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Jet Propulsion Laboratory
California Institute of Technology

Profiling Tropospheric CO_2 using Aura TES and TCCON instruments

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8. BC Consulting Ltd., New Zealand

Kuai, L., et al.: Profiling tropospheric CO_2 using the Aura TES and TCCON instruments, Atmos. Meas. Tech. Discuss., 5, 4495-4534, doi:10.5194/amtd-5-4495-2012, 2012.

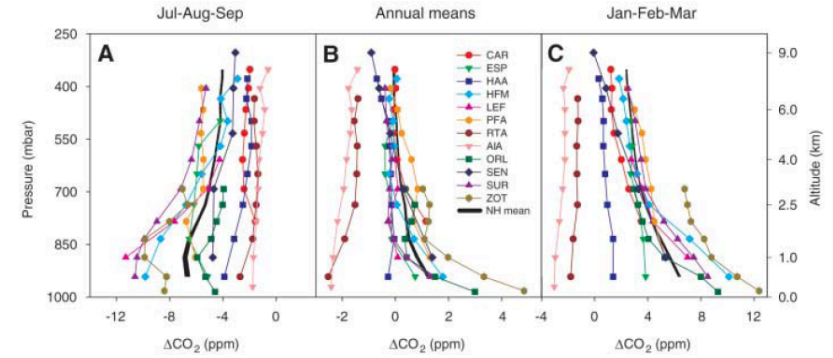
Goal and Motivations

Goal: derive lower tropospheric CO_2 estimates from NIR and TIR instrument measurements.
Motivations:

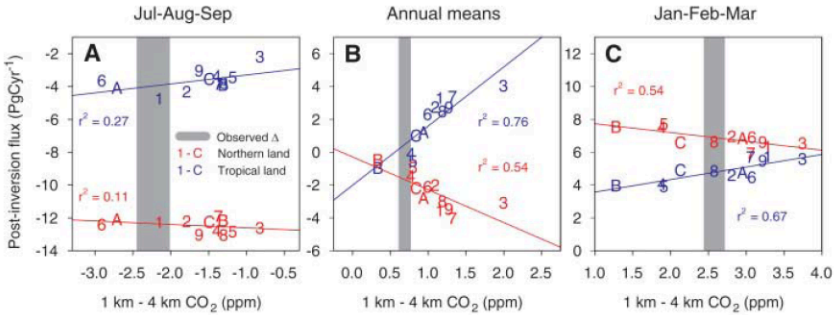
- Lower tropospheric CO_2 respond more quickly to the source and sink than the column averages.
- The vertical distribution of atmospheric CO_2: new constrains on the latitudinal distribution of carbon flux (Stephens et al., 2007).

Seasonal and annual mean midday CO_2 profiles

- Surface flux
- Atmospheric mixing



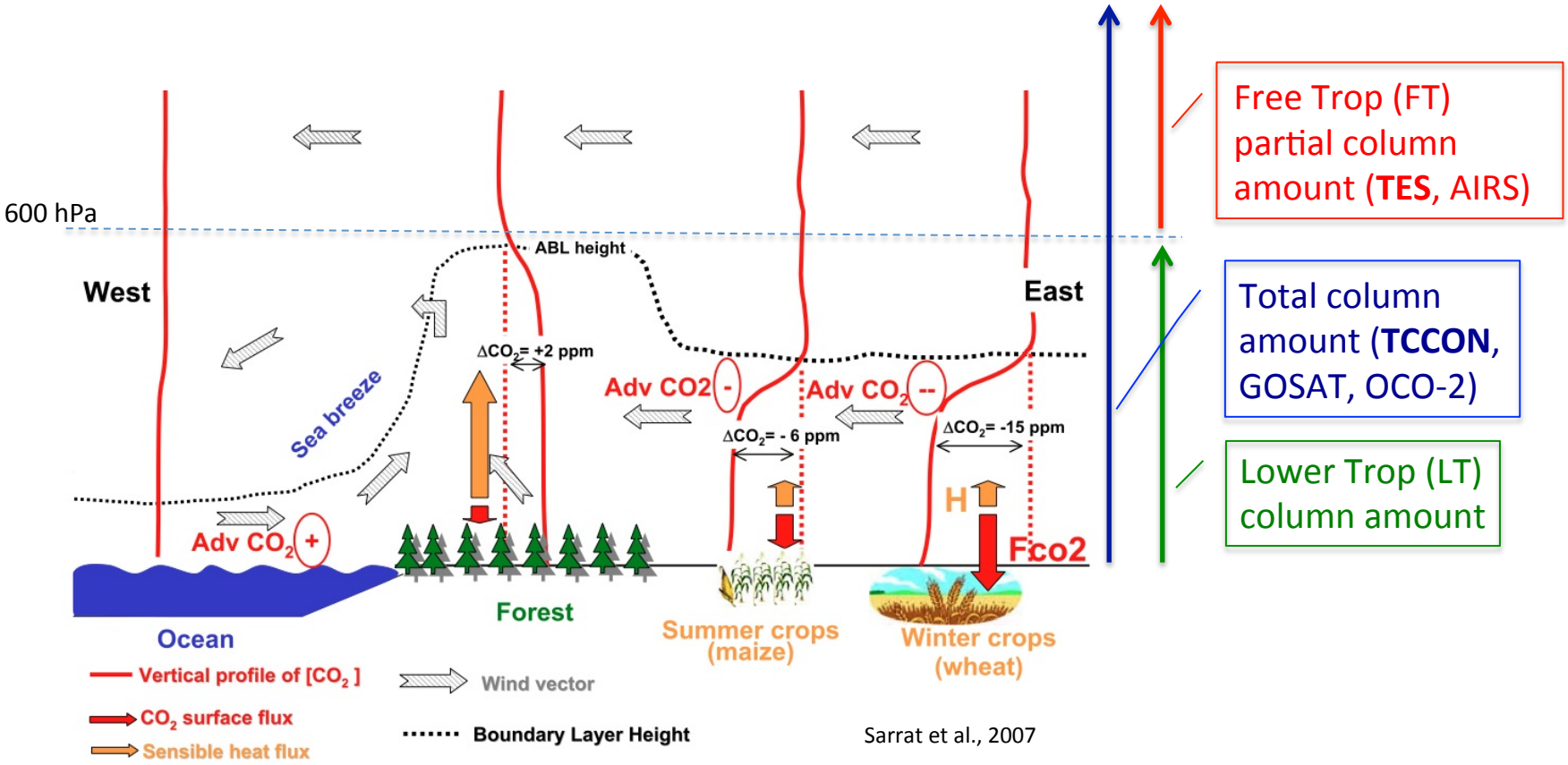
Vertical gradient-flux correlation



Weak Northern and Strong Tropical Land Carbon Uptake from Vertical Profiles of Atmospheric CO2 (Stephens et al., 2007)

Constrains	NH sinks (Pg C/year)	Tropical sources (Pg C/year)
Boundary layer obs. , mass-balance	-2 to -3.5	1 to 2
a recently inverse model comparison study	-0.4 to 4	-1 to 4
Previous consensus	-2.4	1.8
Vertical profile	-1.5	0.1

