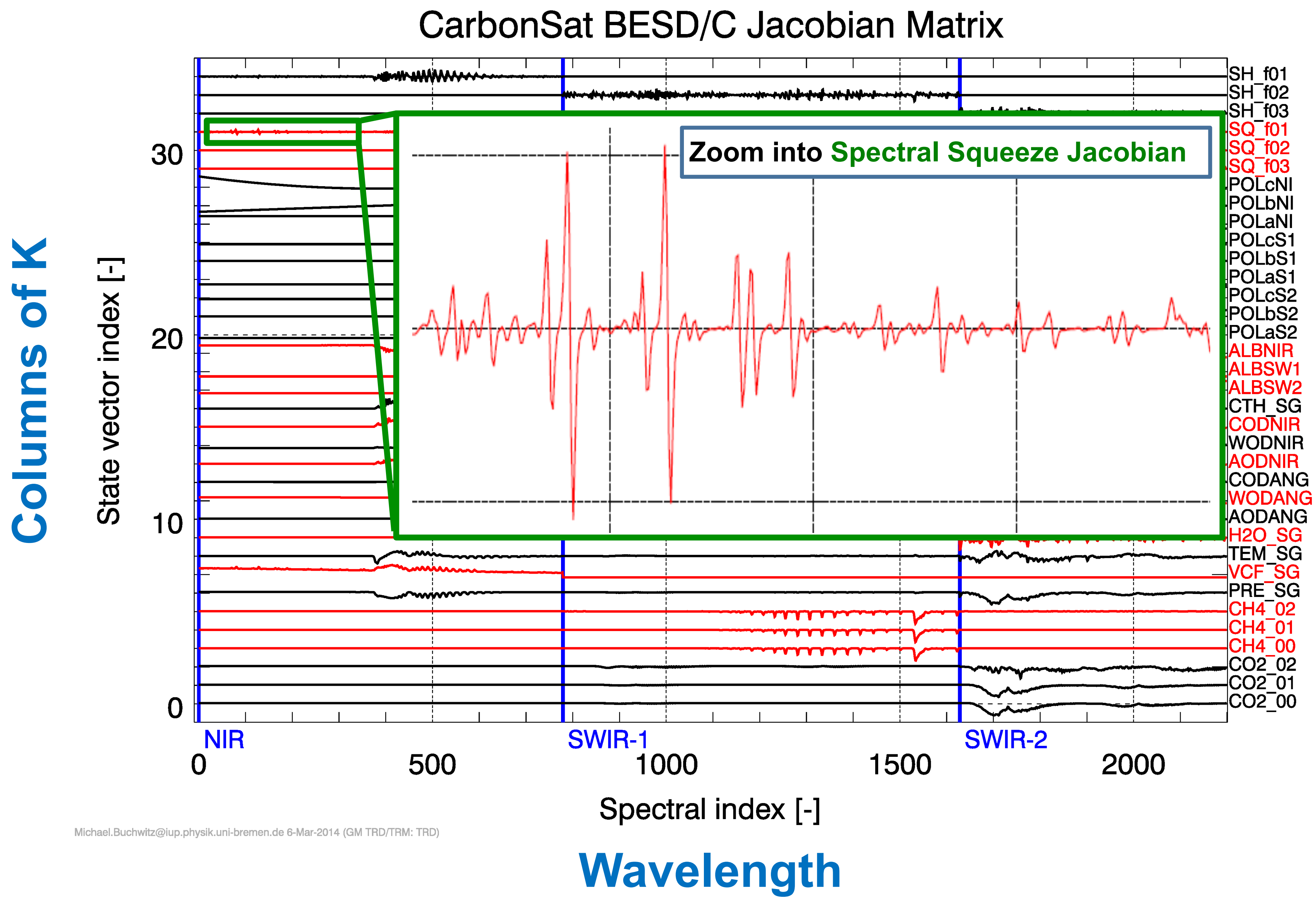
Details: Buchwitz et al., AMT, 2013

Jacobian matrix (K): Example



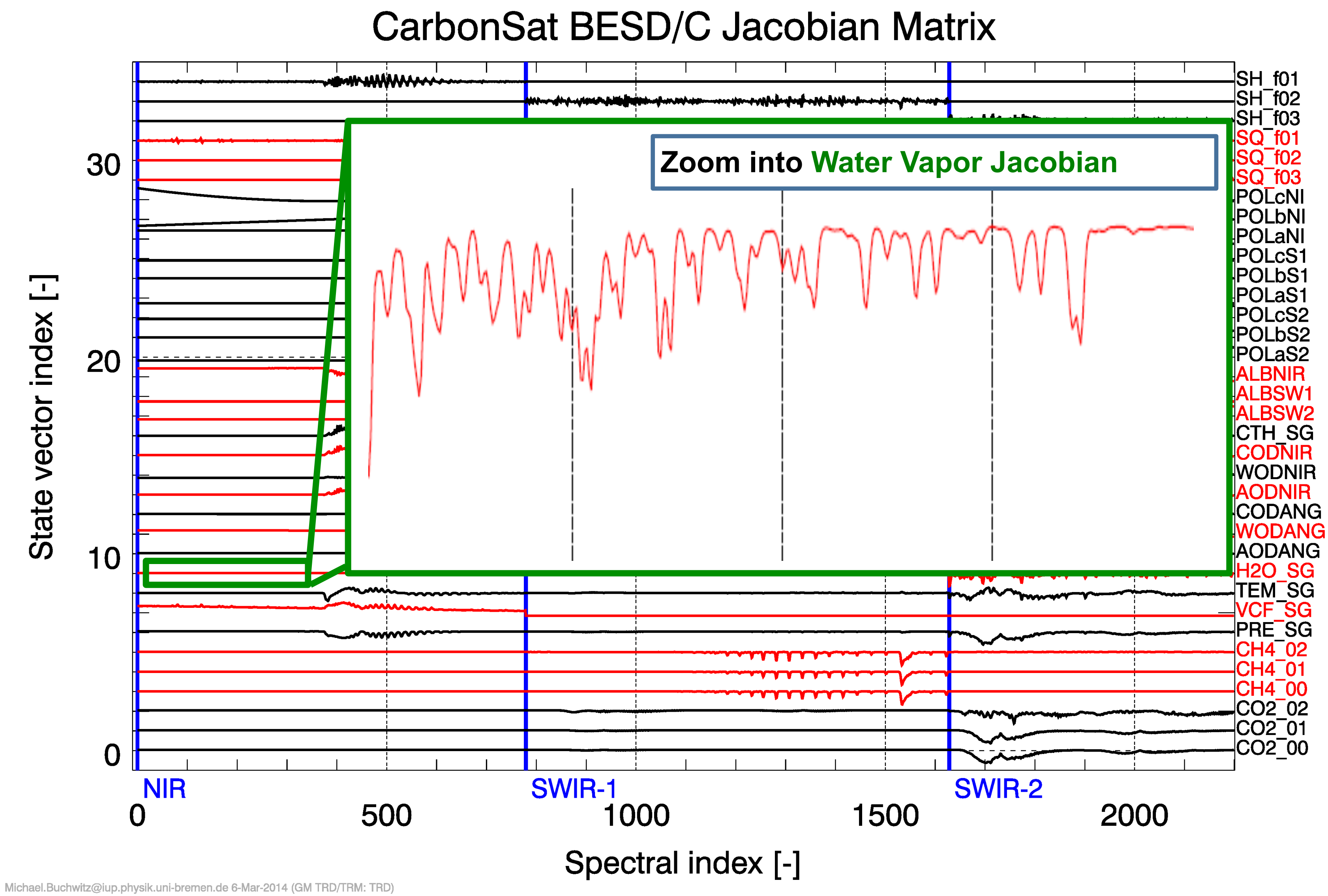
Details: Buchwitz et al., AMT, 2013

