Lessons learned from AIRS mid tropospheric CO2 and the future opportunities

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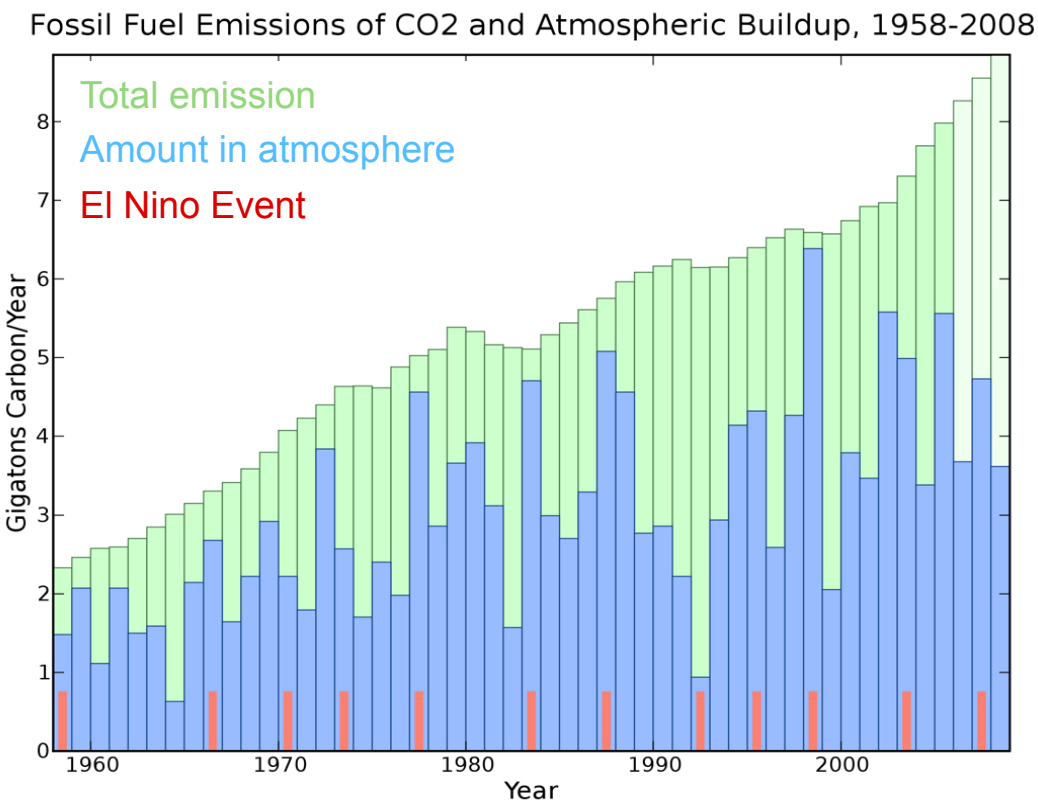
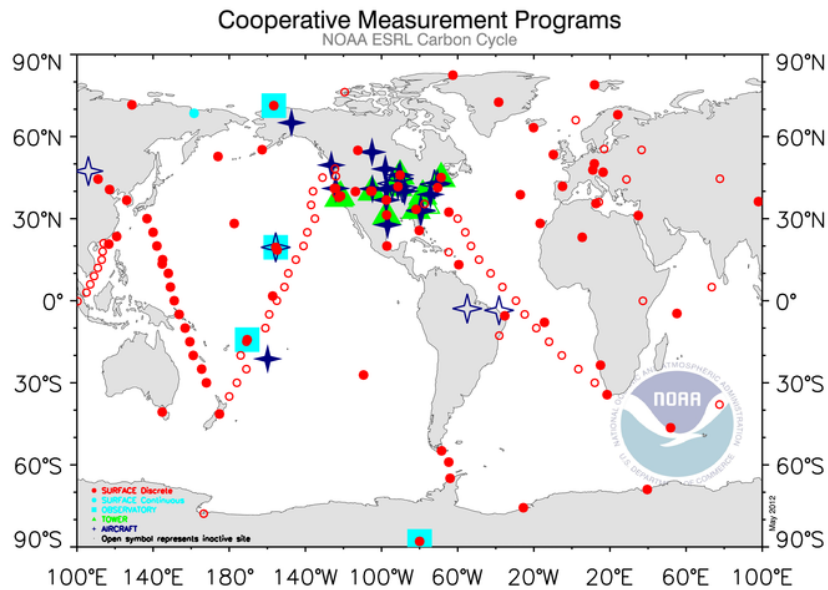
Carbon cycle science questions



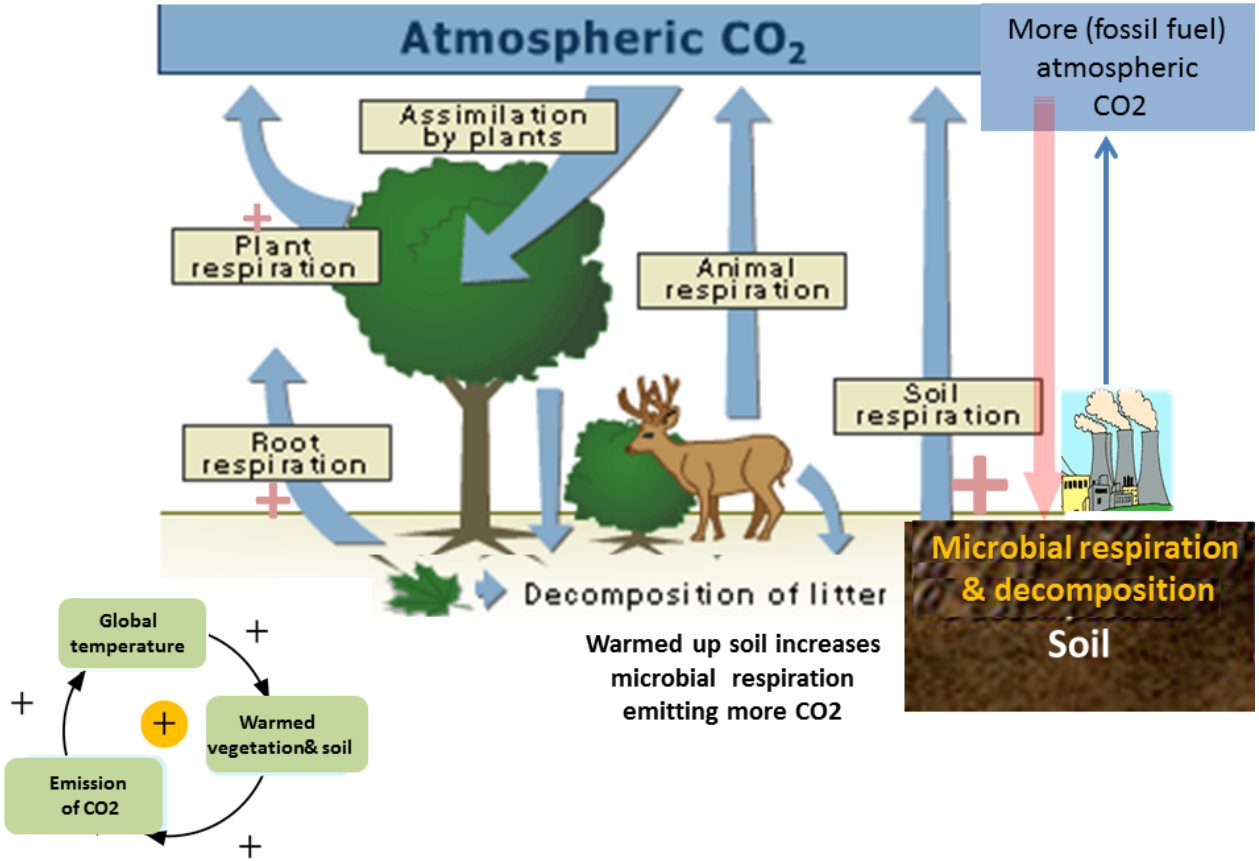
NOAA ESRL Surface Sites



Only about half of the fossil fuel emissions remains in the atmosphere. Where the other half goes and why?

Why we care where the carbon goes?