Method to estimate the lower tropospheric (LT) CO_2

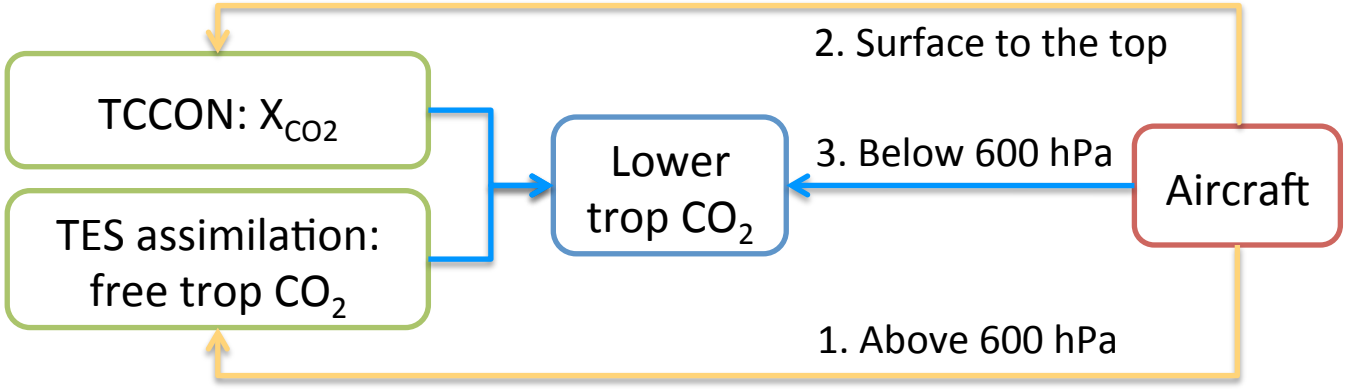


Sarrat et al., 2007

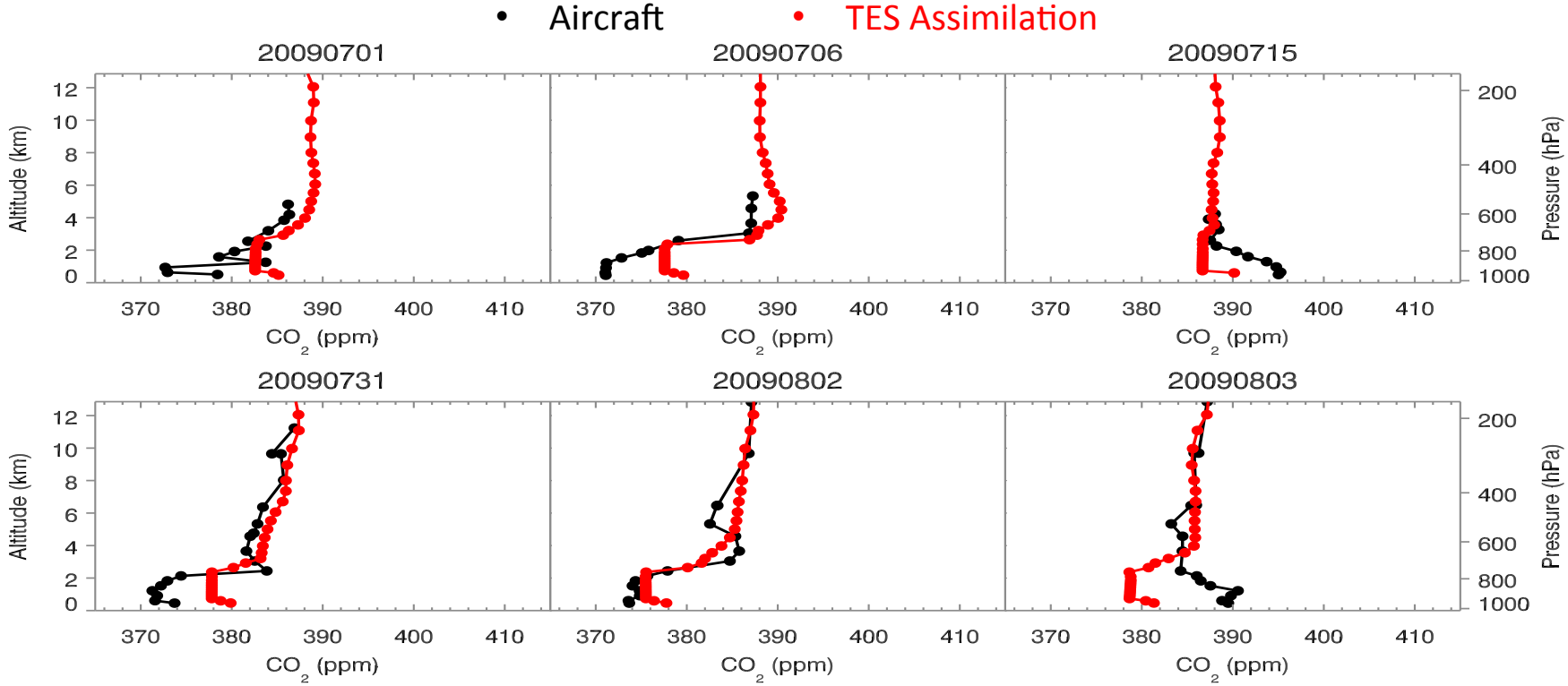
$$X_{CO_2}^{LT} = \frac{\text{Total column amount } [CO_2] - \text{Free trop column amount } [CO_2]}{\text{Low Trop column amount [air]}}$$

Measurements

- Ground-Based Total Column CO_2 Measurements from TCCON
  - Profile retrieval algorithm
  - Error characteriztion
- Satellite-Based free tropospheric CO_2 measurements from TES
  - Aura Tropospheric Emission Spectrometer
  - Peak sensitivity near 500 hPa (Kulawik et al., 2012)
  - TES GEOS-Chem assimilation (Singh et al., 2011)
- Aircraft measurements as a validation standard
  - ARM Airborne Carbon Measurements over southern great plains (SGP)
  - More than 40 profiles in 2009
  - Coincident with TCCON Lamont observations



TES Assimilation & Aircraft Free Tropospheric CO_2



- Aircraft profiles top: ~6 km (450 hPa); Only three ~12 km (200 hPa).
- TCCON *a priori* as an assumption above aircraft profile top.
- Good agreement in free troposphere or above 4 km (600 hPa).
- TES assimilated free tropospheric CO_2: 0.38 ± 0.71 ppm.

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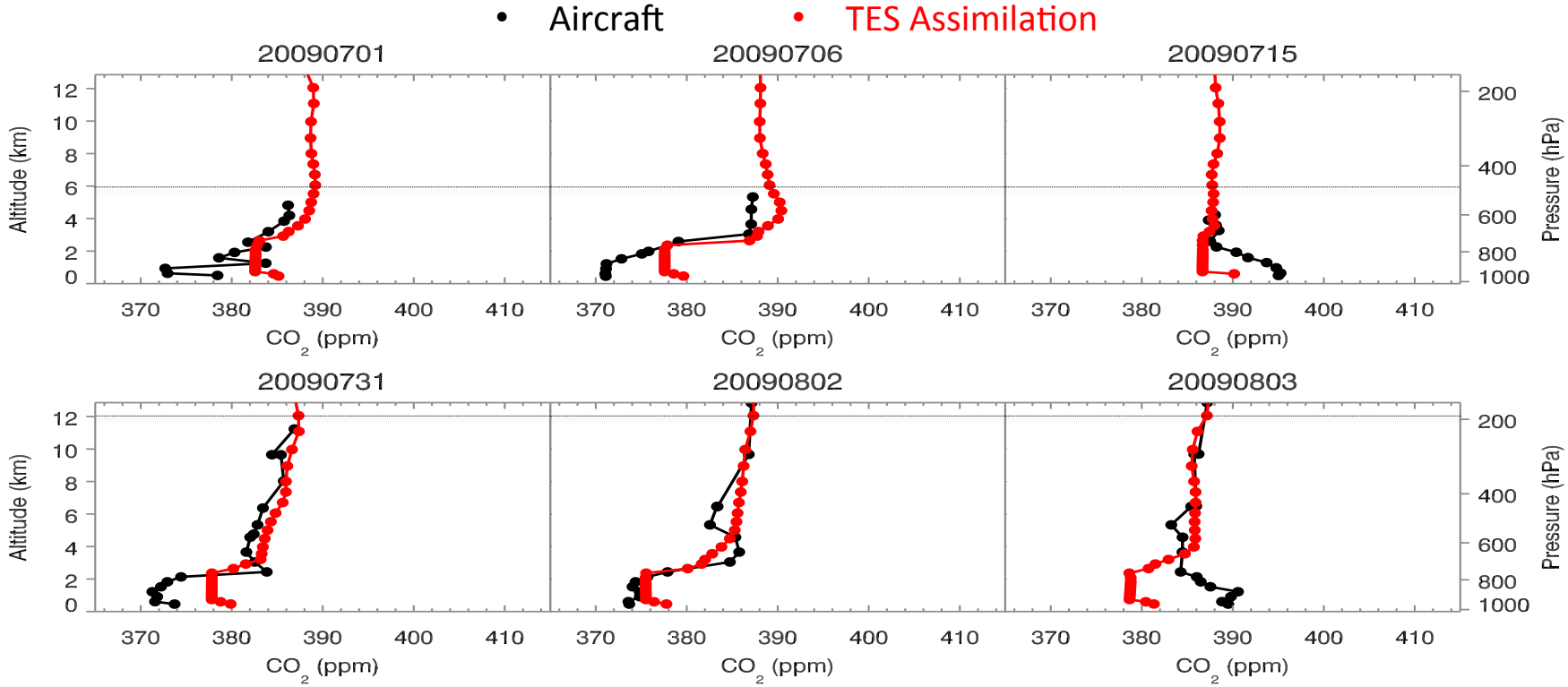

