HIPPO and TCCON

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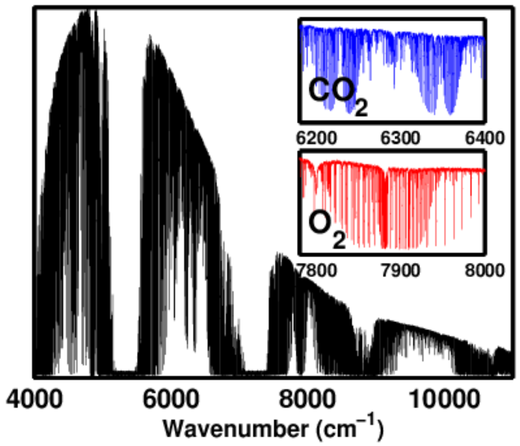
HIPPO Science Team Meeting, Boulder

TCCON Science Objectives

- Constrain global fluxes of carbon and improve our understanding of the carbon cycle
- Provide the primary validation (ground-truth) dataset for satellite instruments (GOSAT, OCO-2, SCIAMACHY, ASCENDS, AIRS, TES, CARBONSAT)
- Provide a transfer standard between the satellite measurements and the ground-based *in situ* network

TCCON Instruments

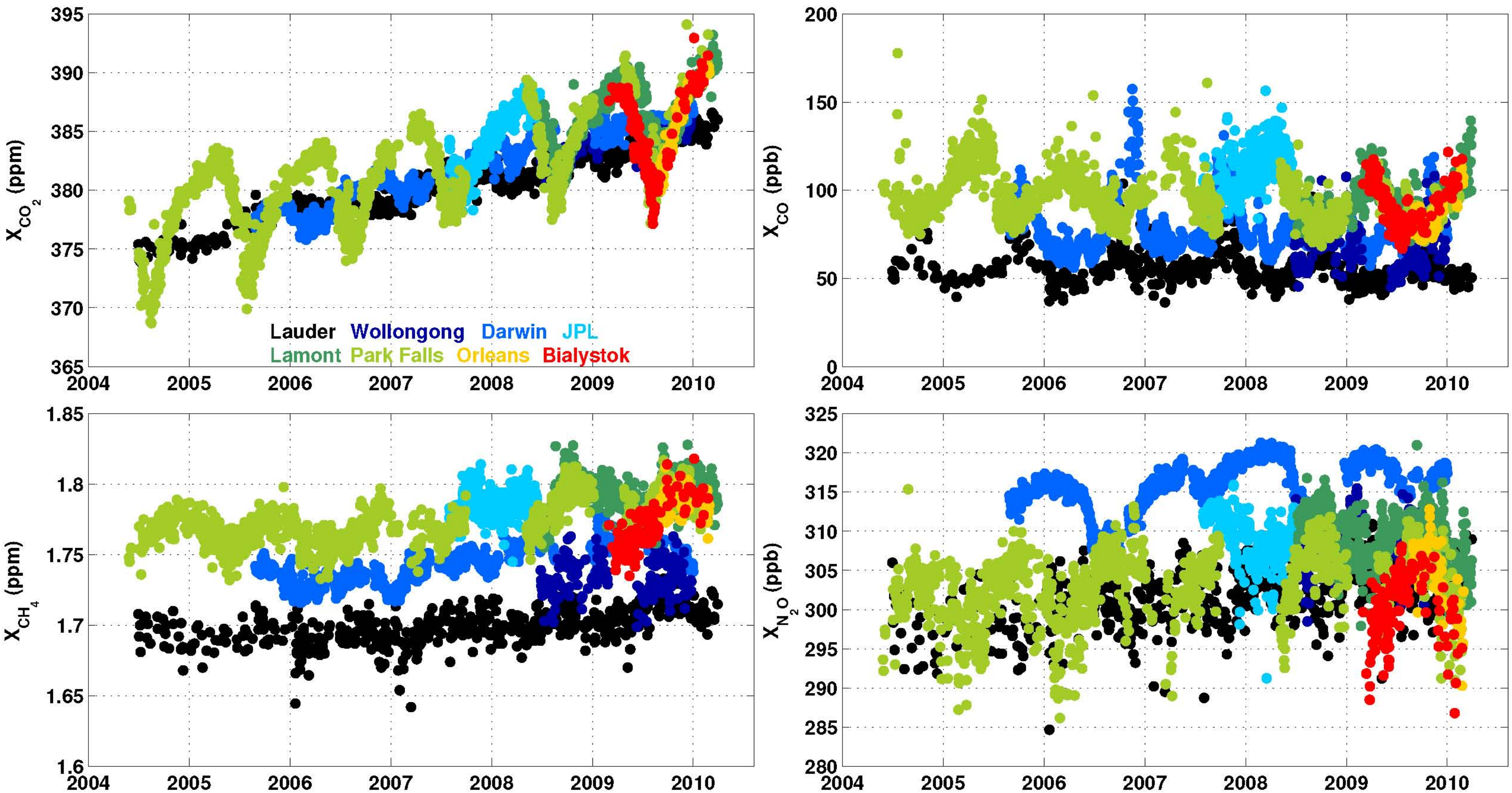
- Ground-based Fourier transform spectrometers
- Remote sensing of total columns of CO_2, CH_4, N_2O, CO, H_2O, HDO, O_2 via solar absorption in the near infrared
- Similar measurement technique to NDACC, but we use a profile scaling retrieval
- Strong dependence on spectroscopic line lists, which are only good to ~1% accuracy
  - Insufficient for carbon cycle science
- Divide trace gas columns by O_2 column to get dry-air mole fractions: X_{CO_2}, X_{CH_4}, X_{N_2O}, X_{CO}, X_{H_2O}, X_{HDO}



$$X_{CO_2} = 0.2095 \frac{\text{column}_{CO_2}}{\text{column}_{O_2}}$$

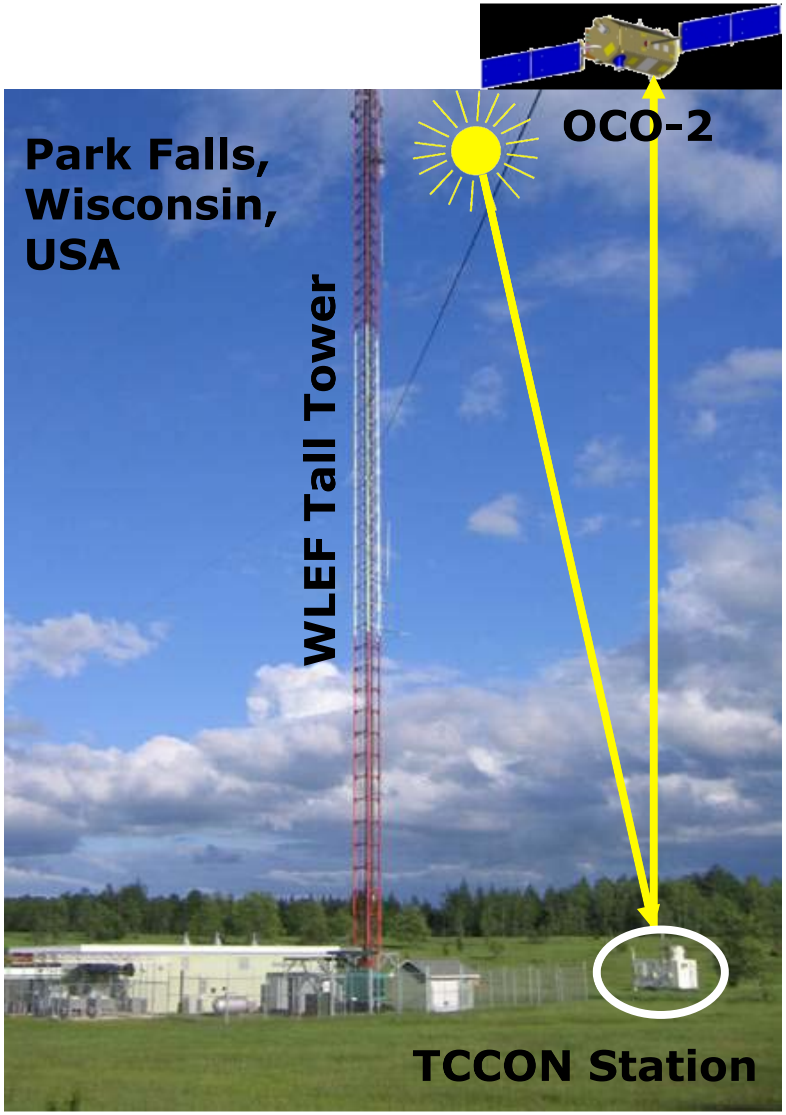
Molecule	Precision	Accuracy
CO_2	~0.8 ppm	~0.8 ppm
CH_4	~5 ppb	~7 ppb
N_2O	~1.5 ppb	~3 ppb
CO	~0.5 ppb	~4 ppb

TCCON Time Series



TCCON as a Transfer Standard

- A main goal of the TCCON is to provide a transfer standard between the surface in situ network and satellite instruments
- In-situ measurements are very precise and accurate, but do not measure total column abundances
- Satellite instruments (GOSAT, SCIAMACHY, AIRS, TES, OCO-2) measure total columns
- TCCON is precise, but inaccurate, so must be calibrated by in situ measurements made over our sites