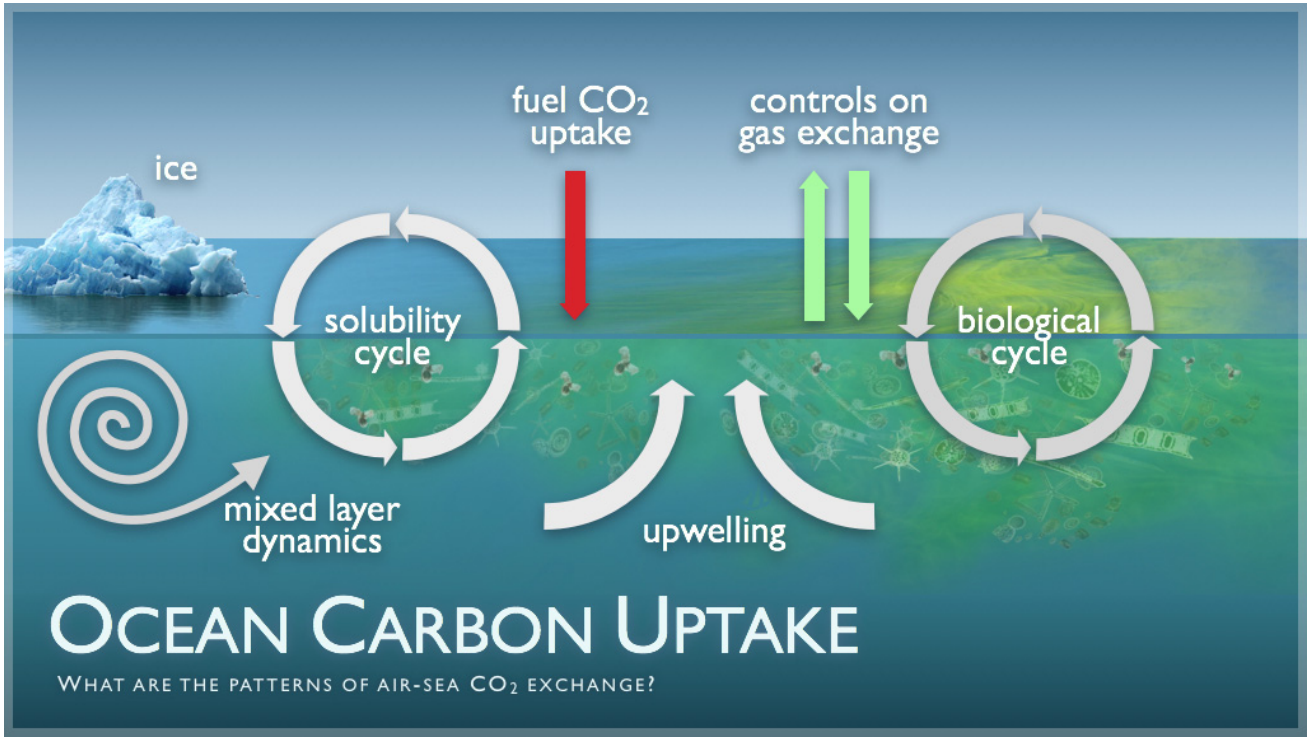
Terrestrial carbon cycle feedback



- Carbon-Climate feedback is poorly understood

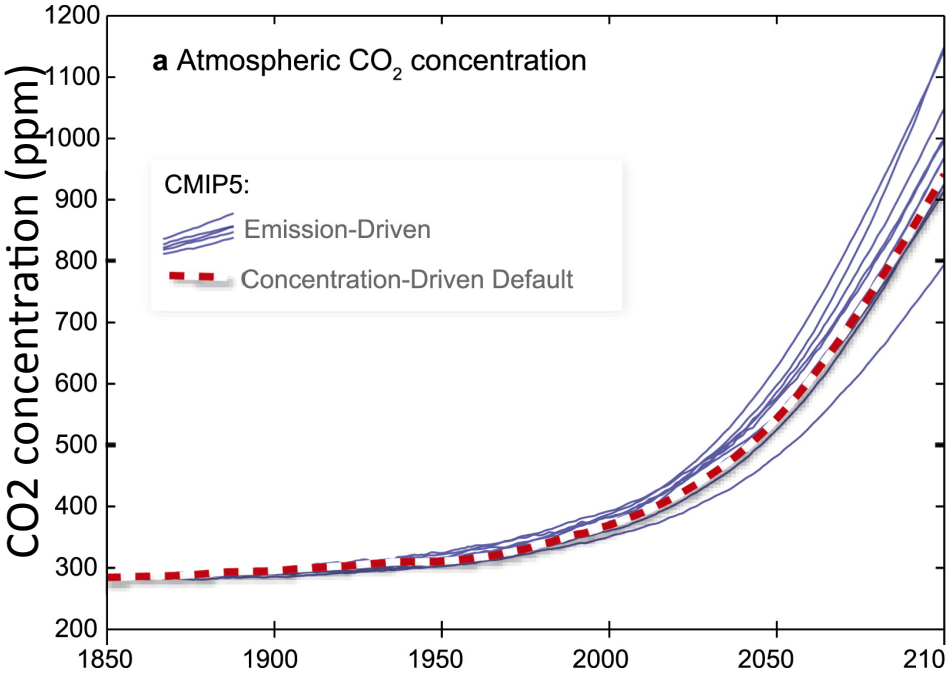
Why we care where the carbon goes?

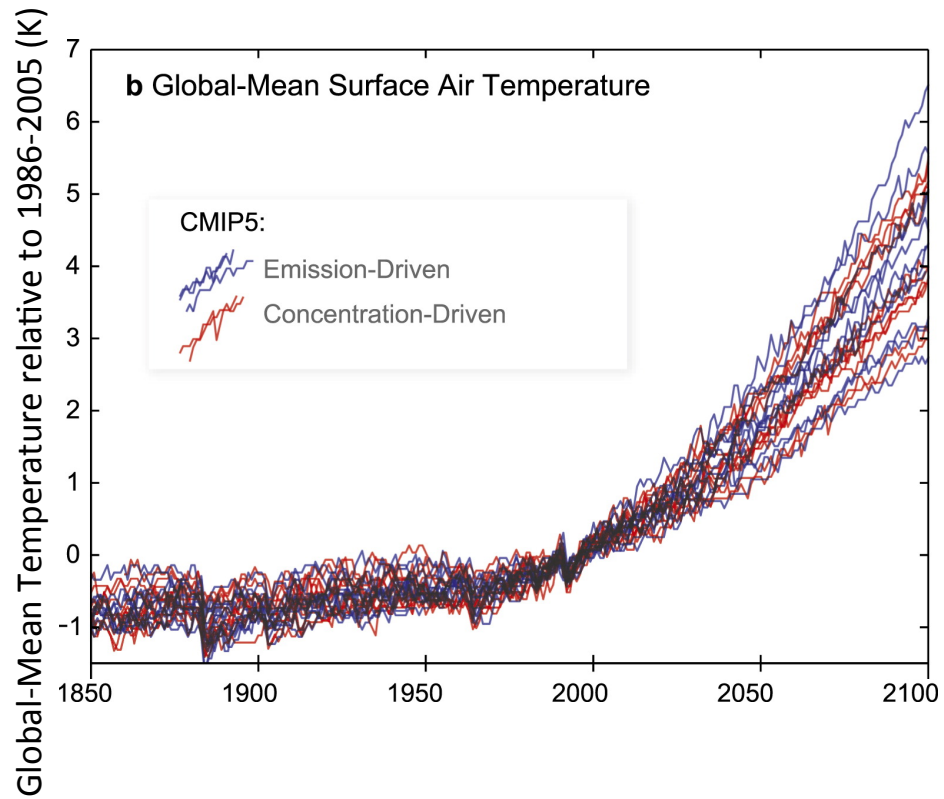
Ocean Carbon Cycle



- **Carbon-Climate feedback is poorly understood**

Temperature projection has larger uncertainties in ESM with carbon-climate feedback



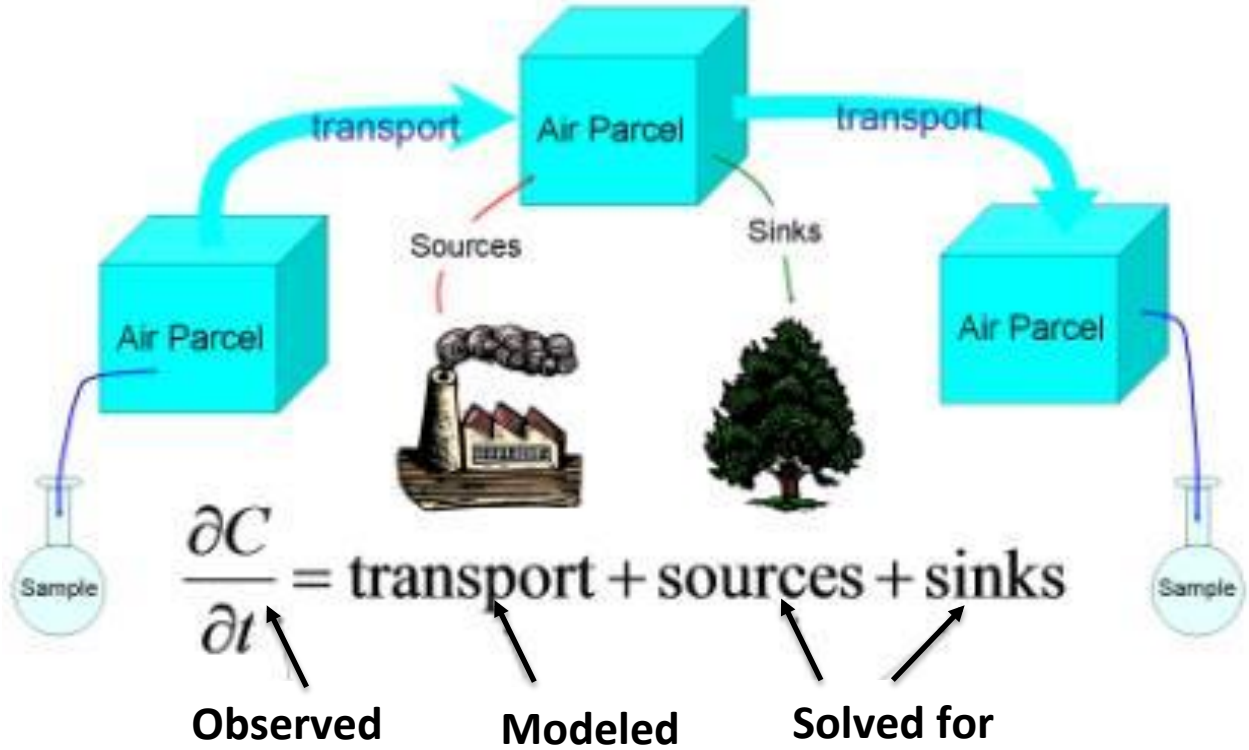


Red: NO carbon cycle feedback; **blue: WITH carbon cycle feedback**

- **Large CO2 spread (795ppm-1145ppm) ; 7 out of 11 simulates larger CO2 concentrations;**
- **Temperature projections are generally higher (3.9°±0.9° vs. 3.7°±0.7°)**

Friedlingstein et al. (J. Climate, 2014)

Atmosphere inverse modeling to pinpoint the source and sink and understand the physical processes



Key elements

- **Atmosphere transport**
- **Observations that are sensitive to the surface flux**
- **Numerical framework.**

How could we use AIRS CO2 to answer these questions?

- The atmosphere transport
- The sensitivity of AIRS CO2 to surface flux
- The impact on flux inversion
- Challenges

How could we use AIRS CO2 to answer these questions?