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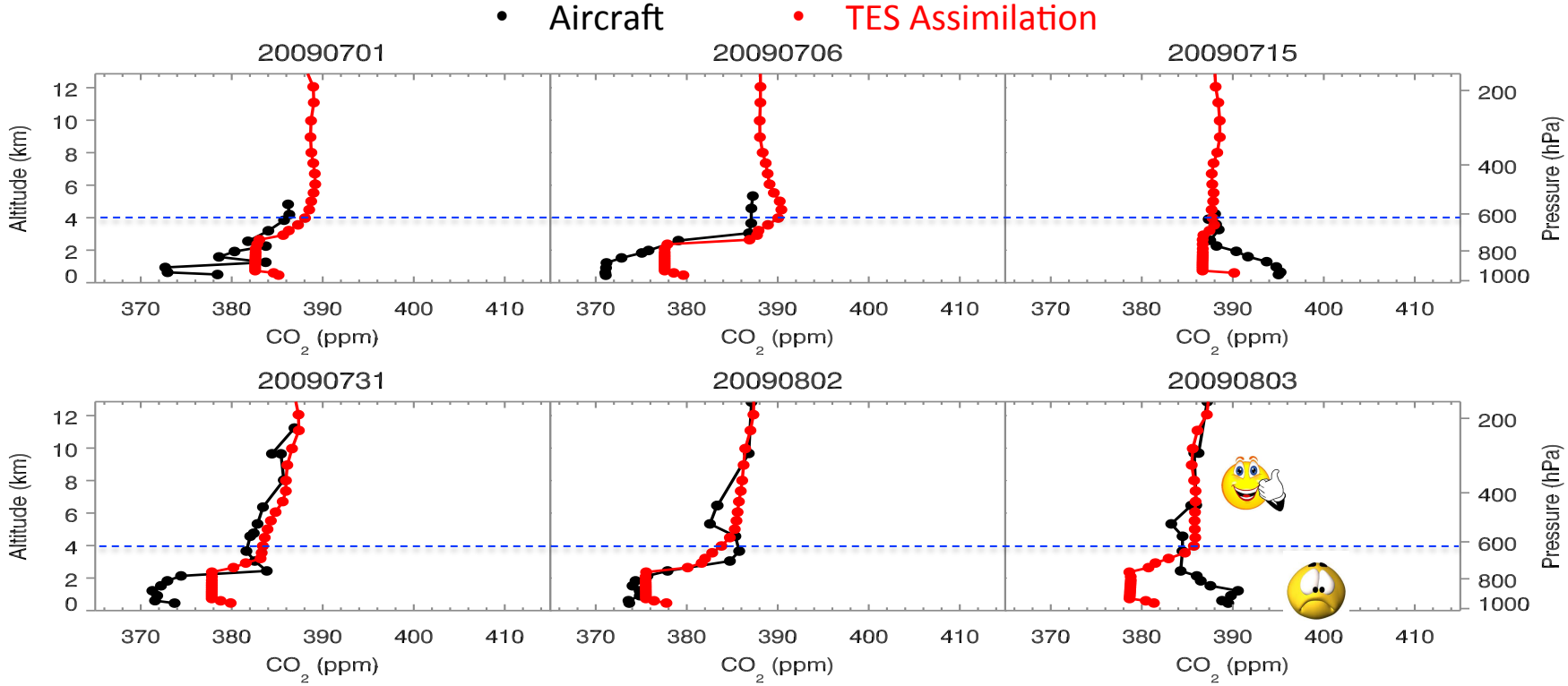

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Total Column-averaged CO_2: TCCON vs Aircraft

Standard retrieval; Multiple TCCON sites

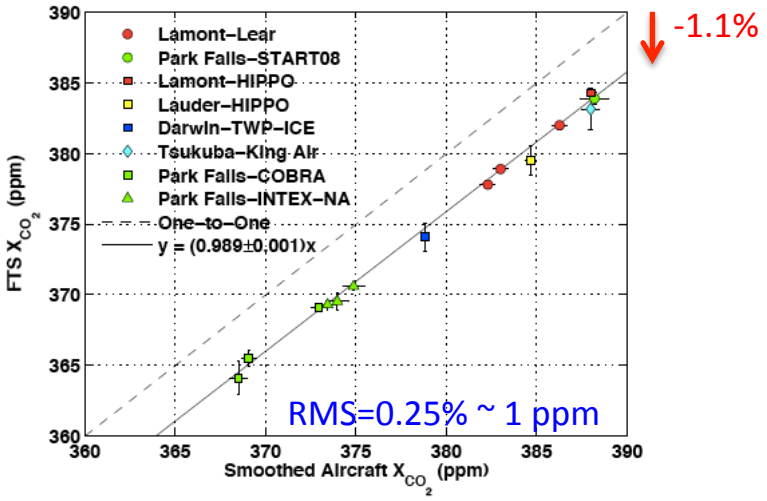
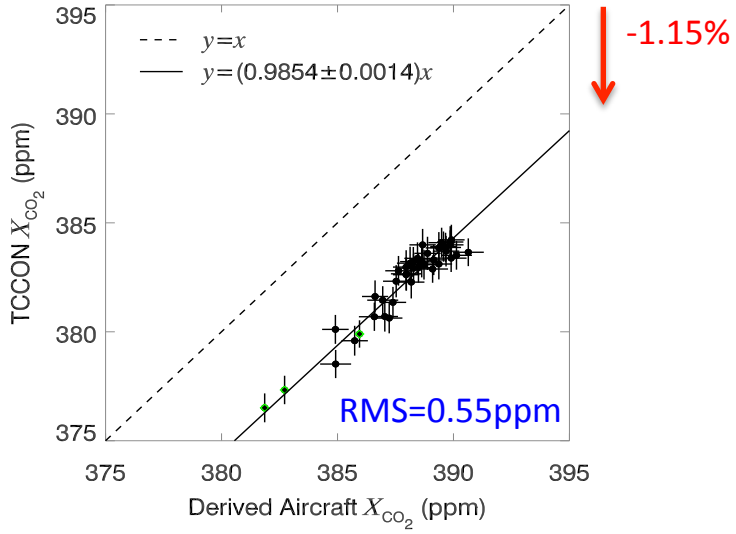


