Is there an Optimal CO_2 Partial Column for Flux Inversions?

Sourish Basu, Frédéric Chevallier, Junjie Liu, Prabir Patra, Susan Kulawik, David Baker

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Motivation

$$y = H(x) + \varepsilon$$

Measurement (y) — Transport and observation operator (H) — Surface flux (x) — Measurement noise (ε)

» Every atmospheric inversion (flux estimation) problem is an attempt to simulate measured concentrations of a tracer from surface fluxes with our best model of atmospheric transport

» Mismatches to observed **y** are minimized by changing **x**, assuming a perfectly known **H**. If **H** has errors, we will get errors in **x**.

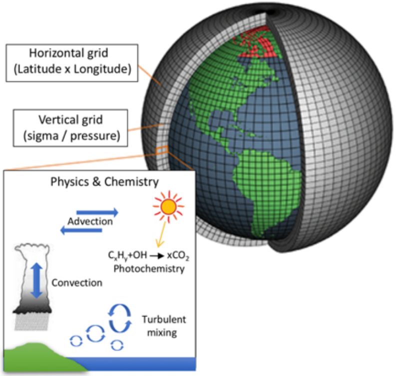
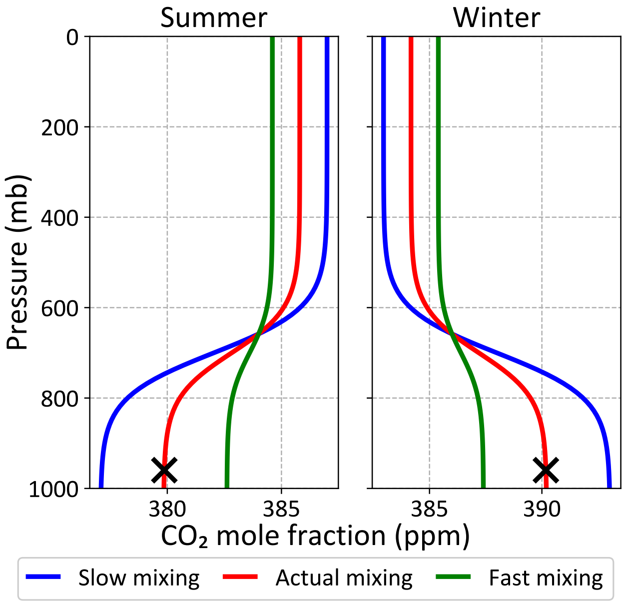


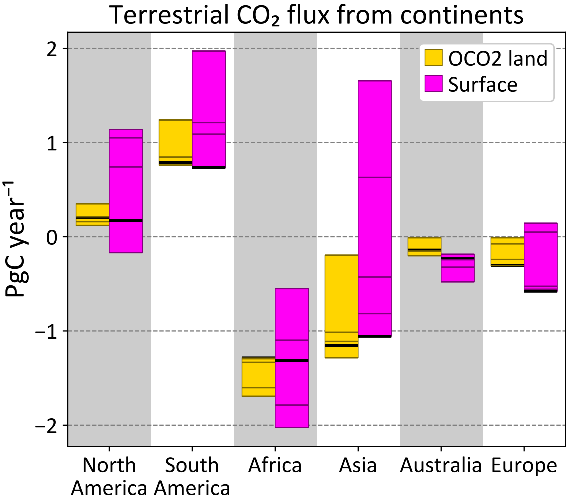
Figure courtesy SRON

Errors in vertical transport



- A model with too fast (slow) vertical mixing will estimate too much (too little) photosynthesis in the summer and respiration in the winter to fit the observed near-surface CO_2
- Assimilating the column average CO_2 makes the flux estimate much less sensitive to differences in modeled vertical mixing

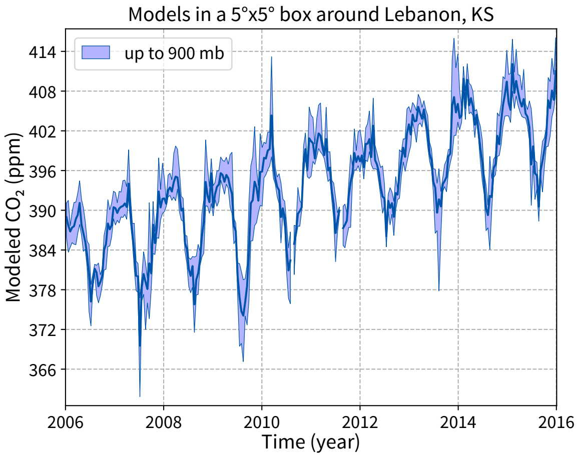
Impact of transport errors in assimilating total column vs surface measurements