Jacobian matrix (K): Example



Details: Buchwitz et al., AMT, 2013

Jacobian matrix (K): Example

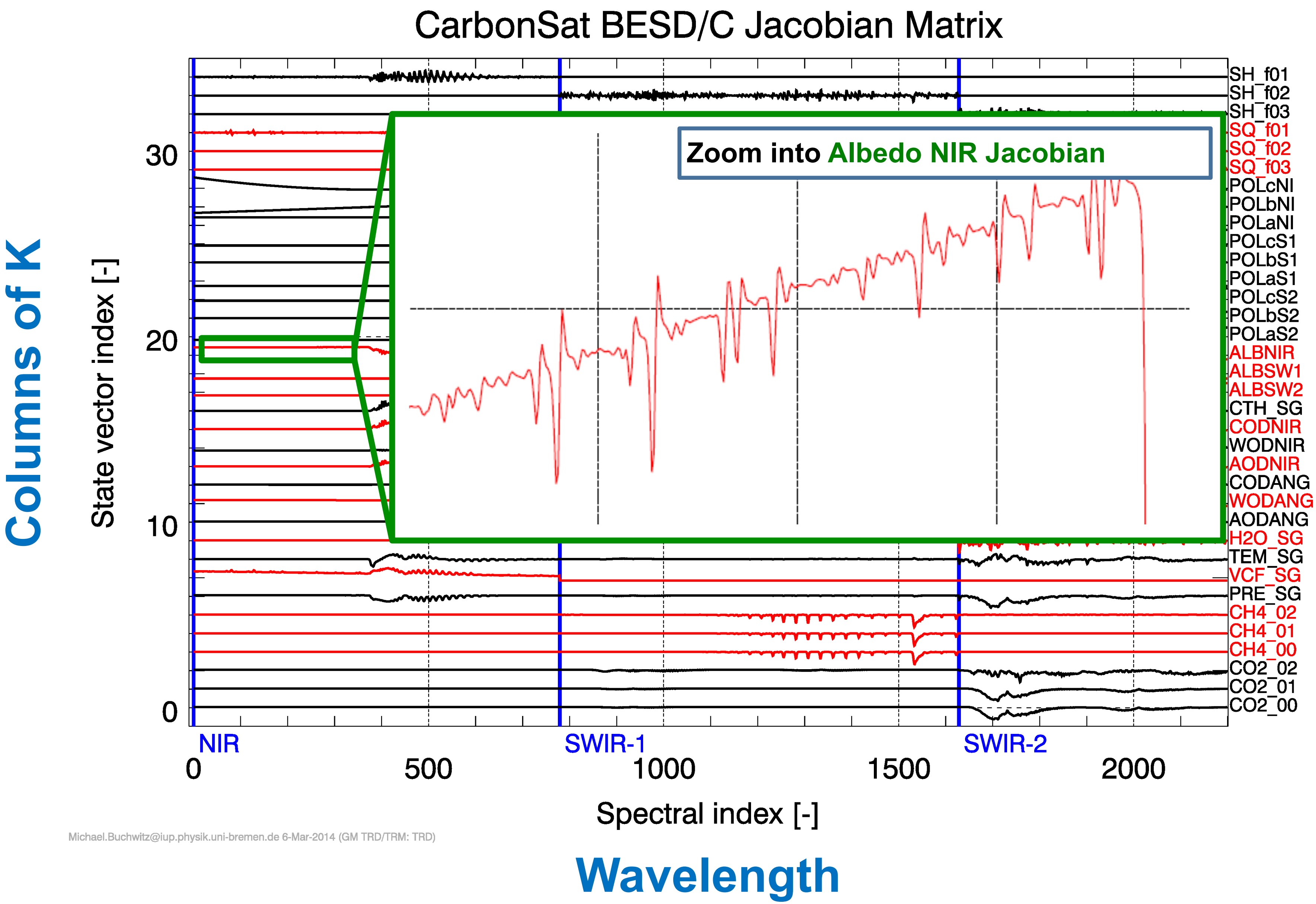


Columns of K

Wavelength

Details: Buchwitz et al., AMT, 2013

Jacobian matrix (K): Example



Details: Buchwitz et al., AMT, 2013

One could say much more …

Retrieval algorithms:

- DOAS (WFM-DOAS, IMAP-DOAS, …), …
- Full Physics (FP) versus Proxy (PR), …

Modelling & inverse modelling:

- …

Other topics:

- …

Satellite XCO_2 retrieval algorithms …

From „First ever“ → to „recent“

Buchwitz et al., 2000

JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 105, NO. D12, PAGES 15,231–15,245, JUNE 27, 2000

WFMD

A near-infrared optimized DOAS method for the fast global retrieval of atmospheric CH_4, CO, CO_2, H_2O, and N_2O total column amounts from SCIAMACHY Envisat-1 nadir radiances

Michael Buchwitz, Vladimir V. Rozanov, and John P. Burrows

Institut für Fernerkundung, Universität Bremen, Bremen, Germany

Abstract. A new method for the fast and accurate retrieval of atmospheric trace gas total column amounts from near-infrared nadir radiances, to be measured by the scanning imaging absorption spectrometer for atmospheric chartography (SCIAMACHY) spectrometer on board the European Space Agency Envisat-1 satellite, has been investigated. It can be characterized as a weighting function modified differential optical absorption spectroscopy approach (WFM-DOAS). The reference spectra of the linear fit include the trace gas total column weighting

Bovensmann et al., 2010

Atmos. Meas. Tech., 3, 781–811, 2010
www.atmos-meas-tech.net/3/781/2010/
doi:10.5194/amt-3-781-2010

BESD/C

Atmospheric Measurement Techniques

A remote sensing technique for global monitoring of power plant CO_2 emissions from space and related applications

H. Bovensmann[1], M. Buchwitz[1], J. P. Burrows[1], M. Reuter[1], T. Krings[1], K. Gerilowski[1], O. Schneising[1], J. Heymann[1], A. Tretner[2], and J. Erzinger[2]

[1]Institute of Environmental Physics (IUP), University of Bremen FB1, Otto Hahn Allee 1, 28334 Bremen, Germany
[2]Helmholtz Centre Potsdam – GFZ German Research Centre for Geosciences, Telegrafenberg, 14473 Potsdam, Germany

Schneising et al., 2011, 2012, 2013, 2014

Atmos. Chem. Phys., 14, 133–141, 2014
www.atmos-chem-phys.net/14/133/2014/
doi:10.5194/acp-14-133-2014

Atmospheric Chemistry and Physics

WFMD

Terrestrial carbon sink observed from space: variation of growth rates and seasonal cycle amplitudes in response to interannual surface temperature variability

O. Schneising, M. Reuter, M. Buchwitz, J. Heymann, H. Bovensmann, and J. P. Burrows

Institute of Environmental Physics (IUP), University of Bremen FB1, Bremen, Germany

Reuter et al., 2010, 2011

Atmos. Meas. Tech., 3, 209–232, 2010
www.atmos-meas-tech.net/3/209/2010/

Atmospheric Measurement Techniques

A method for improved SCIAMACHY CO_2 retrieval in the presence of optically thin clouds

BESD

M. Reuter, M. Buchwitz, O. Schneising, J. Heymann, H. Bovensmann, and J. P. Burrows

University of Bremen, Institute of Environmental Physics, P.O. Box 330440, 28334 Bremen, Germany

Reuter et al., 2013

Atmos. Chem. Phys., 13, 1771–1780, 2013
www.atmos-chem-phys.net/13/1771/2013/
doi:10.5194/acp-13-1771-2013