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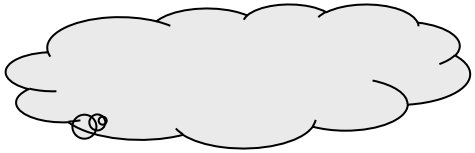
AIRS CO2 data assimilation

Objective: to estimate 6-hourly 3D CO2 fields on regular model grid point

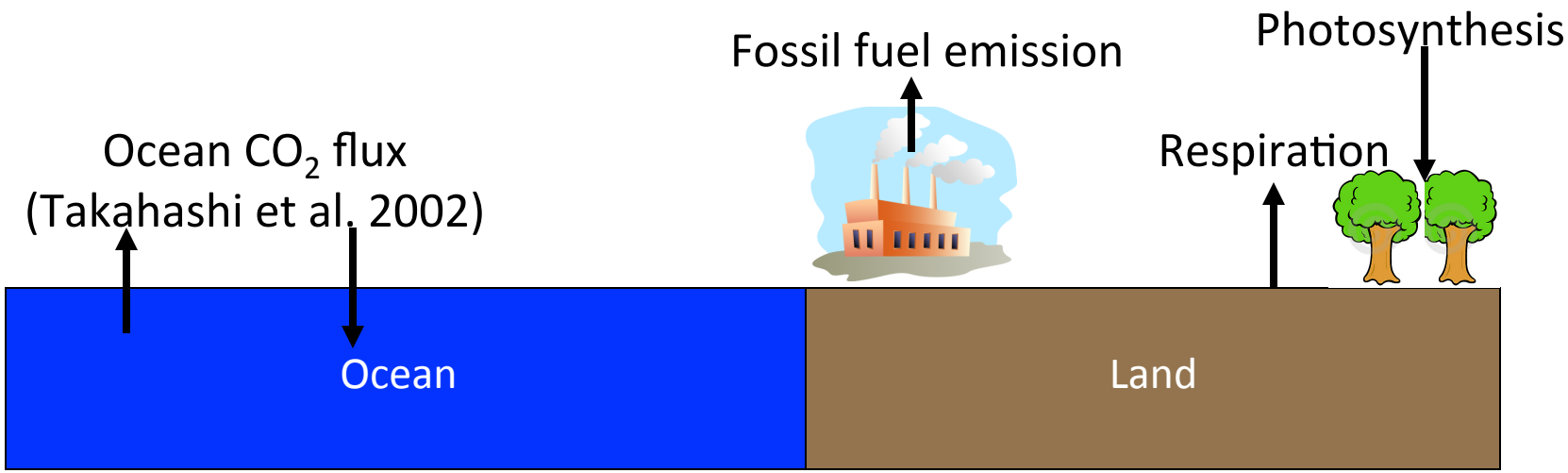
Liu et al. (2012, JGR)

Carbon-Climate Model

Community Atmospheric Model (fvCAM 3.5) (2.5x1.9x26)

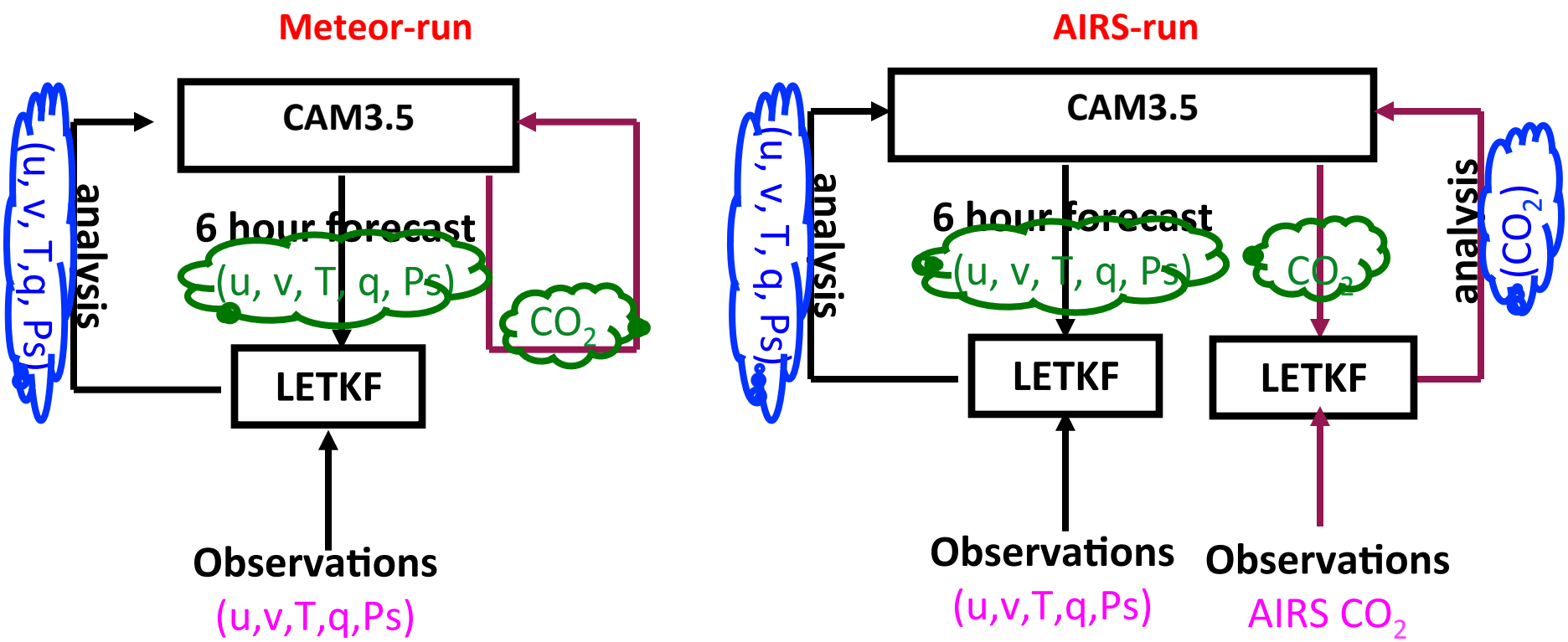


CO_2, winds, q, T, Ps



- CO_2 is transported as a tracer in CAM 3.5.
- Land carbon flux: 6-hourly flux from biogeochemical model.

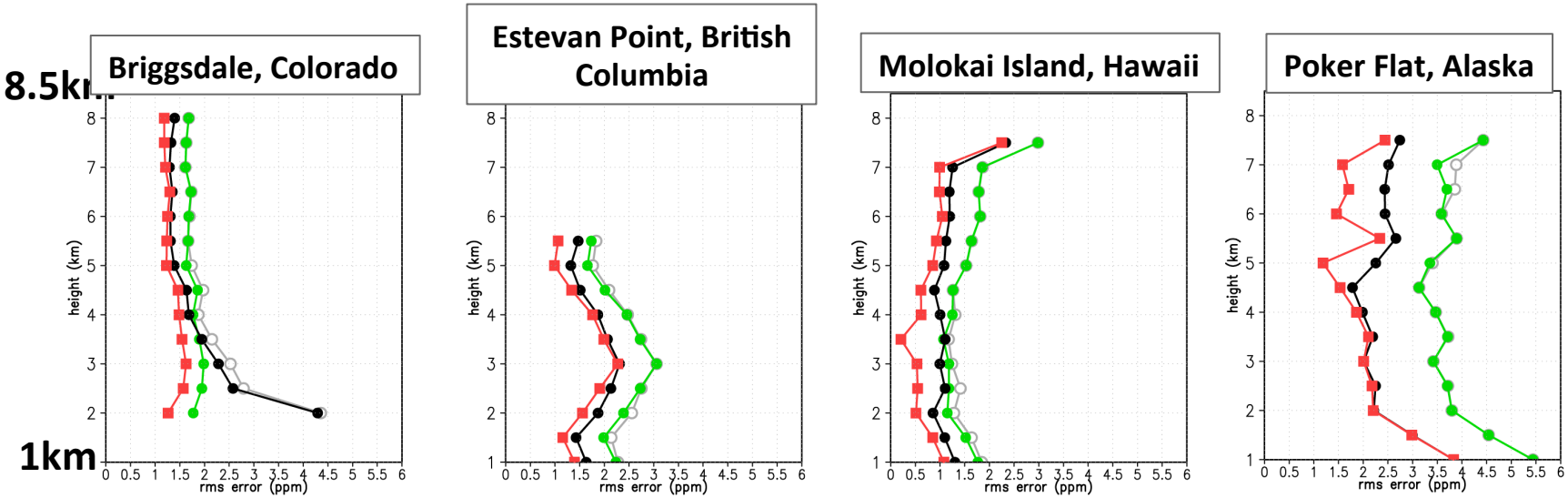
The impact of AIRS CO_2 assimilation on 6-hourly CO_2 3D (x, y, z) fields



- AIRS-run: AIRS CO_2+met obs; Meteor-run: only met obs.
- Year of 2003.
- Prescribed surface carbon flux forcing.

