PEKING UNIVERSITY

The long road towards realistic CO_2 flux maps from satellite column retrievals

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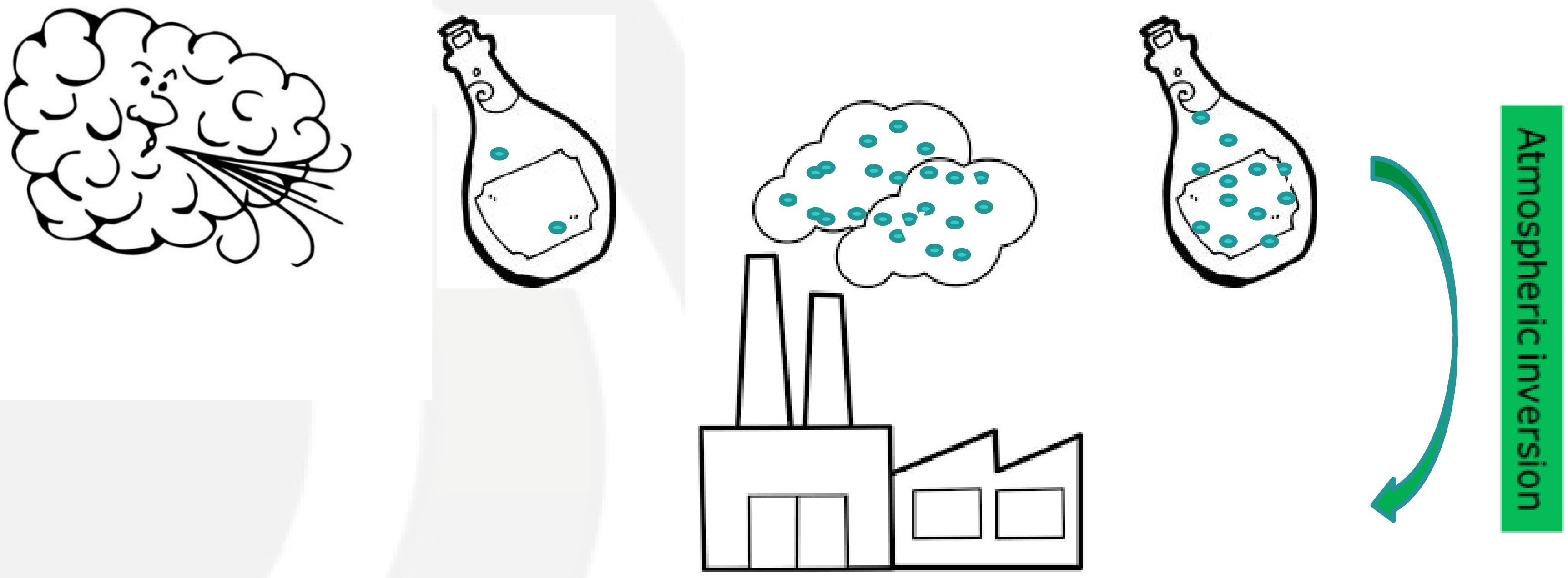
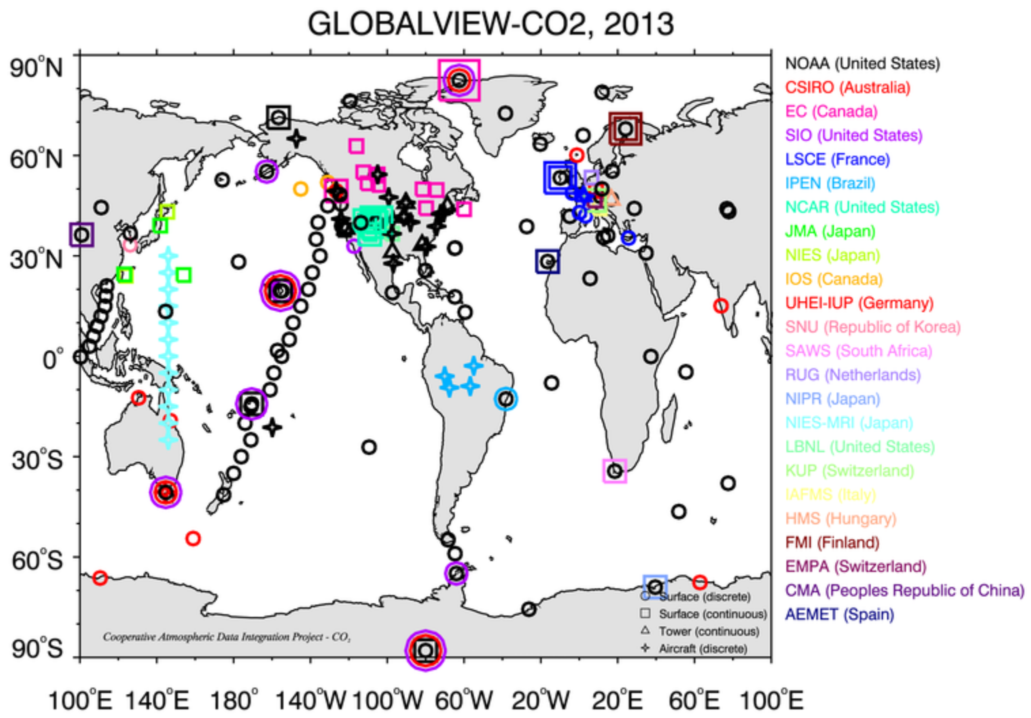
Mapping CO_2 sources and sinks