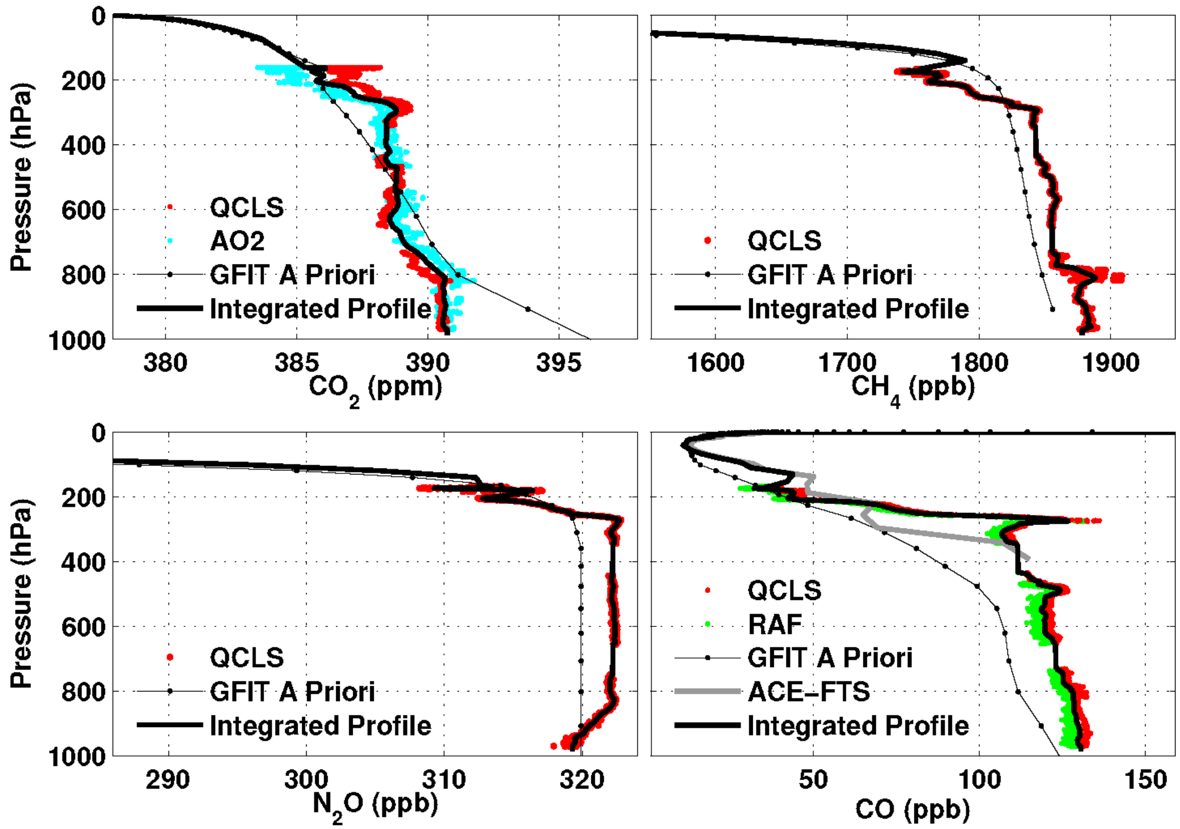


Aircraft Profiles over TCCON Sites

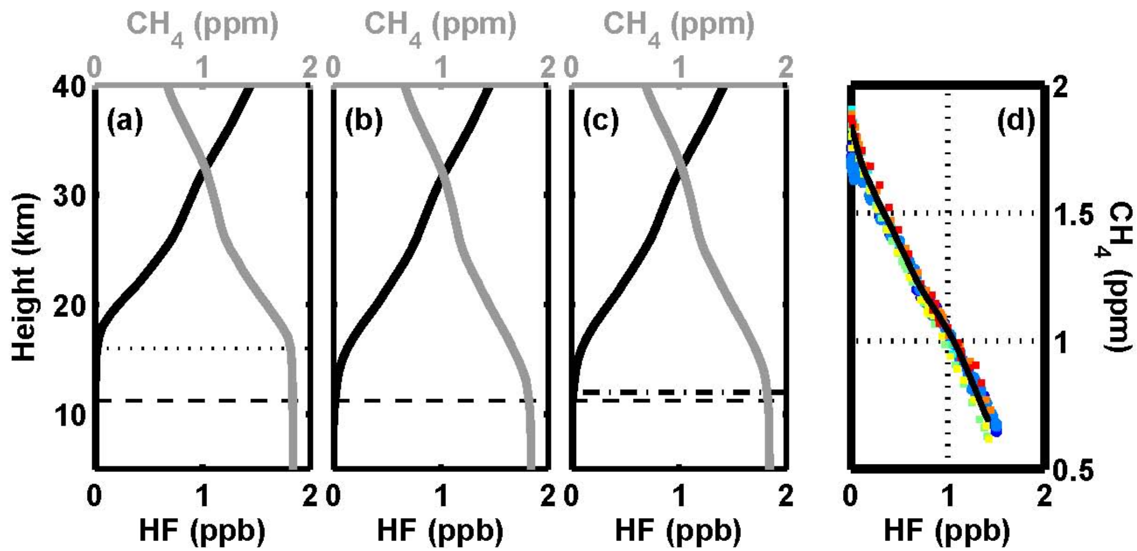
Site	Aircraft Campaign	Gases Measured	Dates	Notes
Park Falls	INTEX-NA COBRA START-08	CO_2, CO, CH_4, H_2O CO_2, CO, H_2O CO_2, CH_4, N_2O, CO, H_2O	Jul 2004 Jul/Aug 2004 May 2008	Washenfelder et al., JGR, 111, D22305, 2006.
Darwin	TWP-ICE	CO_2	Feb 2006	Deutscher et al., AMT, 2010.
Lamont	HIPPO-1,2,3 Lear	CO_2, CH_4, N_2O, CO, H_2O CO_2, CH_4, N_2O, CO	Jan 2009 Aug 2009, July 2010	Wunch et al., AMT, 2010
Lauder	HIPPO-1,2,3	CO_2, CH_4, N_2O, CO, H_2O	Jan 2009	Wunch et al., AMT, 2010
Tsukuba	KingAir	CO_2, CH_4, N_2O	Jan 2009	Wunch et al., AMT, 2010
European Sites	IMECC	CO_2, CH_4, N_2O, H_2O, CO	Sep-Oct 2009	Messerschmidt et al., submitted 2011
Wollongong	HIPPO-2	CO_2, CH_4, N_2O, CO, H_2O	Nov 2009	Macatangay et al., in prep.

TCCON Calibration

- HIPPO-1 flight over Lamont, Oklahoma on Jan 31, 2009
- High vertical resolution
- High precision and accuracy
- Largest errors from lack of stratospheric information.



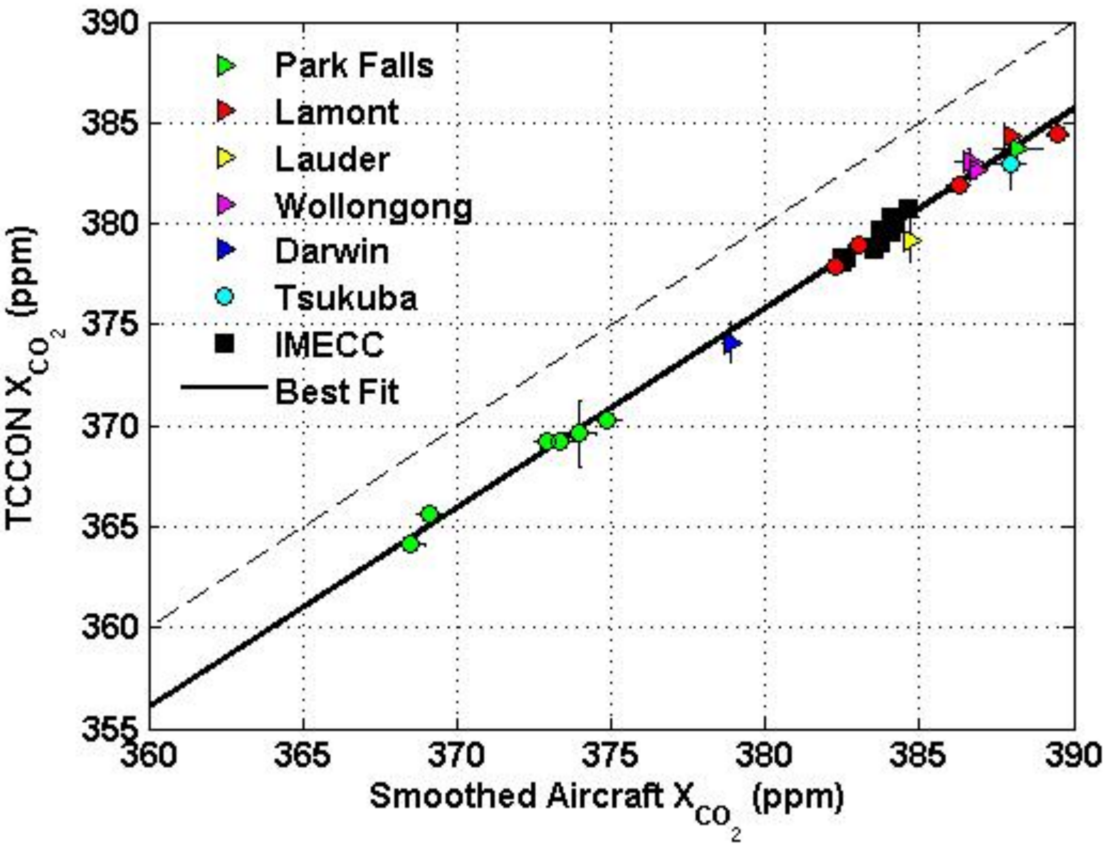
Setting the Stratosphere



- Well-known HF-CH_4 and HF-N_2O correlations are built into the GFIT a priori profiles (Luo et al., 1995; Washenfelder et al., 2003)
- Tropopause height in a priori is set for local noon on a given day, based on NCEP temperature profile
- If tropopause height changes throughout the day, we get the wrong stratosphere, and the wrong column
  - 1 km error gives, on average, 10 ppb CH_4 column error (0.5%); 4 ppb N_2O column error (1%)
- Use measured TCCON HF column during overpass to adjust the stratospheric profile up and down.

TCCON Calibration: XCO_2

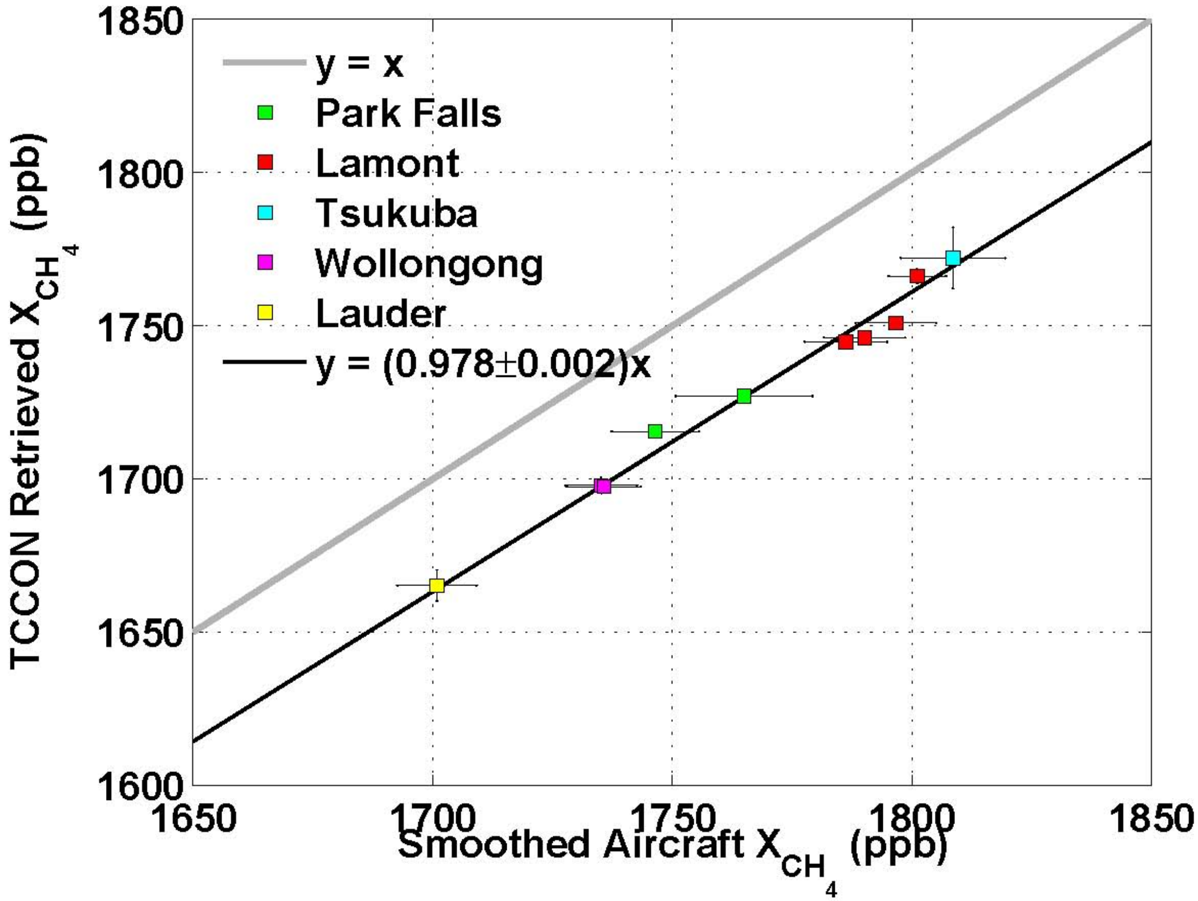
- Excellent consistency between sites, seasons and years
- Single calibration factor sufficient for TCCON calibration to WMO
- Slope:
  - 0.989 ± 0.002
  - 0.2% accuracy (2σ)



Calibration of TCCON column-averaged CO_2: the first aircraft campaign over European TCCON sites. Messerschmidt et al. ACPD, submitted, 2011.