- Rayner & O'Brien (2001) suggested that assimilating total column measurements (e.g., from satellites) might mitigate some errors in vertical transport
- More recently, Basu et al (2018) showed that given the same spatial coverage, assimilating column average CO_2 is indeed less sensitive to the choice of transport model than boundary layer CO_2

Basu et al, ACP (2018)

The quest for an optimal partial column



- The lowest 100 mb simulated by 7 transport models
  - Secular increase of ~2 ppm/yr
  - Seasonal cycle due to photosynthesis & respiration
  - Spread between models reflects transport difference

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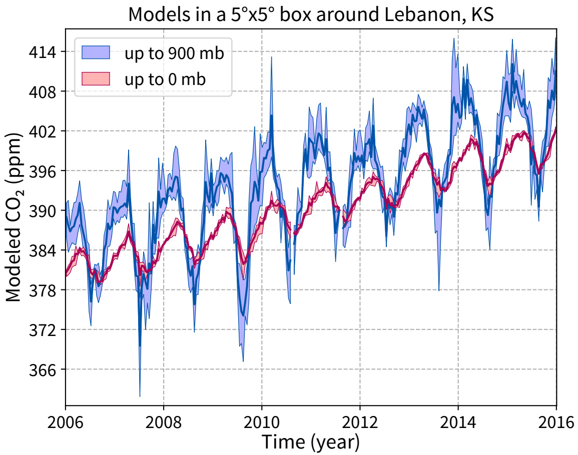

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  - Seasonal signal is smaller
  - So is the inter-model difference

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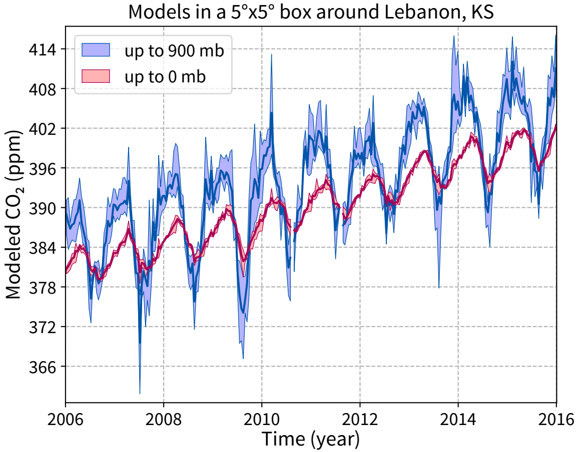

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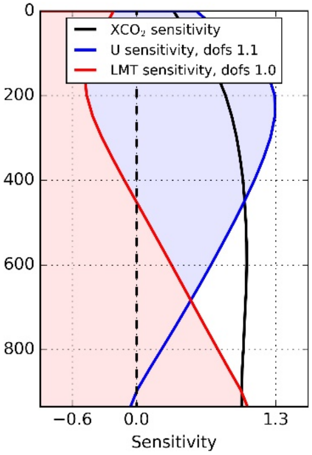
Is there an optimal partial column with the highest signal-to-noise?

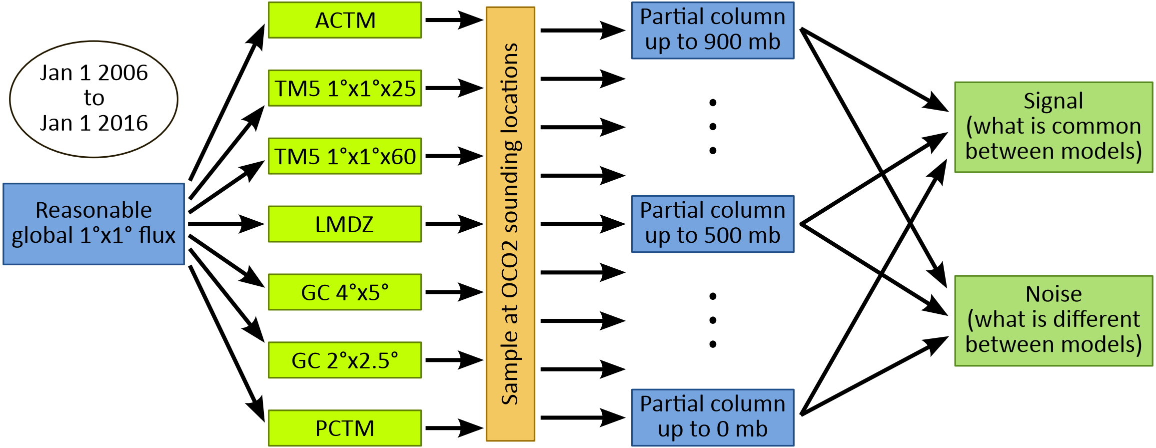
Feasibility with current and future satellite instruments