Assimilating AIRS CO2 improves the accuracy of CO2 vertical profiles

Meteor-run: green: bias; gray: random error
AIRS-run: red: bias; black random error



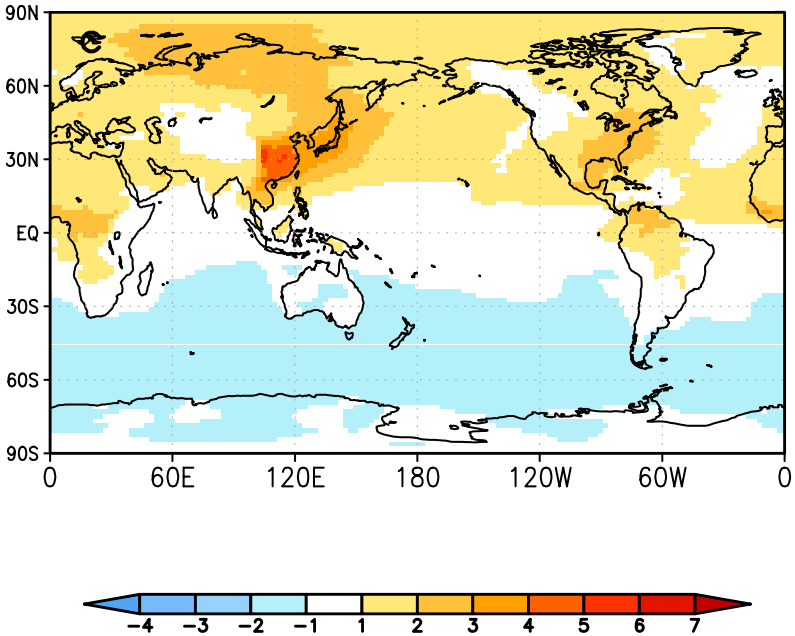
- **The improvement is more than 1ppm over some locations;**
- **The error is below 2.5ppm around 5km at all the aircraft locations.**

The aircraft data is from NOAA ESRL

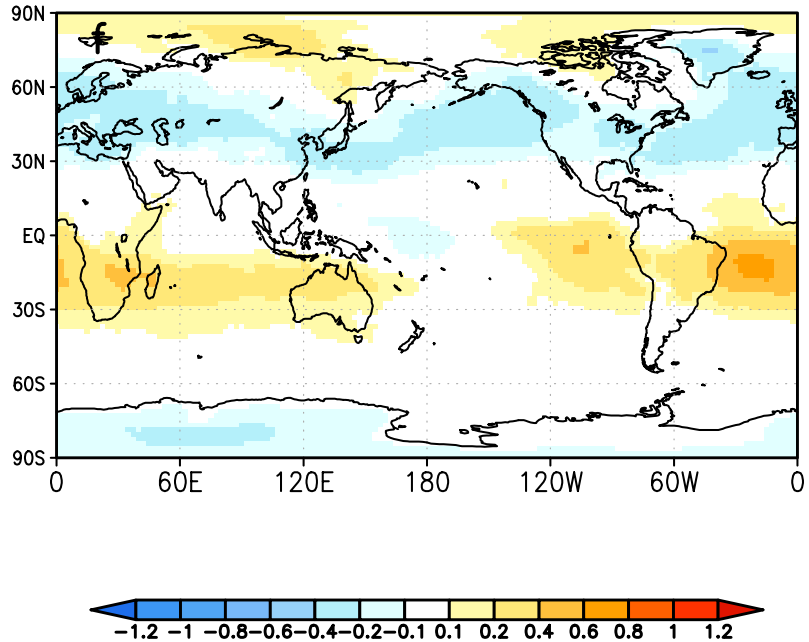
Assimilating AIRS CO2 weakens annual mean CO2 vertical gradient

CO2(929hPa-433hPa)

Meteor-run



(AIRS-run)-(Meteor-run)



Note: the scale of the color bar is different

- **On annual mean, surface CO2 >mid troposphere in the NH (co-varying between PBL height and the terrestrial biosphere activity) ;**
- **Weakening of the CO2 vertical gradient equivalents with intensifying vertical mixing.**

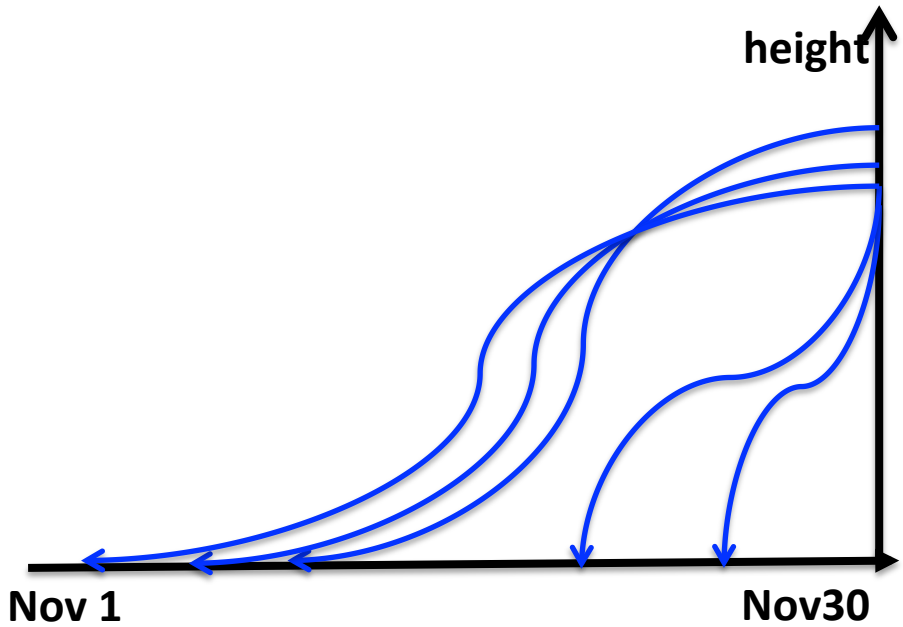
How could we use AIRS CO2 to answer these questions?

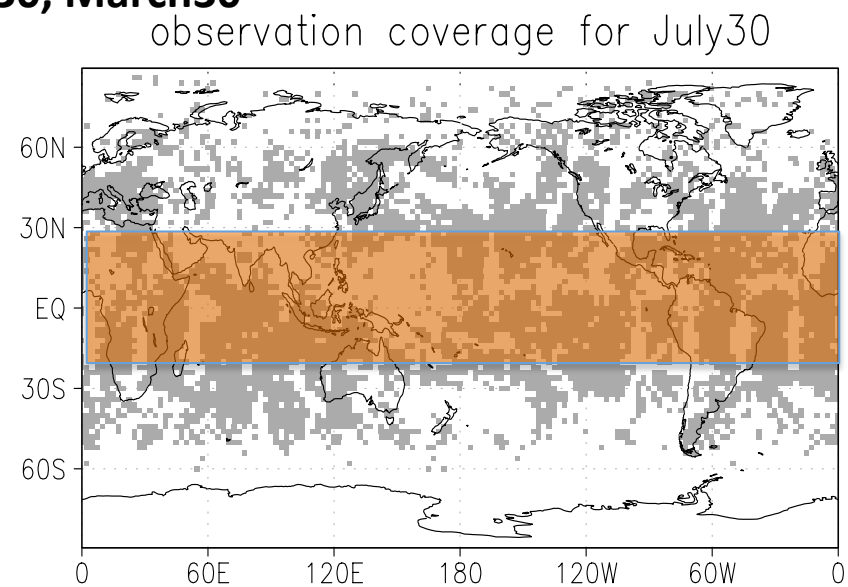
- The transport problem
- The sensitivity of AIRS CO2 to surface flux
  - Adjoint model to calculate the sensitivity of mid-troposphere AIRS CO2 to surface flux
- The impact on flux inversion
- Challenges

Adjoint sensitivity cases

Regions:25S-25N (orange); Date: July30, Nov30, March30

Schematic plot of adjoint sensitivity case

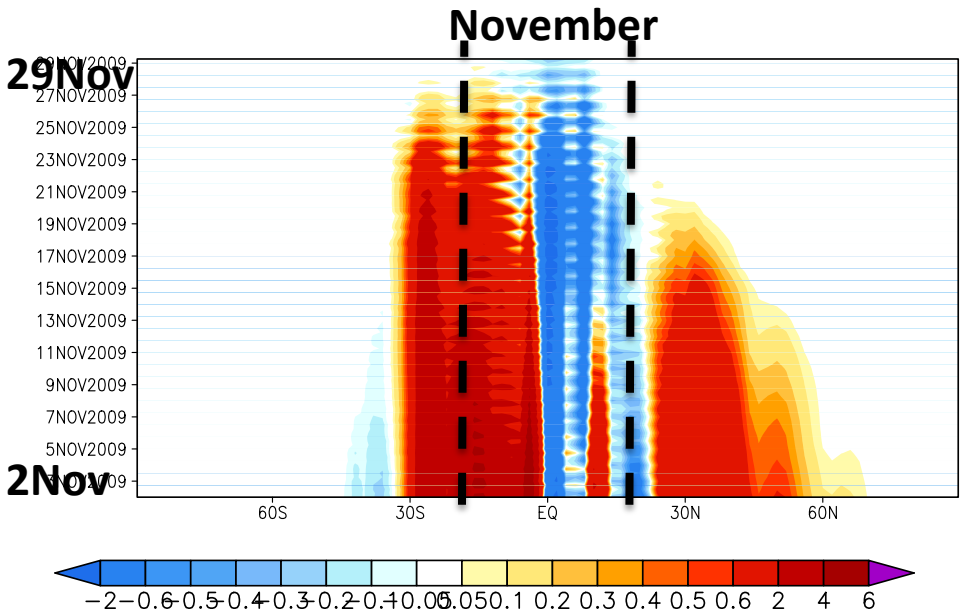




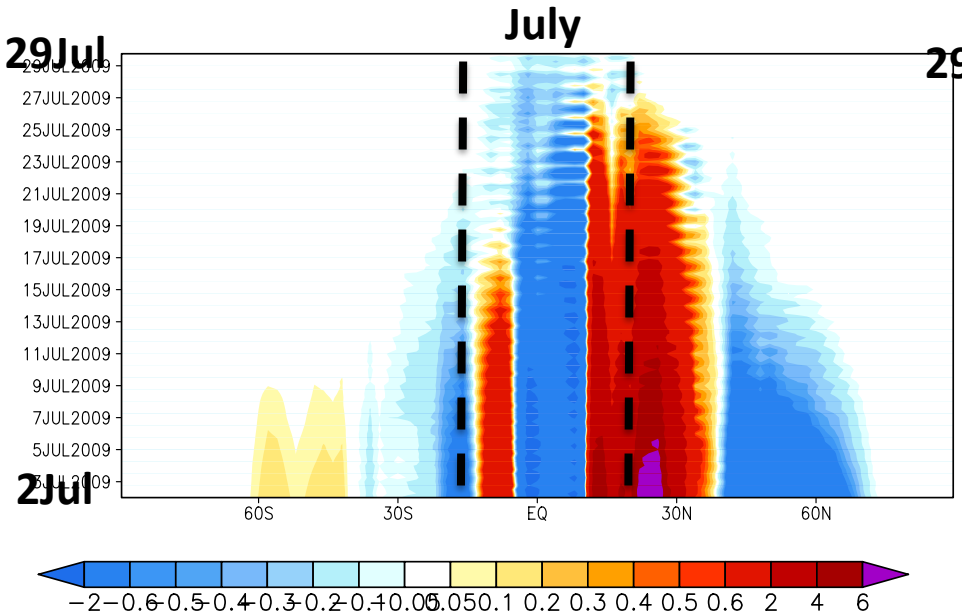
Quantity: J is the AIRS CO2 concentration; f is the surface CO2 flux