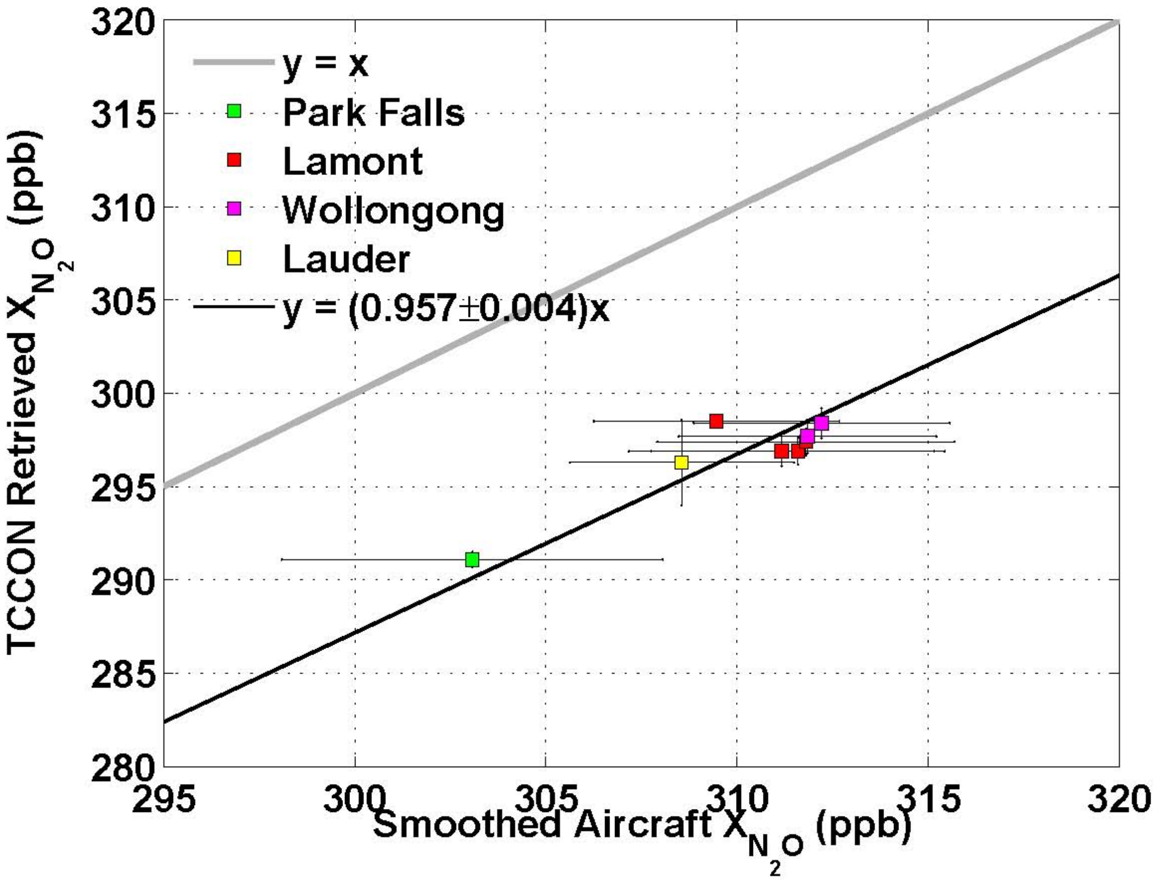
TCCON Calibration: X_{CH_4}

- Good consistency between sites
- Single calibration factor sufficient for TCCON calibration to WMO
- Slope:
  - 0.978 ± 0.004
  - 0.4% accuracy (2σ)



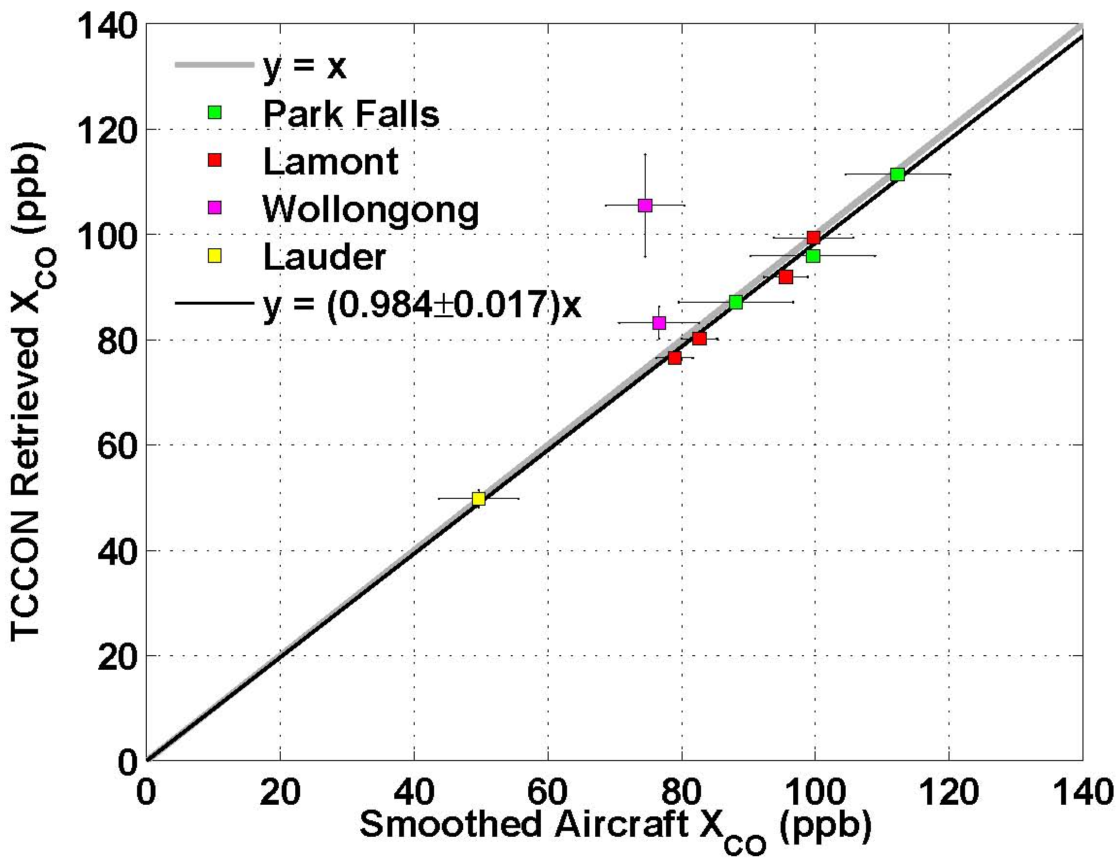
TCCON Calibration: X_{N_2O}

- Good consistency between sites
- Single calibration factor sufficient for TCCON calibration to WMO
- Slope:
  - 0.957 ± 0.01
  - 1% accuracy (2σ)



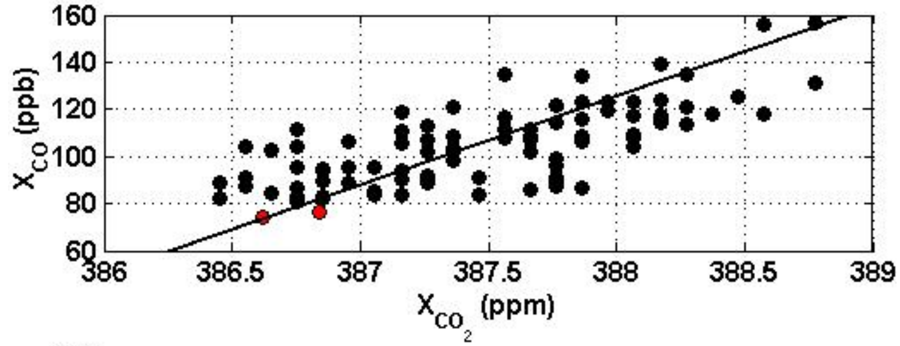
TCCON Calibration: Xco

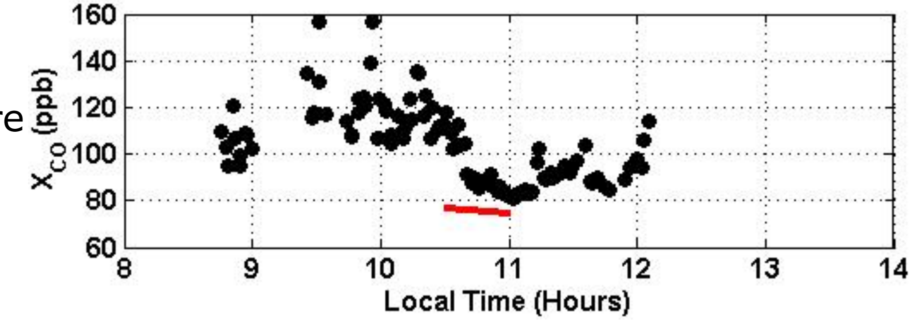
- Reasonably good consistency between sites, seasons and years, except for Wollongong, which has urban pollution
- Single calibration factor sufficient for TCCON calibration to WMO
- Slope:
  - 0.98 ± 0.04
  - 4% accuracy (2σ)
- Stratospheres set by averaging ACE-FTS profiles within 5 degrees latitude and 1 month of the overpass

