The Total Carbon Column Observing Network (TCCON)

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Abstract. A network of ground-based, sun-viewing, near-IR, FTSs has been established to accurately measure atmospheric greenhouse gases (GHGs) such as CO_2, N_2O, and CH_4. It also measures other gases such as CO, HF, and isotopes, which contain information diagnostic of the sources of the GHGs.

Background

TCCON began in 2002 with a group of us wondering how best to validate or ground-truth the NASA Orbiting Carbon Observatory (OCO) satellite.

• Existing NDACC Mid-IR, ground-based FTS Network was not sufficiently precise and didn't cover the same NIR spectral region as OCO

• In Situ observations were precise, but didn't measure the total column

Needed new network of ground-based instruments distributed around the world measuring column CO_2 and O_2 with high precision & inter-calibration accuracy.

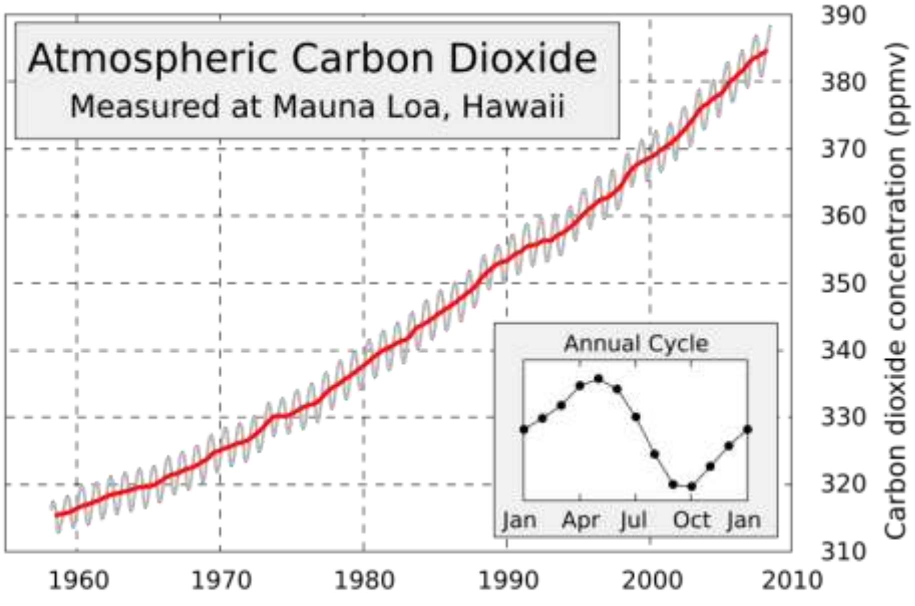
Realized that such a network would have benefits extending beyond OCO, e.g.,
• Validation of other satellites
• Carbon Cycle Science

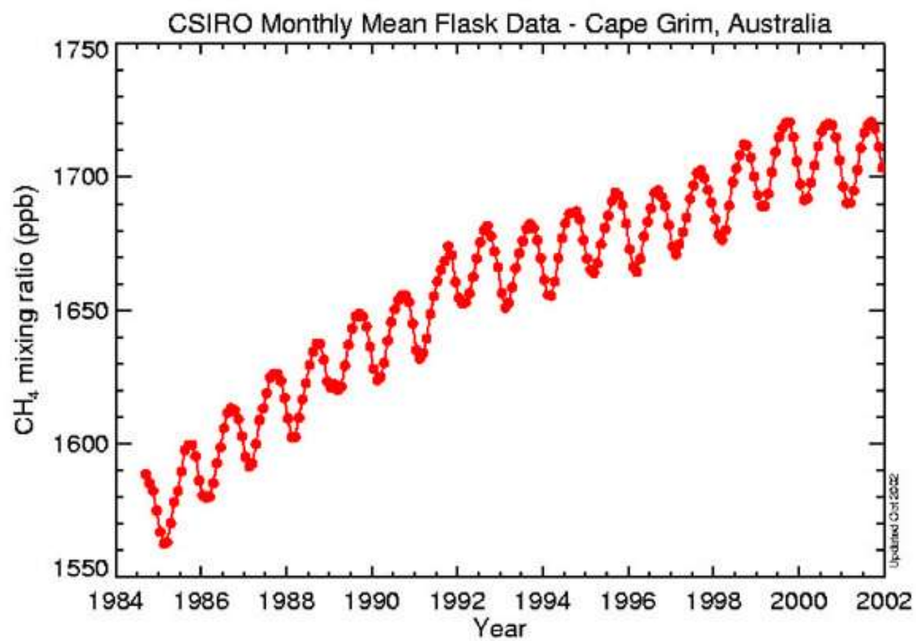
which is just as well….

Motivation and Goals

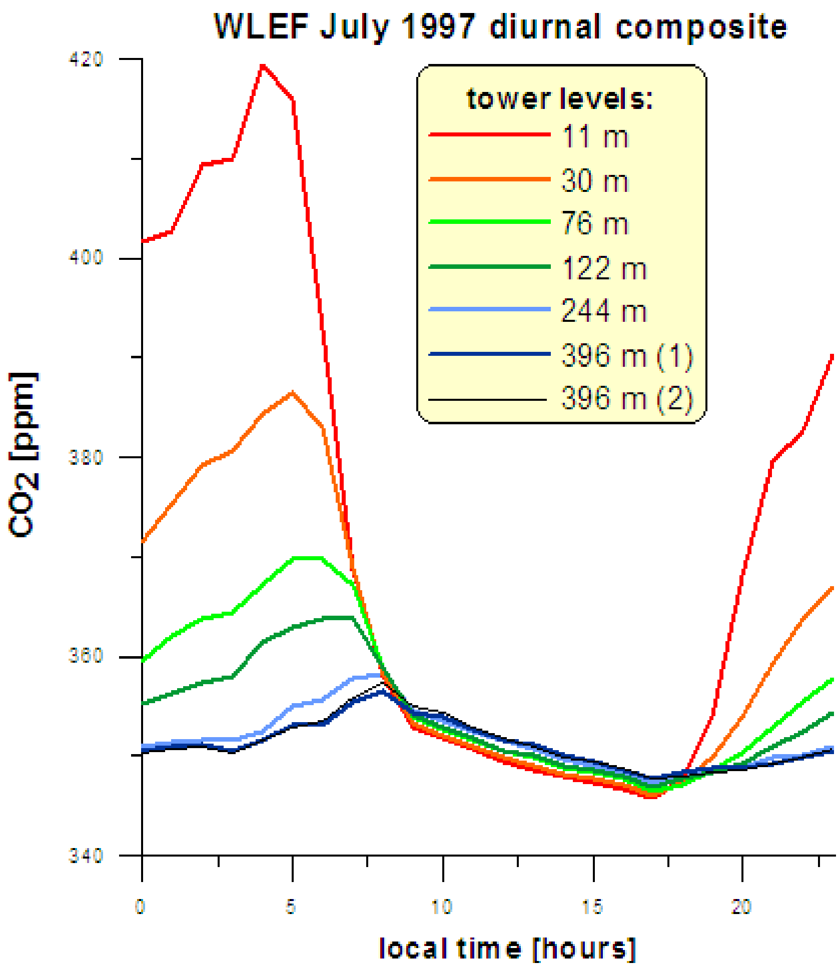
1) To better understand global climate change, in particular, the exchange of Green-House Gases (GHGs) between the atmosphere and the biosphere & ocean (i.e. finding the sources and sinks) of GHGs such as CO_2, CH_4 & N_2O.