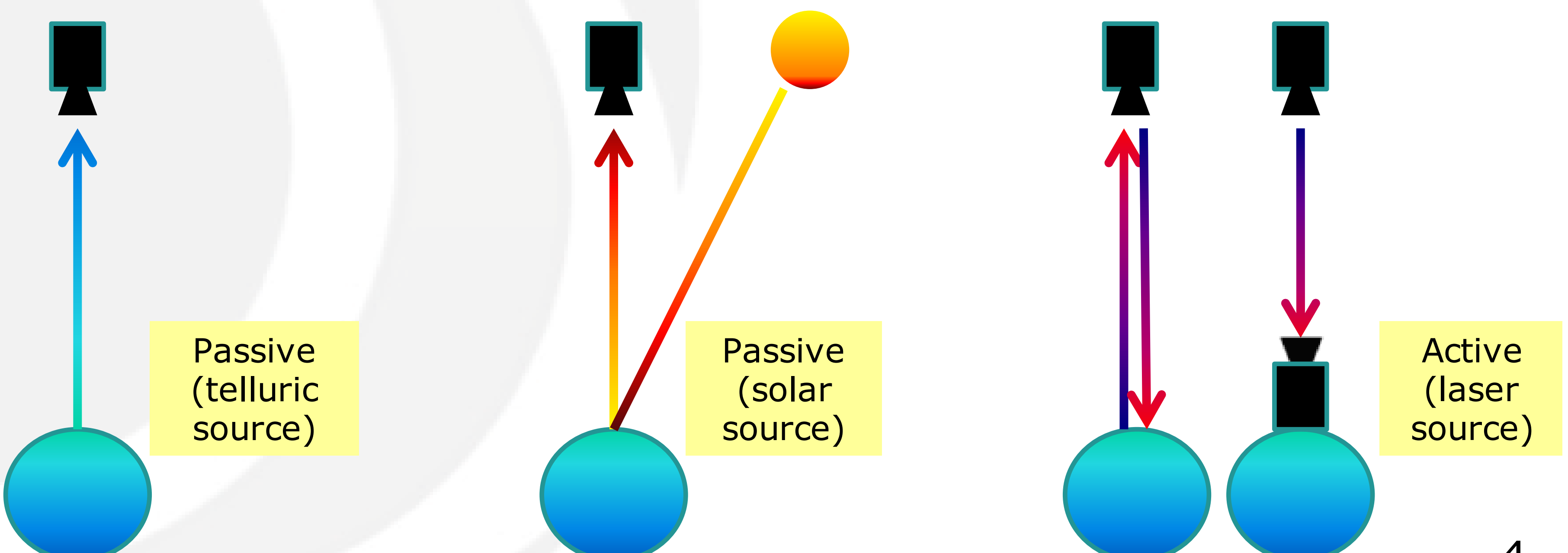
Air sample measurements

- Measurements to monitor CO_2 at the Earth's surface are usually accurate to within 1 ‰ for multi-year means.
  - This specification penalises their spread over the globe.



CO_2 remote sensing from space

- Measuring CO_2 indirectly from its radiative effect.
- CO_2 signal is in competition with that of clouds, aerosols, etc.
- Massive volume of measurements.
  - No sounding in the presence of thick clouds or in the absence of source.



Stringent accuracy requirements for CO_2 column retrievals

Needs for CO_2 flux inversion, given the amplitude of the expected signal:

- Random errors < 2%.
- Systematic errors < 1.25 ‰ (3 ‰ pour CH_4).

Very ambitious for satellite measurements.

	ESA Climate Change Initiative (CCI)	Page 14
ghg cci	**User Requirements Document Version 2 (URDv2)**	Version 2 – Final
	for the Essential Climate Variable (ECV) Greenhouse Gases (GHG)	28 August 2014

Requirements for regional CO_2 and CH_4 source/sink determination

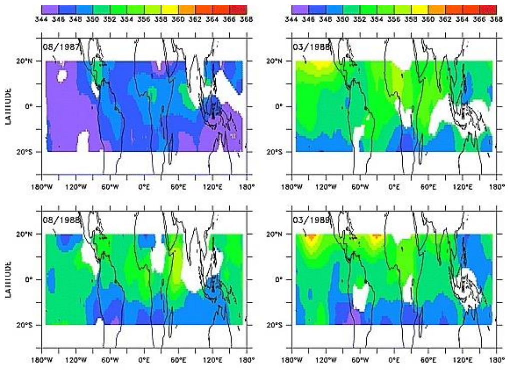
Parameter	Req. type	Random error ("Precision")		Systematic error	Stability
		Single obs.	1000^2 km^2 monthly		
XCO_2	G	< 1 ppm	< 0.3 ppm	< 0.2 ppm (absolute)	As systematic error but per year
	B	< 3 ppm	< 1.0 ppm	< 0.3 ppm (relative §))	-"-
	T	< 8 ppm	< 1.3 ppm	< 0.5 ppm (relative #))	-"-
XCH_4	G	< 9 ppb	< 3 ppb	< 1 ppb (absolute)	As systematic error but per year
	B	< 17 ppb	< 5 ppb	< 5 ppb (relative §))	-"-
	T	< 34 ppb	< 11 ppb	< 10 ppb (relative #))	-"-

Table 1: GHG-CCI XCO_2 and XCH_4 random ("precision") and systematic retrieval error requirements for measurements over **land**. Abbreviations: G=Goal, B=Breakthrough, T=Threshold requirement. §) Required systematic error after an empirical bias correction, that does not use the verification data. #) Required systematic error and stability after bias correction, where bias correction is not limited to the application of a constant offset / scaling factor.

Growing investment from the space agencies

- Partial column products from non-CO_2-dedicated missions:
  - TOVS, AIRS, IASI, TES.

- Total column products from CO_2-dedicated missions:
  - Japan:
    - **GOSAT (JAXA/NIES/MoE), launched in 2009.**
    - **GOSAT-2 (JAXA/NIES/MoE), planned for 2018.**
  - USA:
    - **OCO (NASA), failed launch in 2009.**
    - **OCO-2 (NASA), launched in 2014.**
  - China:
    - **TanSat (CAS, MOST, CMA) planned for 2015.**
  - Europe:
    - **Sciamachy (ESA), 2002-2012.**
  - More satellites are under study (US ASCENDS, France Microcarb, etc.).

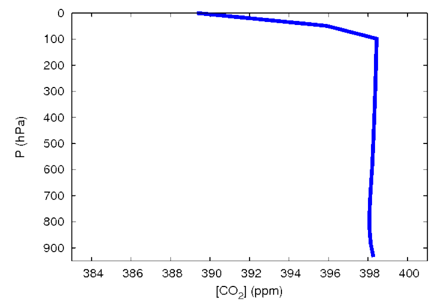


Chédin et al., *JGR*, 2003.
First satellite CO_2 retrievals (upper-trop. and Tropics)

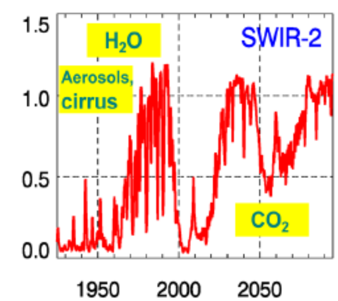
CO_2 remote sensing

- The estimation problem is under-constrained: we complete the measurements with a priori information. The fusion of probabilistic information is rigorously expressed by Bayes' theorem.

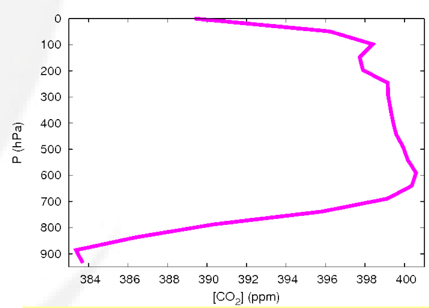
A priori [CO_2]
+
uncertainties.



$$p(\mathbf{x}|\mathbf{y}) = \frac{p(\mathbf{x}).p(\mathbf{y}|\mathbf{x})}{p(\mathbf{y})}$$



Estimated
[CO_2]
+
uncertainties.



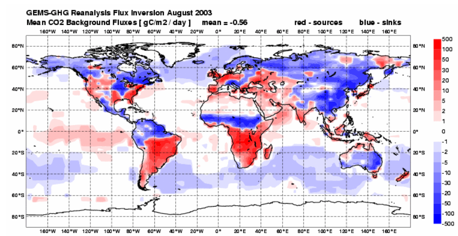
CO_2 Profiles: OCO-2

Observations
+ uncertainties
- measurements (radiances),
- Radiation model.

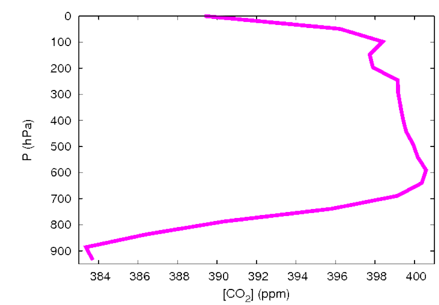
Atmospheric inversions

- The estimation problem is under-constrained: we complete the measurements with a priori information. The fusion of probabilistic information is rigorously expressed by Bayes' theorem.

