Global inverse modelling of CO_2 surface fluxes: towards assimilating satellite data

Frédéric Chevallier,
Philippe Bousquet, Robin Locatelli,
and many data providers

Laboratoire des Sciences du Climat et de l'Environnement
Gif-sur-Yvette
France

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Laboratoire des sciences du climat & de l'environnement

SEVENTH FRAMEWORK PROGRAMME

European Commission

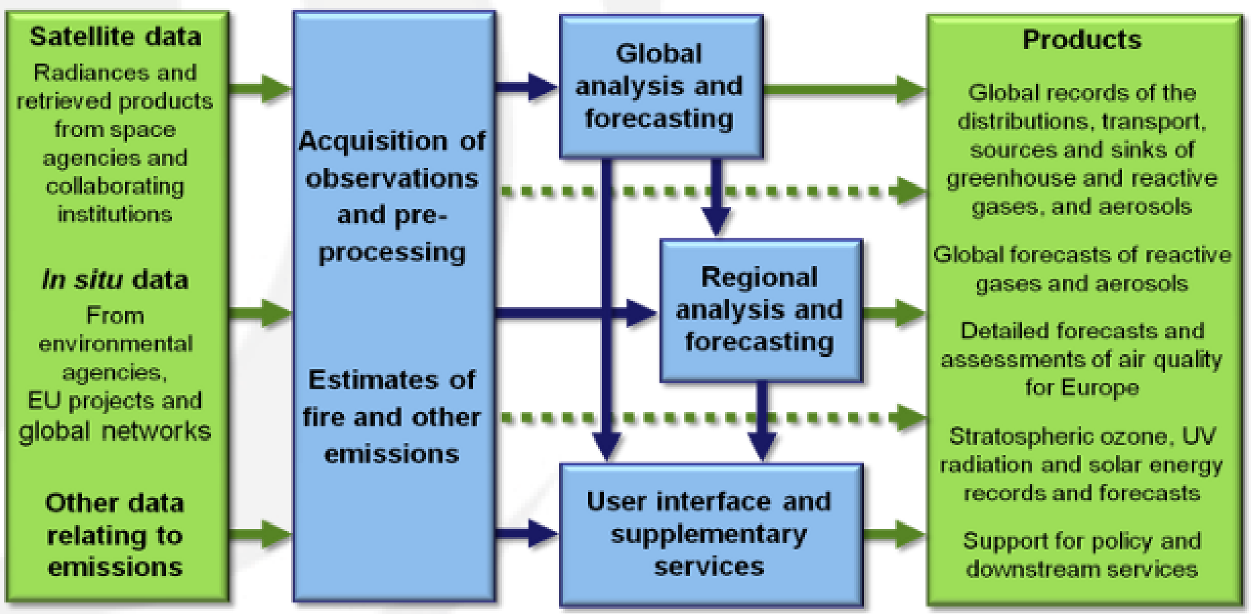
Copernicus The European Earth Observation Programme

esa

The MACC service

Monitoring atmospheric composition & climate – II

- Monitoring Atmospheric Composition and Climate - Interim Implementation - is the current pre-operational Atmosphere Service of the European Earth observation programme (coord. European Comm.).
  - 36 main contributors, lead by ECMWF
  - http://www.gmes-atmosphere.eu/
- MACC-II routinely provides data records on **atmospheric composition** for **recent years**, data for monitoring **present** conditions and forecasts of the distribution of key constituents for a **few days ahead**.



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- **High-resolution** data assimilation systems with **routine delivery** of **observations** and of **assimilated products**

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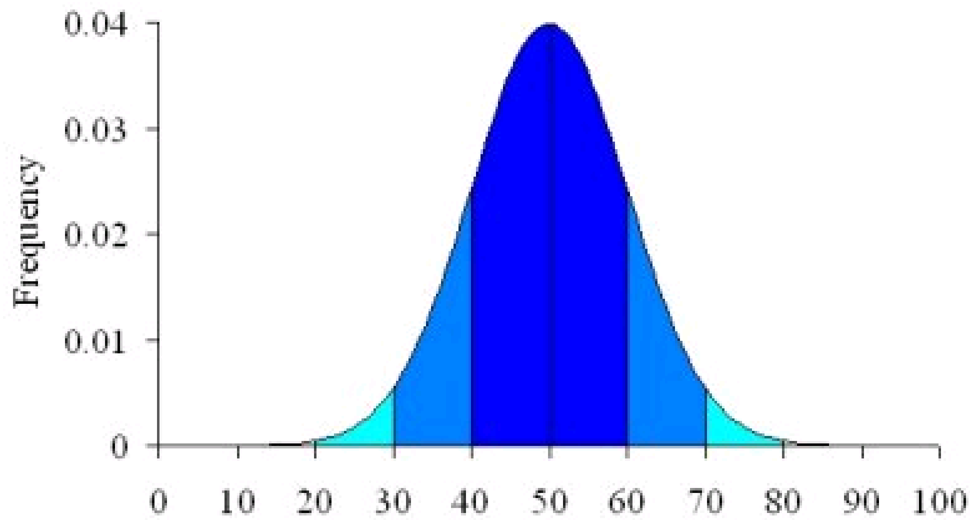
MACC-II hybrid approach for CO_2 inversion

- Purpose: assimilate measurements of CO_2 mole fraction
  - Non-reversible atmospheric mixing
  - Need a statistical approach to revert the sign of time
- Bayesian approach chosen because it is the most generic one

Optim. fluxes | Prior fluxes | $[CO_2]$

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



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MACC-II hybrid approach for CO_2 inversion

- Variational approach for “high”-resolution information
  - Weekly day/night grid point fluxes (3.75x2.5 deg^2 global)
  - Heavily parallelized (patent submitted)
- Ensemble approach for coarse resolution information
  - Mean variance of the flux errors over long periods of time
  - Naturally //