EMMA

Atmospheric Chemistry and Physics

A joint effort to deliver satellite retrieved atmospheric CO_2 concentrations for surface flux inversions: the ensemble median algorithm EMMA

M. Reuter[1], H. Bösch[2], H. Bovensmann[1], A. Bril[3], M. Buchwitz[1], A. Butz[4], J. P. Burrows[1], C. W. O'Dell[5], S. Guerlet[6], O. Hasekamp[6], J. Heymann[1], N. Kikuchi[3], S. Oshchepkov[3], R. Parker[2], S. Pfeifer[7], O. Schneising[1], T. Yokota[3], and Y. Yoshida[3]

Buchwitz et al., 2005

WFMD

Atmos. Chem. Phys., 5, 941–962, 2005
www.atmos-chem-phys.org/acp/5/941/
SRef-ID: 1680-7324/acp/2005-5-941
European Geosciences Union

Atmospheric Chemistry and Physics

Atmospheric methane and carbon dioxide from SCIAMACHY satellite data: initial comparison with chemistry and transport models

M. Buchwitz[1], R. de Beek[1], J. P. Burrows[1], H. Bovensmann[1], T. Warneke[1], J. Notholt[1], J. F. Meirink[2], A. P. H. Goede[2], P. Bergamaschi[3], S. Körner[4], M. Heimann[4], and A. Schulz[5]

Oshchepkov et al., 2008

JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 113, D23210, doi:10.1029/2008JD010061, 2008

PPDF-based method to account for atmospheric light scattering in observations of carbon dioxide from space

PPDF

Sergey Oshchepkov,[1] Andrey Bril,[1] and Tatsuya Yokota[1]

Received 4 March 2008; revised 5 June 2008; accepted 18 August 2008; published 10 December 2008.

[1] We present an original method that accounts for thin clouds in carbon dioxide retrievals from space-based reflected sunlight observations in near-infrared regions. This approach involves a reasonable, simple parameterization of effective transmittance using a set of parameters that describe the path-length modification caused by clouds. The complete retrieval scheme included the following: estimation of cloud parameters

O'Dell et al., 2012

Atmos. Meas. Tech., 5, 99–121, 2012
www.atmos-meas-tech.net/5/99/2012/
doi:10.5194/amt-5-99-2012

Atmospheric Measurement Techniques

ACOS

The ACOS CO_2 retrieval algorithm – Part 1: Description and validation against synthetic observations

C. W. O'Dell[1], B. Connor[2], H. Bösch[3], D. O'Brien[1], C. Frankenberg[4], R. Castano[4], M. Christi[1], D. Eldering[4], B. Fisher[4], M. Gunson[4], J. McDuffie[4], C. E. Miller[4], V. Natraj[4], F. Oyafuso[4], I. Polonsky[1], M. Smyth[4], T. Taylor[1], G. C. Toon[4], P. O. Wennberg[5], and D. Wunch[5]

Butz et al., 2011

RemoTeC

GEOPHYSICAL RESEARCH LETTERS, VOL. 38, L14812, doi:10.1029/2011GL047888, 2011

Toward accurate CO_2 and CH_4 observations from GOSAT

A. Butz,[1,2] S. Guerlet,[2] O. Hasekamp,[2] D. Schepers,[2] A. Galli,[2] I. Aben,[2] C. Frankenberg,[3] J.-M. Hartmann,[4] H. Tran,[4] A. Kuze,[5] G. Keppel-Aleks,[6] G. Toon,[3] D. Wunch,[6] P. Wennberg,[6] N. Deutscher,[7,8] D. Griffith,[7] R. Macatangay,[7] J. Messerschmidt,[8] J. Notholt,[8] and T. Warneke[8]

Received 21 April 2011; revised 14 June 2011; accepted 20 June 2011; published 30 July 2011.