Fig. 5. The TCCON calibration curve for CO_2. The smoothed aircraft value is $\hat{c}_S$ from Eq. (7). (Wunch et al., 2010)

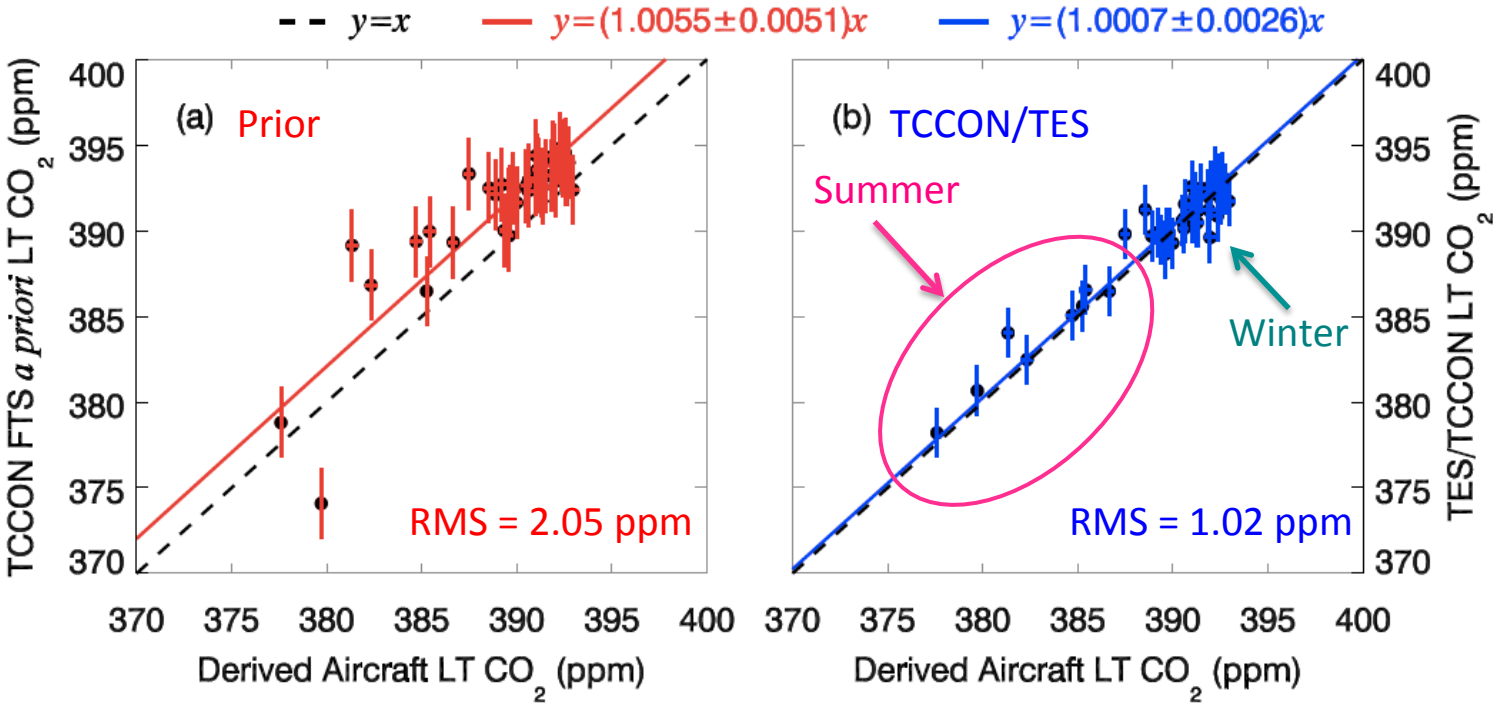
Profile retrieval; One TCCON site (Lamont)



Our column estimates (right) are consistent with standard TCCON column data (left) (Wunch et al., 2010).

Time scale	Predicted error (ppm)	Actual error (ppm)
Observations for 4 hours (precision driven by noise)	$\sigma(\hat{S}_m) = 0.32$	0.35
Observations across multiple days (precision driven by temperature + noise)	$\sigma(\hat{S}_T + \hat{S}_m) = 0.69$	0.55

Lower Tropospheric CO_2: TCCON/TES-assimilation vs Aircraft



- Improvement in the uncertainties of LT CO_2 estimates:
  STD of errors: 2.05 ppm versus 1.02 ppm

- Improvement primarily in summer time when biosphere is active.

Accuracy and Precision Comparisons

Unit (ppm)		Bias	Precision
Total column averages	[TCCON prior]	1.04	1.50
	[TCCON]	-5.66	0.55
Above 600 hPa			
Free tropospheric column averages	[TCCON prior]	2.17	2.05
	[TCCON]	-1.62	1.50
	[GEOS-Chem]	0.91	1.22
	[TES/GEOS-Chem]	0.38	0.71
Surface to 600 hPa			
Lower Tropospheric column averages	[TCCON prior]	2.17	2.05
	[TCCON]	-4.91	1.39
	[TES/GEOS-Chem]	0.73	2.86
	[GEOS-Chem]	0.13	1.92
	[TCCON] – [TES/GEOS-Chem]	0.26	1.02
	[TCCON] – [TCCON prior]	-0.96	2.26
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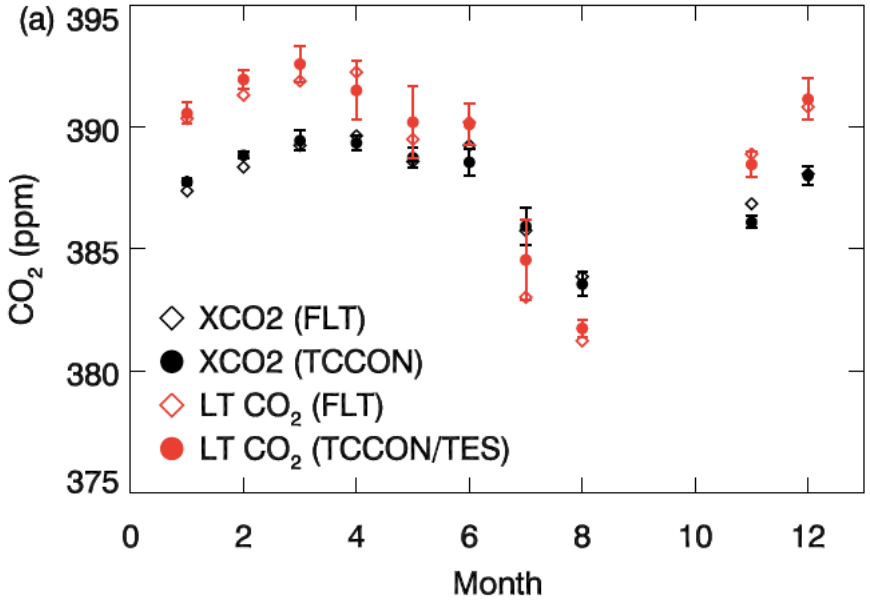
Seasonal Variations

- The TCCON column and LT CO_2 estimates by TCCON and TES/ GEOS-chem assimilations capture the seasonal variability within the uncertainties.

- The amplitude of the seasonal cycle is larger in LT CO_2 than in column averages.



Conclusions

- Total column-averaged CO_2 from TCCON, free trop CO_2 from TES assimilations and LT CO_2 from TCCON and TES assimilations are evaluated by aircraft measurements.