2) Validate satellite measurements (e.g., AIRS, IASI, TES, SCIAMACHY, GOSAT) of the same GHGs. This will be essential for monitoring compliance with agreements (e.g. Kyoto) that will attempt to constrain GHG emissions.





How are GHGs currently monitored?



In situ CO_2 measured from the tall tower, Park Falls, Wisconsin (Scott Denning)

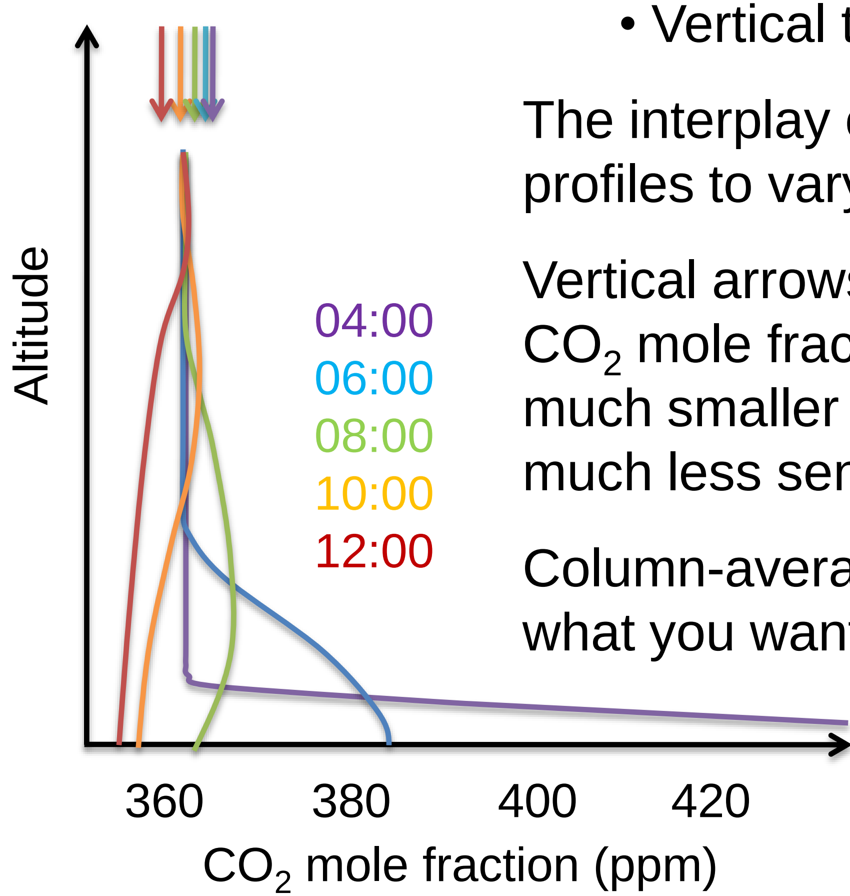
In situ techniques (e.g., NDIR, Mass Spec).

Accuracy is extremely good, but there are sampling issues which limit the value of these data for estimating sources/sinks.

GHG concentrations measured near the surface are not just affected by surface exchange. They are also influenced by vertical transport, which is highly variable and poorly simulated in global models.

In the figure (left) the daily mean in situ CO_2 decreases with altitude. A naïve analysis would therefore suggest a surface source. But the forest is a strong CO_2 sink in July!

Column-Averaged CO_2



The CO_2 profile is affected by:

- Photo-synthesis (removes CO_2)
- Respiration (produces CO_2)
- Vertical transport (re-distributes CO_2)

The interplay of these processes causes the CO_2 profiles to vary diurnally as shown left.

Vertical arrows at the represent column-averaged CO_2 mole fractions. Their diurnal variation is much smaller than that of the surface CO_2 and much less sensitive to vertical transport.

Column-averaged CO_2 is more directly related to what you want to know: surface exchange

Why do we need another GHG measurement network?

Ground-based in situ measurement network

- Derived fluxes are sensitive to the assumed vertical transport
- Limited usefulness for satellite validation (don't measure column)

In situ aircraft profiles

- More useful for satellite (and TCCON) validation, but very sparse.

Ground-based, mid-IR, FTSs of the NDACC network

- Instrument types and operating/analysis procedures differ between sites.
- Operating in the mid-IR, they lack a spectrometric measurement of the total airmass (which TCCON gets from O_2)

Requirements for Network Precision

High absolute accuracy is not necessary because column-averaged CO_2 values can be validated by in-situ aircraft profiles acquired over the FTS sites.

More important is the precision of the CO_2 variations: site-to-site and at different times from the same site (e.g. diurnal, seasonal, inter-annual).

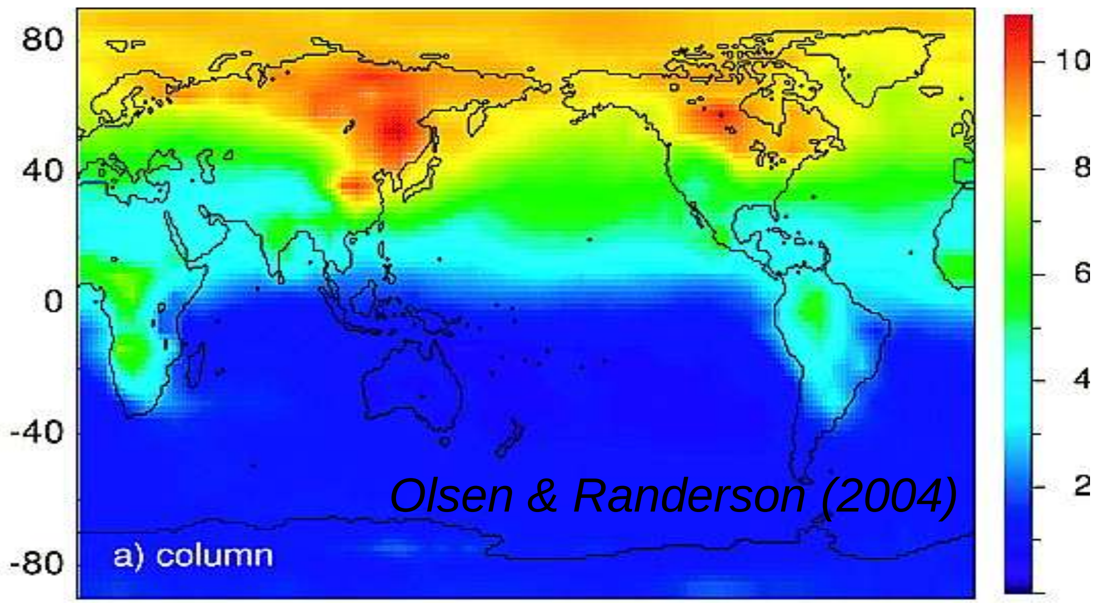
This requires that the instruments be stable and similar from site to site.