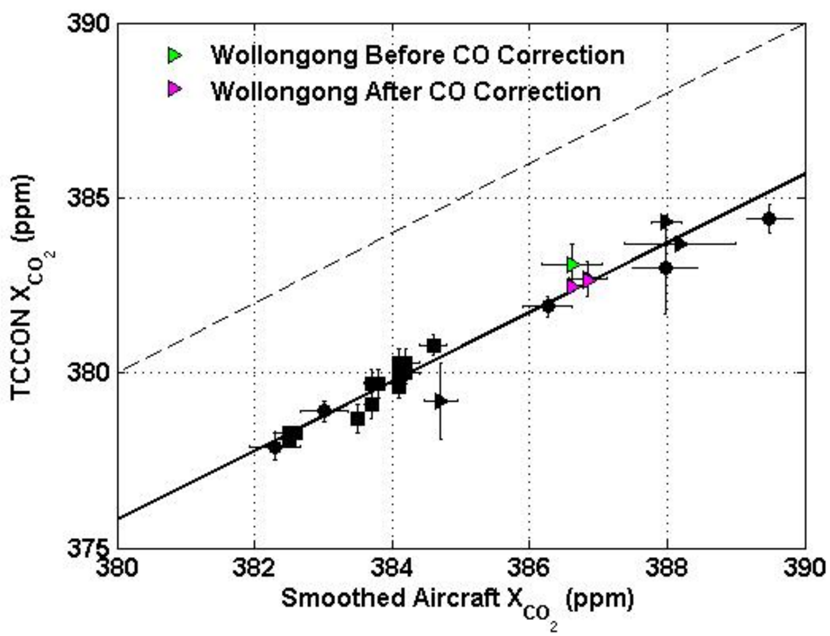


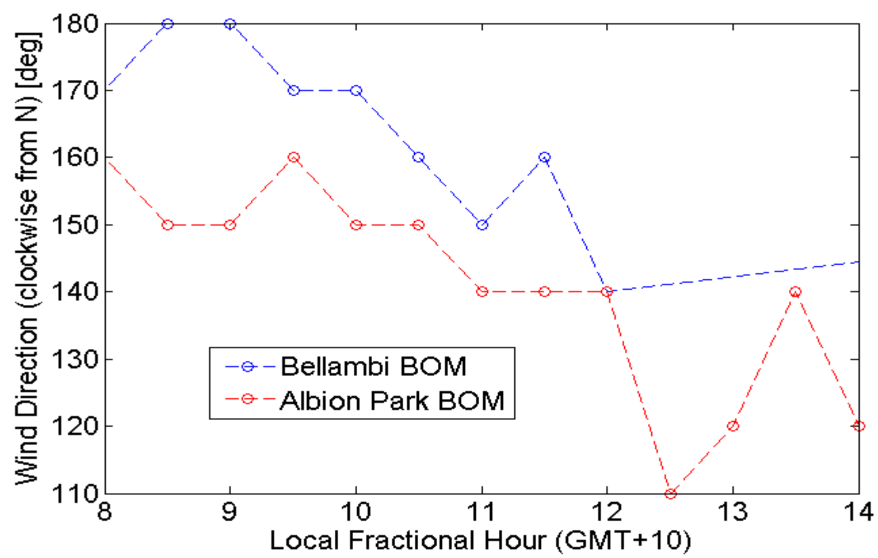
Wollongong CO

- Extremely variable CO during the day in Wollongong
- Back-trajectory and wind direction work looks promising
  - CO is correlated with wind direction – highest when winds from SE, where there is a steel mill
- Can also use CO to correct the CO_2



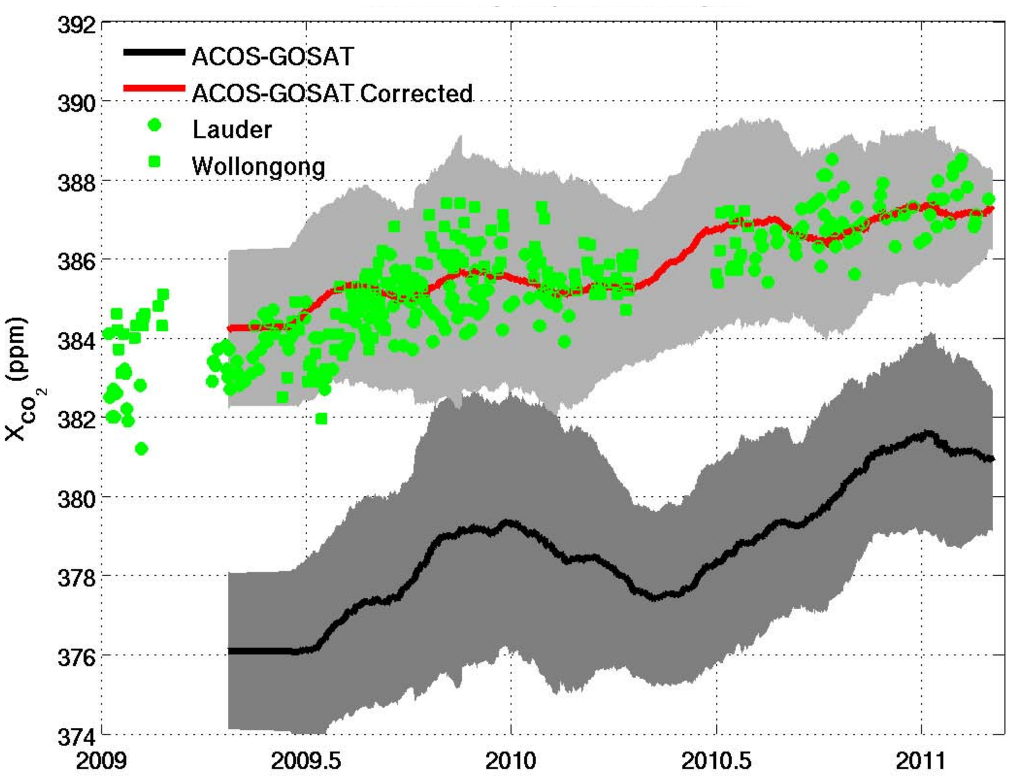






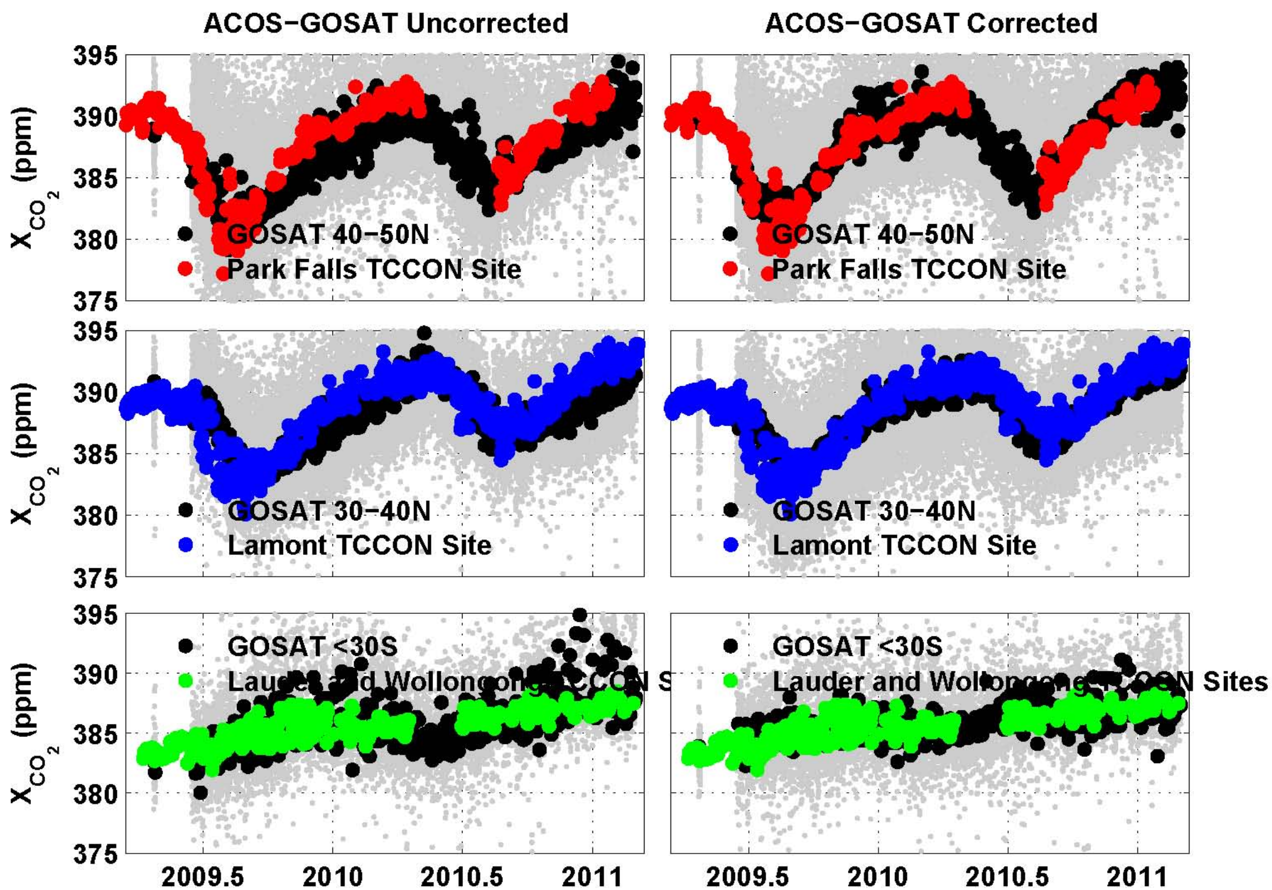
TCCON as "Ground Truth" for ACOS-GOSAT Xco_2 Data

- Southern hemisphere is crucial for Xco_2 validation because the field is relatively flat
- Use southern hemisphere TCCON data:
  - Remove large-scale bias
    - ~2% (or ~8 ppm)
  - Remove spurious relationships with retrieval parameters
    - Mean radiances, airmass, albedo, etc.
- Use Northern Hemisphere TCCON data:
  - Evaluate Northern hemisphere seasonal cycles and hemispheric gradients



Improved Northern Hemisphere Seasonal Cycle

- Seasonal cycle in NH is much more realistic after calibration with SH TCCON data



Conclusions

- The TCCON can be calibrated with a single calibration factor for each molecule
- Aircraft profiles with in situ instrumentation on board, tied to the WMO scale are *crucial* for TCCON calibration and in turn for GOSAT validation
  - Southern hemisphere TCCON sites are very important for the ACOS-GOSAT validation effort
- Lack of stratospheric information is the largest source of error

Molecule	Stratospheric Error	Surface Error	Aircraft Error	Total Error
CO_2	0.3 ppm (0.1, 0.5)	0.03 ppm (0, 0.2)	0.3 ppm (0.1, 0.7)	0.4 ppm (0.2, 0.8)
CO	3 ppb (1, 5)	0.04 ppb (0.01, 0.08)	4 ppb (1, 8)	5 ppb (2, 9)
CH_4	10 ppb (7, 14)	0.1 ppb (0.02, 0.3)	3 ppb (1.5, 6)	10 ppb (7, 15)
N_2O	4 ppb (4, 5)	0.02 ppb (0, 0.09)	0.4 ppb (0.3, 0.8)	4 ppb (4, 5)

Acknowledgments

TCCON is a network of ground-based FTSs for the accurate measurement of atmospheric gases in the near-IR spectral region. TCCON has a strong association with the **Network for the Detection of Atmospheric Composition Change – Infrared Working Group**, with which it shares know-how, hardware and many members

TCCON Science Team: P. Ahonen, J.-F. L. Blavier, T. Borsdorff, T. Blumenstock, B. J. Connor, N. Deutscher, D. Feist, M. Geibel, D. W. T. Griffith, F. Hase, P. Heikkinen, G. Keppel-Aleks, E. Kyro, R. Macatangay, M. de Maziere, J. Messerschmidt, I. Morino, J. Notholt, M. Rettinger, J. Robinson, C. M. Roehl, M. Schneider, V. Sherlock, K. Strong, R. Sussmann, T. Tanaka, G. C. Toon, O. Uchino, T. Warneke, R. A. Washenfelder, P. O. Wennberg, D. Wunch, Z. Yang