- The error characterization for TCCON column averages show the calculated errors are consistent with the actual errors on two different time scales.

- The estimates are able to capture the seasonal variability in both total column averages and LT CO_2 within the estimated uncertainties.

- Highlights the potential of combining simultaneous measurements from reflected sunlight (e.g. GOSAT, OCO-2) and thermal IR (e.g. TES, AIRS) to obtain vertical information of CO_2.

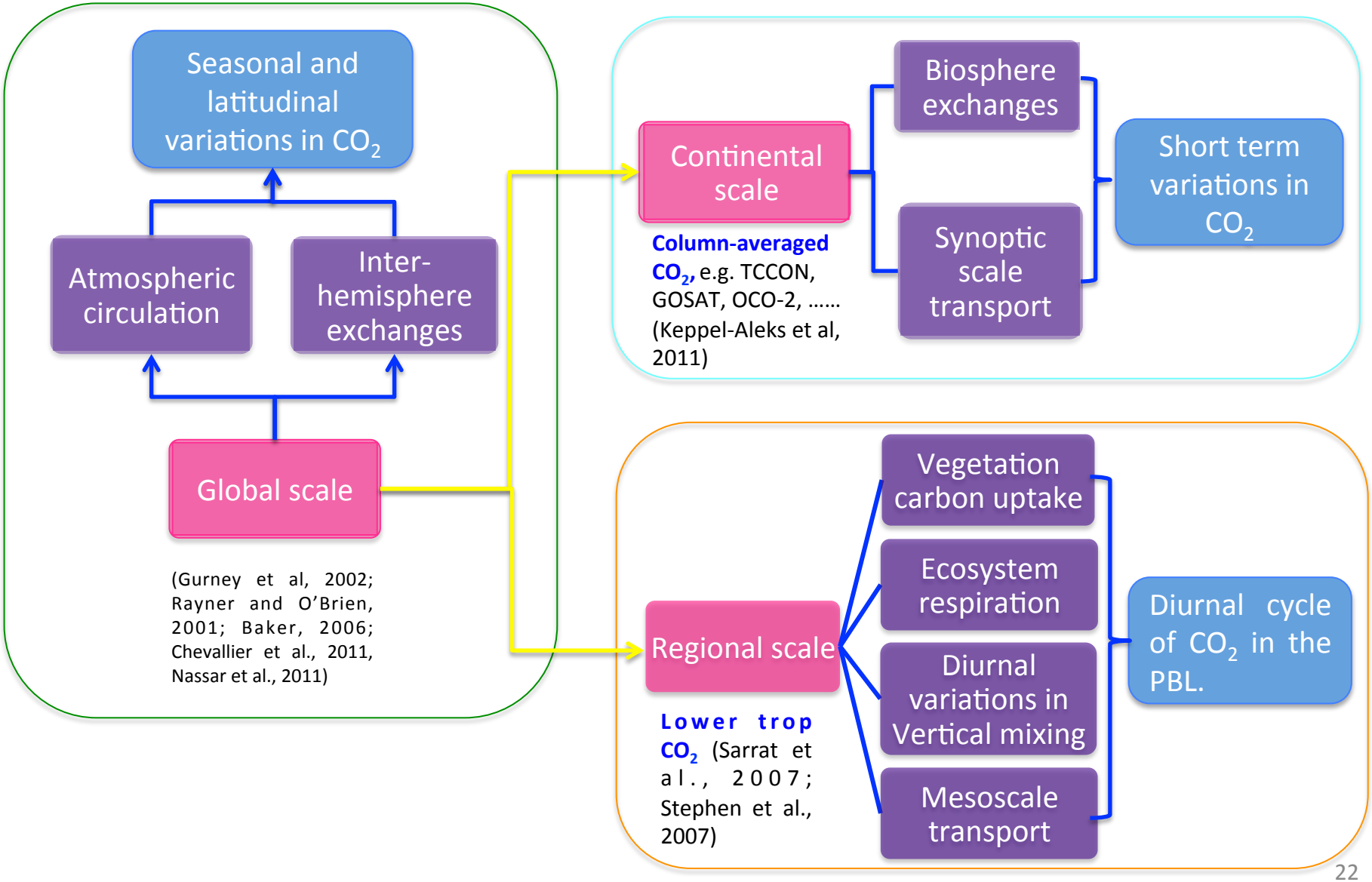
- Supports the joint retrievals of Multi-Spectra, Multi-Species, Multi-Satellite instruments $(MS)^3$ for profiling CO_2.

Acknowledgements

- Paul Wennberg, Caltech
- Geoffrey Toon, JPL

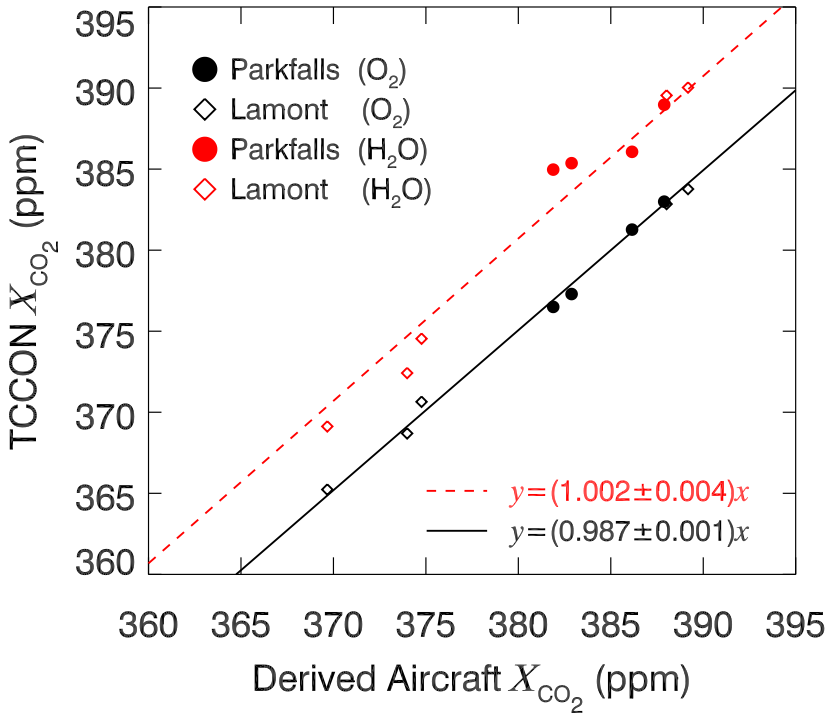
Questions?

Surface Flux Constraints on Different Scales



Out looking

- Apply this approach using GOSAT and TES data for a global view.
- Understand the uncertainties in the derived LT CO_2 due to the variations in boundary layer height.
- Increased vertical coverage from aircraft measurements are desired to reduce uncertainty in satellite/aircraft comparisons so that the error analysis can better characterize actual errors and biases.