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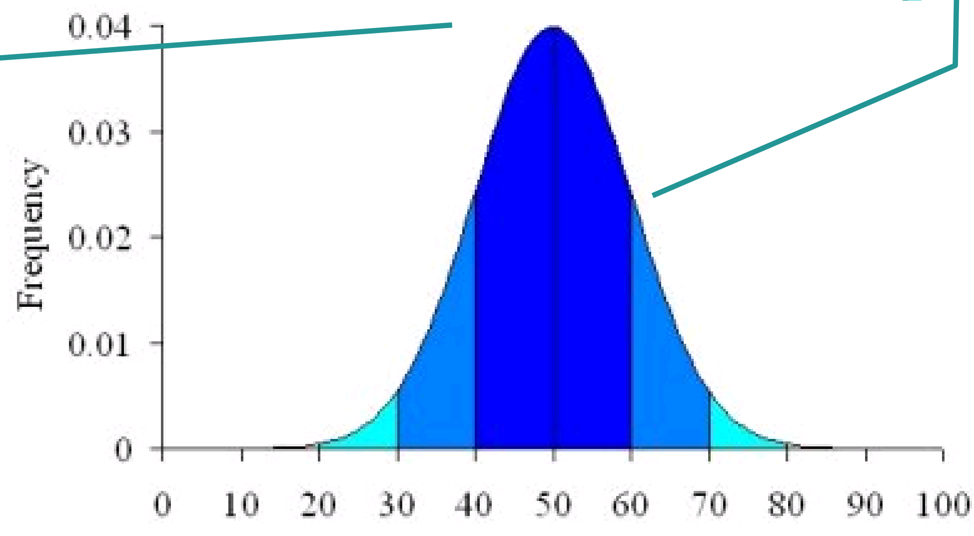
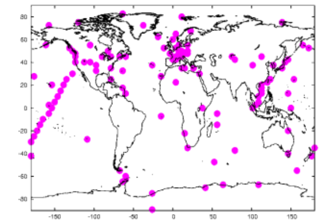
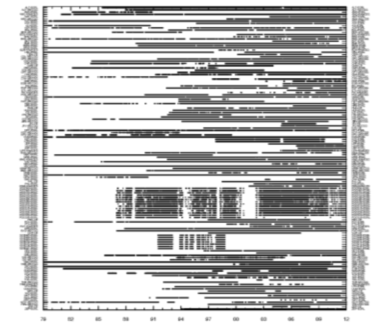


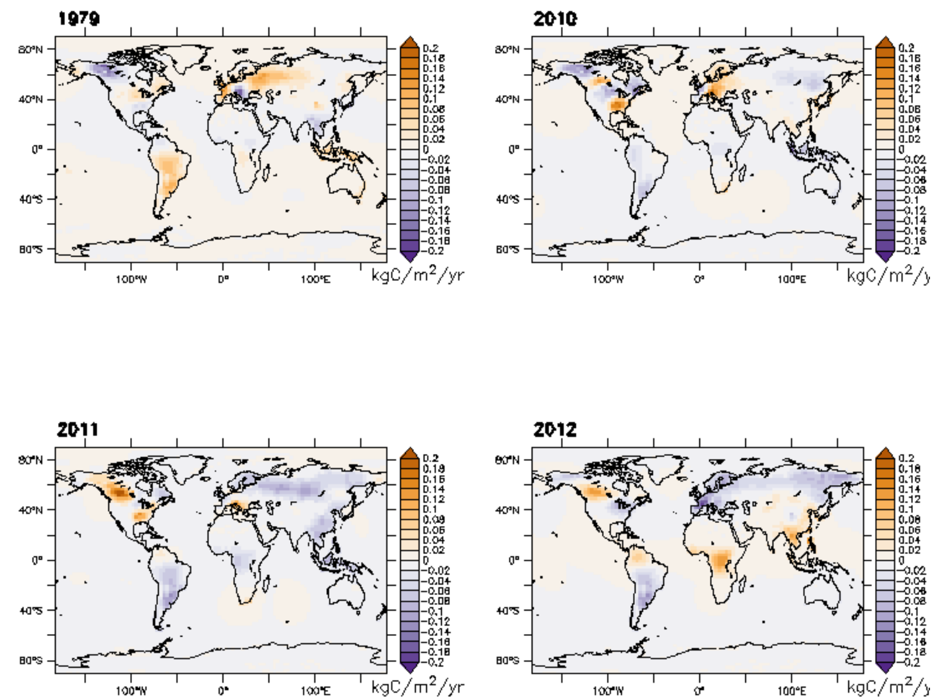
1979-2012 CO_2 inversion





- [CO_2] from 136 surface stations
  - NOAA, WDCGG, RAMCES, CarboEurope databases
    1.5 M obs
- 34-yr 4D inversion
  - 34 yrs processed in a unique assimilation window to ensure physical and statistical consistency
  - Variational approach to allow high resolution (3.75x2.5 deg^2 and weekly) – 7.5 M var
  - Large parallelisation effort
  - Preliminary results obtained 2 weeks only after the 2012 NOAA flask data were made available