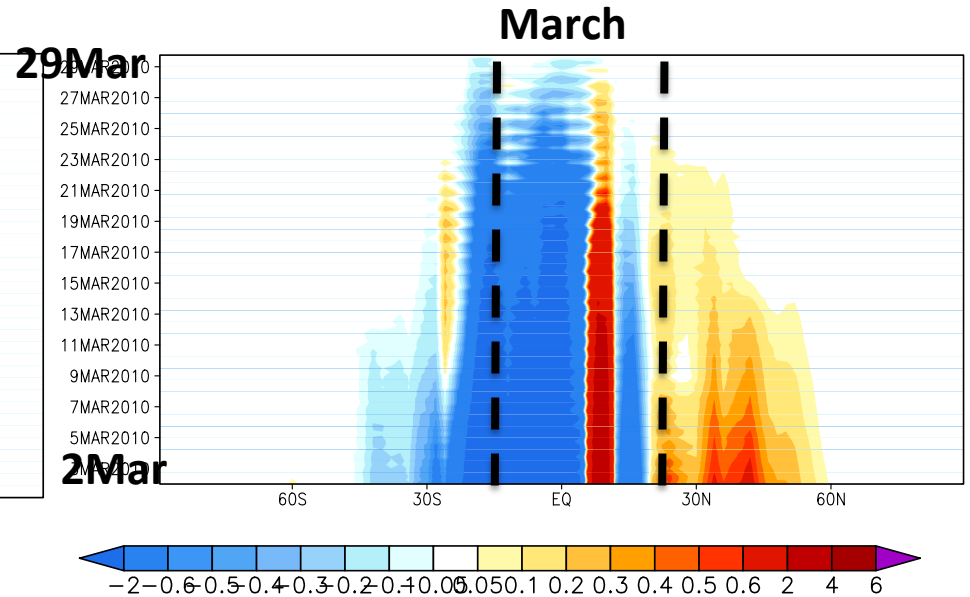
$$\sum_{i=1}^{T} \frac{\partial J}{\partial \mathbf{f}_i} \mathbf{f}_i$$

The sensitivity of AIRS CO2 over 25S-25N to surface CO2 flux



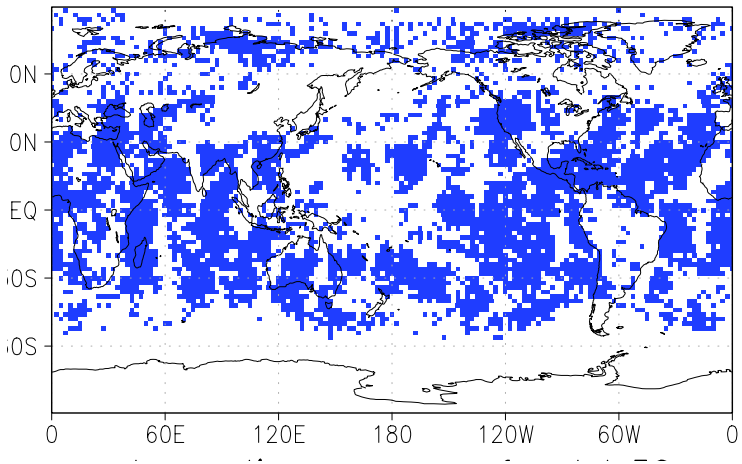
- Surface CO2 flux quickly transports to $(AIRS_{CO2})_{25S\text{-}25N}$ (less than three days);
- July: ITCZ is at the north of Equator, surface flux beyond 60N affects$(AIRS_{CO2})_{25S\text{-}25N}$;



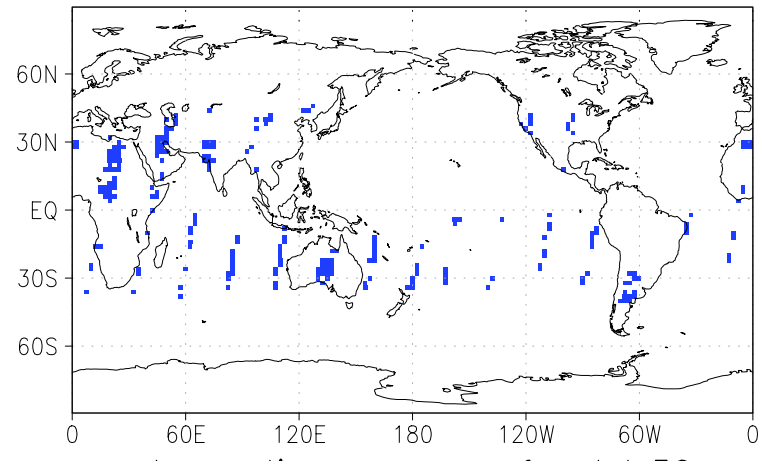


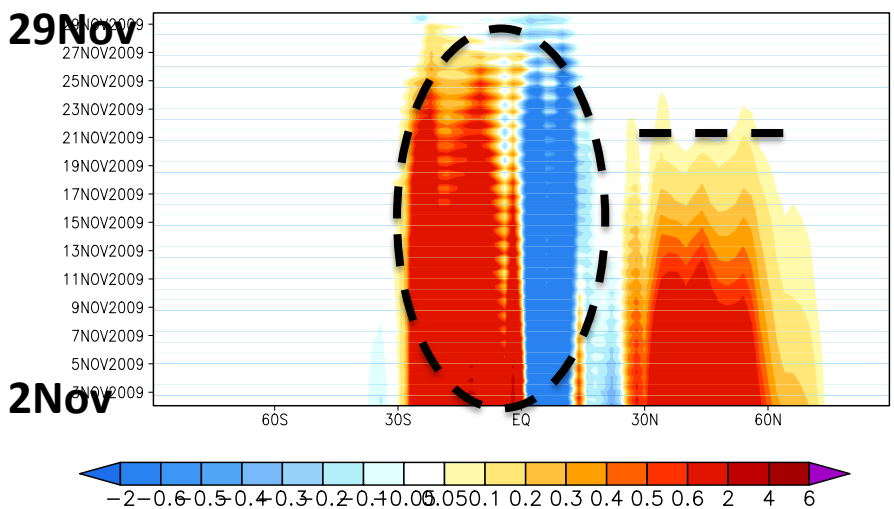
AIRS has larger sensitivity over tropics; GOSAT is more sensitive to surface flux over NH in Nov

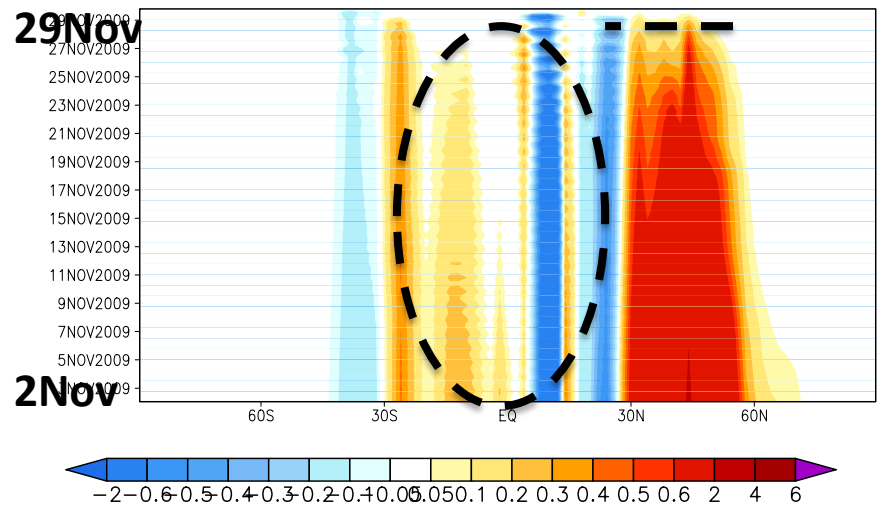
AIRS CO2 (good quality) on Nov 30



GOSAT CO2 (good) on Nov 30





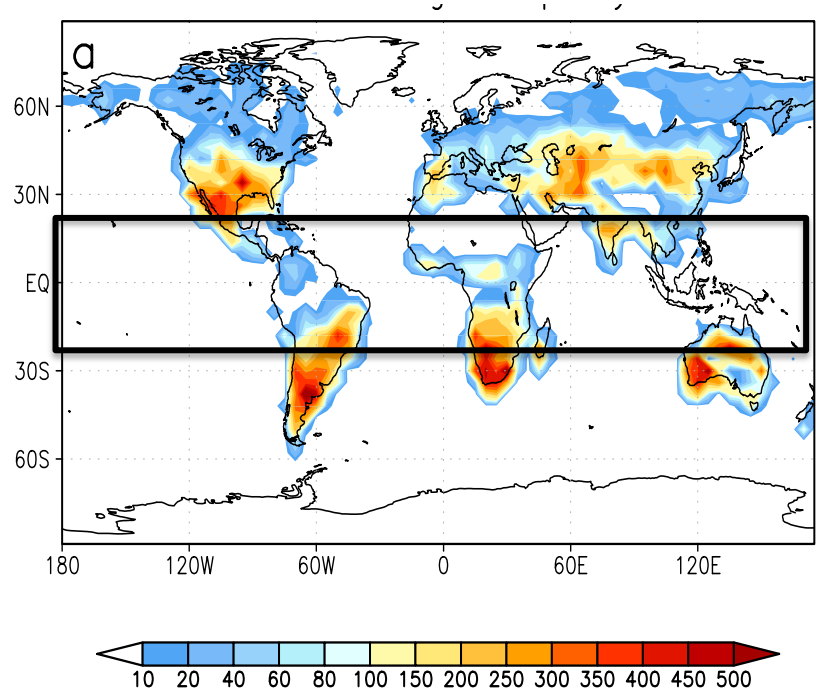


How could we use AIRS CO2 to answer these questions?