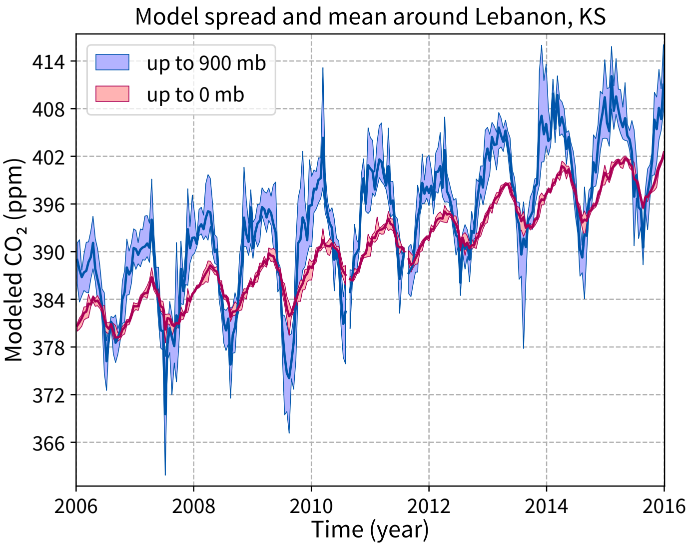
- This is not a purely theoretical exercise
- For OCO2 and GOSAT retrievals of CO_2, $DOF > 1$, even though we mostly work with the column average, i.e., use one piece of information
- Splitting into two columns, one mostly sensitive to the lower troposphere, the other to the upper troposphere and stratosphere, is possible

Kulawik et al, ACP (2017)

Design of experiment



The “signal” we want depends on the question we ask



- Models sampled at 2016-2017 OCO2 soundings every year, time series binned in bi-weekly bins
- The secular increase is the same for all partial columns. It is also not the signal we are after from satellites.

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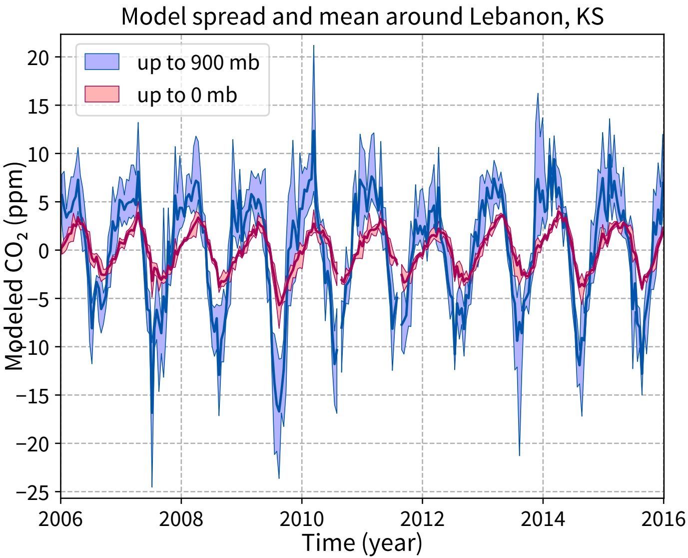


- Models sampled at 2016-2017 OCO2 soundings every year, time series binned in bi-weekly bins
- The secular increase is the same for all partial columns. It is also not the signal we are after from satellites.
- The seasonal cycle is a first order signal we are after. While it is reasonably well constrained over North America, the same cannot be said for most of the world.