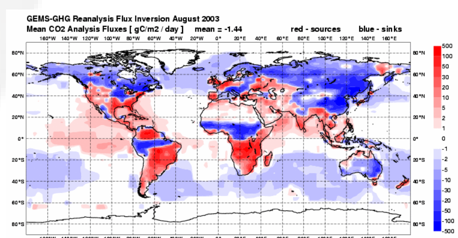
A priori fluxes
+
uncertainties.



$$p(\mathbf{x}|\mathbf{y}) = \frac{p(\mathbf{x}).p(\mathbf{y}|\mathbf{x})}{p(\mathbf{y})}$$

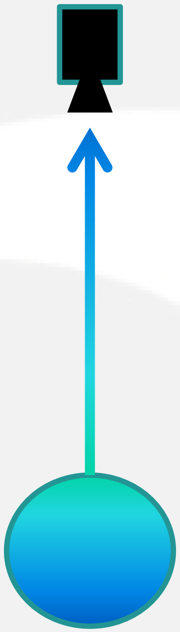


Estimated
fluxes
+
uncertainties.



Observations
+ uncertainties
- of measurements,
- of chem.-transport model.

Processing chain of the satellite measurements



- Level 0 product: Raw measurements
- L1: Calibrated measurements expressed in terms of radiances

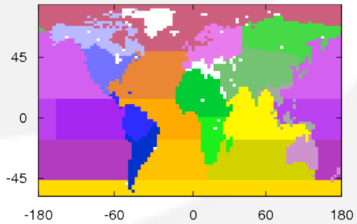
$$p(\mathbf{x}|\mathbf{y}) = \frac{p(\mathbf{x}).p(\mathbf{y}|\mathbf{x})}{p(\mathbf{y})}$$

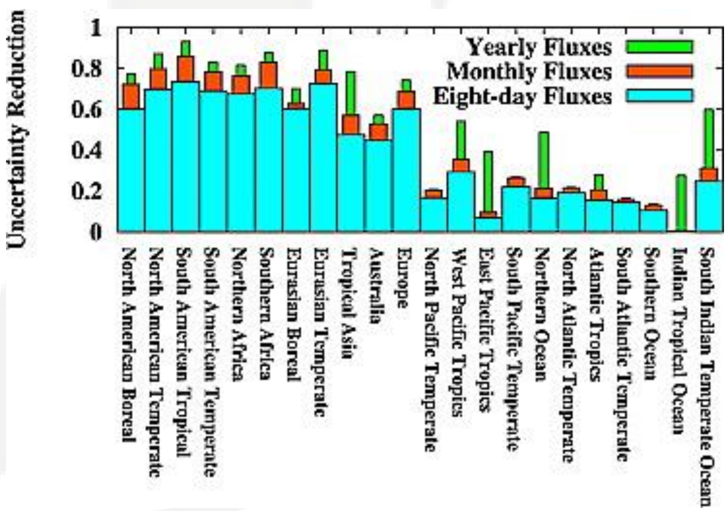
- L2: Profiles or columns of CO_2

$$p(\mathbf{x}|\mathbf{y}) = \frac{p(\mathbf{x}).p(\mathbf{y}|\mathbf{x})}{p(\mathbf{y})}$$

- L4: Maps of sources and sinks of CO_2

We expect the end product to significantly increase our knowledge about CO_2 surface fluxes.



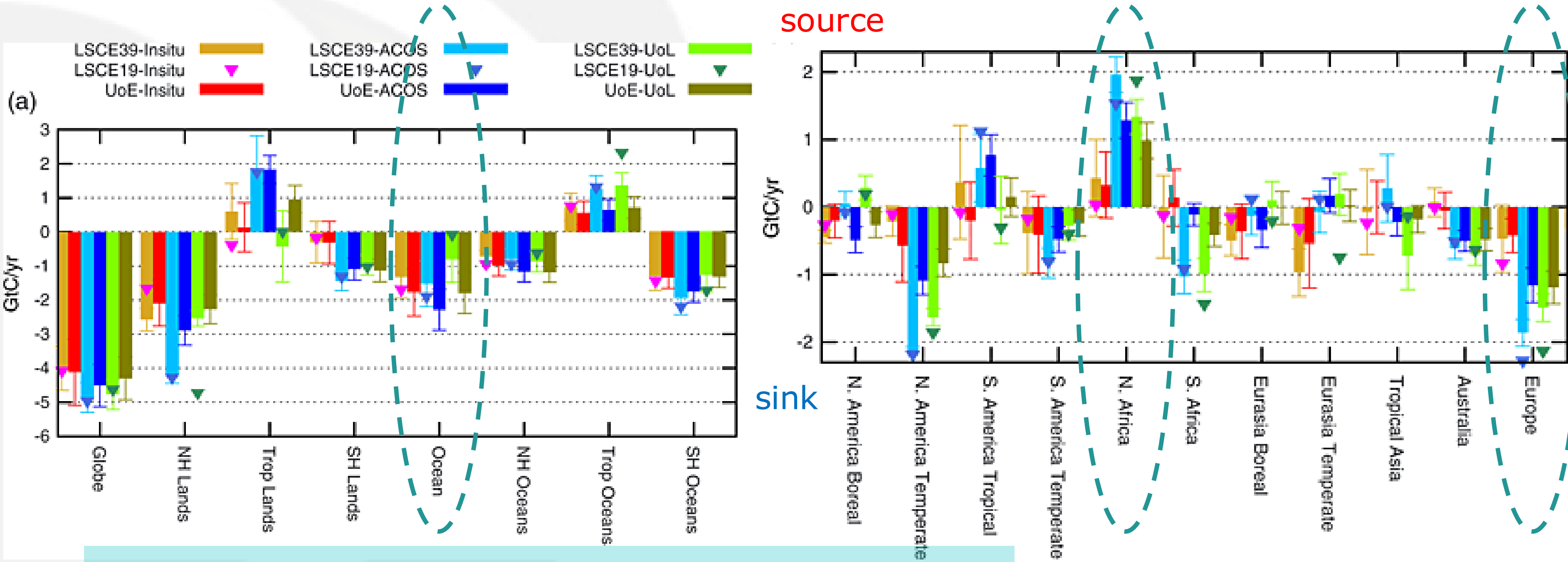


Theoretical uncertainty reduction for the GOSAT satellite
(0=neutral; 1=perfect)

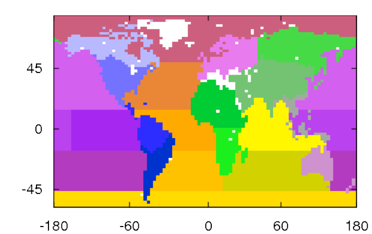
Chevallier et al. (*GRL*, 2009)

Spread and biased GOSAT CO_2 global inversions (1/2)

- 2 GOSAT products or surface air sample measurements (2010), 2 inversion systems, 2 versions of 1 of the transport models.