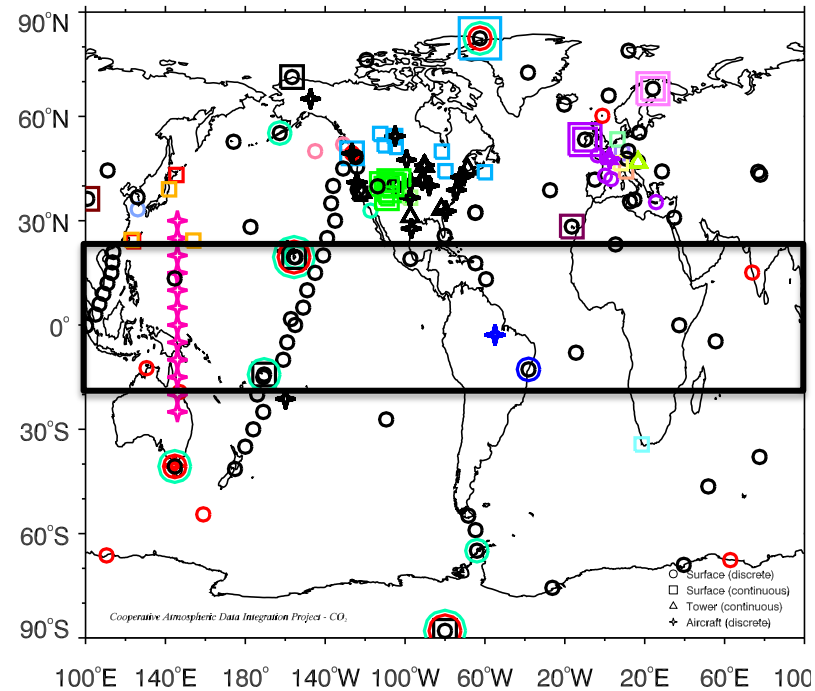
- The transport problem
- The sensitivity of AIRS CO2 to the flux
- The impact on flux inversion
  - The impact of AIRS CO2 on tropical flux estimation
- Challenges

Sparse observation coverage of GOSAT and conventional CO2 observations over the tropics

2010 GOSAT Xco2 observation coverage



Flask and insitu CO2 observations



CO2 flux estimation with OSSE

- **4D-Var flux inversion with GEOS-Chem adjoint model**

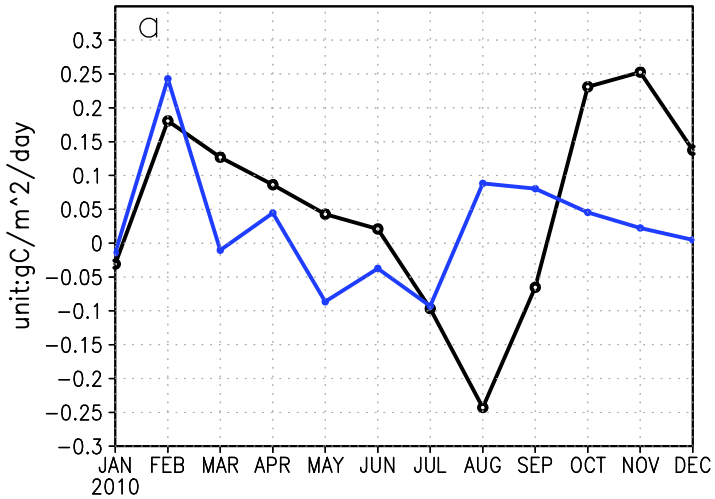
Background term — Observation term

$$J = (\mathbf{s} - \mathbf{s}_o)^T \mathbf{B}^{-1} (\mathbf{s} - \mathbf{s}_o) + \sum_{t=1}^{T} [\mathbf{y}_t - (h(\mathbf{s}))_t]^T \mathbf{R}^{-1} [\mathbf{y}_t - (h(\mathbf{s}))_t]$$

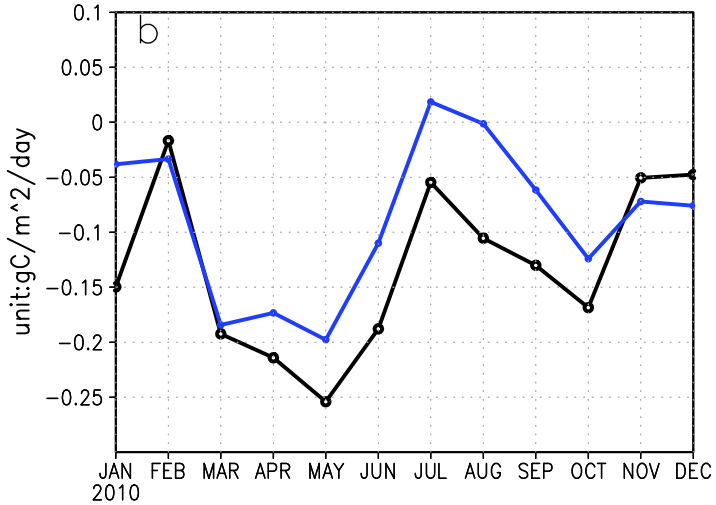
- **Time period: year 2010.**
- **Fluxes:**
  - **True fluxes (generate pseudo observations)**
  - **Prior fluxes (first guess in inversions)**
  - **Posterior fluxes (estimated from inversions)**
- **Experiments:**
  - **AIRS CO2 over tropics (25°S-25°N)**
  - **GOSAT Xco2**
  - **AIRS CO2 over tropics + GOSAT Xco2**

Different seasonality between the prior and the true CO2 fluxes

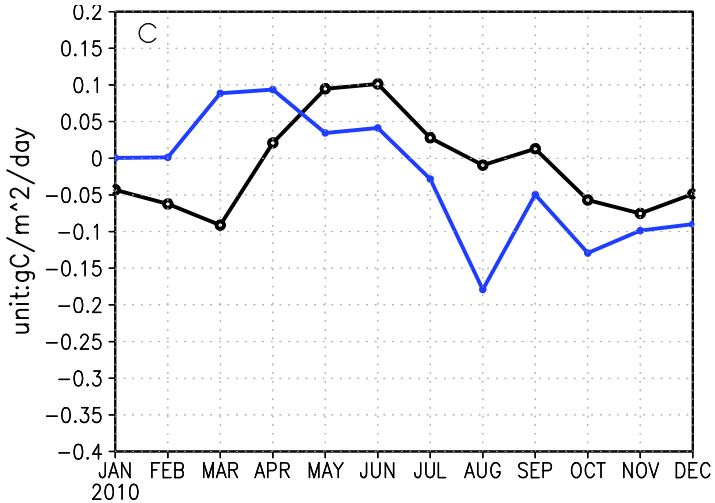
Amazon (25°S-25°N, 90°W-30°W)



Tropical Africa (25°S-25°N, 10°W-60°E)



South East Asia (25°S-25°N, 80°E-120°E)

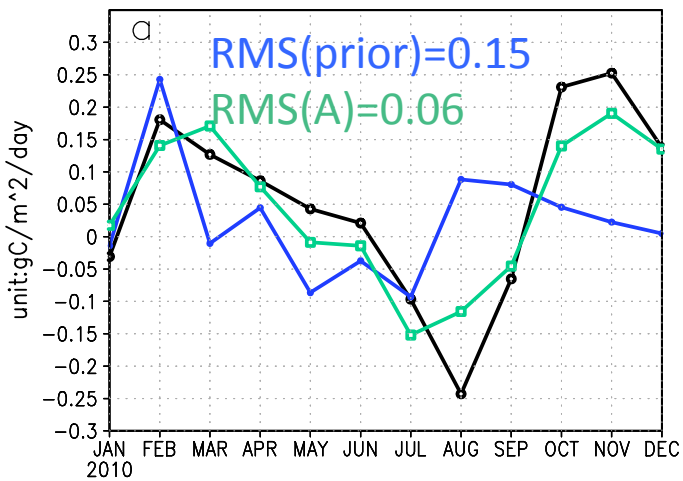


Black: true flux

Blue: prior

The posterior CO2 fluxes assimilating AIRS CO2 over tropics has smaller error than the prior flux

Amazon (25°S-25°N, 90°W-30°W)



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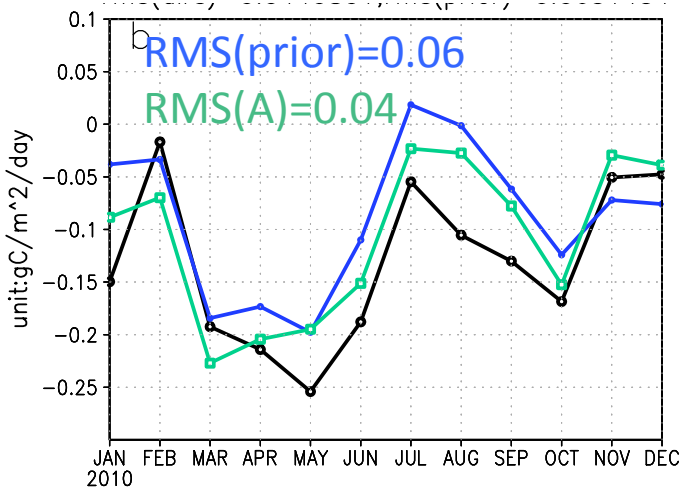