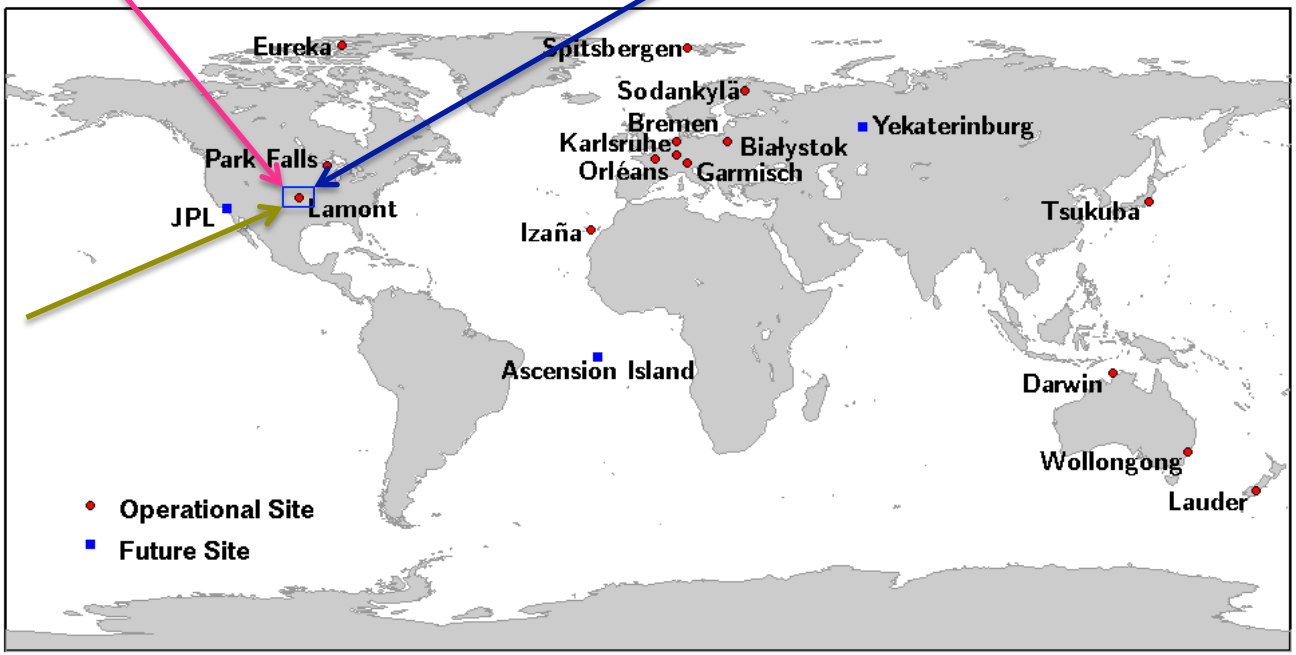

395
390
385
380
375
370
365
360
TCCON X_{CO_2} (ppm)
Parkfalls (O_2)
Lamont (O_2)
Parkfalls (H_2O)
Lamont (H_2O)
$y=(1.002\pm0.004)x$
$y=(0.987\pm0.001)x$
360 365 370 375 380 385 390 395
Derived Aircraft X_{CO_2} (ppm)

Geographic View

Lamont: 36.604°N 97.486°W

ARM Airborne Carbon Measurements (ARM-ACME) over Southern Great Plains (SGP)

TES/GEOS-Chem: 1° × 1° box



Accuracy comparison

Unit (ppm)		**Bias**	**Precision**
Total column averages	TCCON	-5.71	0.67
	TCCON prior	1.04	1.50
PBL column averages; Combining two data set; [Total column amount – free troposphere column amount (above 600 hPa)]	TCCON – TES/GEOS-Chem	0.32	1.40
	TCCON – TCCON prior	-0.96	2.26
	TCCON prior – TES/GEOS-Chem	1.24	3.65
PBL column averages; Single data set; [Surface to 600 hPa]	TCCON	-4.91	1.39
	TCCON prior	2.17	2.05
	TES/GEOS-Chem	0.73	2.86

TCCON / Aircraft Comparison in Total Column CO_2

Our column estimates (right) are consistent with standard TCCON column data (left) (Wunch et al., 2010).

$$\hat{x}_{FLT} = x_a + \mathrm{A}_x(x_{FLT} - x_a)$$

Standard retrieval; Multiple TCCON sites

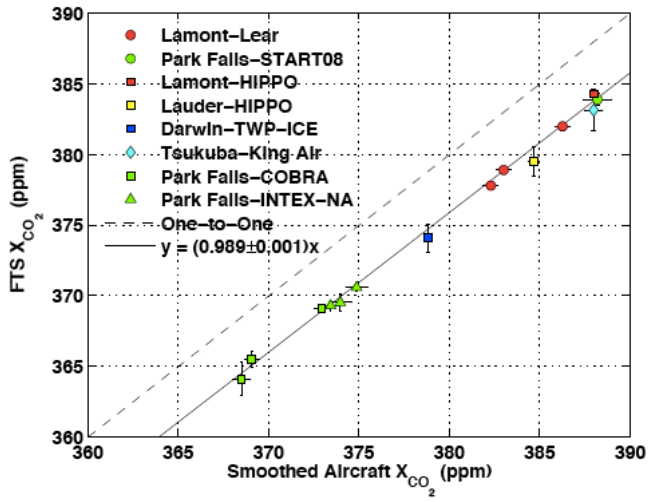
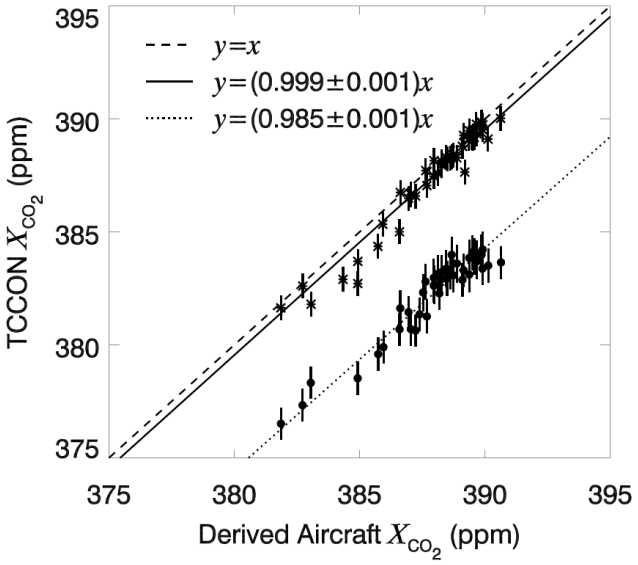


Fig. 5. The TCCON calibration curve for CO_2. The smoothed aircraft value is $\hat{c}_S$ from Eq. (7). (Wunch et al., 2010)