[1] The column-average dry air mole fractions of atmospheric carbon dioxide and methane (X_{CO_2} and X_{CH_4}) are inferred from observations of backscattered sunlight conducted by the Greenhouse gases Observing SATellite (GOSAT). Comparing the first year of GOSAT retrievals over land with colocated ground-based observations of the Total Carbon Column Observing Network (TCCON), we

the requirement for X_{CH_4} is somewhat less stringent than for X_{CO_2} [e.g., *Chevallier et al.*, 2007; *Meirink et al.*, 2006].

[3] Currently, the SCanning Imaging Absorption spectroMeter for Atmospheric CartographY (SCIAMACHY) in orbit since 2002, and the Greenhouse gases Observing SATellite (GOSAT), in orbit since January 2009, aim at achieving this goal by exploiting absorption spectra of

Buchwitz et al., 2013

Atmos. Meas. Tech., 6, 3477–3500, 2013
www.atmos-meas-tech.net/6/3477/2013/
doi:10.5194/amt-6-3477-2013

BESD/C

Atmospheric Measurement Techniques

Carbon Monitoring Satellite (CarbonSat): assessment of atmospheric CO_2 and CH_4 retrieval errors by error parameterization

M. Buchwitz[1], M. Reuter[1], H. Bovensmann[1], D. Pillai[1], J. Heymann[1], O. Schneising[1], V. Rozanov[1], T. Krings[1], J. P. Burrows[1], H. Boesch[2], C. Gerbig[3], Y. Meijer[4], and A. Löscher[4]

Satellite XCH_4 retrieval algorithms …

From „First ever" → to „recent"

Buchwitz et al., 2000

JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 105, NO. D12, PAGES 15,231–15,245, JUNE 27, 2000

WFMD

A near-infrared optimized DOAS method for the fast and global retrieval of atmospheric CH_4, CO, CO_2, H_2O, and N_2O total column amounts from SCIAMACHY Envisat-1 nadir radiances

Michael Buchwitz, Vladimir V. Rozanov, and John P. Burrows
Institut für Fernerkundung, Universität Bremen, Bremen, Germany

Abstract. A new method for the fast and accurate retrieval of atmospheric trace gas total column amounts from near-infrared nadir radiances, to be measured by the scanning imaging absorption spectrometer for atmospheric chartography (SCIAMACHY) spectrometer on board the European Space Agency Envisat-1 satellite, has been investigated. It can be characterized as a weighting function modified differential optical absorption spectroscopy approach (WFM-DOAS). The reference spectra of the linear fit include the trace gas total column weighting

Buchwitz et al., 2005

WFMD

Atmos. Chem. Phys., 5, 941–962, 2005
www.atmos-chem-phys.org/acp/5/941/
SRef-ID: 1680-7324/acp/2005-5-941
European Geosciences Union

Atmospheric Chemistry and Physics

Atmospheric methane and carbon dioxide from SCIAMACHY satellite data: initial comparison with chemistry and transport models

M. Buchwitz[1], R. de Beek[1], J. P. Burrows[1], H. Bovensmann[1], T. Warneke[1], J. Notholt[1], J. F. Meirink[2], A. P. H. Goede
P. Bergamaschi[3], S. Körner[4], M. Heimann[4], and A. Schulz[5]

Bovensmann et al., 2010

BESD/C

Atmos. Meas. Tech., 3, 781–811, 2010
www.atmos-meas-tech.net/3/781/2010/
doi:10.5194/amt-3-781-2010
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Atmospheric Measurement Techniques

A remote sensing technique for global monitoring of power plant CO_2 emissions from space and related applications