The amplitude of the seasonal cycle in column-average CO_2 varies from <1 ppm in the SH to 10 ppm in the NH (< 3%).

It has been known for 50 years that CO_2 has a seasonal cycle.

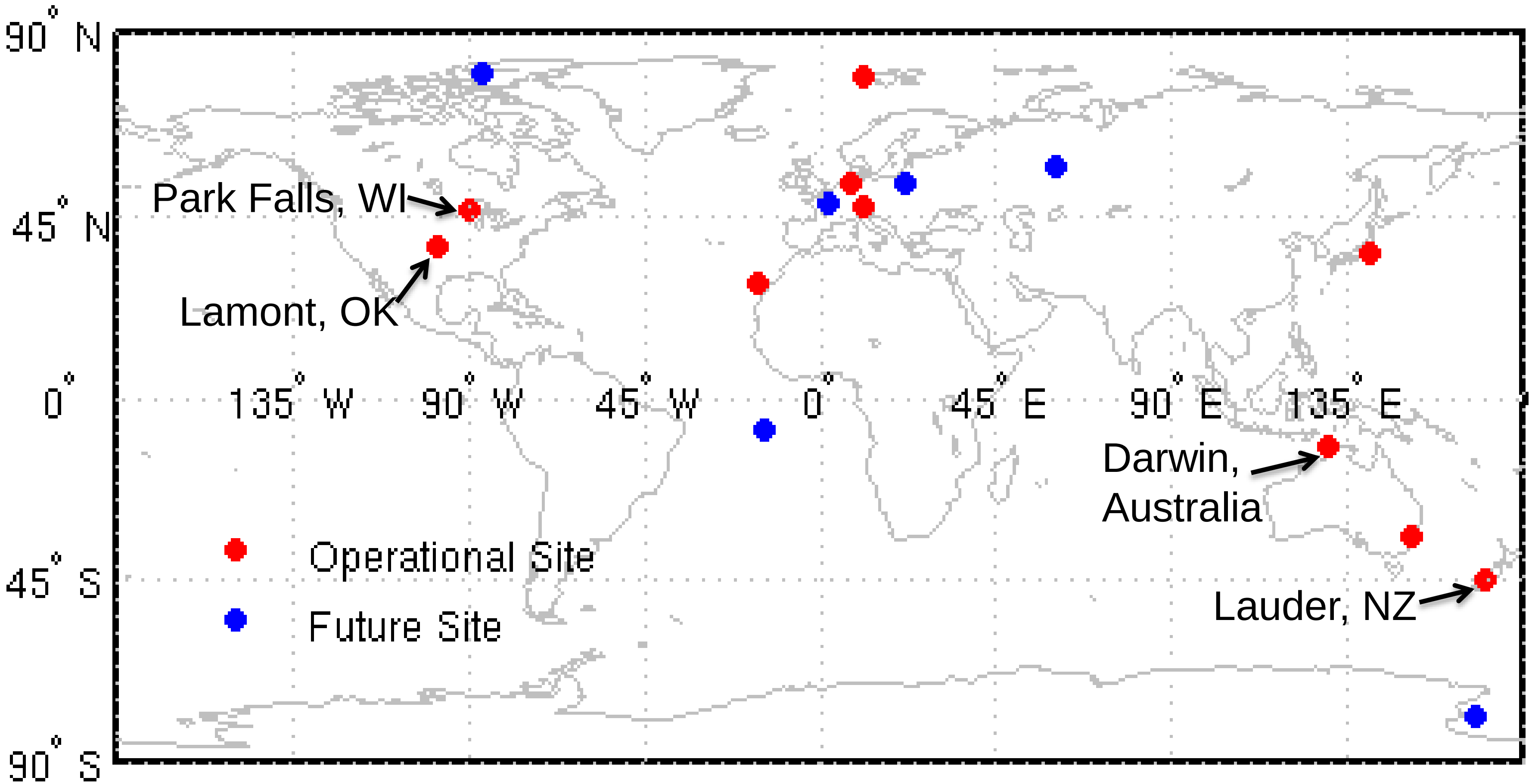
The CO_2 variations of interest today are <½ ppm (~0.1%).

XCO_2 column seasonal cycle (ppm)



This level of precision is very difficult to achieve in an "open path" observation geometry since the "sample" conditions (T, P, H_2O, SZA) are uncontrolled.

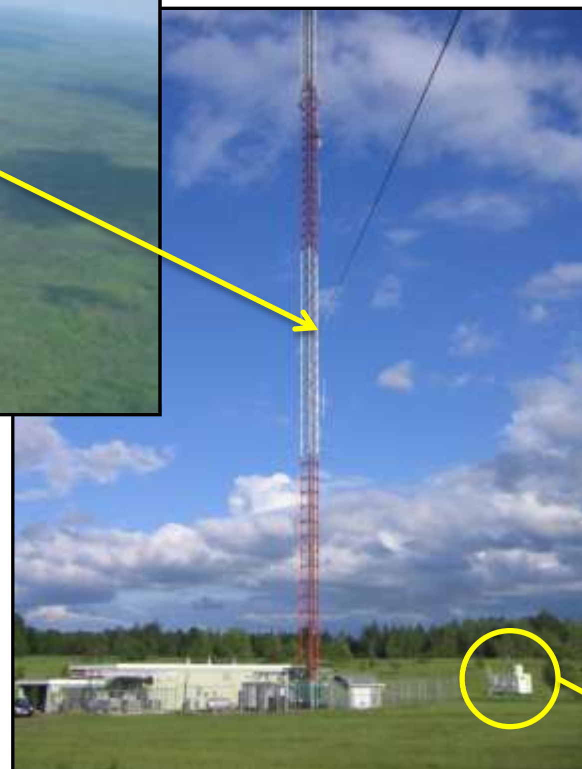
TCCON Site Locations



TCCON is a network of ground-based, open-path, NIR, solar absorption FTSs (Bruker IFS12X HR) that agree to standard procedures for operations, processing, and analysis.

TCCON Site in Park Falls, Wisconsin

The first TCCON FTS was located in Park Falls, WI, adjacent to the WLEF tall tower.



This facilitates comparison with CMDL in situ data acquired on the tower itself and from aircraft spiraling down.

TCCON FTS at ARM SGP, Oklahoma

Visible in photograph:
- 20’ shipping container
- Dome protecting suntracker
- Camera viewing dome & sky
- Weather station (T, P, RH, rain)

Inside container:
- Bruker IFS125HR
- Computer (control & data acq)
- Scroll pump, internet access
- GPS (time), UPS, Heaters, A/C

Autonomous operation. Internal (Hercules QNX4) computer controls everything (dome, suntracker, Bruker, pump, data acquisition & analysis)
- checks the weather station data before opening the dome
- checks the suntracker intensity before requesting the Bruker FTS to scan
- gathers the interferogram slices from the Bruker using its web interface

Data are analyzed (FFT, spectral fitting) nightly for QC purposes.
Raw data are sent out every 1-3 months on interchangeable disk drives.