Annual anomalies



Evaluation of the inverted fluxes

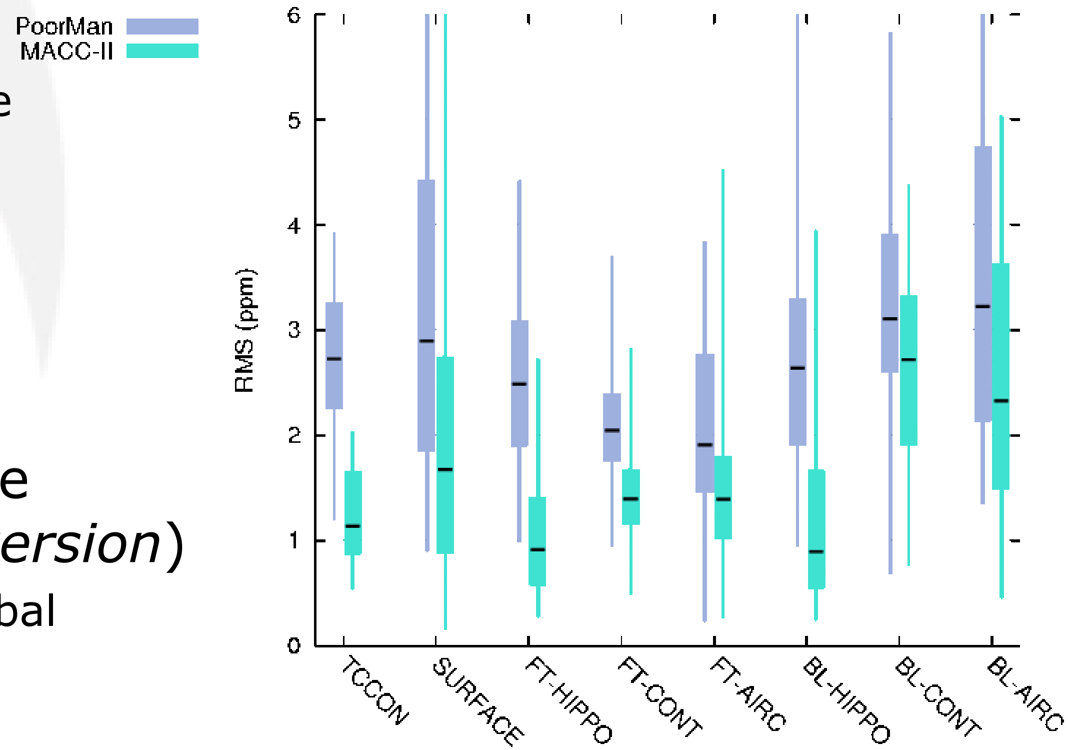
- Inverted fluxes ~ 10^5 km^2

- Ground truth (eddy covariance measurements) ~ 1 ha
  - Too different from inversion resolution
- Indirect evaluation with atmospheric measurements
  - Need transport model again
- Expert knowledge
  - We know how much carbon an ecosystem is able to lose or gain

MACC-II global system vs.:

- TCCON XCO_2 measurements
- Surface $[CO_2]$ measurements
  - Dependent data (assimilated)
- Aircraft $[CO_2]$ measurements
  - from the HIPPO campaigns
  - from the GEOMON database
  - from the Contrail database

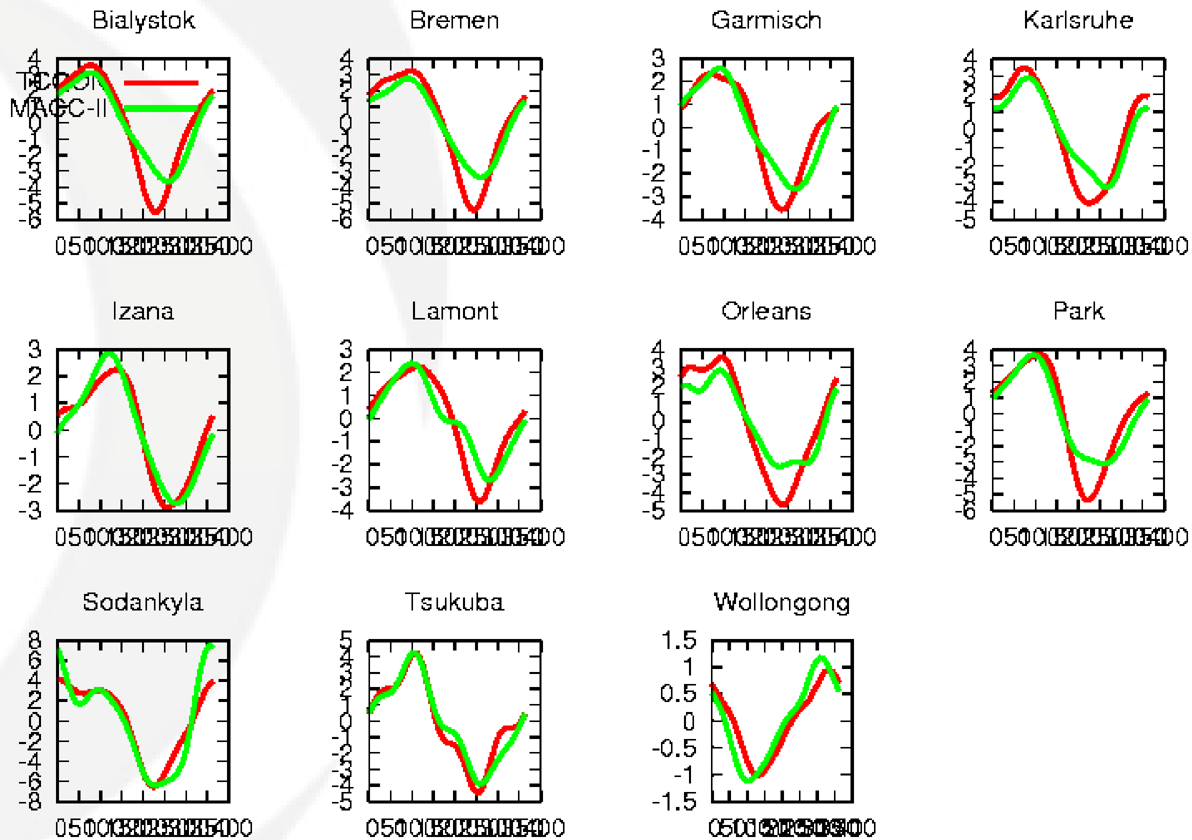
  - FT = free troposphere
  - BL = boundary layer



○ Skill compared to baseline inversion (*Poor Man's inversion*)
  - Driven by NOAA annual global growth rate