H. Bovensmann[1], M. Buchwitz[1], J. P. Burrows[1], M. Reuter[1], T. Krings[1], K. Gerilowski[1], O. Schneising[1], J. Heymann[1], A. Tretner[2], and J. Erzinger[2]
[1]Institute of Environmental Physics (IUP), University of Bremen FB1, Otto Hahn Allee 1, 28334 Bremen, Germany
[2]Helmholtz Centre Potsdam – GFZ German Research Centre for Geosciences, Telegrafenberg, 14473 Potsdam, Germany

Frankenberg et al., 2005

IMAP

Sciencexpress Report

Assessing Methane Emissions from Global Space-Borne Observations

C. Frankenberg[1], J.F. Meirink[2], M. van Weele[2], U. Platt[1] & T. Wagner[1]
[1]Institute of environmental physics, University of Heidelberg, INF 229, 69120 Heidelberg, Germany. [2]Royal Netherlands Meteorological Institute, Section of Atmospheric Composition, P.O.Box 201, 3730 AE De Bilt, The Netherlands.

In the past two centuries, atmospheric methane has more than doubled and now constitutes 20% of the anthropogenic climate forcing by greenhouse gases. Yet its sources are not well quantified, introducing uncertainties in its global budget. We retrieved the global methane distribution using space-borne near-infrared absorption spectroscopy. In addition to the expected … CO_2) can be derived (7, 8). The near infrared spectrometers are employed for global measurement of total columns of carbon monoxide and greenhouse gases carbon dioxide and methane. ENVISAT operates in a nearly polar, sun-synchronous orbit at an altitude of 800 km, crossing the equator at 10:00 AM local time. SCIAMACHY offers a variety of measurement geometries. For column retrievals, we

Butz et al., 2011

RemoTeC

GEOPHYSICAL RESEARCH LETTERS, VOL. 38, L14812, doi:10.1029/2011GL047888, 2011

Toward accurate CO_2 and CH_4 observations from GOSAT

A. Butz,[1,2] S. Guerlet,[2] O. Hasekamp,[2] D. Schepers,[2] A. Galli,[2] I. Aben,[2] C. Frankenberg,[3] J.-M. Hartmann,[4] H. Tran,[4] A. Kuze,[5] G. Keppel-Aleks,[6] G. Toon,[3] D. Wunch,[6] P. Wennberg,[6] N. Deutscher,[7,8] D. Griffith,[7] R. Macatangay,[7] J. Messerschmidt,[8] J. Notholt,[8] and T. Warneke[8]

Received 21 April 2011; revised 14 June 2011; accepted 20 June 2011; published 30 July 2011.

[1] The column-average dry air mole fractions of atmospheric carbon dioxide and methane (X_{CO_2} and X_{CH_4}) are inferred from observations of backscattered sunlight conducted by the Greenhouse gases Observing SATellite (GOSAT). Comparing the first year of GOSAT retrievals over land with colocated ground-based observations of the Total Carbon Column Observing Network (TCCON), we … the requirement for X_{CH_4} is somewhat less stringent than for X_{CO_2} [e.g., *Chevallier et al.*, 2007; *Meirink et al.*, 2006].
[3] Currently, the SCanning Imaging Absorption spectroMeter for Atmospheric CartographY (SCIAMACHY), in orbit since 2002, and the Greenhouse gases Observing SATellite (GOSAT), in orbit since January 2009, aim at achieving this goal by exploiting absorption spectra of

Schneising et al., 2011, 2012

WFMD

Atmos. Chem. Phys., 12, 1527–1540, 2012
www.atmos-chem-phys.net/12/1527/2012/
doi:10.5194/acp-12-1527-2012
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Atmospheric Chemistry and Physics

Atmospheric greenhouse gases retrieved from SCIAMACHY: comparison to ground-based FTS measurements and model results