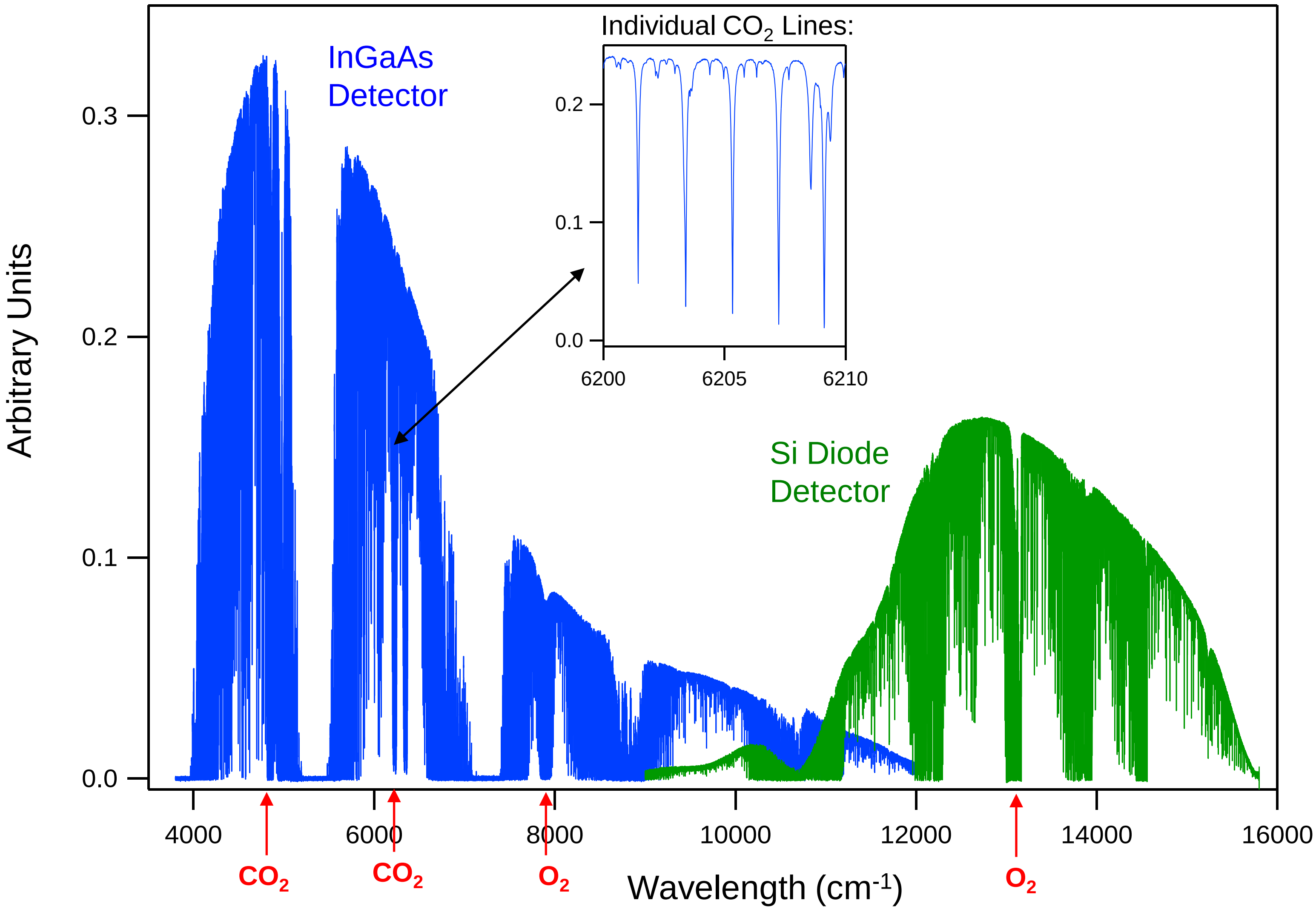
IFS 125HR Instrument Details

Beamsplitter: CaF_2
Detectors (Room-T):
- InGaAs (3900-9000 cm^{-1})
- Si (9000-15500 cm^{-1})

Acquisition: DC, Dual-Channel
ADC: 24-bit Delta-Sigma
Sample Rate: 15-20 KHz
SNR: 800:1 (75s scan)
Resolution: $0.02cm^{-1}$ (45cm)

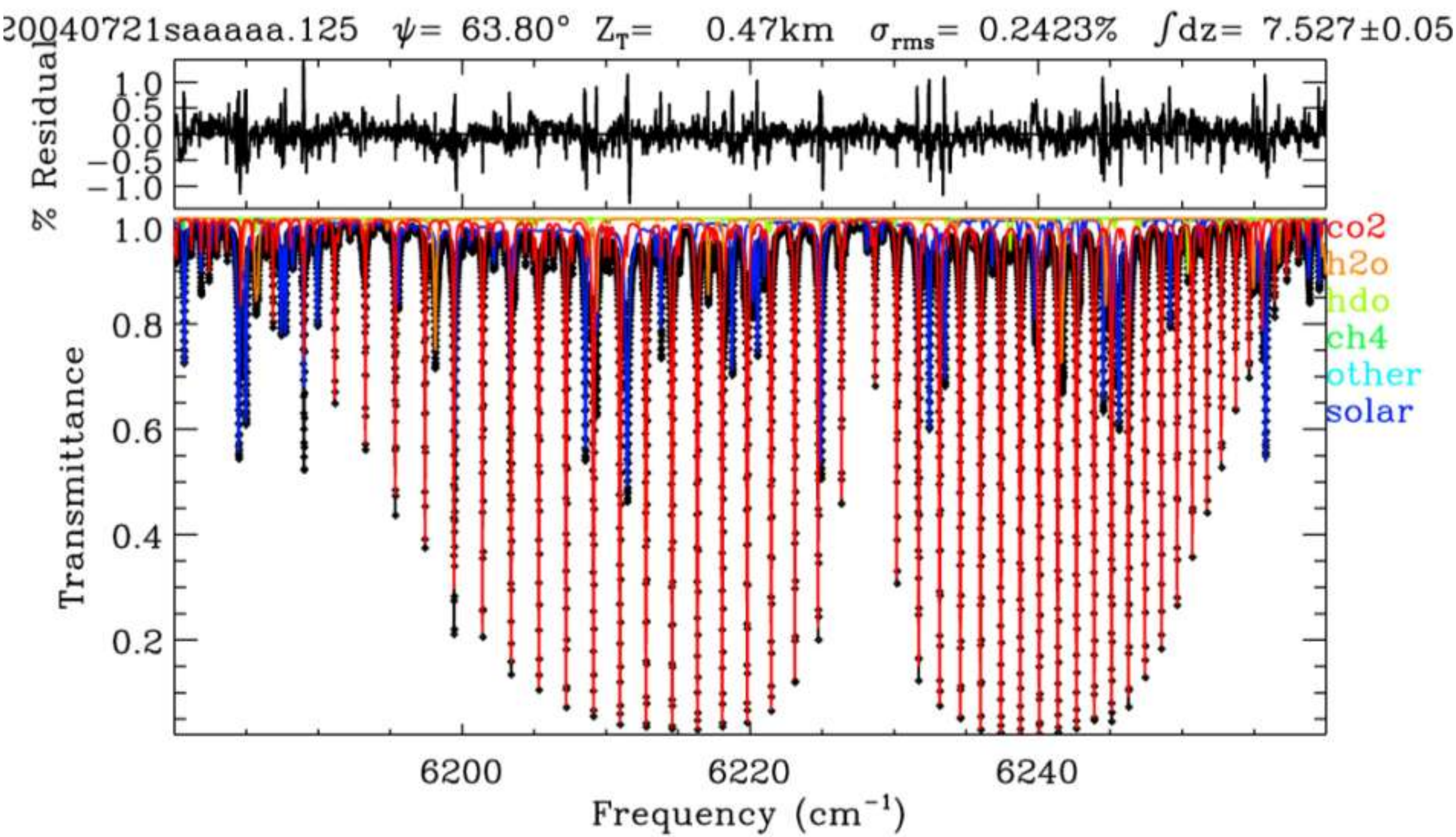
Modifications / Additions:
- No sample compartment
- Gold-coated mirrors
- Dichroic beamsplitter
- Red filter (absorbs visible)
- Added Heaters & Insulation
- Internal HCl gas cell (ILS)
- Aperture-limiting stop