Global ocean mondial: sink between 0 and 2 GtC.
Europe: sink between 1 and 2 GtC ?
North Africa: source between 1 and 2 GtC ?
Chevallier et al. (*GRL*, 2014)

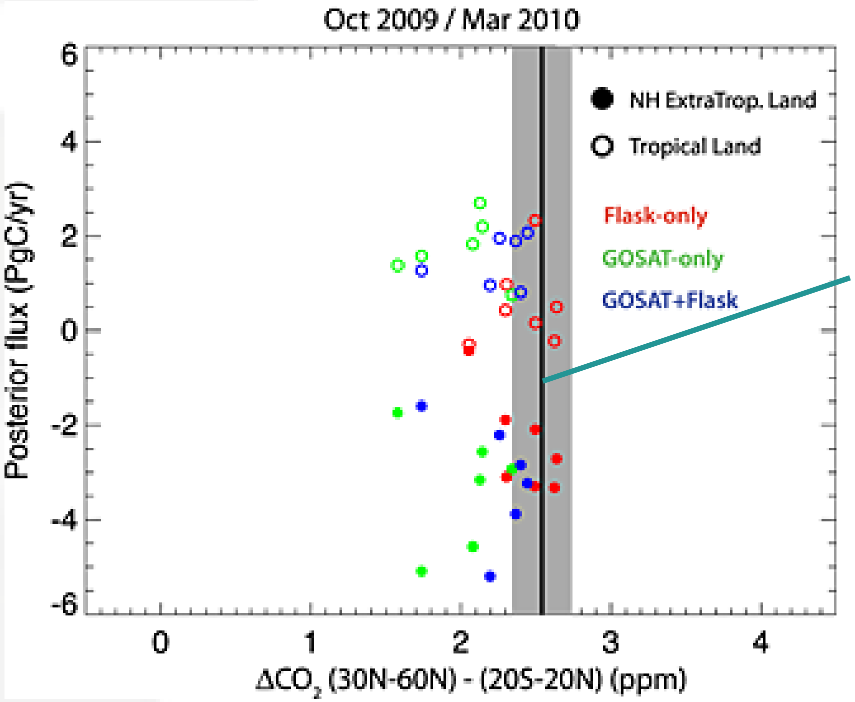


Spread and biased GOSAT CO_2 global inversions (2/2)

- Aircraft measurement campaigns in the Pacific do not support the CO_2 meridional gradient inferred by the GOSAT retrievals.

Comparison between simulated and measured meridional gradients of CO_2, and their relationship with inversion-derived carbon fluxes.

Houweling et al. (*JGR*, 2015)



Mean and range of meridional gradients that are supported by HIPPO aircraft measurements between 900 hPa and 300 hPa collected during HIPPO 2 (Oct. 2009) and HIPPO 3 (Mar. 2010).

ΔCO_2 denotes the difference in CO_2 between 30°N–60°N and 20°S–20°N.

Processing chain

L0 (raw measurements)

↓

L1 (calibrated radiances)

↓ $p(\mathbf{x}|\mathbf{y}) = \frac{p(\mathbf{x}).p(\mathbf{y}|\mathbf{x})}{p(\mathbf{y})}$

L2 (CO_2 retrievals)

↓ $p(\mathbf{x}|\mathbf{y}) = \frac{p(\mathbf{x}).p(\mathbf{y}|\mathbf{x})}{p(\mathbf{y})}$

L4 (CO_2 fluxes)

- The steps are spread between various institutes.
- Is the resulting chain consistent from end to end?
- Only mitigation measure so far: averaging kernels **KH** (linear representation of the weighting of information content of the retrieval).
  - $\mathbf{x}^{sim} = \mathbf{x}^b + \mathbf{KH}(\mathbf{x}^{model} - \mathbf{x}^b)$

x: retrieval vector (mostly CO_2 profile)
$\mathbf{x}^b$: retrieval prior of **x**
$\mathbf{x}^{model}$: direct model output
$\mathbf{x}^{sim}$: model-equivalent of **x**
K: retrieval gain matrix
H: linear retrieval observation operator (mostly radiation model)

Processing chain

- From satellite radiances to CO_2 retrievals (using a radiation model $\mathbf{H}$).
  - Optimal state $\mathbf{x}^a = \mathbf{x}^b + \mathbf{K}(\mathbf{y} - \mathbf{H}\mathbf{x}^b)$ (1)
  - $\mathbf{K} = \mathbf{B}\mathbf{H}^T(\mathbf{H}\mathbf{B}\mathbf{H}^T + \mathbf{R})^{-1}$
  - Uncertainty $\mathbf{A} = (\mathbf{I} - \mathbf{K}\mathbf{H})\,\mathbf{B}$

y: observation vector
B: prior error covariance matrix
R: observation error covariance matrix

- From CO_2 retrievals to estimated fluxes (using a transport model $\mathbf{H}$ and – indicated with primes – the averaging kernel $\mathbf{KH}$).
  - Optimal state $\mathbf{x}^a = \mathbf{x}^b + \mathbf{K'}(\mathbf{y'} - \mathbf{H'}\mathbf{x}^b)$ (2)
    $= \mathbf{x}^b + \mathbf{K'}(\mathbf{K}\mathbf{y} - \mathbf{K}\mathbf{H}\mathbf{H}\mathbf{x}^b)$ (3)
    $= \mathbf{x}^b + \mathbf{K'}\mathbf{K}(\mathbf{y} - \mathbf{H}\mathbf{H}\mathbf{x}^b)$ (4)
  - $\mathbf{K'} = \mathbf{B}\mathbf{H'}^T(\mathbf{H'}\mathbf{B}\mathbf{H'}^T + \mathbf{R})^{-1}$, with $\mathbf{H'} = \mathbf{K}\mathbf{H}\mathbf{H}$
  - Uncertainty $\mathbf{A} = (\mathbf{I} - \mathbf{K'}\mathbf{H'})\,\mathbf{B}$