O. Schneising[1], P. Bergamaschi[2], H. Bovensmann[1], M. Buchwitz[1], J. P. Burrows[1], N. M. Deutscher[1,3], D. W. T. Griffith[3], J. Heymann[1], R. Macatangay[3], J. Messerschmidt[4], J. Notholt[1], M. Rettinger[5], M. Reuter[1], R. Sussmann[5], V. A. Velazco[1], T. Warneke[1], P. O. Wennberg[4], and D. Wunch[4]
[1]Institute of Environmental Physics (IUP), University of Bremen FB1, Bremen, Germany
[2]Institute for Environment and Sustainability (IES), European Commission Joint Research Centre (EC-JRC), Ispra, Italy
[3]School of Chemistry, University of Wollongong, Wollongong, New South Wales, Australia
[4]California Institute of Technology, Pasadena, California, USA
[5]Institute for Meteorology and Climate Research (IMK-IFU), Garmisch-Partenkirchen, Germany

Parker et al., 2011

GEOPHYSICAL RESEARCH LETTERS, VOL. 38, L15807, doi:10.1029/2011GL047871, 2011

UoL-FP/PR

Methane observations from the Greenhouse Gases Observing SATellite: Comparison to ground-based TCCON data and model calculations

Robert Parker,[1] Hartmut Boesch,[1] Austin Cogan,[1] Annemarie Fraser,[2] Liang Feng,[2] Paul I. Palmer,[2] Janina Messerschmidt,[3] Nicholas Deutscher,[3,4] David W. T. Griffith,[4] Justus Notholt,[3] Paul O. Wennberg,[5] and Debra Wunch[5]

Received 20 April 2011; revised 21 June 2011; accepted 27 June 2011; published 6 August 2011.

[1] We report new short-wave infrared (SWIR) column retrievals of atmospheric methane (X_{CH_4}) from the Japanese Greenhouse Gases Observing SATellite (GOSAT) and compare observed spatial and temporal variations with correlative ground-based measurements from the Total Carbon … importance to the Earth's radiative budget. Recent unexpected changes in surface concentrations of CH_4 emphasize gaps in our current understanding of the CH_4 budget [*Bousquet et al.*, 2006; *Rigby et al.*, 2008; *Dlugokencky et al.*, 2009], which has relied on highly accurate but sparse ground-

Schepers et al., 2012

JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 117, D10307, doi:10.1029/2012JD017549, 2012

RemoTeC

Methane retrievals from Greenhouse Gases Observing Satellite (GOSAT) shortwave infrared measurements: Performance comparison of proxy and physics retrieval algorithms

D. Schepers,[1] S. Guerlet,[1] A. Butz,[2] J. Landgraf,[1] C. Frankenberg,[3] O. Hasekamp,[1] J.-F. Blavier,[3] N. M. Deutscher,[4,5] D. W. T. Griffith,[5] F. Hase,[2] E. Kyro,[6] I. Morino,[7] V. Sherlock,[8] R. Sussmann,[9] and I. Aben[1]

Received 1 February 2012; revised 12 April 2012; accepted 15 April 2012; published 30 May 2012.

[1] We compare two conceptually different methods for determining methane column-averaged mixing ratios (X_{CH_4}) from Greenhouse Gases Observing Satellite (GOSAT) shortwave infrared (SWIR) measurements. These methods account differently for light scattering by aerosol and cirrus. The proxy method retrieves a CO_2 column which, in conjunction with prior knowledge on CO_2 acts as a proxy for scattering effects. The physics-based method accounts for scattering by retrieving three effective parameters of a scattering layer. Both retrievals are validated on a 19-month data set using ground-based

Buchwitz et al., 2013

BESD/C

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Atmospheric Measurement Techniques

Carbon Monitoring Satellite (CarbonSat): assessment of atmospheric CO_2 and CH_4 retrieval errors by error parameterization

M. Buchwitz[1], M. Reuter[1], H. Bovensmann[1], D. Pillai[1], J. Heymann[1], O. Schneising[1], V. Rozanov[1], T. Krings[1], J. P. Burrows[1], H. Boesch[2], C. Gerbig[3], Y. Meijer[4], and A. Löscher[4]


The End
of talk 1