Spectral Coverage



Single spectrum recorded at 9:30 am on 9 Sept 2004, Park Falls, WI.
Signal-to-noise: InGaAs Detector ~885; Si Diode Detector ~465

Example of Spectral Fit – Park Falls CO_2



Data Processing and Analysis

The retrieved column abundances are converted to a column-averaged dry-air mole fraction, by division by the O_2 column and multiplication by the dry-air mole fraction of O_2 (=0.2095), which is highly constant.

$$\mathbf{XCO2 = 0.2095 \times Column_{CO2} / Column_{O2}}$$

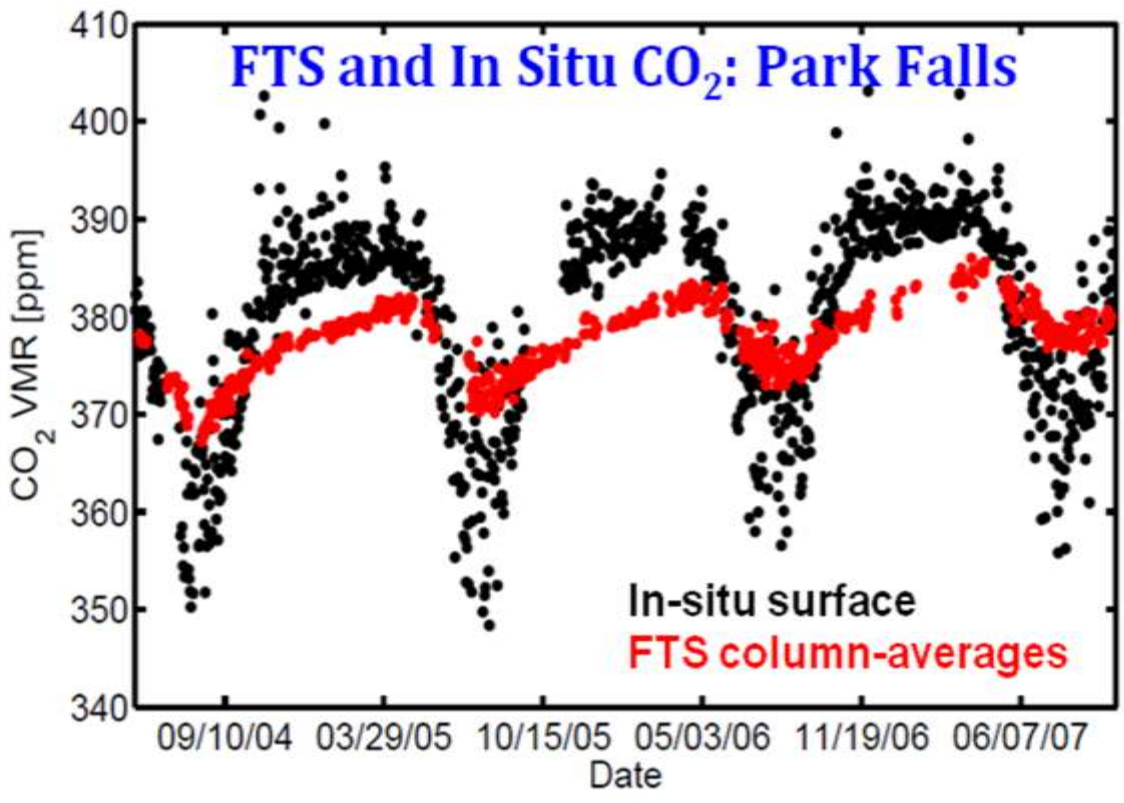
This ratioing helps cancel several potentially damaging systematic errors:

- pointing errors (i.e., mis-tracking the center of the solar disk)
- surface pressure uncertainties
- ILS uncertainty,
- zero level offsets
- solar intensity variations (e.g. clouds)

To minimize algorithmic biases between sites, TCCON plans to use the same software for data processing and analysis at all sites. This includes:

- Correction of solar intensity variations
- Phase-correction and FFT of the interferograms
- Spectral fitting (GFIT)
- QC of the retrieved column abundances

Park Falls FTS / in situ CO_2 Comparison



These are not supposed to agree – completely different vertical sensitivities

Variations in XCO_2 are muted in comparison with CO_2 variations at the surface.