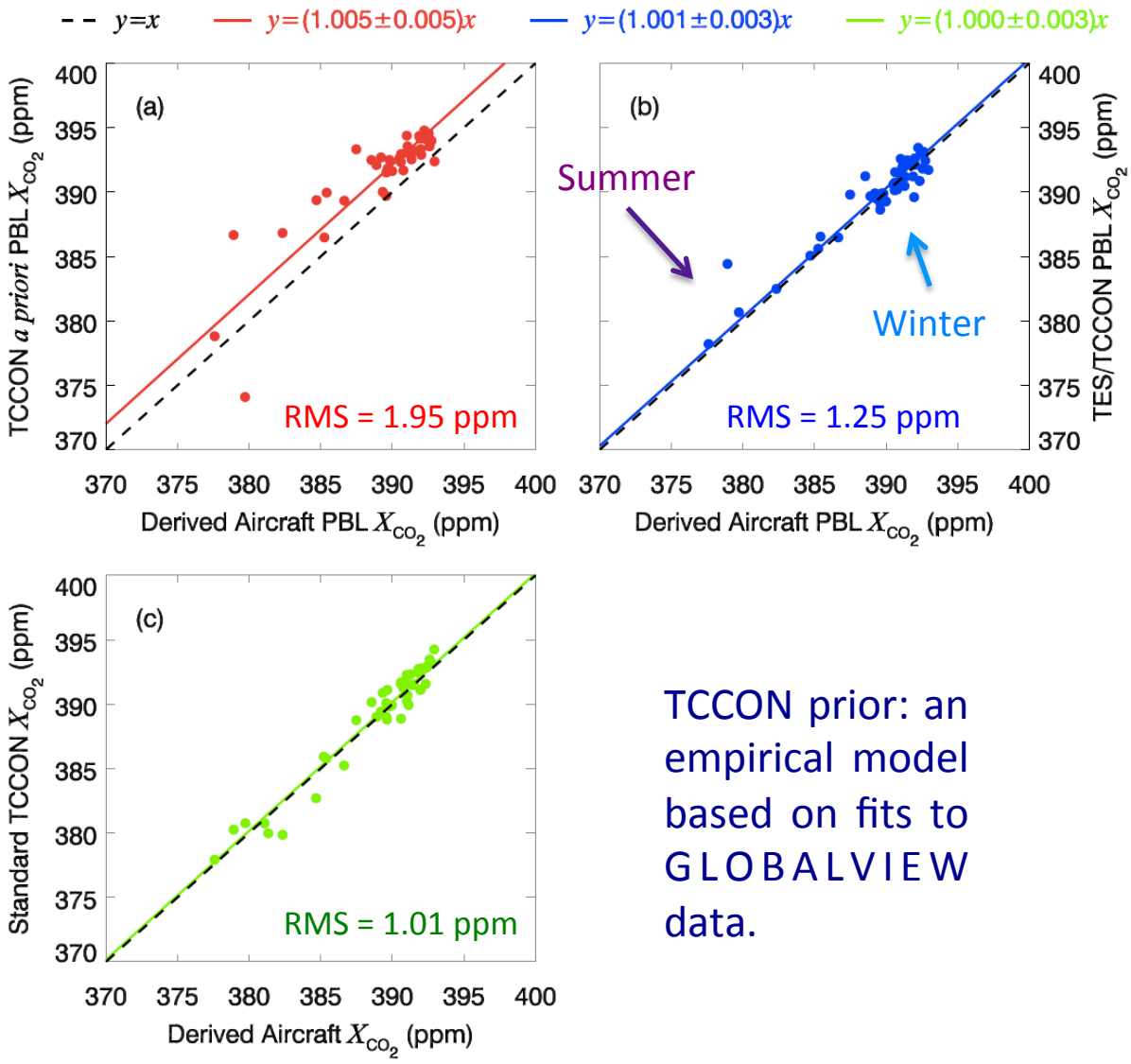
Profile retrieval; One TCCON site (Lamont)



RMS (ppm)	Predicted error	Actual error
Observations for each day (precision driven by noise)	0.32 $\sigma(\hat{\mathrm{S}}_m) = (h^T \hat{\mathrm{S}}_m h)^{\frac{1}{2}}$	0.39
Observations across multiple days (precision driven by noise + temperature)	0.78 $\sigma(\hat{\mathrm{S}}_m + \hat{\mathrm{S}}_m) = (h^T \hat{\mathrm{S}}_m h + h^T \hat{\mathrm{S}}_s h)^{\frac{1}{2}}$	0.67

TCCON/TES GOES-Chem and Aircraft Comparison in PBL CO_2

- Improvement in the knowledge of PBL CO_2:
- Improvement primarily in summer time when biosphere is active.



TCCON prior: an empirical model based on fits to GLOBALVIEW data.

Outlines

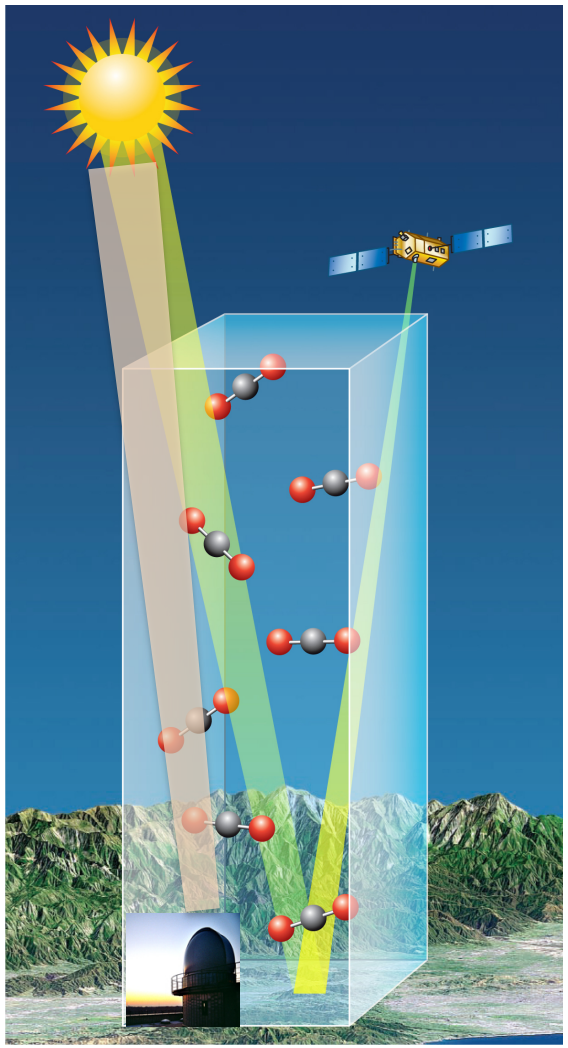
- Importance of the atmospheric CO_2 measurements
- What are roles of different measurements playing constraints on surface fluxes?
- Importance of the planetary boundary layer (PBL) CO_2 estimates
- Combining IR and NIR data for PBL CO_2 estimates
- Evaluation of the estimates; Error characterization: actual versus predicted errors.
- Conclusions and future works

Varieties of CO_2 Measurements

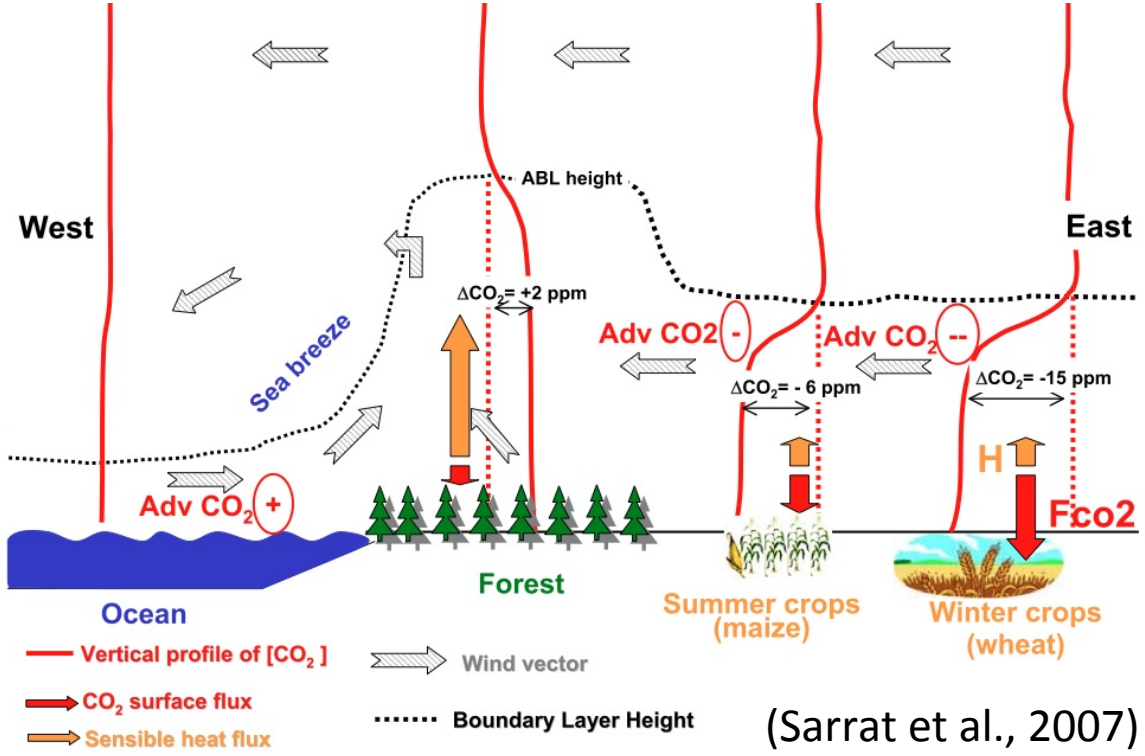
- Surface station networks: good temporal coverage and accurate but lack of vertical structure
  - Column abundance: TCCON
  - Surface data: Tower, flask, in situ.