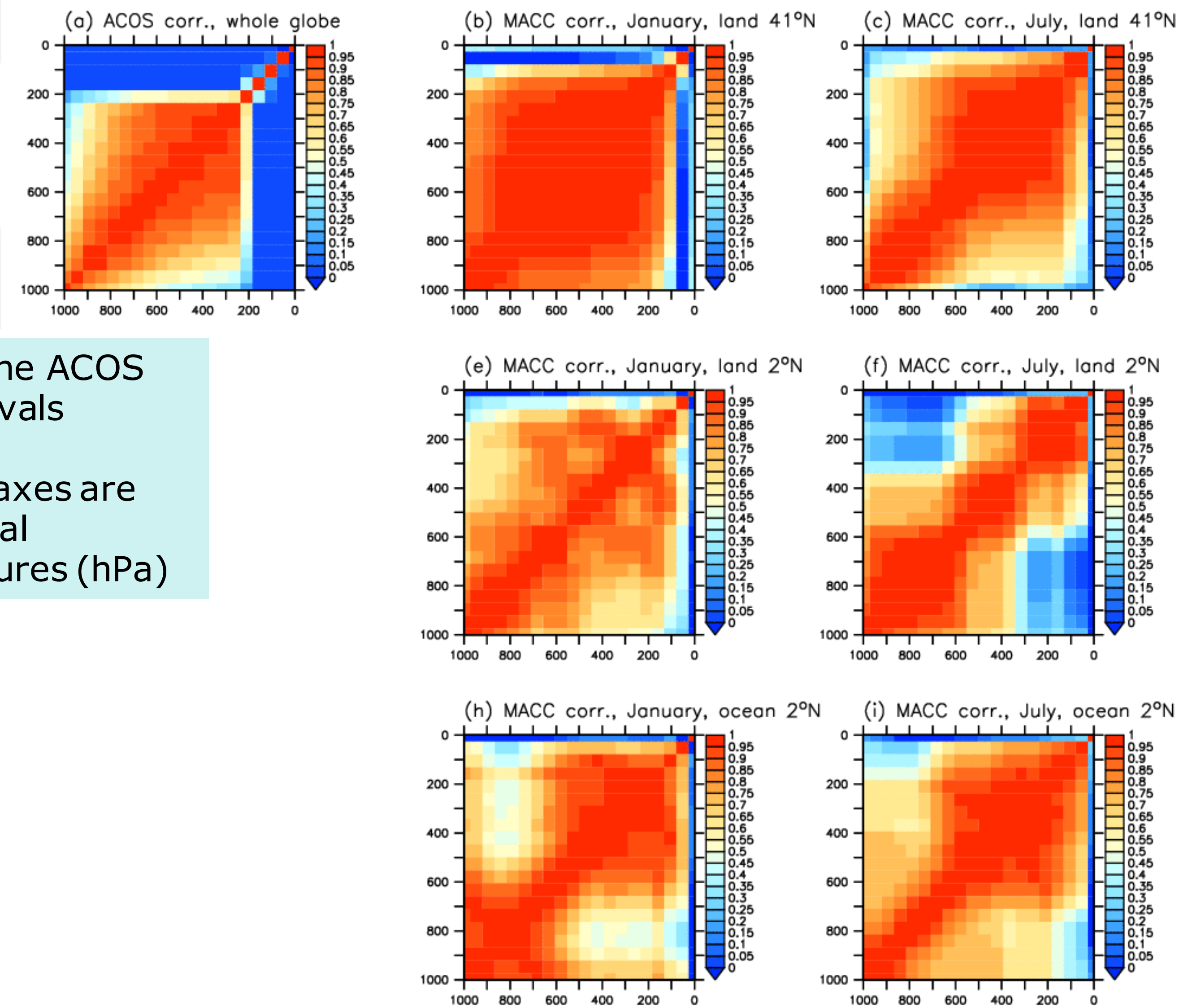
Gain matrices **K**

- From CO_2 retrievals to estimated fluxes.

- $\mathbf{K'K} = \mathbf{BH'}^T(\mathbf{H'BH'}^T + \mathbf{R})^{-1}\ \mathbf{BH}^T(\mathbf{HBH}^T + \mathbf{R})^{-1}$
- We want this product to be a gain matrix itself so that:
  - $\mathbf{K'K} = \mathbf{BH}^T\mathbf{H}^T(\mathbf{HHBH}^T\mathbf{H}^T + \mathbf{R})^{-1}$
- If $\mathbf{H} \neq \mathbf{I}$, we need:
  1. $\mathbf{HBH}^T = \mathbf{HHBH}^T\mathbf{H}^T$ -> consistent prior error statistics in radiance space
  2. $\mathbf{H}^T\mathbf{K}^T(\mathbf{KHBH}^T\mathbf{K}^T + \mathbf{R})^{-1}\ \mathbf{B} = \mathbf{I}$ -> $\mathbf{KH} \approx \mathbf{I}$

Chevallier (*ACPD*, 2015)

Consistent prior error statistics?
Correlations



HBH^T in the LSCE inversion system

Both axes are vertical pressures (hPa)

B in the ACOS retrievals

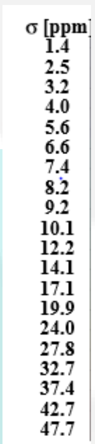
Both axes are vertical pressures (hPa)

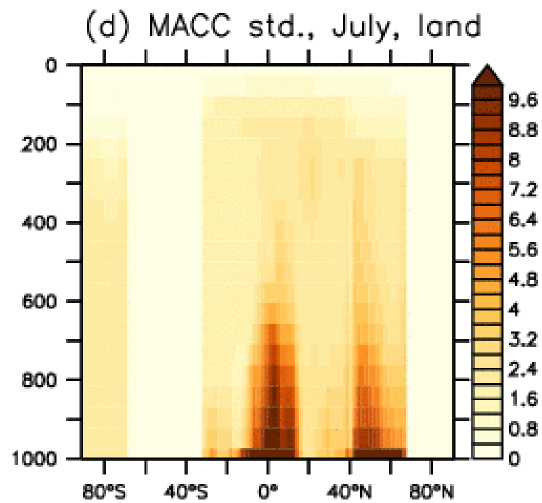
Consistent prior error statistics?
Standard deviations

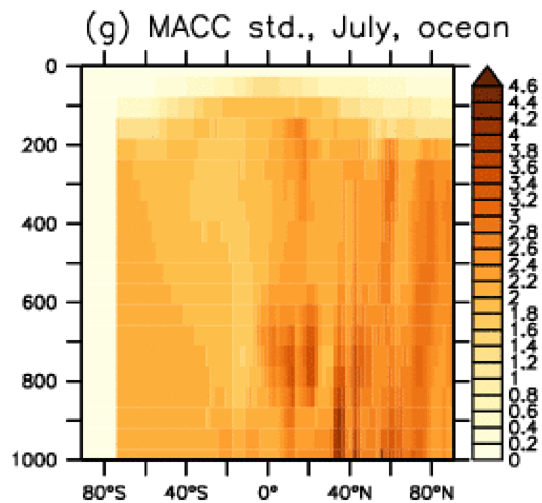
B in the ACOS retrievals
σ^{col} = 12 ppm

The vertical axis shows pressures (hPa)

O'Dell et al. (2012)







HBH^T in the LSCE inversion system
σ^{col} ≈ 1-4 ppm

The vertical axis shows pressures (hPa)

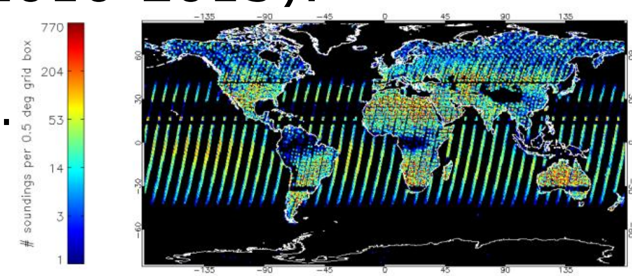
Changing B

- Regenerating the retrievals with a different **B** (collab. with C. O'Dell, CSU).

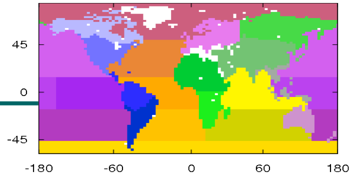
- ACOS b3.5, high-gain, medium-gain, nadir, glint.
- New **B** (hereafter **B'**) from a frozen climatology of prior error statistics (latitude, month, geotype).