MACC-II global system vs.:

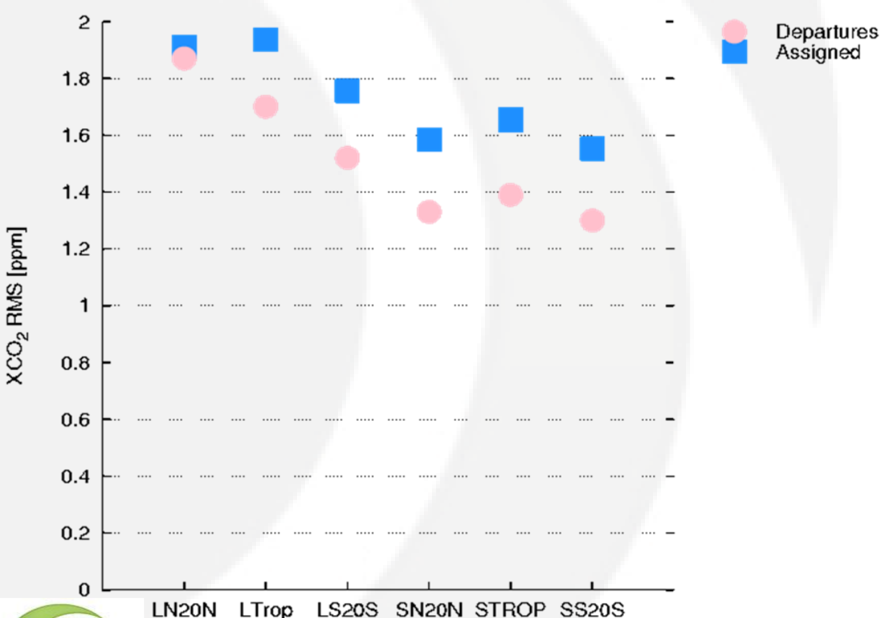
- TCCON XCO_2 measurements
  - Look at seasonal cycle for year 2010 (ppm)
  - Smooth curve computed from both model and measurements



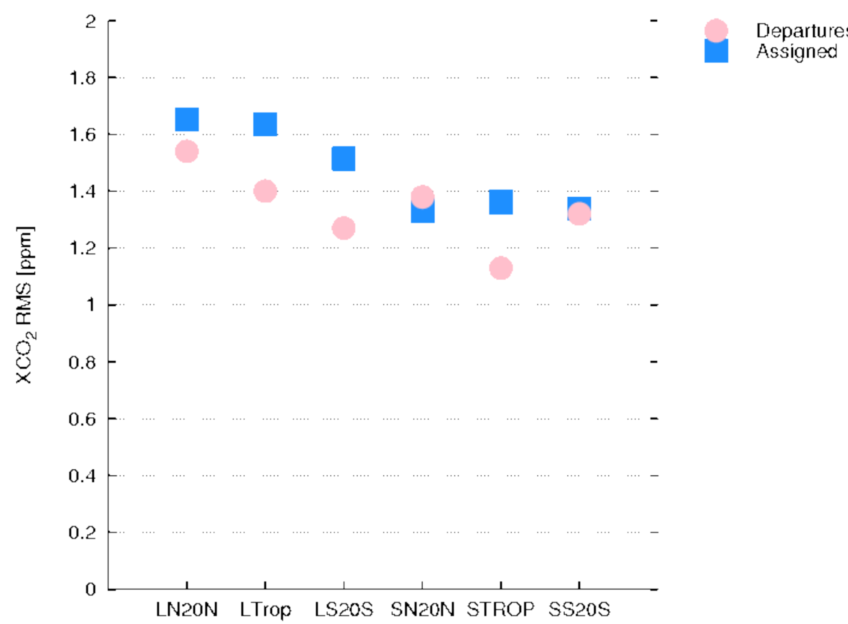
Evaluating the assigned error statistics with XCO_2 data

- Transport prior fluxes and air-sample inversion
- Compare with **y** = GOSAT/ ACOS b2.10 retrievals (not assimilated!) in 3 latitude bands, for land and ocean

$E[\,(\mathbf{Hx_b} - \mathbf{y})(\mathbf{Hx_b} - \mathbf{y})^T\,] = \mathbf{HBH^T+R}$



$E[\,(\mathbf{Hx_a} - \mathbf{y})(\mathbf{Hx_a} - \mathbf{y})^T\,] = \mathbf{HAH^T+R}$



=> We fairly close the error budget

Chevallier and O'Dell (2013)