- Aircraft: accurate with vertical structure but less dense of temporal coverage
  - Vertical profiles: HIPPO (up to 10 Km)

- Satellite remote sensing: powerful tool for a global view
  - Column abundance: GOSAT; SCIAMACHY
  - Tropospheric CO_2: TES; AIRS;IASI
  - Future missions: GOSAT-2;OCO-2;Carbonsat



Importance of the estimates of PBL CO_2



(Sarrat et al., 2007)

- Horizontal gradient of CO_2 concentration in PBL:
  - Flux (Surface type)
  - Wind (advection)
- Boundary layer height ⇔ sensible heat flux

Current challenges in CO_2 profile retrieval

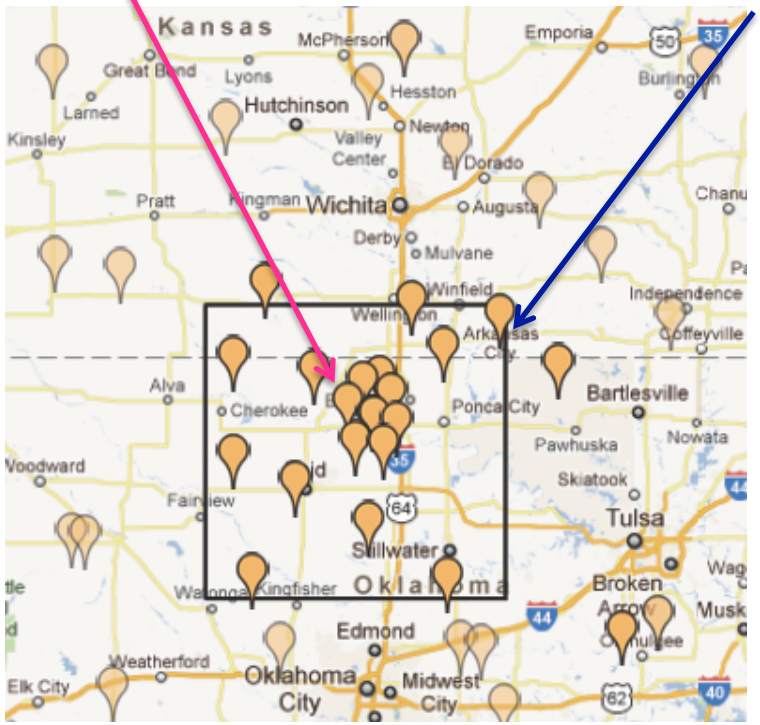
- A long-lived trace gas with small variation
- Systematic residuals in spectra
- Spectroscopy is more important
  - Voigt line shape
  - Not included in radiative transfer model for TCCON:
    - Line mixing
    - speed dependent
    - Broadening of CO_2 by H_2O

Geographic view

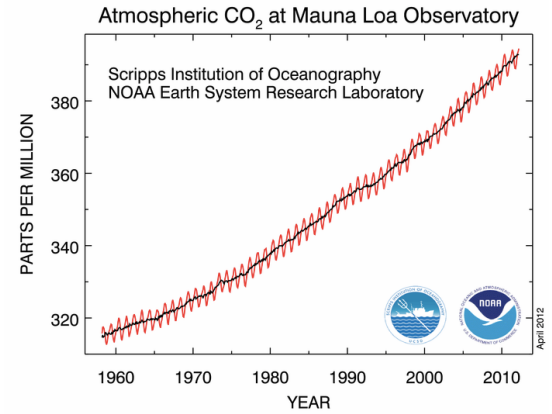
Lamont: 36.604°N 97.486°W

ARM Airborne Carbon Measurements (ARM-ACME) over southern great plains

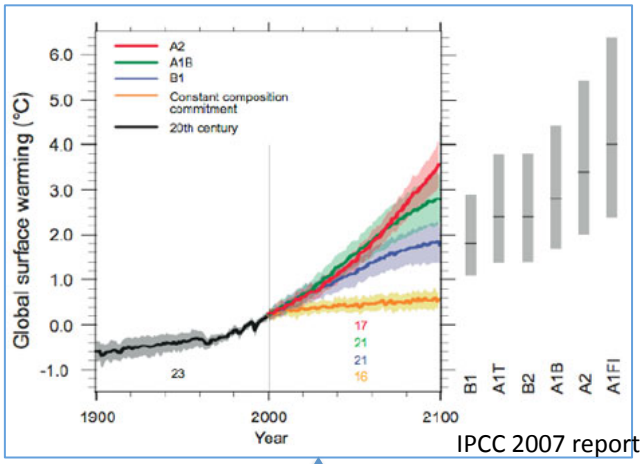
TES/GEOS-Chem:
2° × 2° box



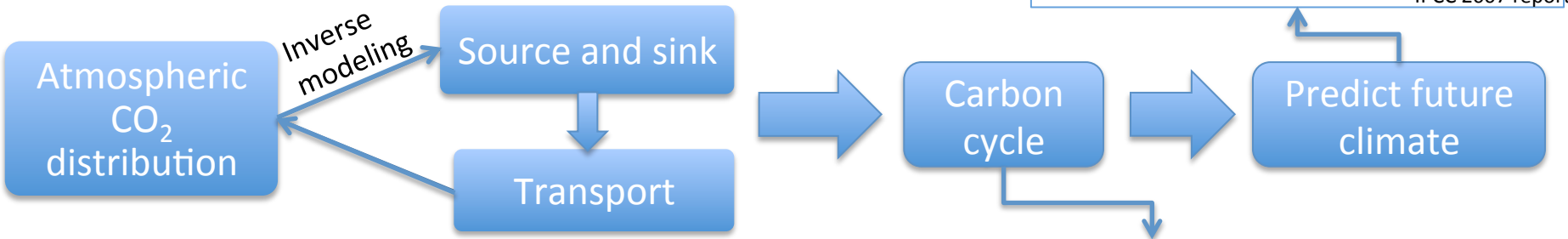
Importance of the Atmospheric CO_2 Measurements

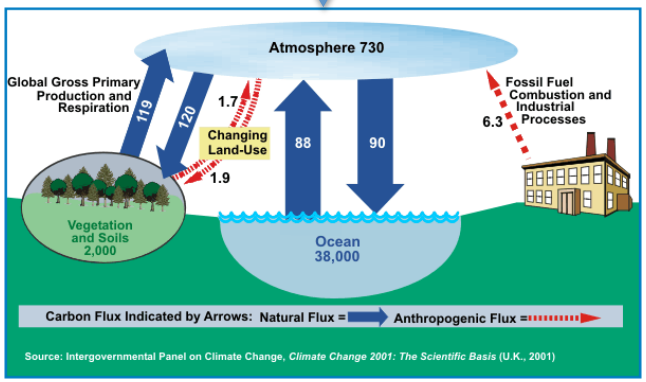


http://www.esrl.noaa.gov/gmd/ccgg/trends/



IPCC 2007 report





http://www.esrl.noaa.gov/research/themes/carbon/