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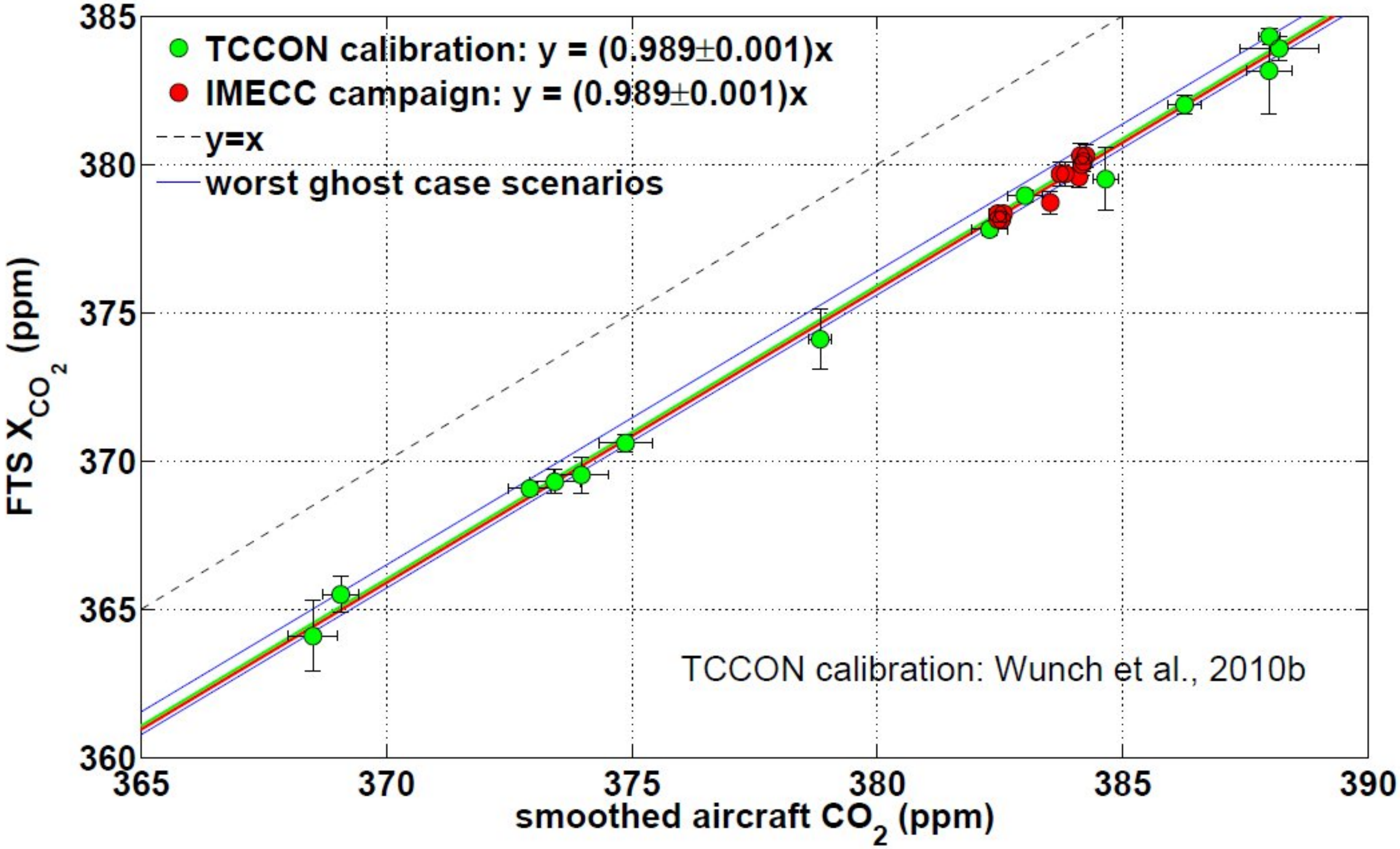
TCCON Calibration: Infrastructure for Measurement of the European Carbon Cycle (IMECC)