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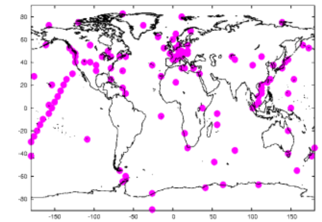
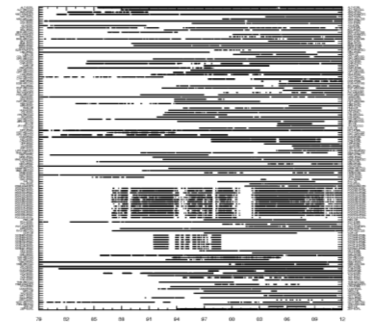
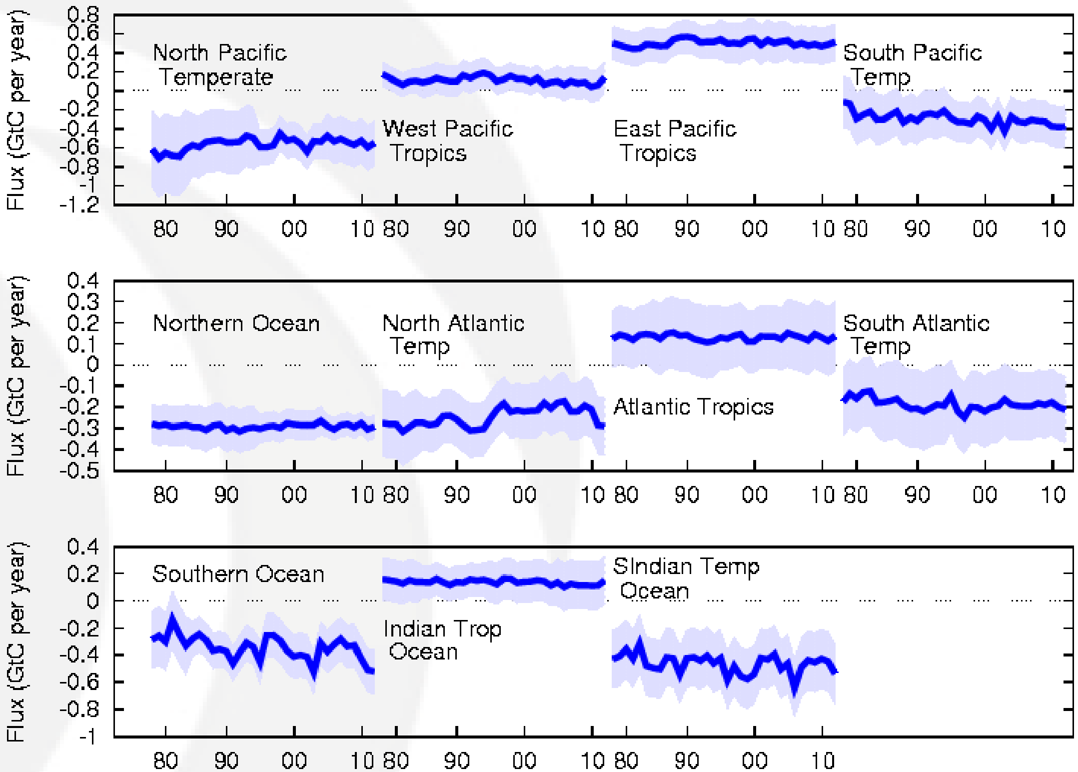
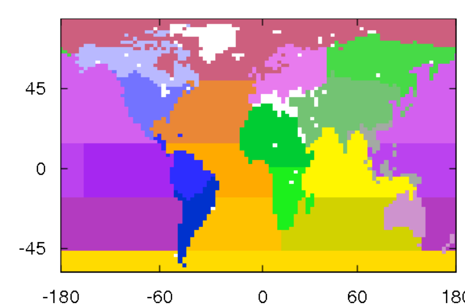
Time series over ocean









Annual budgets with 1 sigma uncertainty

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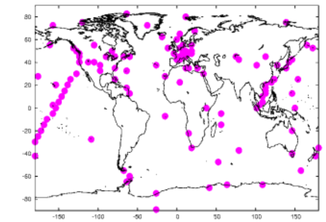
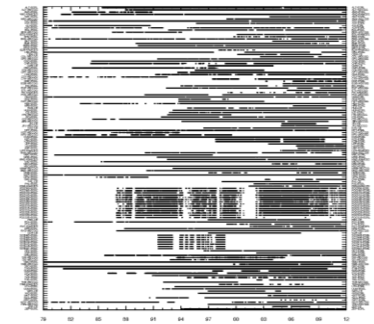
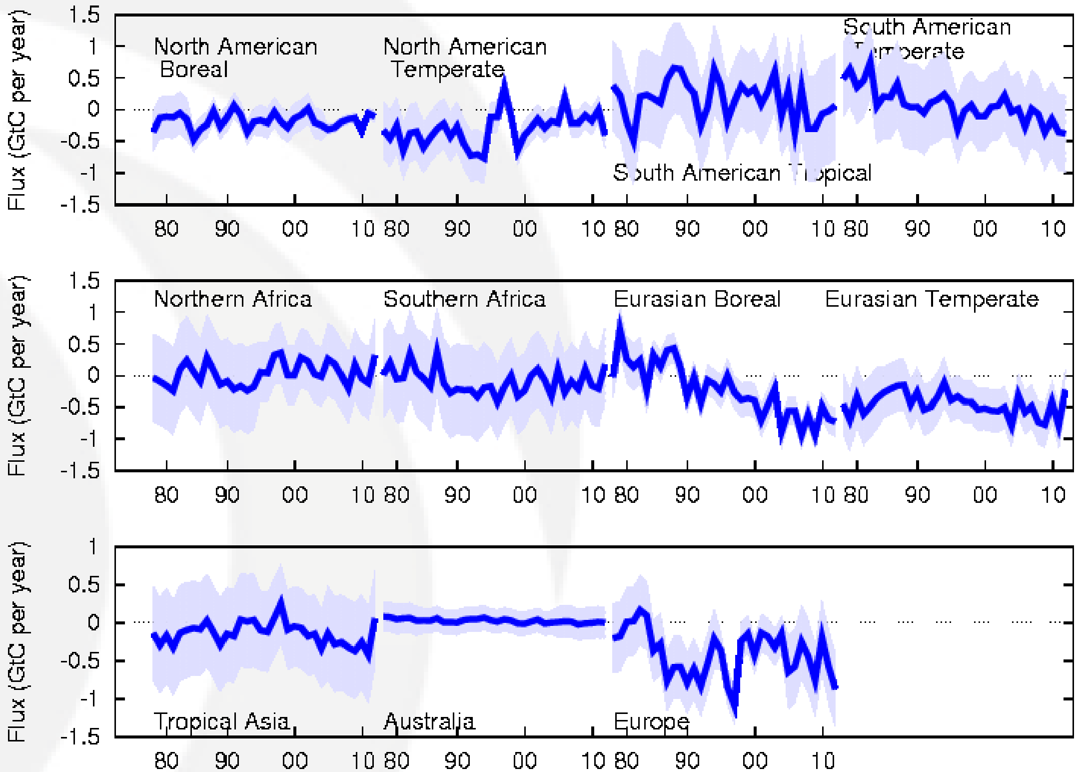
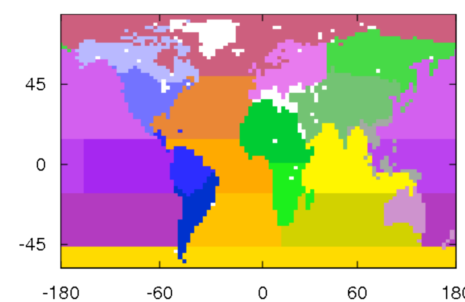
Time series over land