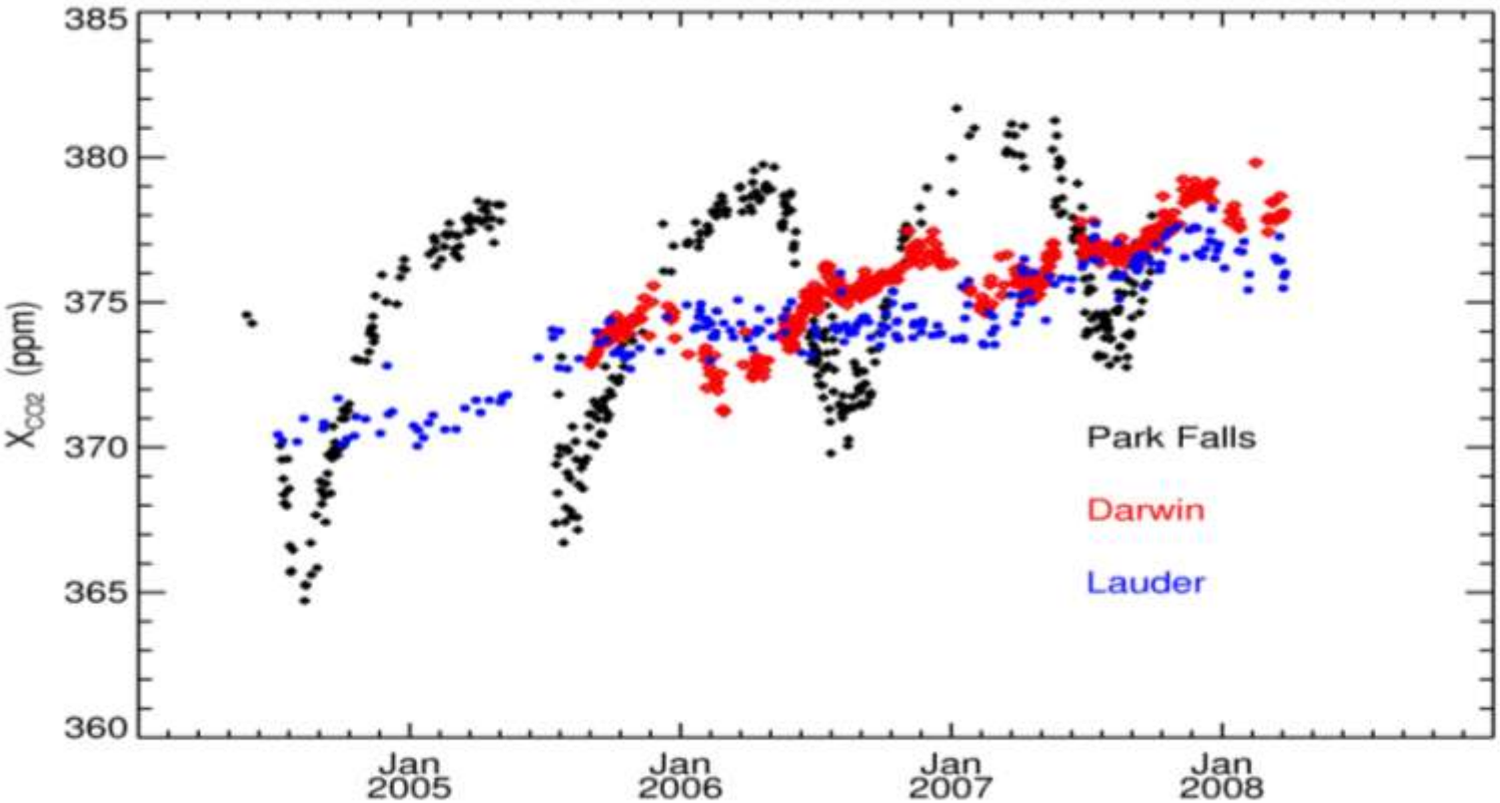
Seasonal cycle of XCO_2 over Park Falls is ~ 11ppm (3%)

Long-term increase ~0.5%/yr

Note the increased variability of CO_2 during the summertime minimum: a result of N/S gradients in CO_2. These correlate well with tropospheric potential temperature, which allows estimation of the meridional gradient in CO_2 concentration and hence surface fluxes (Keppel-Aleks et al., 2009).