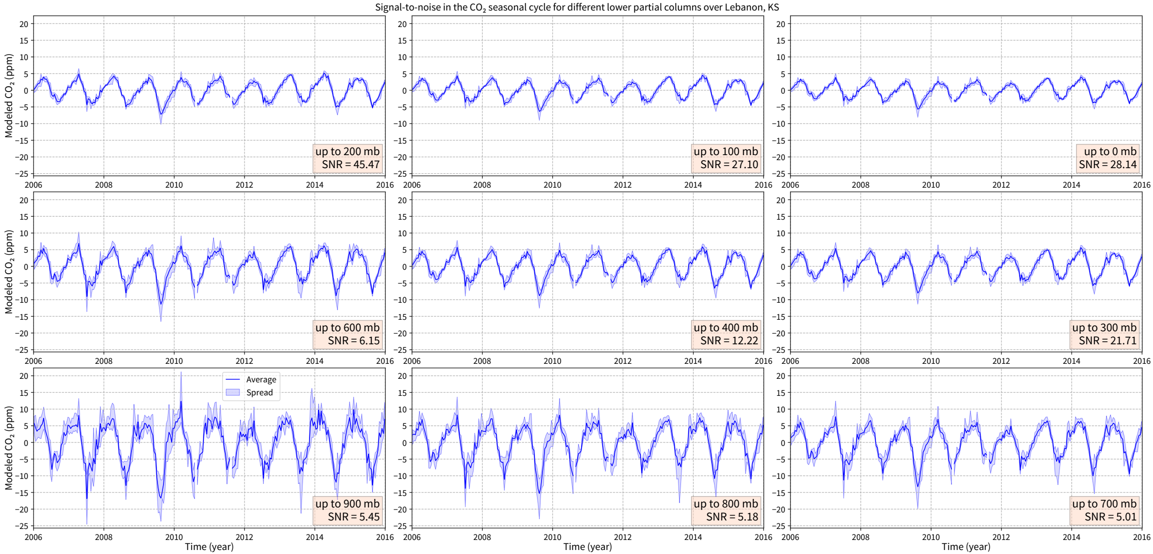
Signal to noise in the seasonal cycle

Estimate the seasonal cycle by fitting three harmonics to each modeled time series

$$x(t) = x_0 + x_1 t + \sum_{n=1}^{n=3} \left(\alpha_n \cos(n\omega t) + \beta_n \sin(n\omega t)\right)$$

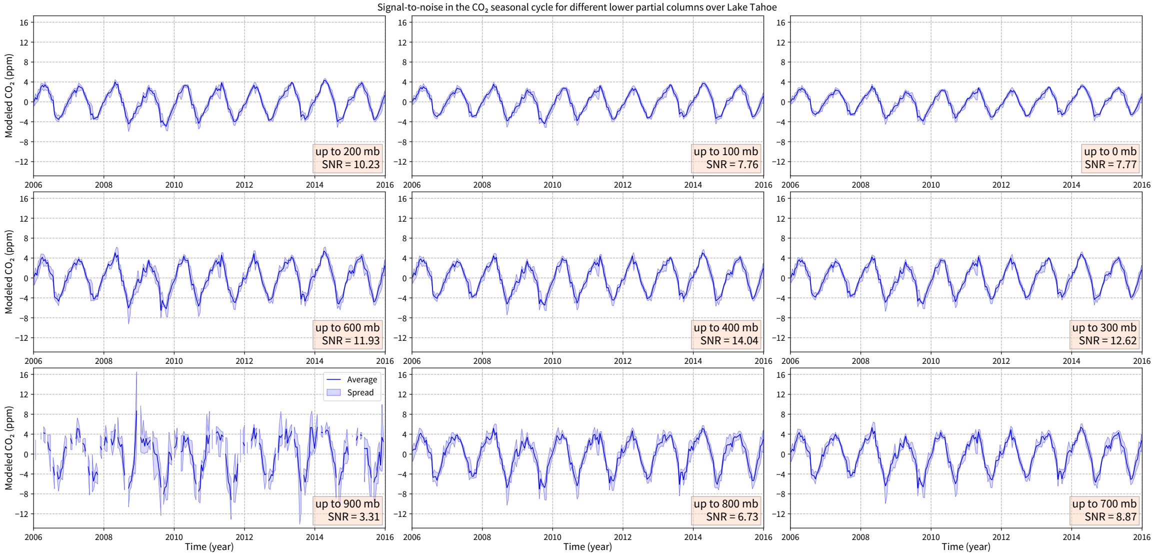
where $\omega = 2\pi/(1 \text{ year})$. The mean amplitude of the harmonic part is the "signal", the spread in the amplitude the "noise".