Annual budgets with 1 sigma uncertainty

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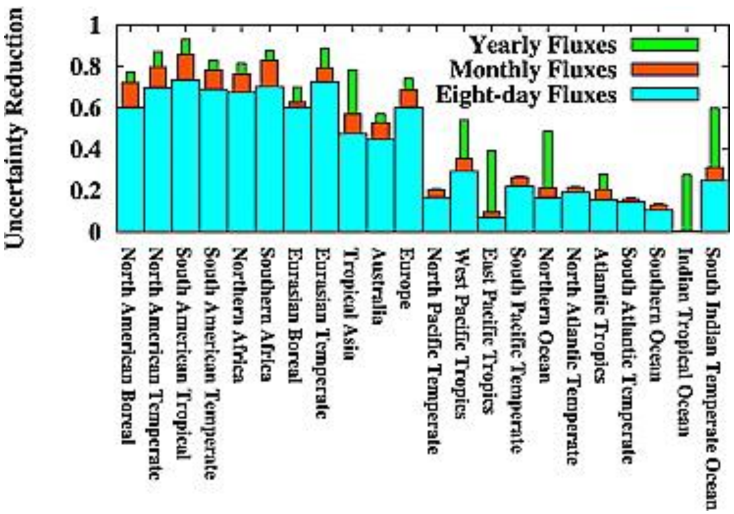
Towards assimilating satellite data

- Uneven spatial coverage of the surface measurements
- Long delays to get most of them (flasks, …)
- Dedicated satellite programs aiming at filling the gap
  - GOSAT since mid-2009
  - OCO-2 to be launched in summer 2014
  - OCO-3, TANSAT, etc.

Assimilating column retrievals

- Testing the assimilation of simulated data
  - OCO (Chevallier et al. 2007a,b)
  - A-SCOPE (Hungershoefer et al. 2009, Houweling et al. 2010)
  - GOSAT (Chevallier et al. 2009, 2010)

  - Large potential of the satellite data



Theoretical uncertainty reduction expected from GOSAT at regional scale

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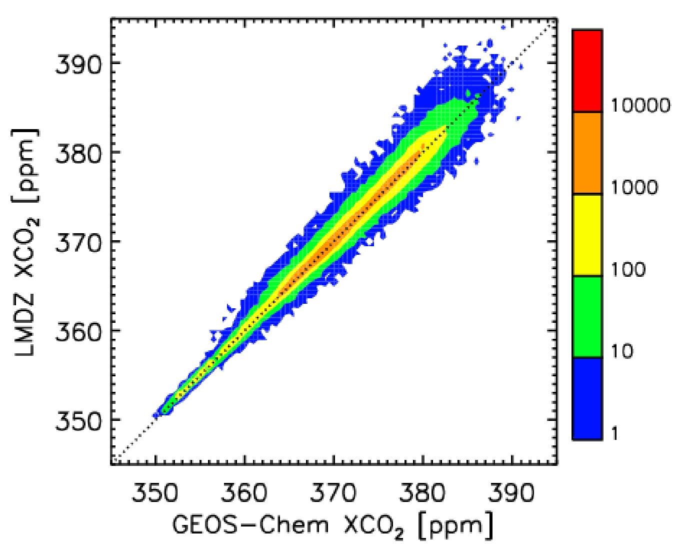
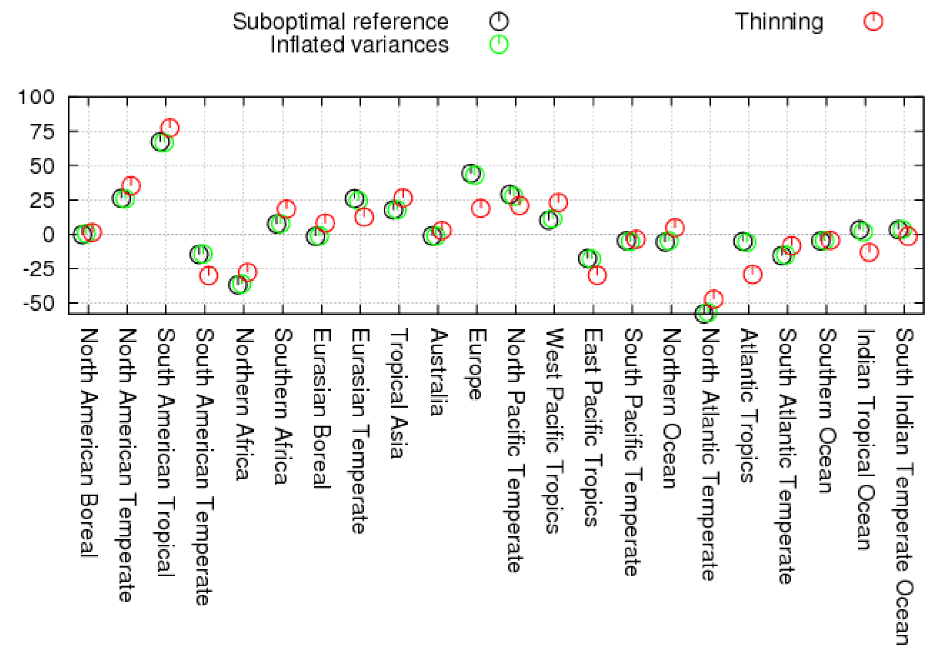
  - Large potential of the satellite data
  - Large sensitivity to transport errors



bias = 0.04 ppm, std. dev. = 0.6 ppm



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- Large potential of the satellite data
- Large sensitivity to transport errors
- Large sensitivity to retrieval errors

http://www.esa-ghg-cci.org/

G = goal
B = breakthrough
T = target

ghg cci | ESA Climate Change Initiative (CCI)
User Requirements Document Version 1 (URDv1)
for the Essential Climate Variable (ECV) Greenhouse Gases (GHG) | Page 19
Version 1 – Final
3 Feb 2011