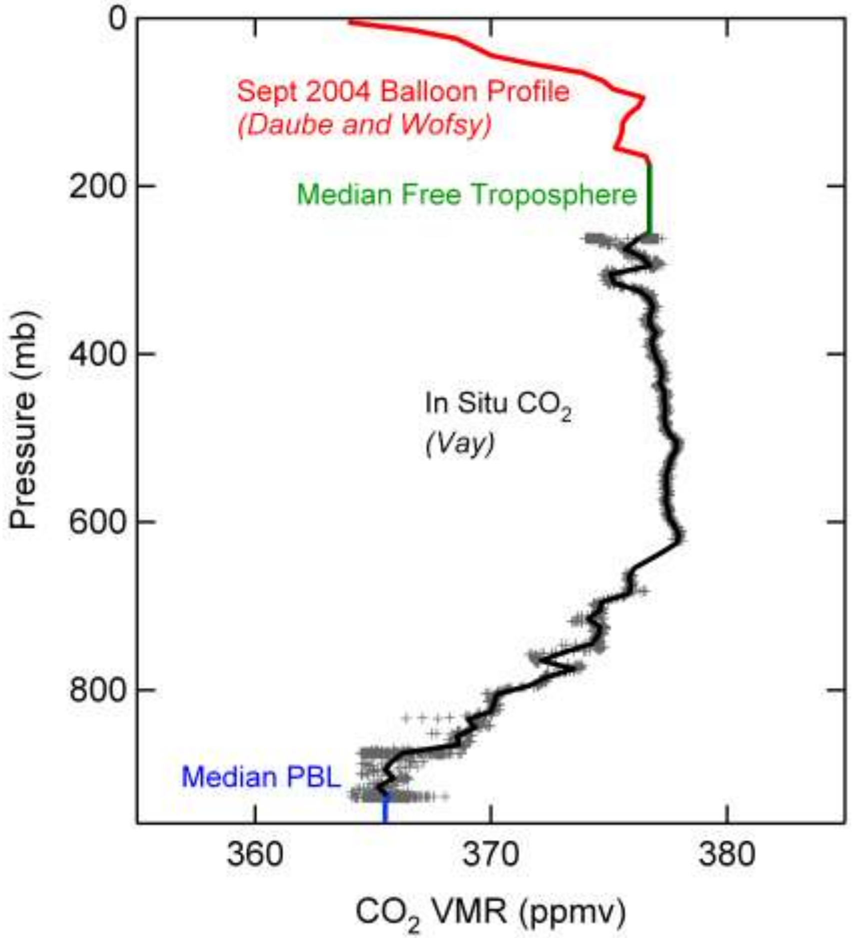
Comparison of different TCCON sites

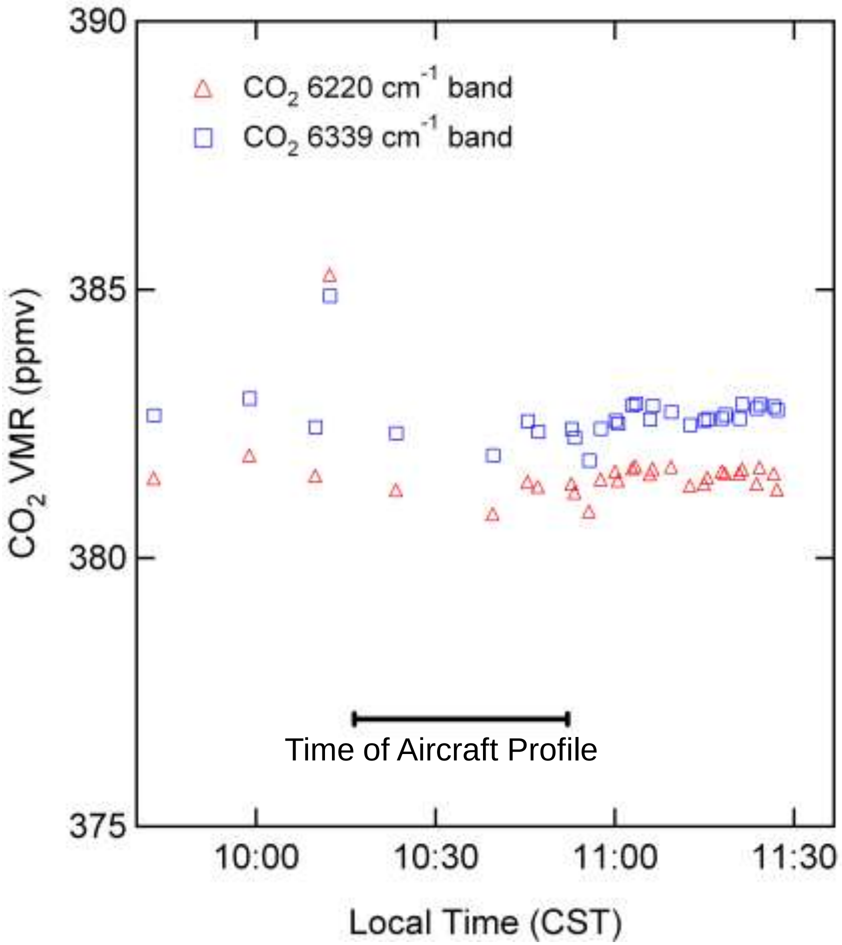
Comparisons of XCO2 from Park Falls (46 N, black), Darwin (12 S, red), and Lauder (45 S, blue). It is immediately evident that the seasonal cycle is much smaller in amplitude in the SH, due to the much smaller land area at mid-latitudes in the SH. All sites show similar increasing CO_2 trends.