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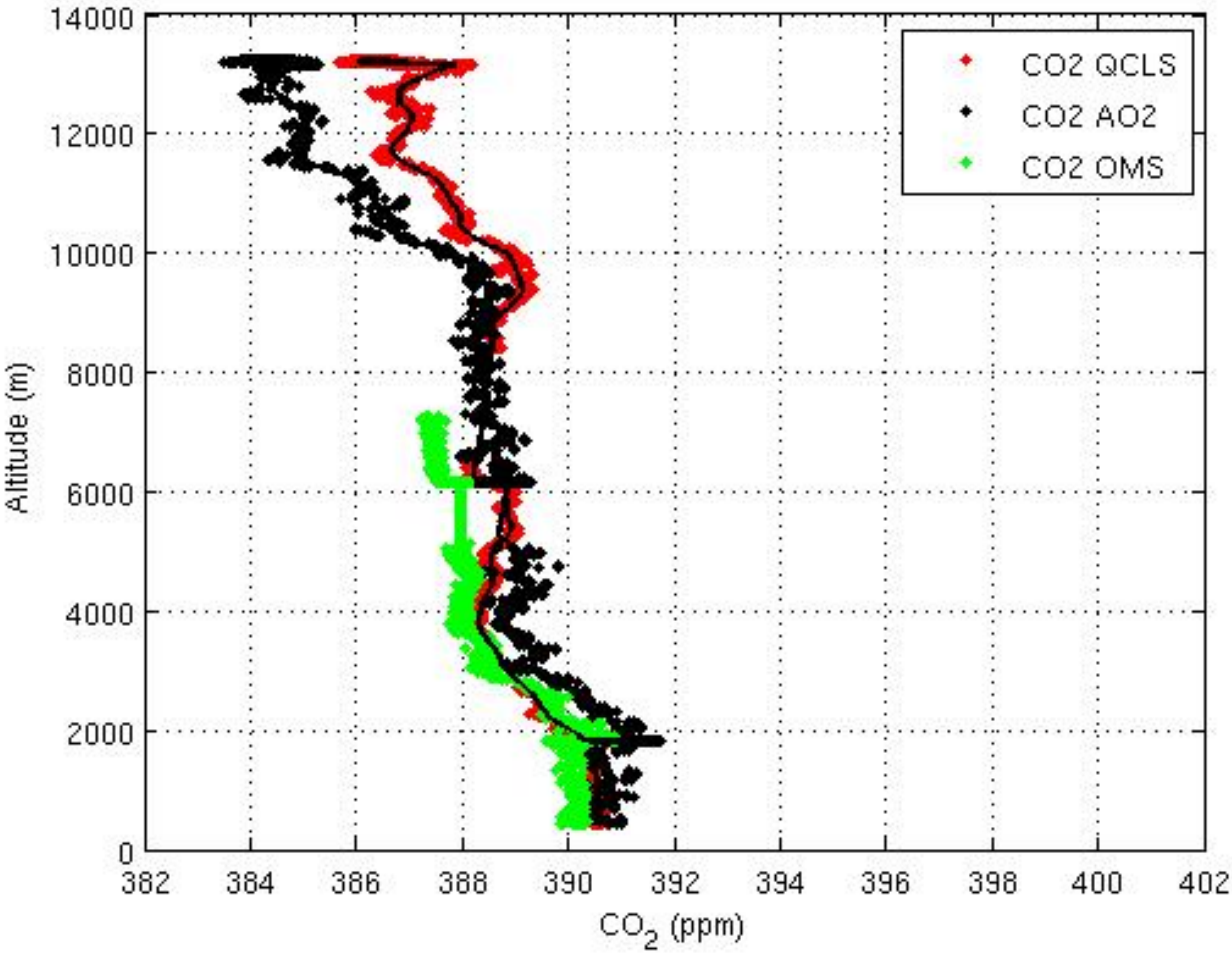
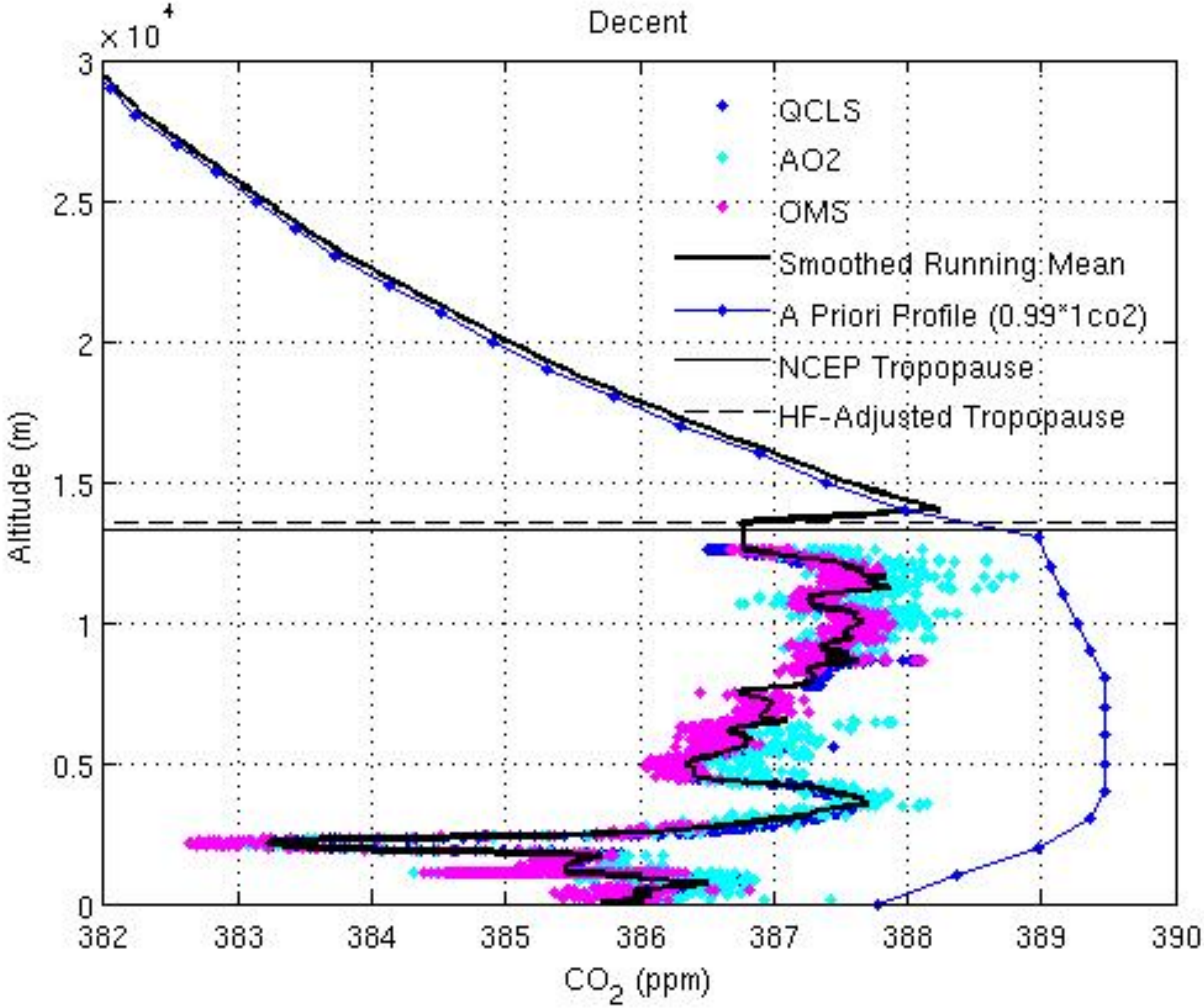
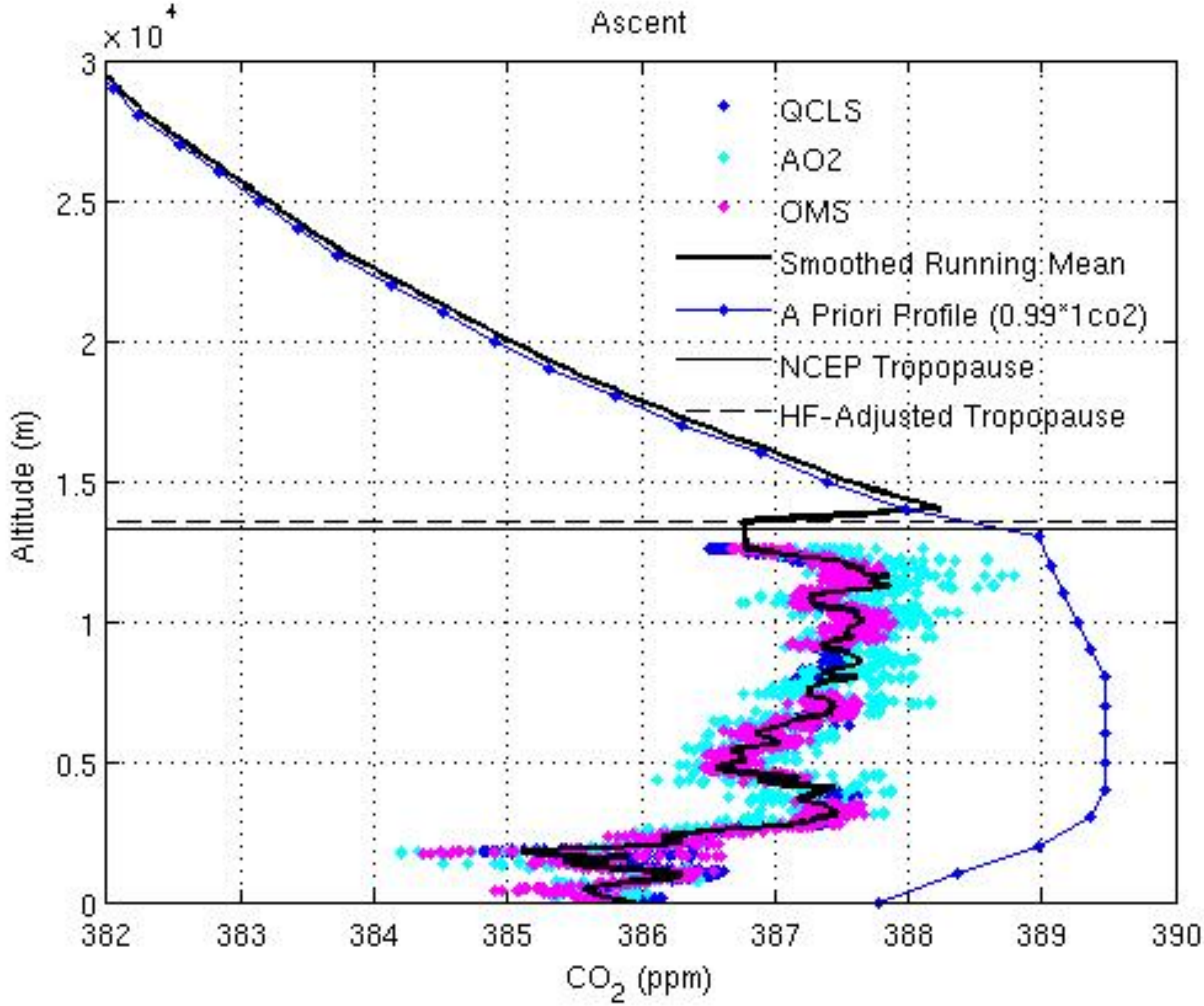
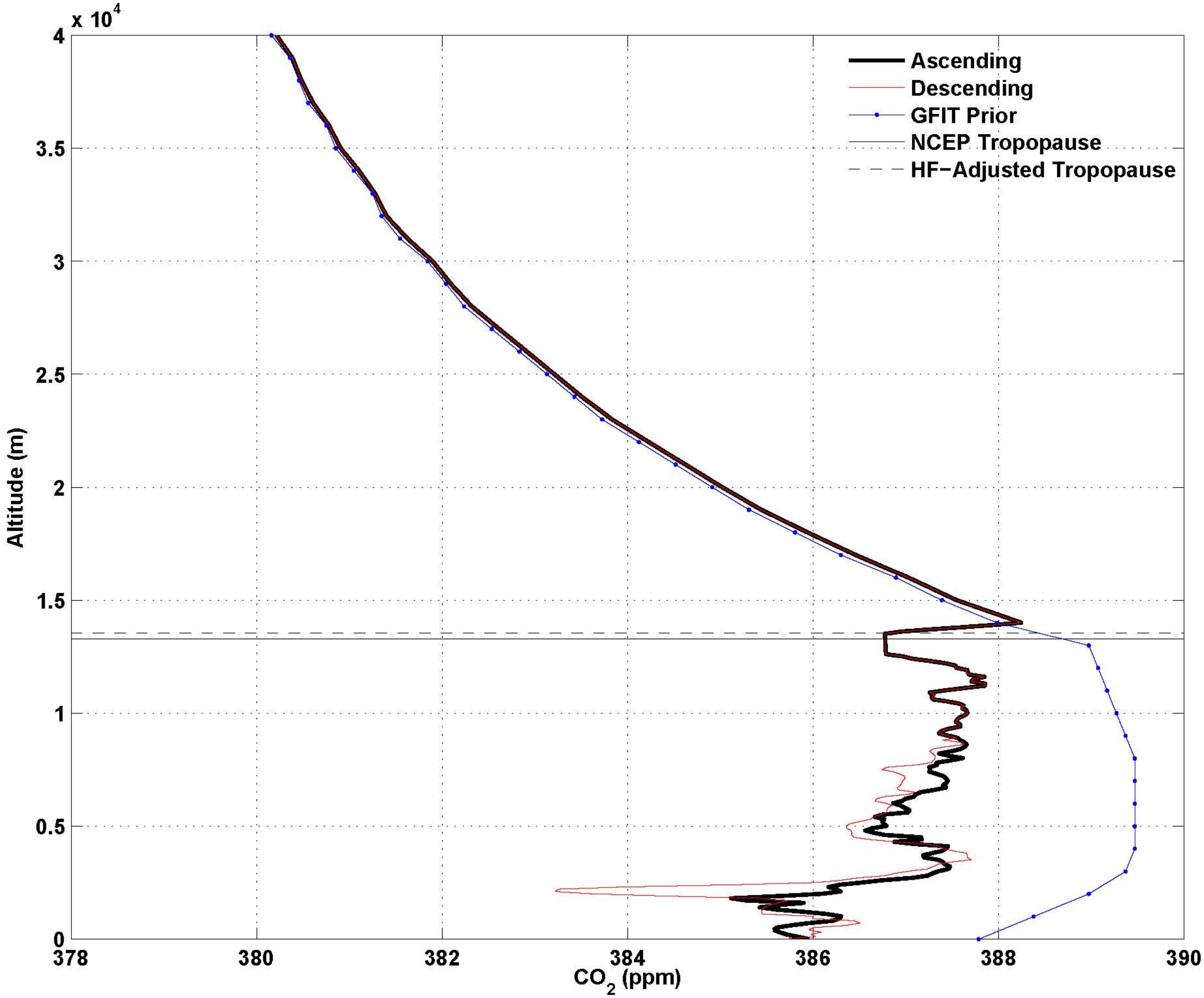
Flight	Instrument	Species	Precision, Accuracy	Notes
HIPPO	HAIS/Harvard Quantum Cascade Laser Spectrometer (QCLS)	CO_2	0.02 ppm, 0.1 ppm	1 s, 1σ precision; 1σ accuracy
		CH_4	0.5 ppb, 1 ppb	1 s, 1σ precision; 1σ accuracy
		CO	0.15 ppb, 3.5 ppb	1 s, 1σ precision; 1σ accuracy
		N_2O	0.09 ppb, 0.2 ppb	1 s, 1σ precision; 1σ accuracy
	Harvard OMS	CO_2	0.1 ppm, 0.1 ppm	1 s, 1σ precision; 1σ accuracy
	NCAR Airborne Oxygen (AO2) Li-840	CO_2	0.3 ppm, 0.1 ppm	10 s, 1σ precision; long-term (>1 min) 1σ accuracy
	NCAR Research Aviation Facility (RAF)	CO	2 ppb, $\pm$ 2 ppb + 5%	10 s, 1σ precision; 1σ accuracy
	HAIS/Princeton Vertical Cavity Surface Emitting Laser Hygrometer (VCSEL)	H_2O	<3%, 5%	1 s, 1σ precision
START-08/ pre-HIPPO	HAIS/Harvard Quantum Cascade Laser Spectrometer (QCLS)	CO_2	0.16 ppm, 0.16 ppm	10 s, 1σ precision; 1σ accuracy
		CH_4	4.5 ppb, 4.5 ppb	10 s, 1σ precision; 1σ accuracy
		CO	1.3 ppb, 3.5 ppb	10 s, 1σ precision; 1σ accuracy
		N_2O	0.7 ppb, 0.7 ppb	10 s, 1σ precision; 1σ accuracy
	NCAR Airborne Oxygen (AO2) Li-840	CO_2	0.3 ppm, 0.1 ppm	10 s, 1σ precision; long-term (>1 min) 1σ accuracy
	NCAR Research Aviation Facility (RAF)	CO	2 ppb, $\pm$ 2 ppb + 5%	10 s, 1σ precision; 1σ accuracy
	HAIS/Princeton Vertical Cavity Surface Emitting Laser Hygrometer (VCSEL)	H_2O	<3%, 5%	1 s, 1σ precision
	NOAA Unmanned Aircraft Systems Chromatograph for Atmospheric Trace Species (UCATS)	CH_4	13 ppb, <13 ppb	1σ precision and accuracy
		H_2O	5%,7%	1σ precision
Learjet	NOAA Flask Samplers	CO_2	0.03 ppm, 0.155 ppm	1σ for 12 flasks (~28 day) precision and accuracy
		CH_4	1.2 ppb, 1.06 ppb	1σ for 12 flasks (~28 day) precision and accuracy
		CO	0.3 ppb, 0.8 ppb	1σ for 12 flasks (~28 day) precision and accuracy
		N_2O	0.4 ppb, 0.3 ppb	1σ for 12 flasks (~28 day) precision and accuracy
Beechcraft King Air 200T	CO_2 Continuous Measurement Equipment (CME) Li-COR 840 non-dispersive infrared analyser	CO_2	0.2 ppm, 0.12 $\pm$ 0.02 ppm	10 s, 1.645σ (90%) precision; 1σ accuracy
	Hand-operated Flask Sampling Equipment (HSE)	CH_4	1.7 ppb, 4.1 $\pm$ 0.6 ppb	1σ precision and accuracy
COBRA-ME	Harvard OMS	CO_2	0.1 ppm, 0.1 ppm	1 s, 1σ precision; 1σ accuracy
	Harvard Aerolaser VUV	CO	2 ppb, $\pm$ 3 ppb + 3%	1 s, 1σ precision; 1σ accuracy
INTEX-NA	LI-COR 6252	CO_2	0.1 ppm, $\pm$0.25 ppm	1 s, 1σ precision; 1σ accuracy
	UCI Grab samples analyzed with GC and GC/MS	CH_4	$\pm$0.1%, 1%	1σ precision; 1σ accuracy
TWP-ICE	Harvard OMS	CO_2	0.1 ppm, 0.1 ppm	1 s, 1σ precision; 1σ accuracy