Requirements for regional CO_2 and CH_4 source/sink determination using SCIAMACHY/ENVISAT and TANSO/GOSAT

Parameter	Req. type	Random error ("Precision")		Systematic error ("Accuracy")	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	As systematic

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Assimilating column retrievals

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  - A-SCOPE (Hungershoefer et al. 2009, Houweling et al. 2010)
  - GOSAT (Chevallier et al. 2009, 2010)

  - Large potential of the satellite data
  - Large sensitivity to transport errors
  - Large sensitivity to retrieval errors

- Real data
  - TOVS (Chevallier et al. 2005a)
  - AIRS (Chevallier et al. 2005b, 2009)
  - TCCON (Chevallier et al. 2011)
  - SCIAMACHY, GOSAT (unpublished)

  - Realistic results using TCCON
  - Unrealistic results using satellite retrievals so far

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Estimating surface fluxes from XCO_2 data

- Invert grid-point 8-day CO_2 fluxes from existing XCO_2 retrieval products
  - GOSAT-TANSO
    - University of Leicester (OCFP)
    - SRON/KIT (SRFP)
  - SCIAMACHY (late Envisat mission)
    - University of Bremen (BESD)
  - TCCON
- Ensemble product (EMMA, University of Bremen)

- Comparison with surface air sample inversion using two vertical resolutions of the LMDZ model (19 layers and 39 layers)

Many thanks to all data providers!

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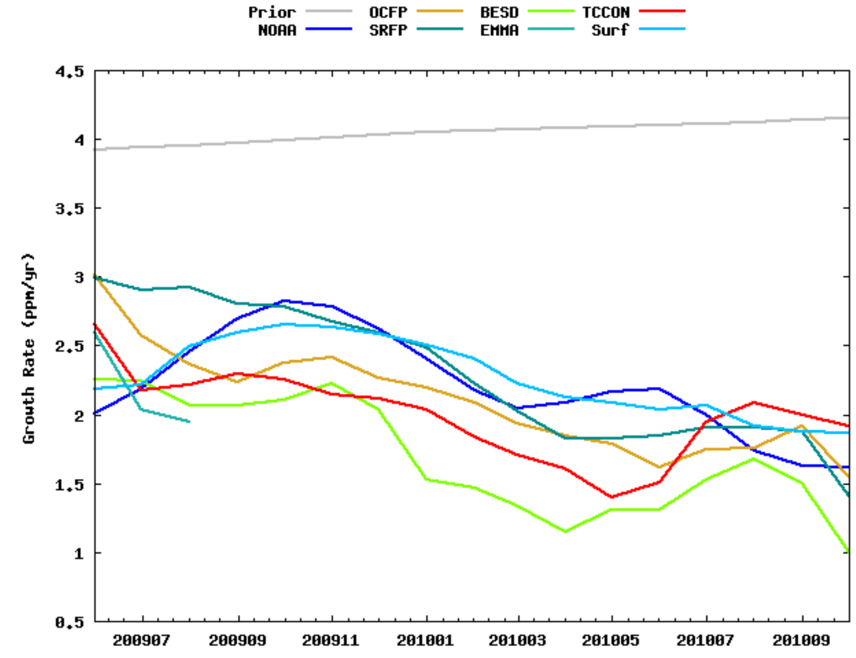
Inverted growth rates



LMDZ-39. Global 12-month atmospheric growth rate from NOAA computed month after month from the prior fluxes, from the surface air-sample inversion and from the CRDP-based inversions. The *x* axis corresponds to the month at the beginning of the 12-month period.

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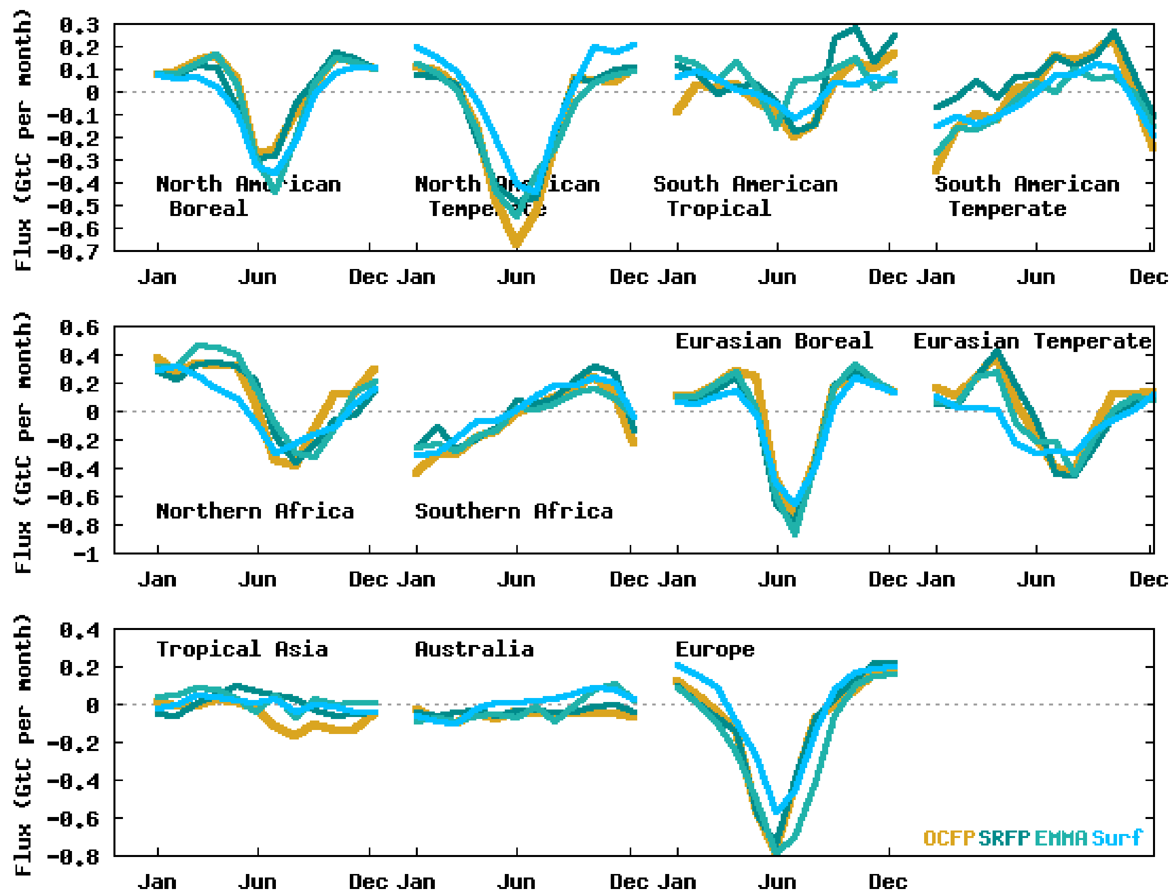
Inverted seasonal cycles