Validation by in situ aircraft profiles

FTS Column and Aircraft In Situ Data – Park Falls 12 July 2004

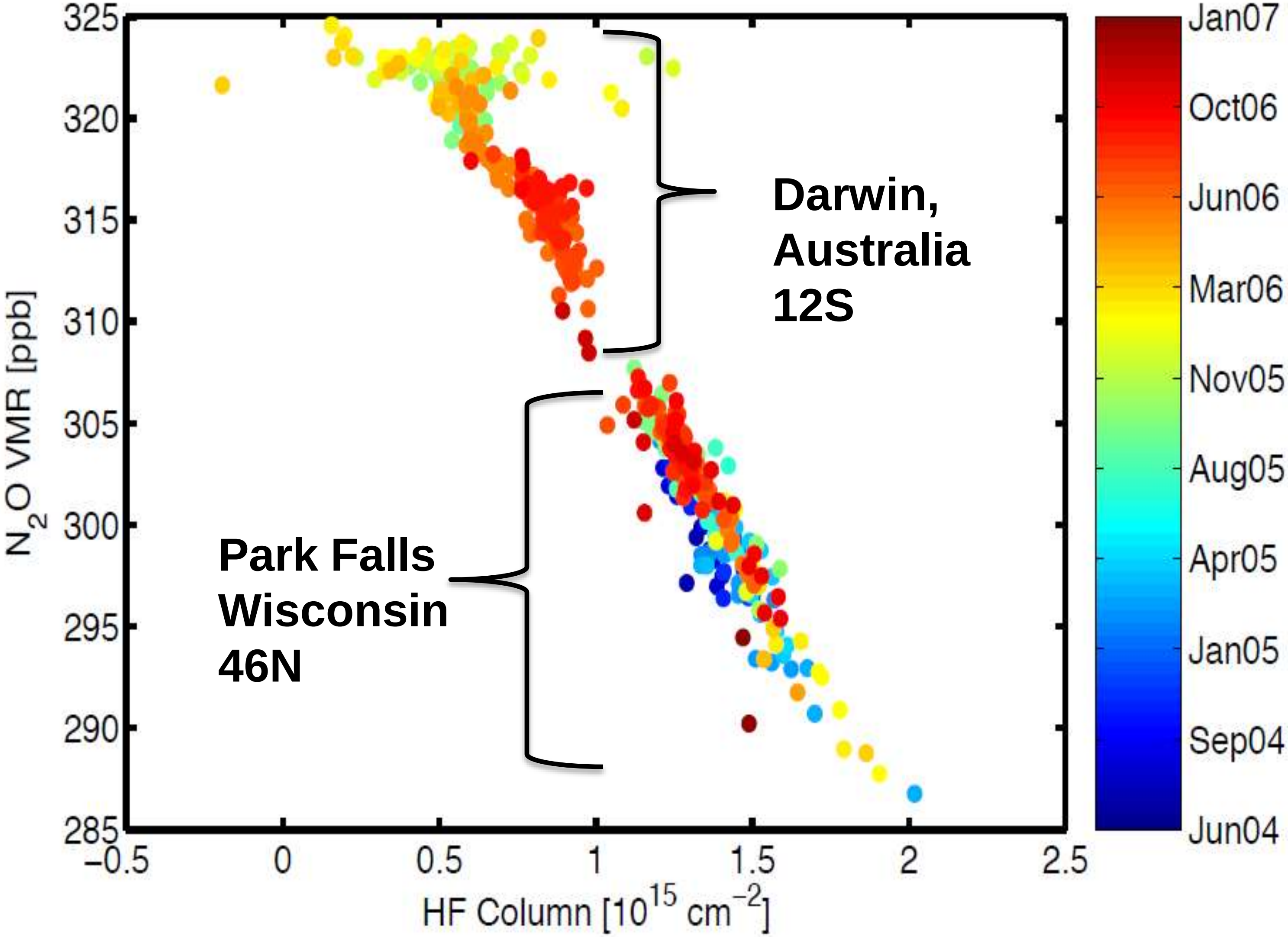




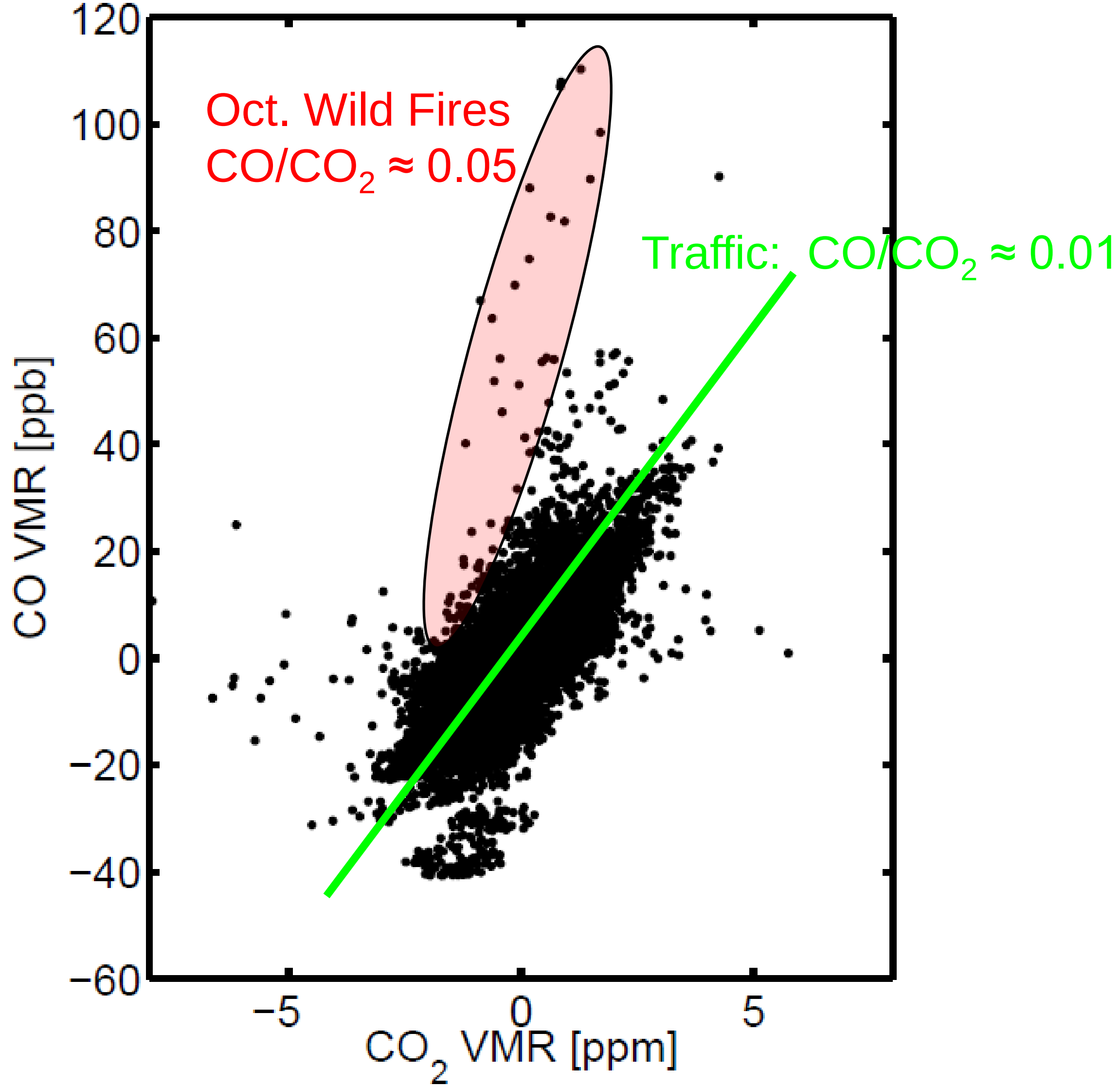
Aircraft Column / Total Dry Column =
373.6 ± 0.52 ppmv

FTS Column / Total Dry Column =
381.5 ± 0.19 ppmv (6220)
382.6 ± 0.24 ppmv (6339)

Other Gases – N_2O/HF



Other Gases – CO at JPL/Pasadena



Summary and Conclusions

TCCON demonstrates the ability of ground-based FTS to make highly precise (~0.1 to 0.3%) column measurements of atmospheric GHGs.

To significantly constrain the inter-hemispheric gradient, the network must maintain precisions of ~0.1%. We have not yet achieved this, but are continually working to remove bias via close collaboration among partners.

This capability nevertheless enables useful Carbon Cycle science (e.g., Yang et al., 2007; Keppel-Aleks et al., 2009, Wunch et al. 2009).

Simultaneous measurements of gases other than CO_2, e.g., CH_4, CO, N_2O and HF provide important diagnostics for understanding CO_2 variations.

Column measurements, in conjunction with in situ measurements, provide a tighter constraint on Carbon Cycle models than either alone.

There are several Earth-orbiting sensors with a CO_2 measurement capability (TOVS, SCIAMACHY, AIRS, TES, IASI, GOSAT, ACE) which could benefit from TCCON data.

For more information see: http://www.tccon.caltech.edu/

Acknowledgements

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Yael Yavin for building the Darwin and Lamont containers

Additional Material

The superior performance achieved by the TCCON instruments is due to:

1) Use of the atmospheric O_2 column as a reference
2) Correction for source brightness variations (e.g. clouds)
3) The use of dedicated, high-quality FTS instruments
4) Consistency of operation, data processing, and analysis between sites
5) Traceability to the global in situ network via airborne profiles over FTSs
6) Improved spectroscopy enabling e.g., the fitting of wider windows

TCCON-related Publications

Yang, Z., G. C. Toon, J. S. Margolis, and P. O. Wennberg, Atmospheric CO_2 retrieved from ground-based near-IR solar spectra, GRL, 29, 1339, 2002

Washenfelder, R.A., P.O. Wennberg, and G.C. Toon, Tropospheric methane retrieved from ground-based near-IR solar absorption spectra, *GRL*, 30, L017969, 2003

Yang, Z., et al., Ground-based photon path measurements from solar absorption spectra of the O_2 A-band, JQSRT, 90, 309-321, 2005

Washenfelder, R.A., G.C. Toon, J-F. Blavier, Z. Yang, N.T. Allen, P.O. Wennberg, S.A. Vay, D.M. Matross, and B.C. Daube, Carbon dioxide column abundances at the Wisconsin Tall Tower site, *JGR*, 111, D22305, 2006

Bösch, H., et al., Space-based near-infrared CO_2 measurements: Testing the OCO retrieval algorithm and validation concept using SCIAMACHY observations over Park Falls, Wisconsin, *JGR*, 111, D23302, 2006

de Beek, R. et al., Atmospheric carbon gases retrieved from SCIAMACHY by WFM-DOAS: improved global CO and CH_4 and initial verification of CO_2 over Park Falls (46° N, 90° W), ACPD, 6, 363-399, 2006

Keppel-Aleks, G., G.C. Toon, P.O. Wennberg, and N. Deutscher, Reducing the impact of source brightness fluctuations on spectra obtained by FTS, Applied Optics, 46, 4774-4779, 2007

Yang, Z., R.A. Washenfelder, G. Keppel-Aleks, N.Y. Krakauer, J.T. Randerson, P.P. Tans, C. Sweeney, and P.O. Wennberg, New constraints on Northern Hemisphere growing season net flux, *GRL*, 34, L12807, 2007

Barkley, M.P. et al., Assessing the near surface sensitivity of SCIAMACHY atmospheric CO_2 retrieved using (FSI) WFM-DOAS, ACPD, 7, 2477-2530, 2007

Keppel Aleks, Gretchen, Paul Wennberg, Tapio Schneider, and Stephanie Vay, High latitude carbon exchange estimated from co-variation of CO_2 and potential temperature, submitted to Nature Geosciences, 2009

Wunch et al., Emissions of Greenhouse Gases in the Los Angeles Area, submitted to GRL, 2009

Deutscher, N.M., et al., Total column CO_2 measurements at Darwin, Australia - Site description and calibration against in situ aircraft profiles, submitted to JGRd, 2009