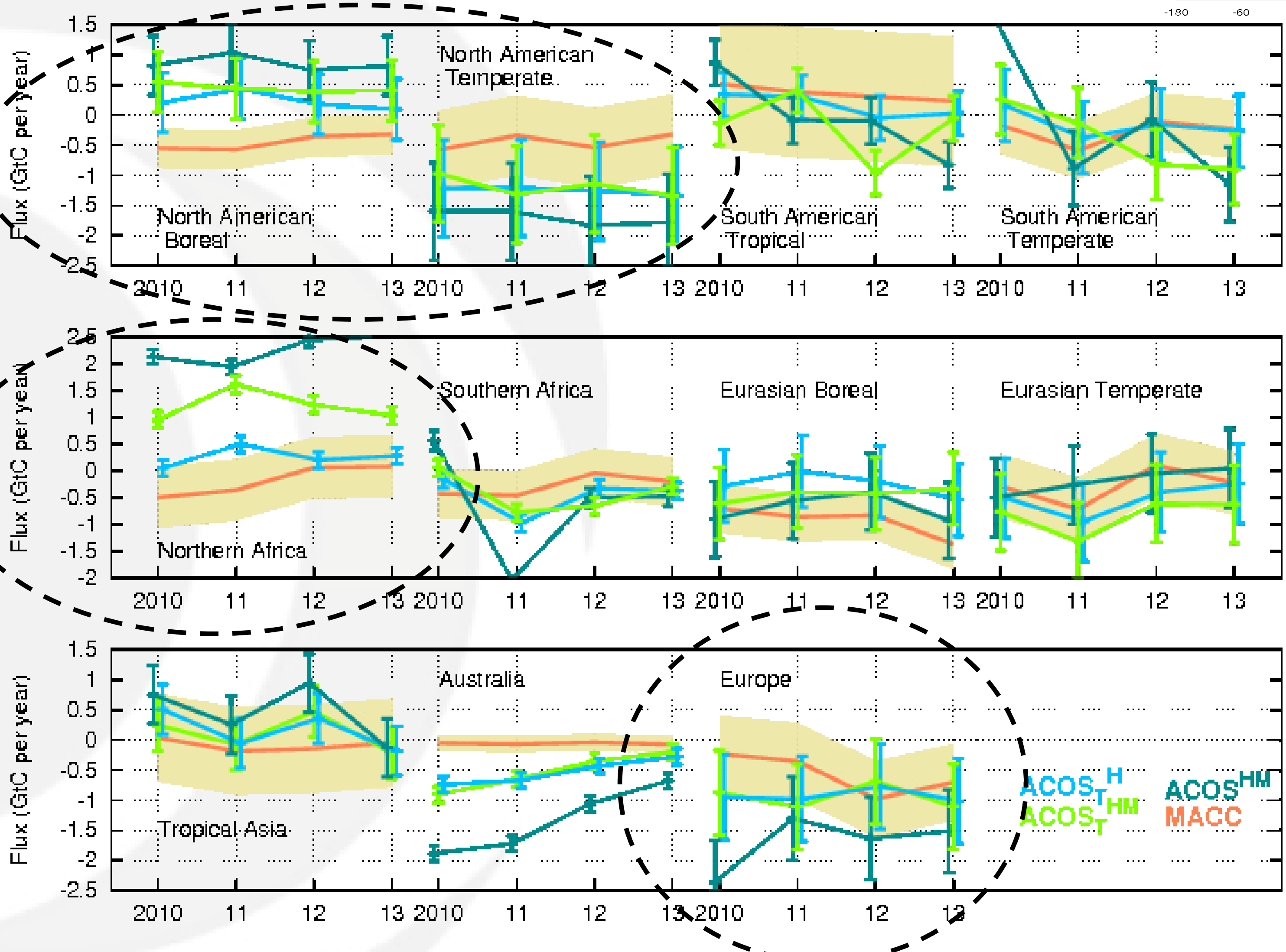
- Ad hoc bias-correction based on MACCv13.1 and using the same parametric formula than ACOS-GOSAT (2×5+4 parameters).

- 4 inversions compared over 4 years (2010-2013):
  - MACCv14.2 (surface).
  - $ACOS^{HM}$: Standard b3.5, H-gain and M-gain.
  - $ACOS_T^{HM}$: b3.5 with **B'**, H-gain and M-gain.
  - $ACOS_T^{H}$: b3.5 with **B'**, H-gain only.



Inverted annual regional budgets over land with 1 σ





Conclusions

- Satellite-based atmospheric inversions use small XCO_2 signals, that need to be carefully extracted and characterized.
  - Renews the problem of remotely sensing atmospheric composition.
- Need of better statistical consistency from radiances to fluxes.
  - Official retrievals do not properly account for prior information.
    - Averaging kernels do not peak at the right altitude.
  - Noticeable impact on subcontinental annual budgets (not just random noise).
  - Solutions to tailor existing retrievals to each individual inversion scheme should be offered (through linear algebra) in the same way as averaging kernels are systematically provided.
  - Other smaller issues in the retrievals remain to be solved:
    - Underestimation of atmospheric growth rate,
    - Inclusion of medium-gain data,
    - High latitudes.

Acknowledgements

- This work could not have existed without the work of many organisations that have made, archived or distributed surface air sample measurements (e.g., NOAA, WDCGG, RAMCES, ICOS).

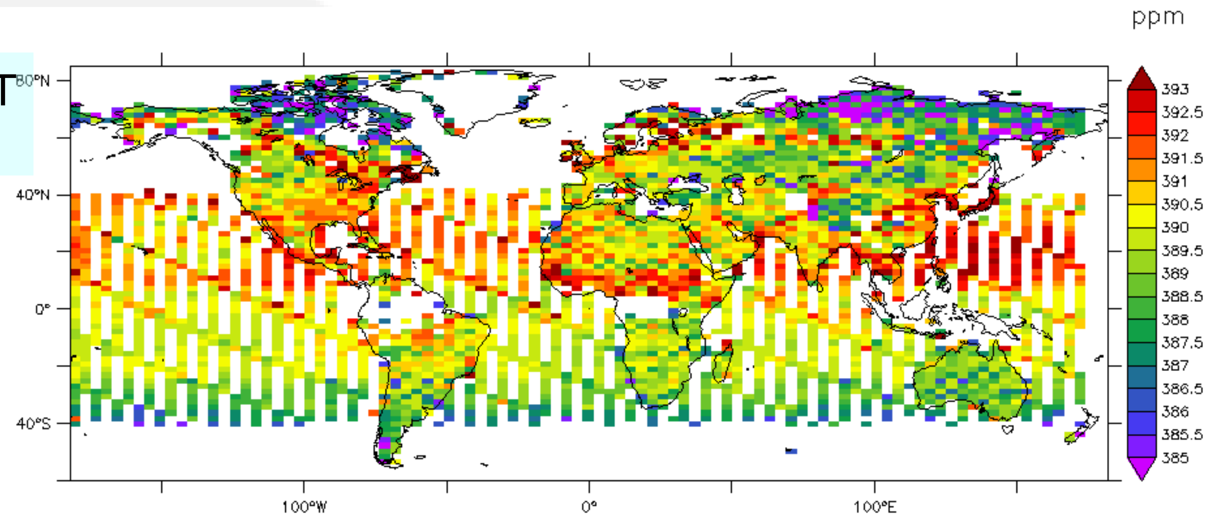
- The ACOS GOSAT data can be obtained from http://co2.jpl.nasa.gov. They were produced by the ACOS/OCO-2 project at the Jet Propulsion Laboratory, California Institute of Technology, using GOSAT observed spectral radiances made available by the GOSAT project.