CO2 QCLS
CO2 AO2
CO2 OMS
Altitude (m)
CO2 (ppm)
0
2000
4000
6000
8000
10000
12000
14000
382
384
386
388
390
392
394
396
398
400
402

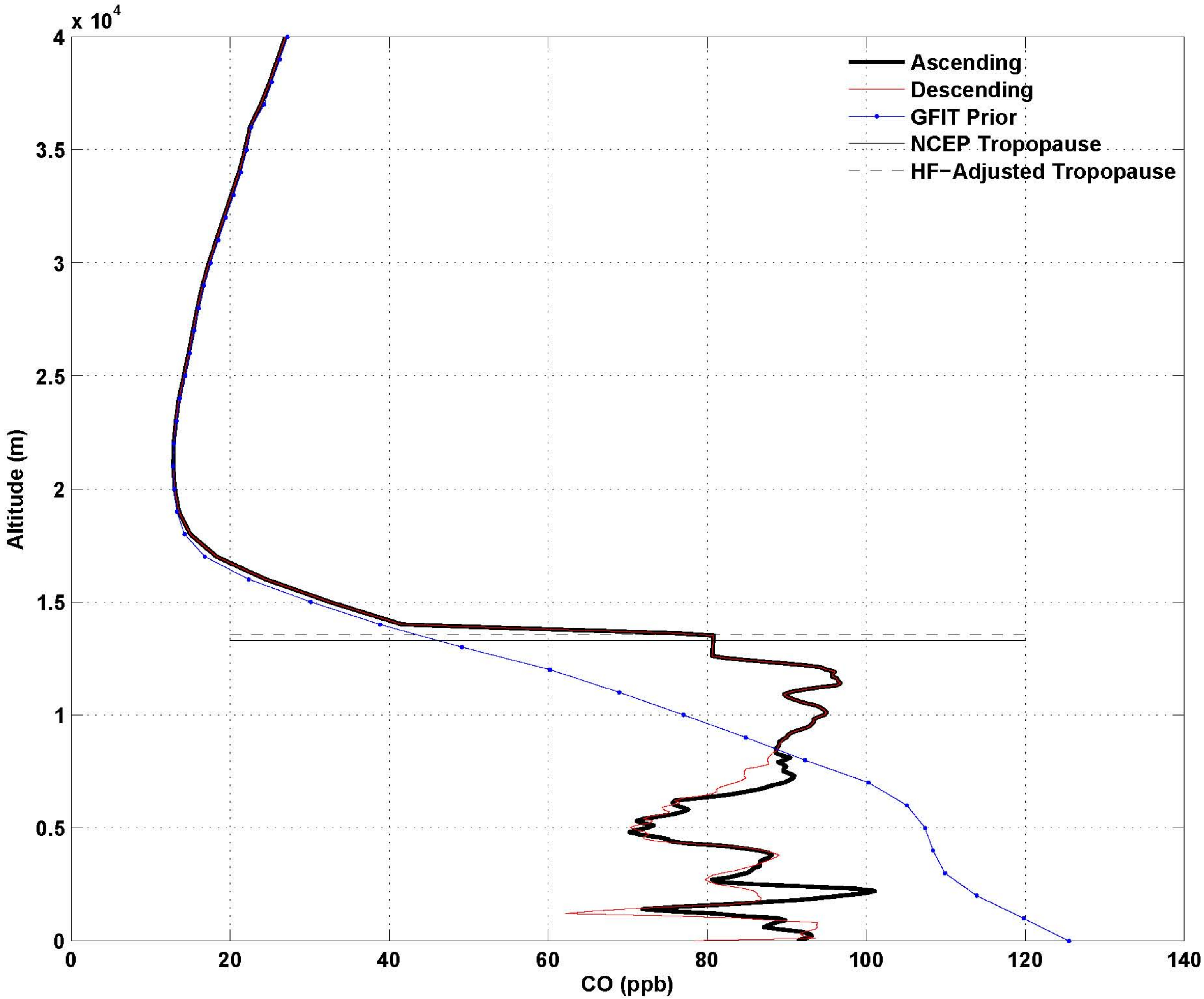


Decent
× 10⁴
3
2.5
2
1.5
1
0.5
0
Altitude (m)
382
383
384
385
386
387
388
389
390
CO2 (ppm)
QCLS
AO2
OMS
Smoothed Running Mean
A Priori Profile (0.99*1co2)
NCEP Tropopause
HF-Adjusted Tropopause

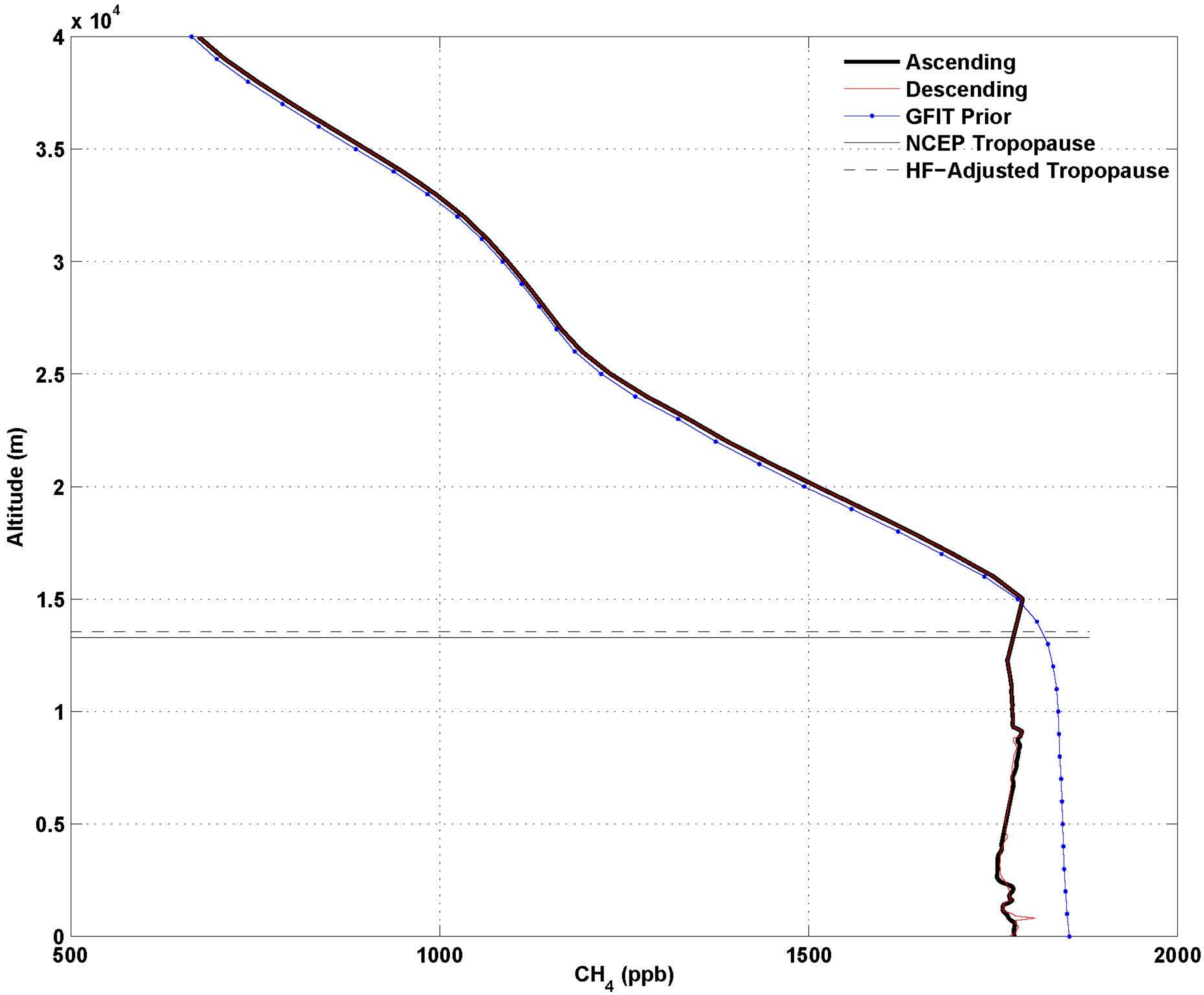

Ascent
× 10^4
3
2.5
2
1.5
1
0.5
0
Altitude (m)
382
383
384
385
386
387
388
389
390
CO2 (ppm)
QCLS
AO2
OMS
Smoothed Running Mean
A Priori Profile (0.99*1co2)
NCEP Tropopause
HF-Adjusted Tropopause



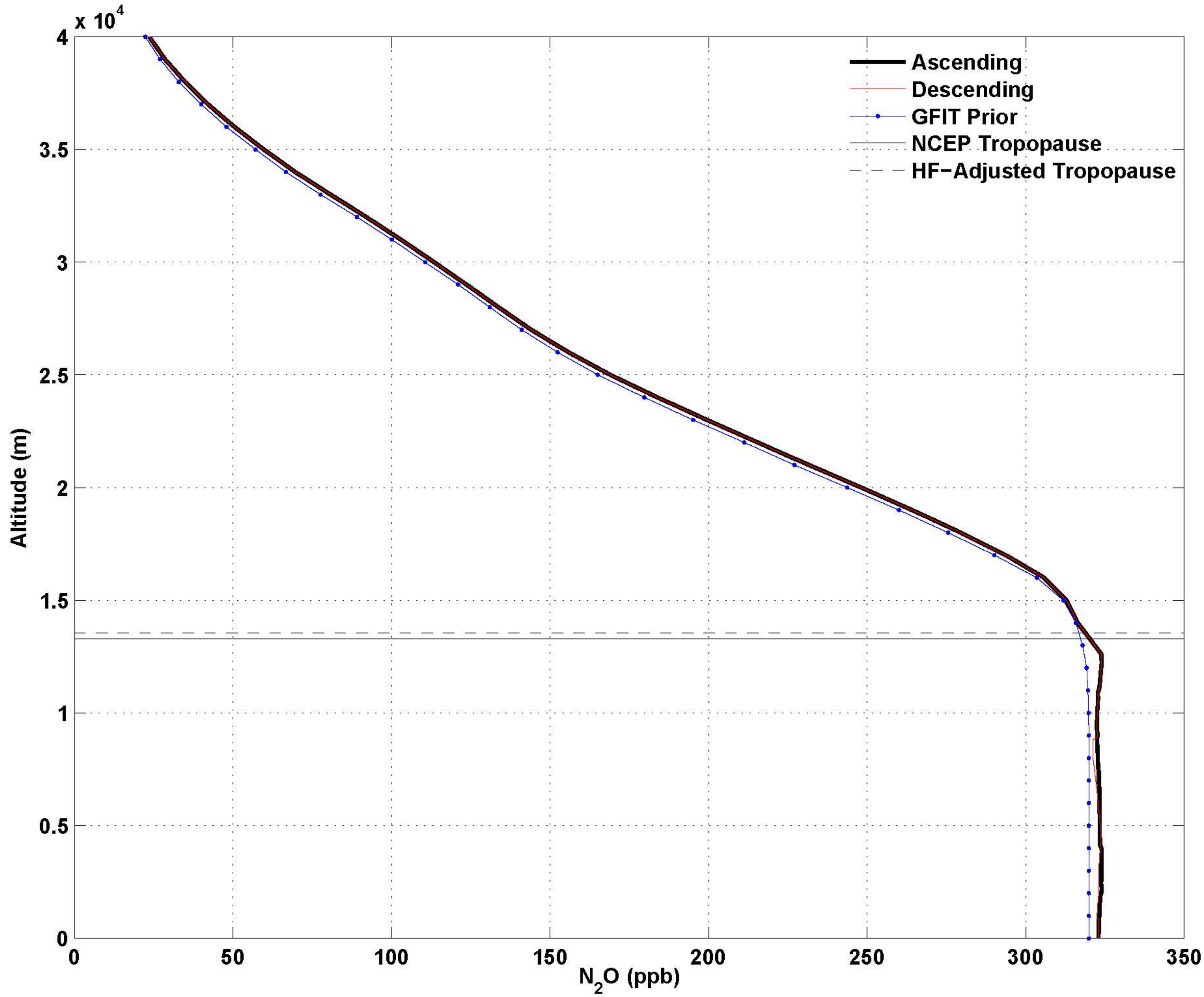
x 10^4
4
3.5
3
2.5
2
1.5
1
0.5
0
Altitude (m)
378
380
382
384
386
388
390
CO2 (ppm)
Ascending
Descending
GFIT Prior
NCEP Tropopause
HF−Adjusted Tropopause