LMDZ-39. Seasonal cycle of the natural CO_2 fluxes derived through inversion (without fossil fuel fluxes).

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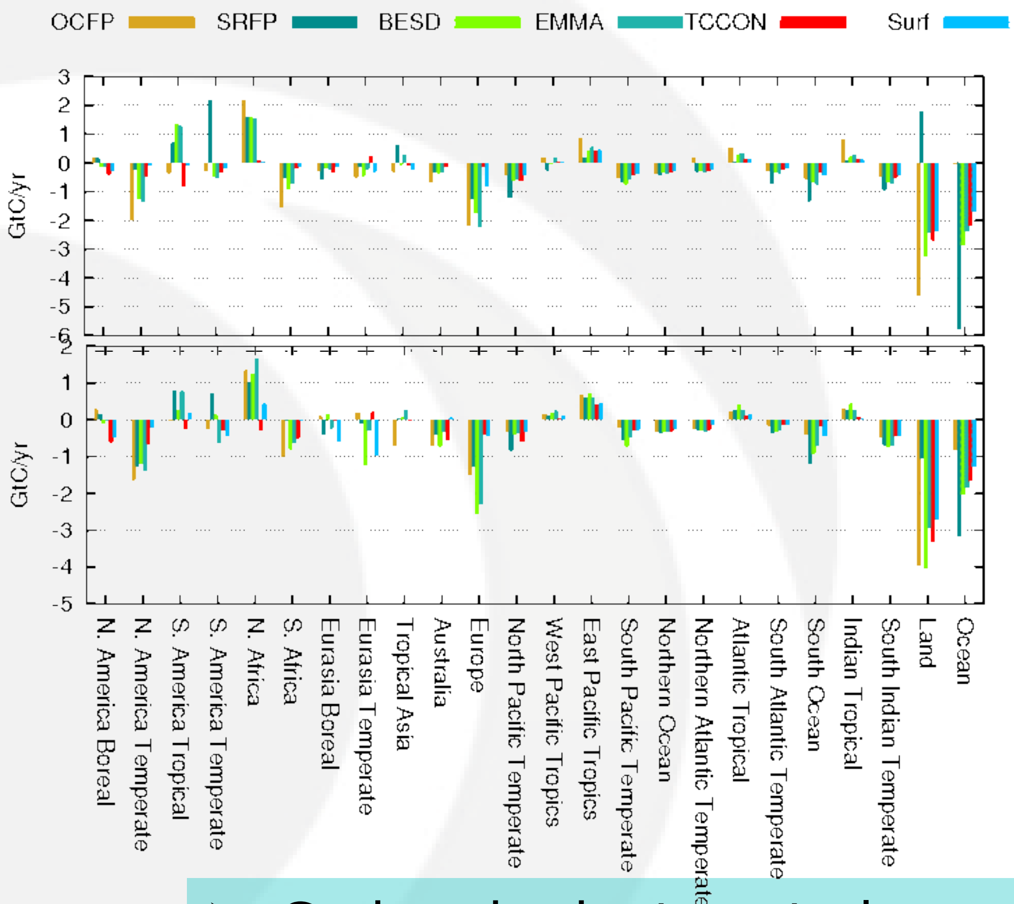
Inverted annual budgets



LMDZ-19

LMDZ-39

- Carbon budgets not always consistent with independent data (e.g., from the CarboEurope synthesis)
- Large sensitivity to the choice of the L2 product
- Large sensitivity to the choice of the transport model

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Conclusions

- Strong constraint seen from the satellite retrievals on atmospheric inversion.
- The stringent users requirements on systematic errors for the satellite products are not met yet despite better-than expected precision (0.5×).
- The transport model errors significantly degrade the inversion results as well.
  - Try higher resolution, new physical packages
- Finally, prior error assignment seems to control the amplitude of the inverted seasonal cycle.
  - Reinforce robustness of the assigned errors
- Analysis made complicated by large flux footprint of XCO_2

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Conclusions

- Surface inversions are considerably more realistic than satellite ones, but not fully satisfactory
  - Validation with TCCON shows seasonal biases
  - Sensitive to the transport model
- 34 years of inverted weekly fluxes represent a considerable amount of data to investigate
- This is only the beginning…

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Thank you