Signal to noise in the seasonal cycle



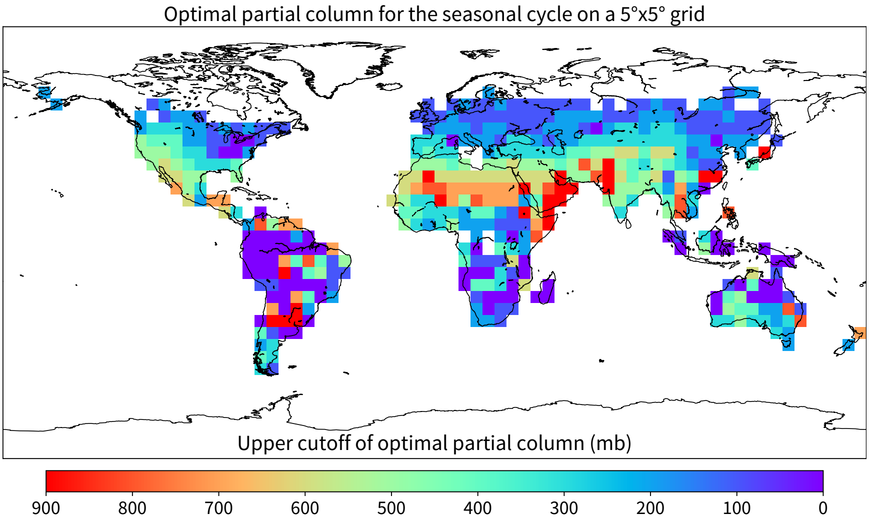
And the winner is ... 200 mb!

The optimal partial column is location dependent



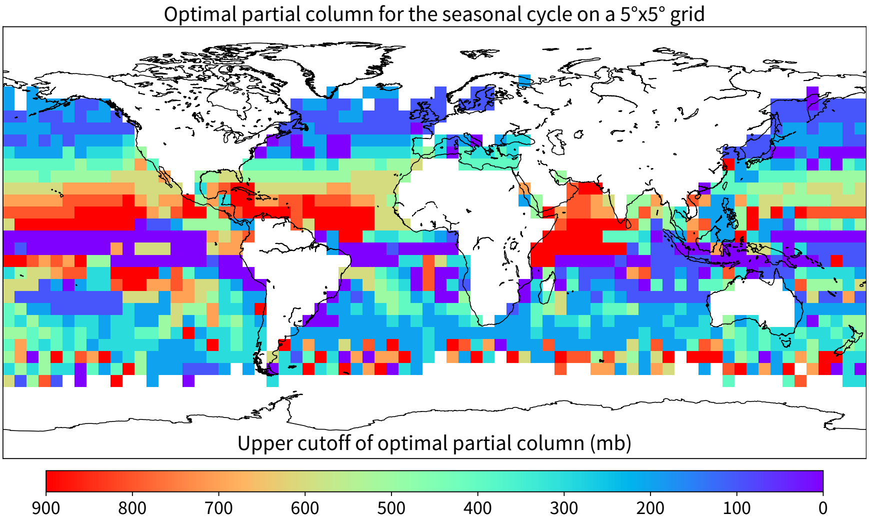
Elsewhere, the optimal partial column could be shallower or deeper

Global patterns in the optimal partial column



The message here is only that there is such as thing as the optimal partial column, rather than the exact numbers on this map

Global patterns in the optimal partial column



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Lots left to do

- What about other flux signals, like the interannual variability?
- How would the optimal partial column change for a different satellite instrument?
- If we add the accuracy of the retrieved partial column into the mix, would that change our picture of the optimality?
- What are the physical mechanisms behind the patterns on the map?
- How robust is this to a different specification of the surface flux?
- We will try to estimate this optimal partial column for OCO2 CO_2

“The spread between models is not the model error”

Yes, but these models are use routinely used in CO_2 inversions with satellite data. So the difference between these models affects the uncertainty of flux estimates, or what might be the best partial column to assimilate given these models.

Placing all transport models on a common footing

- Some differences between transport models stem from different histories. These are (in principle) easy to fix/standardize.
  - Different total dry air mass
  - Different radii for the Earth
  - Different molar masses for C and CO_2

- Some differences are hard to fix *post facto*, but relatively easy to adjust for
  - Different regridding and interpolation schemes for fluxes
  - Different ways of specifying the initial field

- The remaining differences are what we consider fundamental transport model differences

Disagreement between global models

Model	Gravity (m s^{-2})	Radius of Earth (km)	Dry air mass (kg)	Molar mass of C (g mol^{-1})	Molar mass of air (g mol^{-1})
ACTM	9.806 65	6370	5.1341×10^{18}	12.011 15	28.94
GEOS Chem	9.8	6375	5.0855×10^{18}	12.0	28.97
LMDZ	9.806 65	6400	5.1703×10^{18}	12.0	28.94
PCTM	9.806 16	6371	5.1274×10^{18}	12.011 15	28.97
TM5	9.806 65	6371	5.1232×10^{18}	12.011 15	28.94