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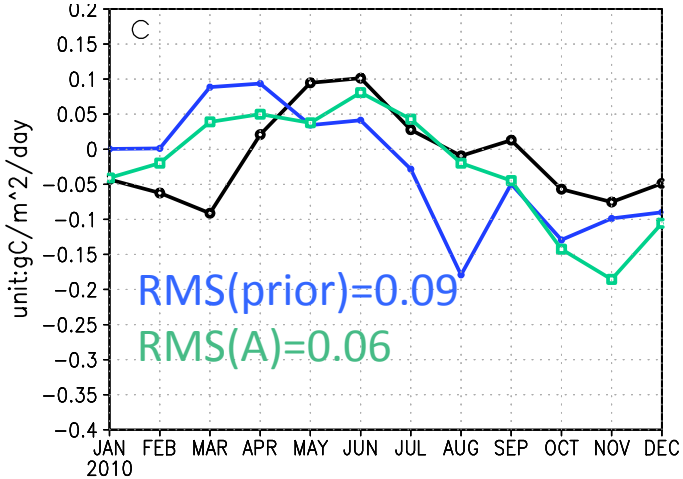


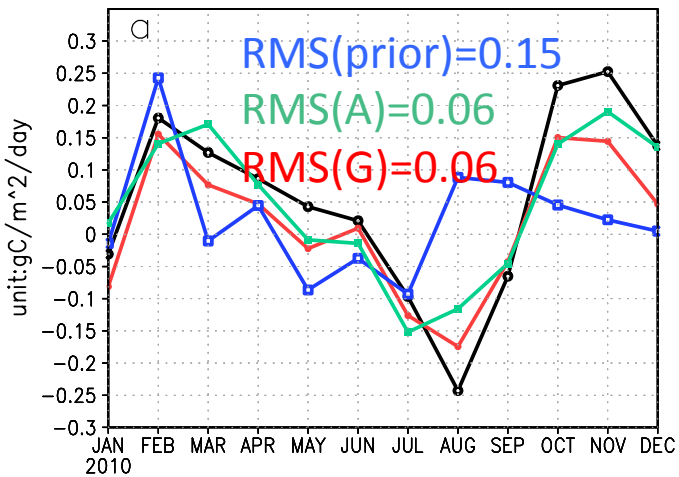
Black: true fluxes

Blue: prior fluxes

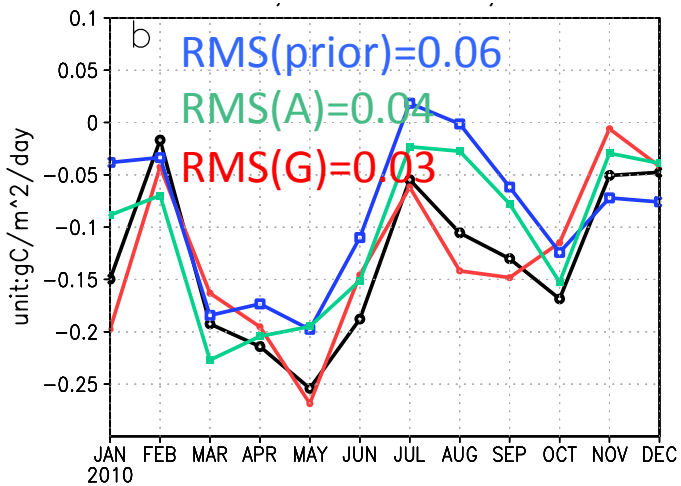
Aqua: posterior fluxes assimilating AIRS CO2 over tropics

The performance is comparable between AIRS-tropics only and GOSAT-only experiments

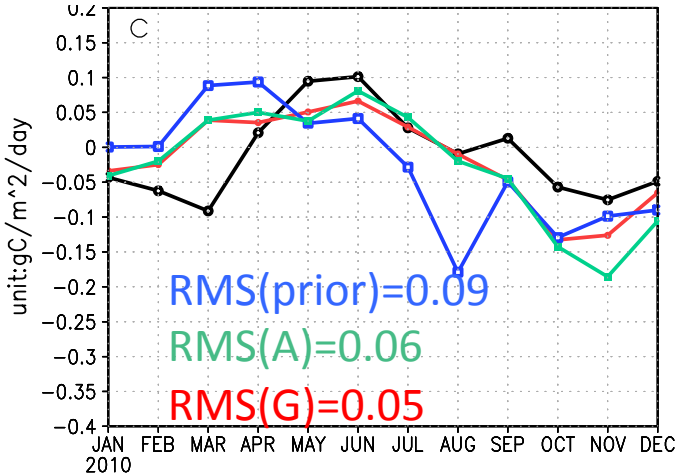
Amazon (25°S-25°N, 90°W-30°W)



Tropical Africa (25°S-25°N, 10°W-60°E)



South East Asia (25°S-25°N, 80°E-120°E)



Black: true flux

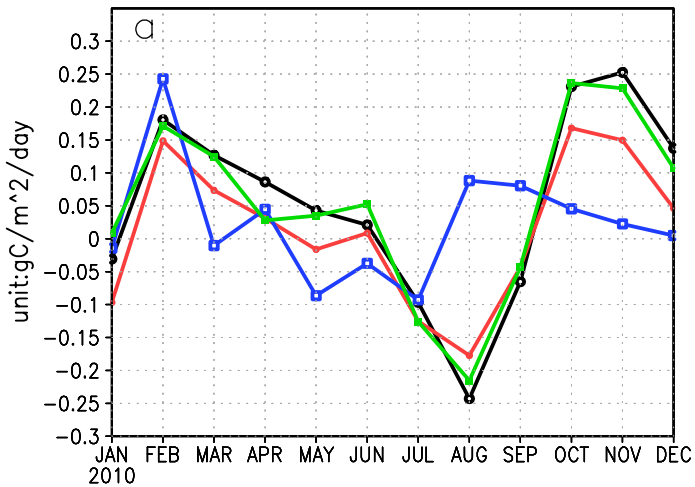
Blue: prior

Aqua: posterior fluxes assimilating AIRS CO2 over tropics

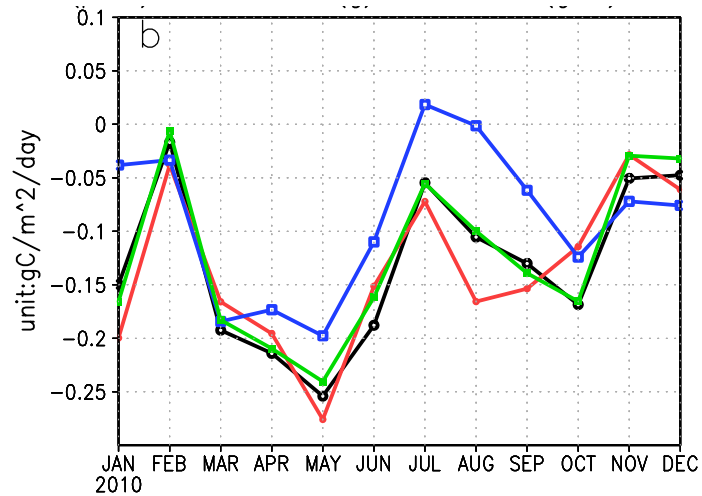
Red: posterior flux assimilating GOSAT

Adding AIRS tropical CO2 further improves tropical flux estimation

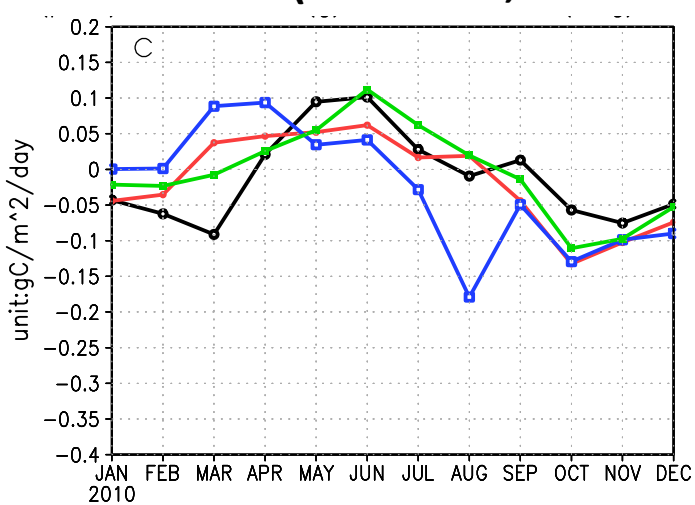
Amazon (25°S-25°N, 90°W-30°W)



Tropical Africa (25°S-25°N, 10°W-60°E)



South East Asia (25°S-25°N, 80°E-120°E)