- Christopher O'Dell provided critical help to tailor the ACOS-GOSAT retrievals to the LSCE inversion system.

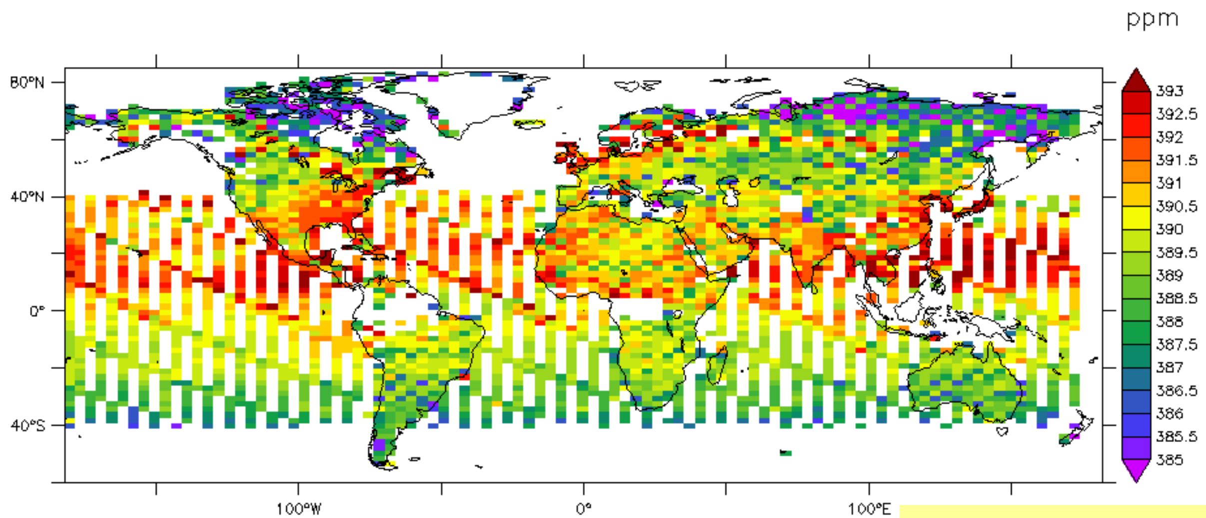
Back-up slides

XCO_2 4-yr mean GOSAT and MACC surface inversion

ACOS-GOSAT b3.4



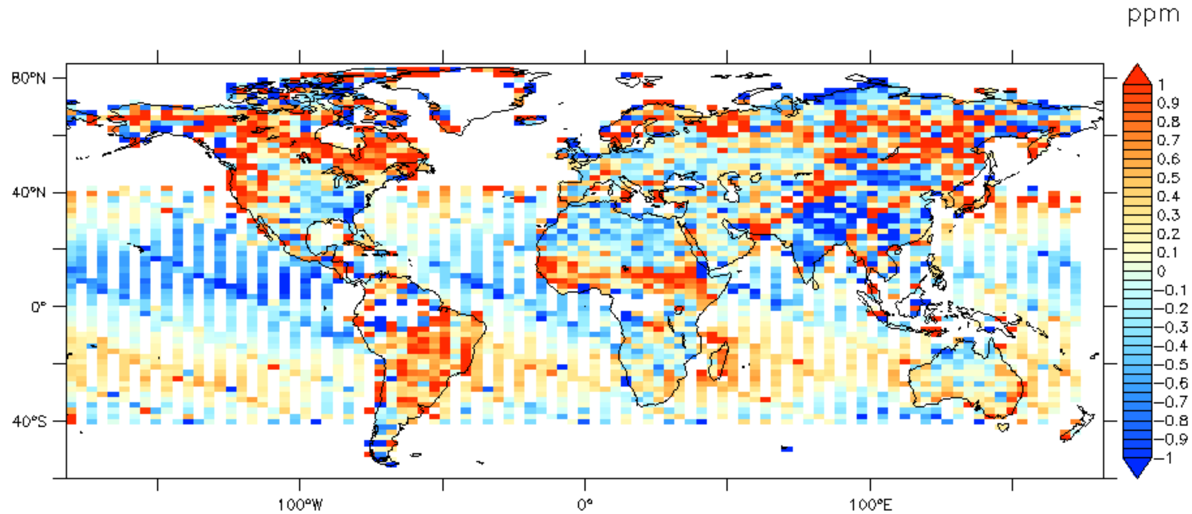
MACC v13.1



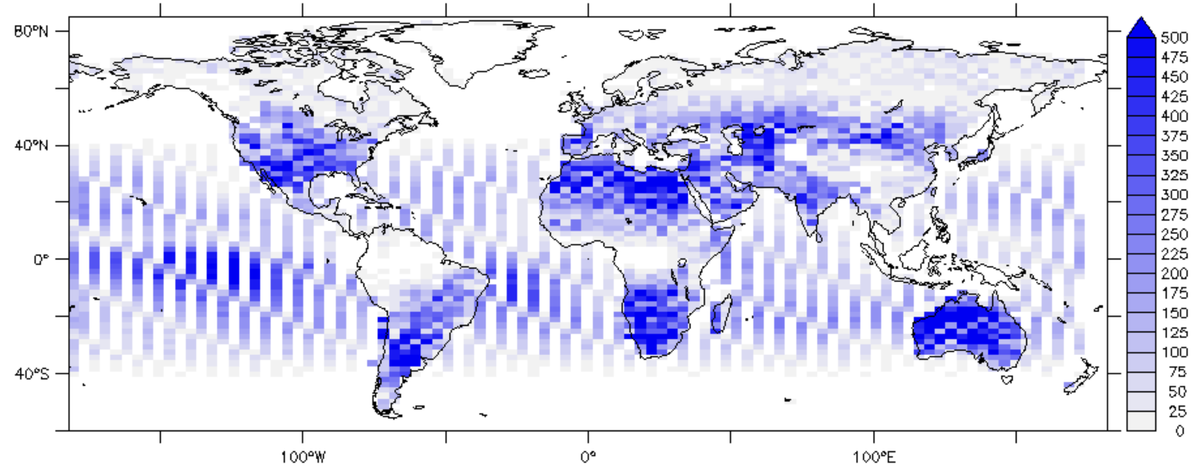
Chevallier (*ACPD*, 2015)