Black: true flux

Blue: prior

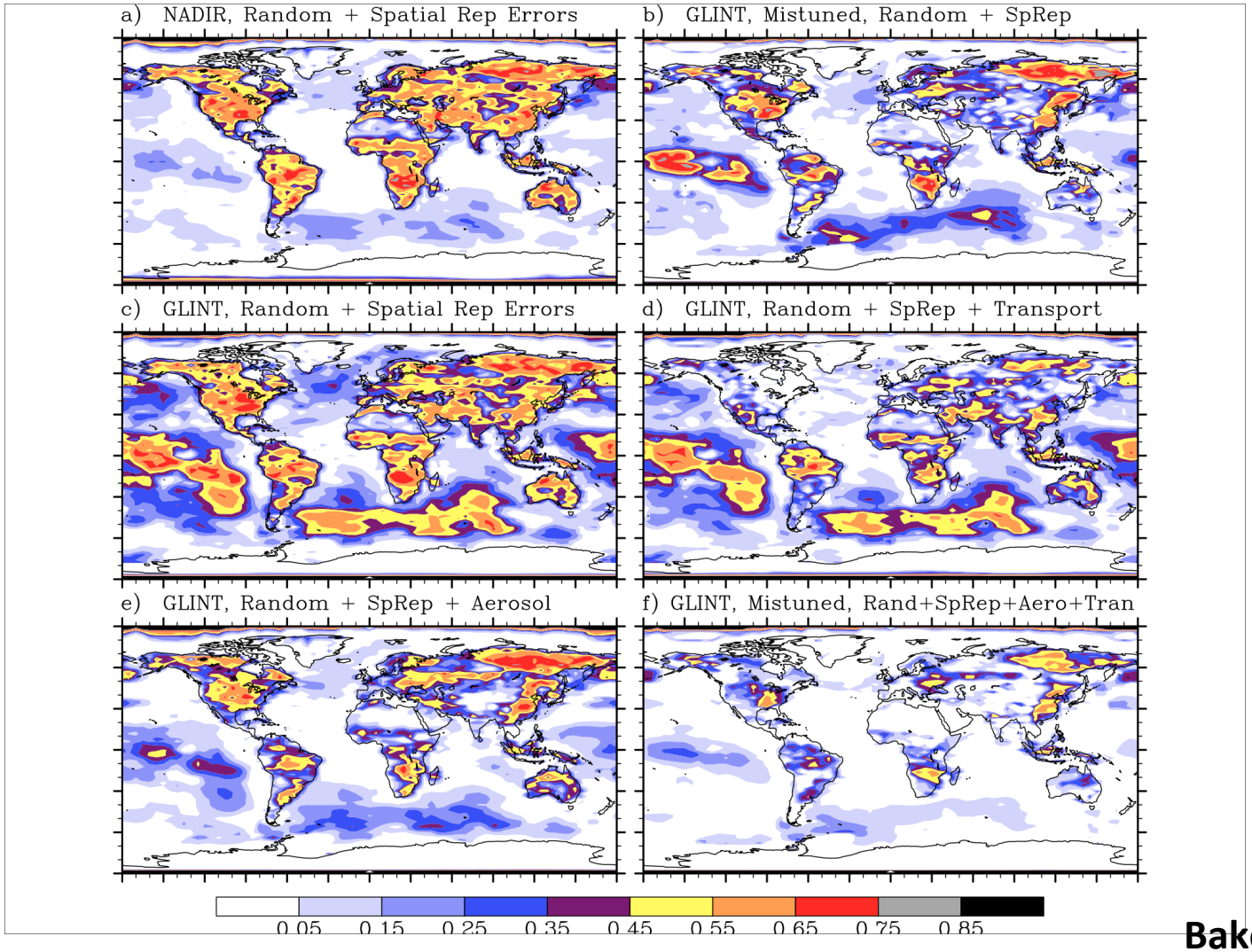
Red: posterior flux assimilating GOSAT observations

Green: posterior flux assimilating both GOSAT and AIRS observations over tropics

How could we use AIRS CO2 to answer these questions?

- The transport problem
- The sensitivity of AIRS CO2 to the flux
- The impact on flux inversion
- Challenges
  - Potential bias in real observations

The flux estimation is sensitive to the bias in CO2 observations



Baker et al. (2010)

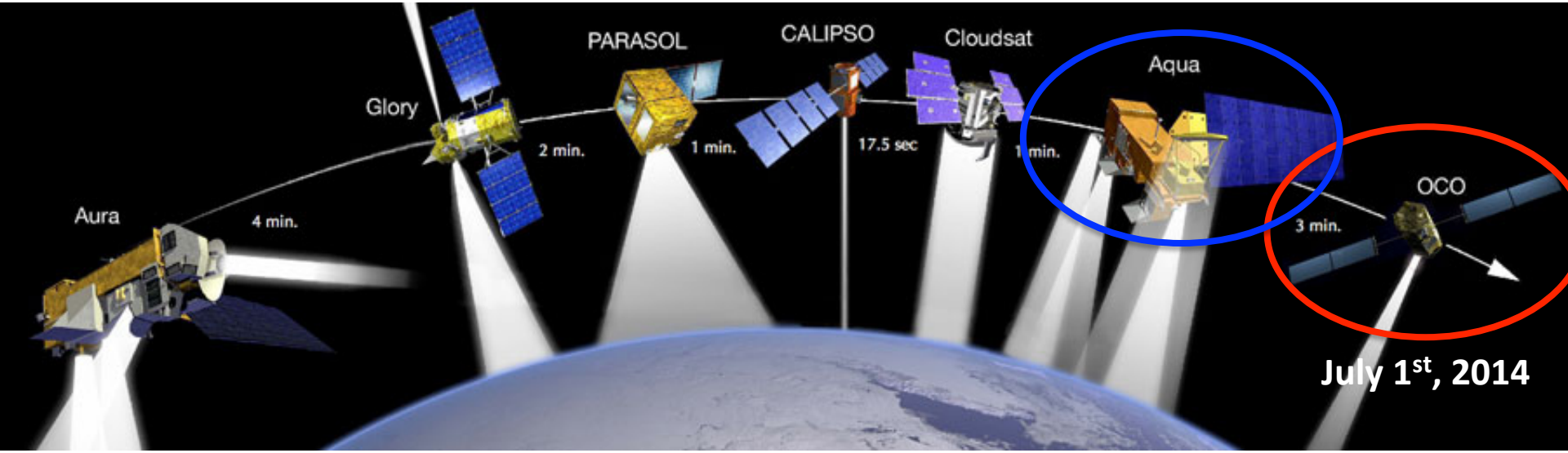
Take-home messages

- Understanding where the carbon goes would improve our understanding of carbon-climate feedback, and improve the climate projections.
- Constraining CO2 distribution by assimilating AIRS CO2 observations can help us understand atmosphere transport.
- AIRS CO2 over tropical region is sensitive to the surface flux.
- Theoretically, AIRS CO2 can improve our understanding of the sources and sinks.

Challenges:

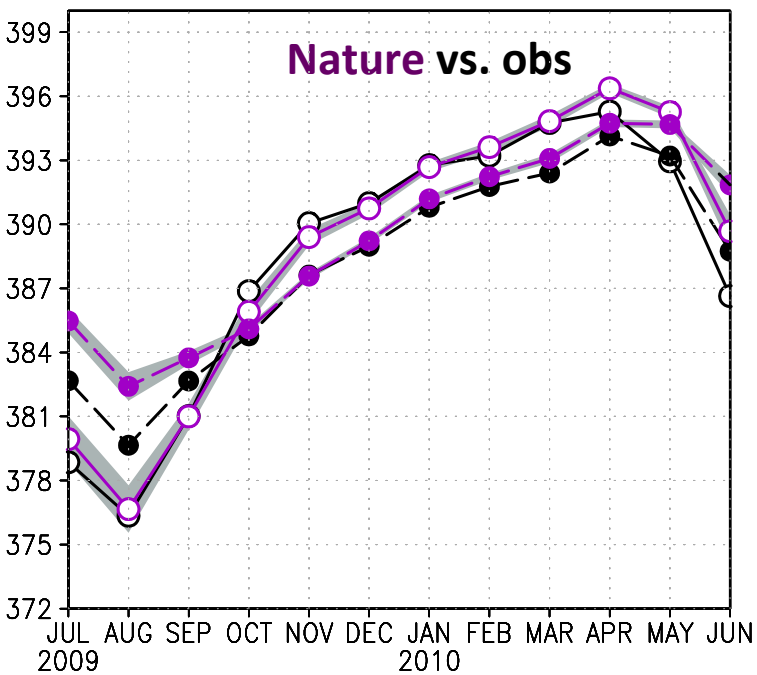
- Potential biases in the real observations.

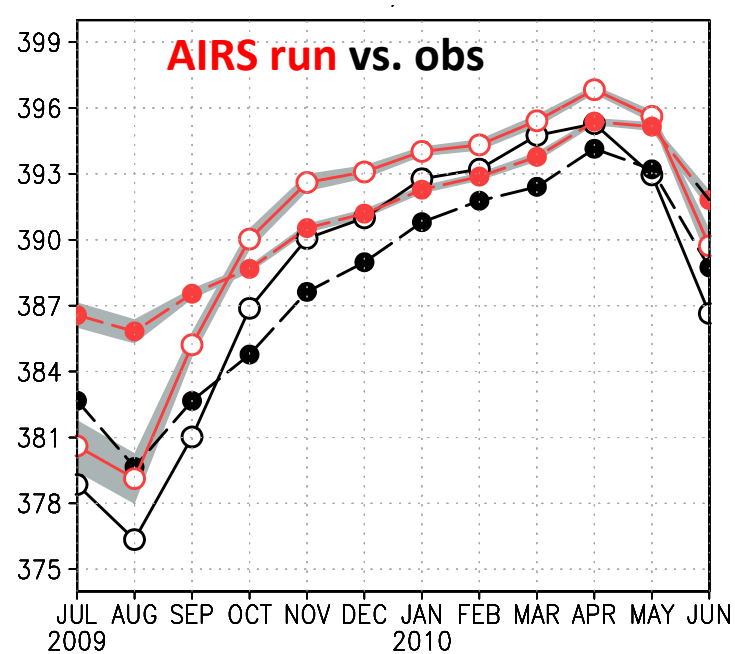
Future directions



- Combination use of AIRS CO2 and OCO-2 X_{CO2}
  - CO2 vertical profile retrievals
  - Flux inversion
  - Atmosphere transport

CO2 analysis vs. aircraft obs (o:< 2.5km;•:2.5km-5.5km)





period1: Jul-Sep (2009) & Apr-June (2010); period2: Oct (2009)-March (2010)

Bias(AIRS run)=3.5±0.4ppm, 2.2±0.2ppm