XCO_2 4-yr mean GOSAT and MACC surface inversion

ACOS-GOSAT minus MACC

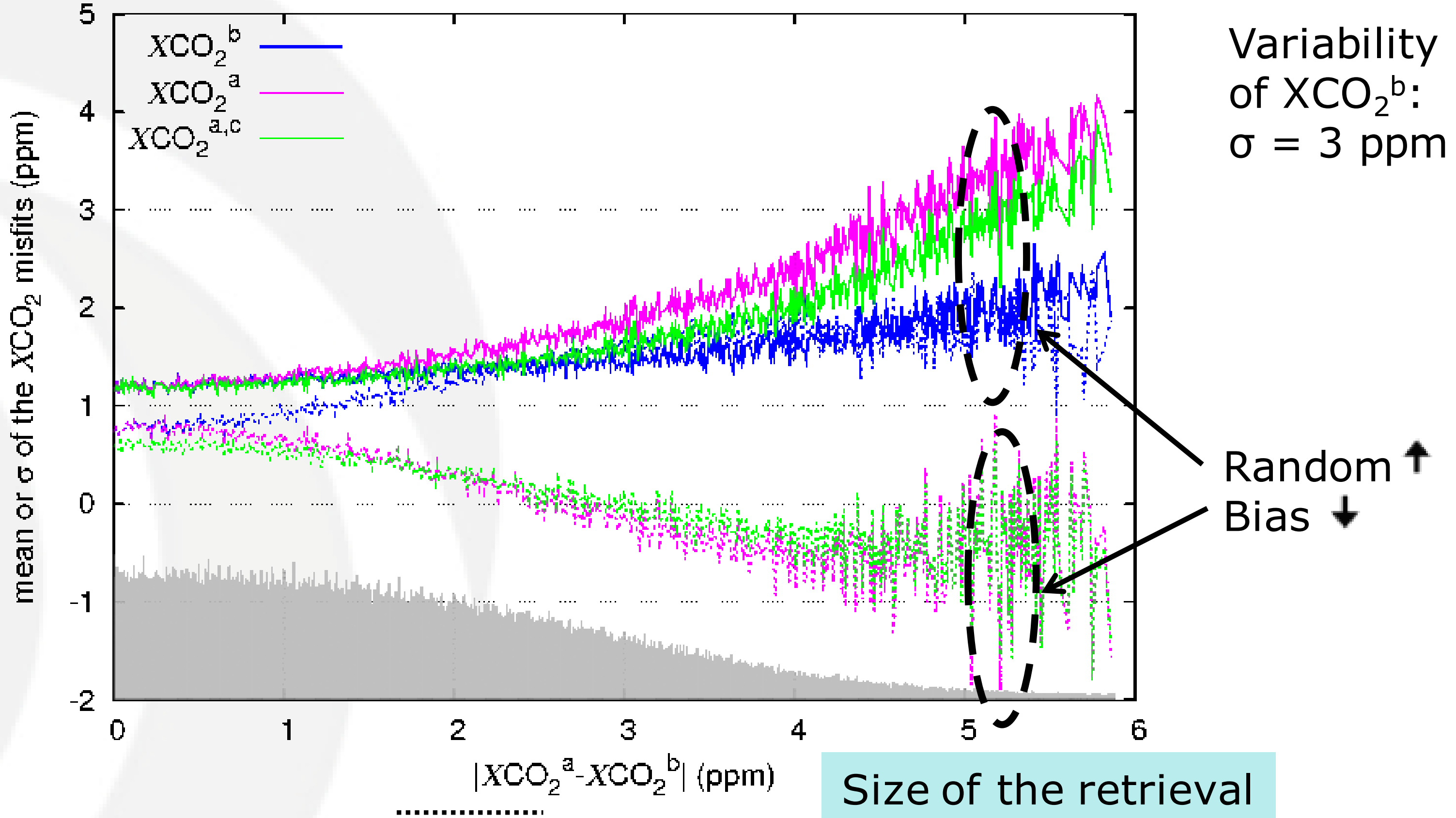


# of data



Chevallier (*ACPD*, 2015)

Misfits vs. retrieval increment – H gain (land)



Variability of XCO_2^b: σ = 3 ppm

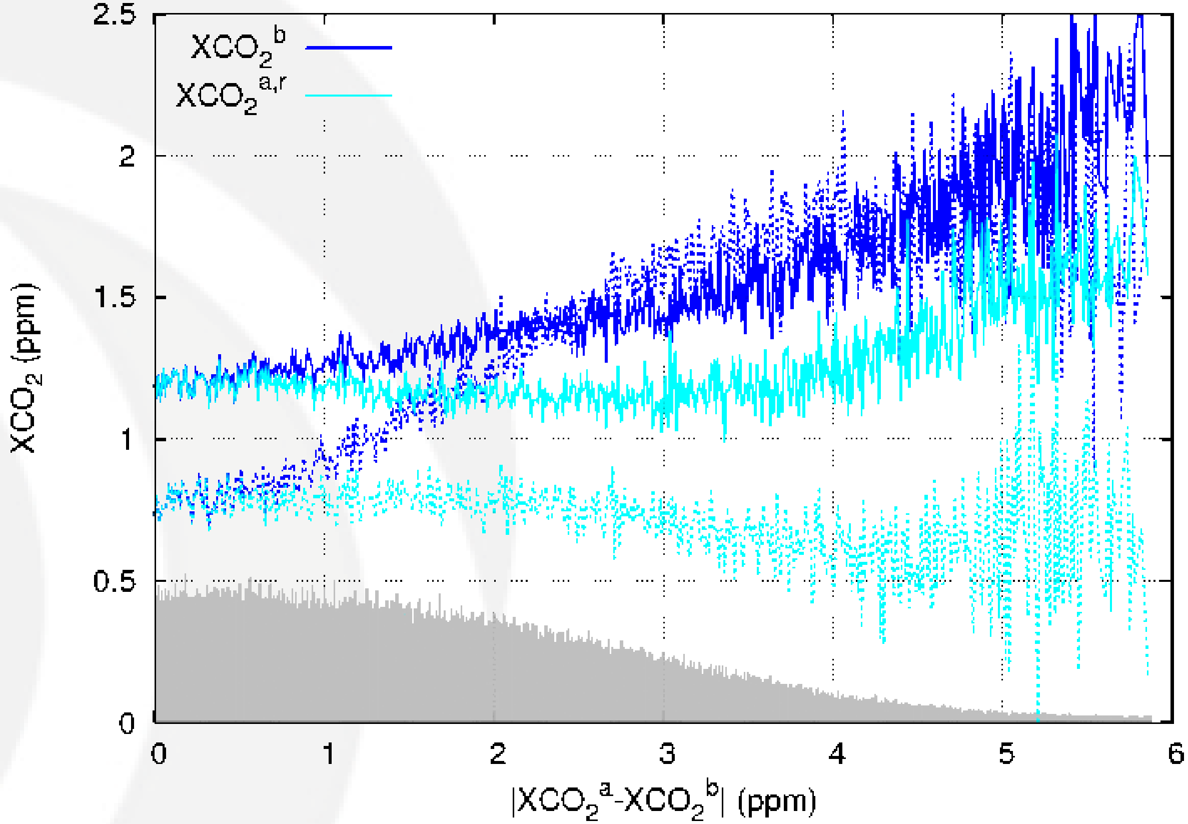
Size of the retrieval increment

- Misfit bias
- b: retrieval prior
- a: raw retrieval
- a,c: bias-corrected retrieval
- MACC = no AK

MACC vs. TCCON ~ 0±0.9 ppm

Chevallier (*ACPD*, 2015)

Misfits vs. retrieval increment – H gain (land)



Random ↓
Bias ↓

- Misfit bias .... and std. ――――
- b: retrieval prior
- a,r: revised retrieval (AK/2), without any bias-correction
- Unchanged abscissa
- MACC = no AK   MACC vs. TCCON ~ 0±0.9 ppm

Chevallier (*ACPD*, 2015)