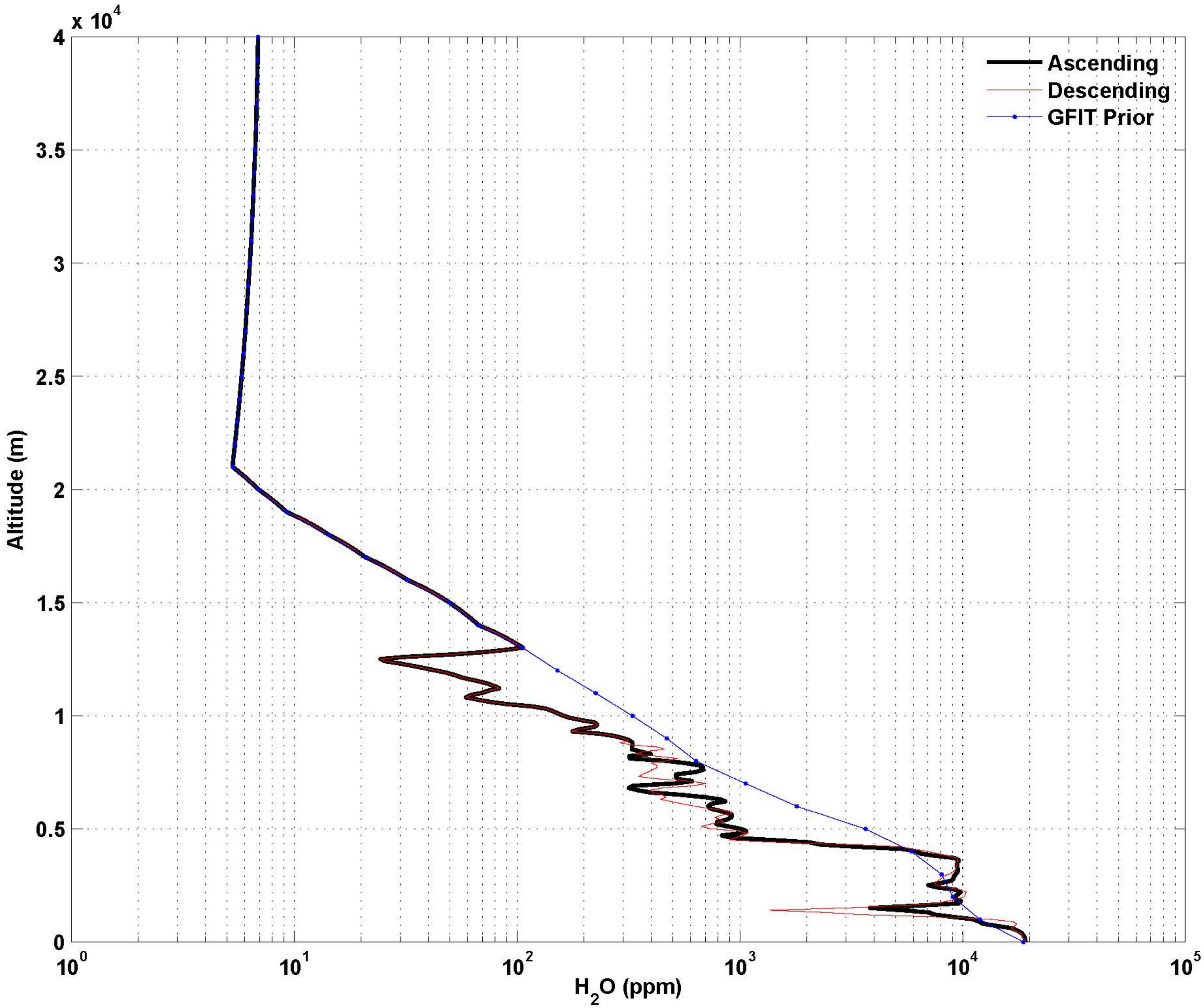
x 10^4
4
3.5
3
2.5
2
1.5
1
0.5
0
Altitude (m)
0
20
40
60
80
100
120
140
CO (ppb)
Ascending
Descending
GFIT Prior
NCEP Tropopause
HF−Adjusted Tropopause



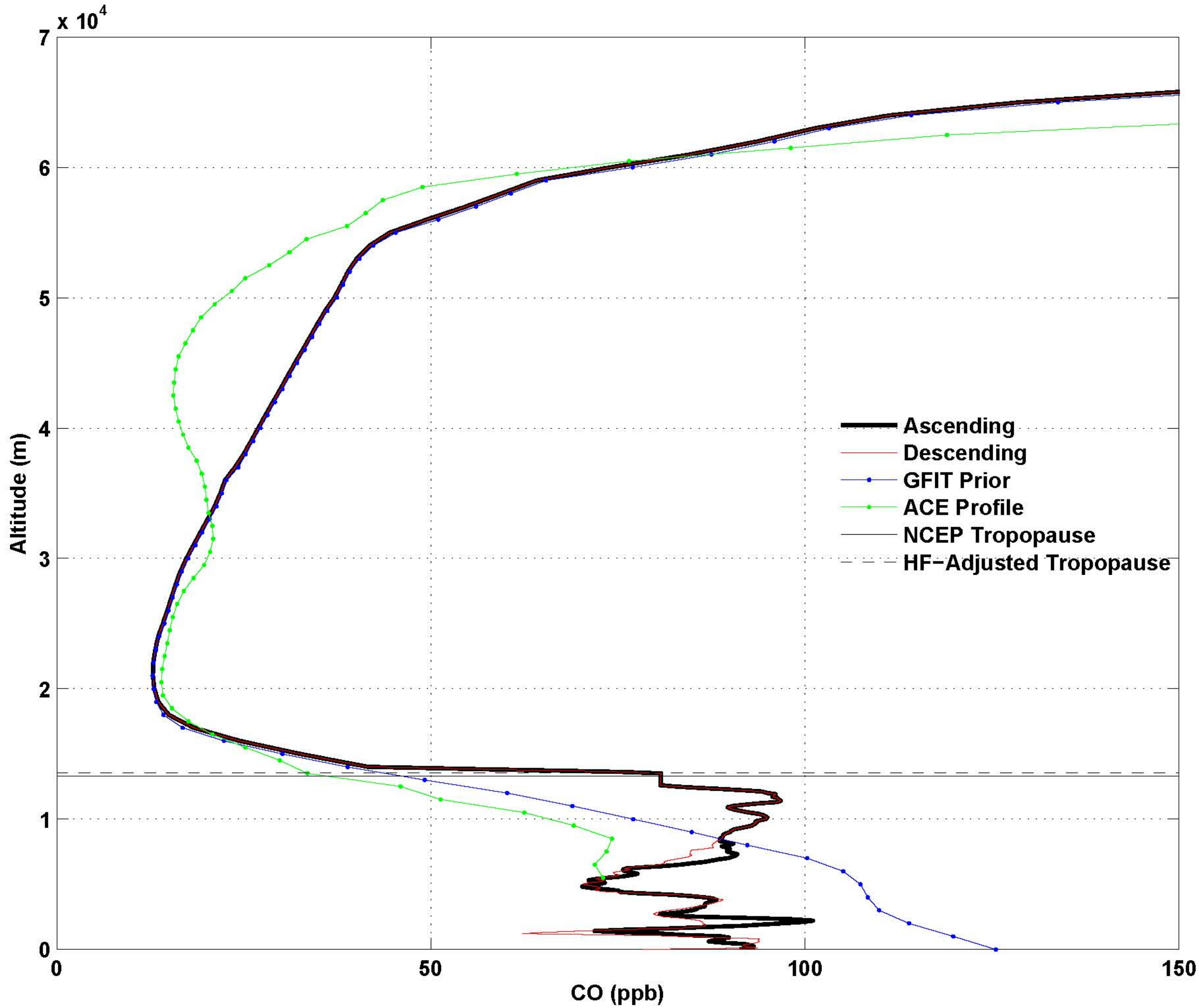
x 10^4
4
3.5
3
2.5
2
1.5
1
0.5
0
Altitude (m)
500
1000
1500
2000
CH4 (ppb)
Ascending
Descending
GFIT Prior
NCEP Tropopause
HF−Adjusted Tropopause



x 10^4
Altitude (m)
N2O (ppb)
Ascending
Descending
GFIT Prior
NCEP Tropopause
HF−Adjusted Tropopause
0
0.5
1
1.5
2
2.5
3
3.5
4
0
50
100
150
200
250
300
350



x 10^4
4
3.5
3
2.5
2
1.5
1
0.5
0
Altitude (m)
10^0
10^1
10^2
10^3
10^4
10^5
H2O (ppm)
Ascending
Descending
GFIT Prior


x 10^4
7
6
5
4
3
2
1
0
Altitude (m)
0
50
100
150
CO (ppb)
Ascending
Descending
GFIT Prior
ACE Profile
NCEP Tropopause
HF−Adjusted Tropopause

TCCON – Computing Dry-air Mole Fractions

- Divide trace gas columns by dry air column to get dry-air mole fractions: X_{CO_2}, X_{CH_4}, X_{N_2O}, X_{CO}
- Column-averaged dry-air mole fractions are useful for carbon-cycle science
  - Because they are a column measurement, they are less sensitive to vertical transport
  - Because they are a dry-air mole fraction, they are relatively insensitive to surface pressure or atmospheric water vapour variations
- Can compute the dry-air mole fraction using the measured O_2 column or the measured surface pressure
- Using O_2 has significant advantages
  - Errors that are common to the target gases (mis-pointing or zero-level offsets) will generally cancel in the division
  - There is no need for a water column correction
  - Produces a higher precision data product

$$\mathrm{Xco_2} = \frac{\mathrm{column}_{\mathrm{CO_2}}}{\mathrm{column\ dry\ air}}$$

$$\mathrm{column\ dry\ air} = \frac{\mathrm{column}_{\mathrm{O_2}}}{0.2095}$$

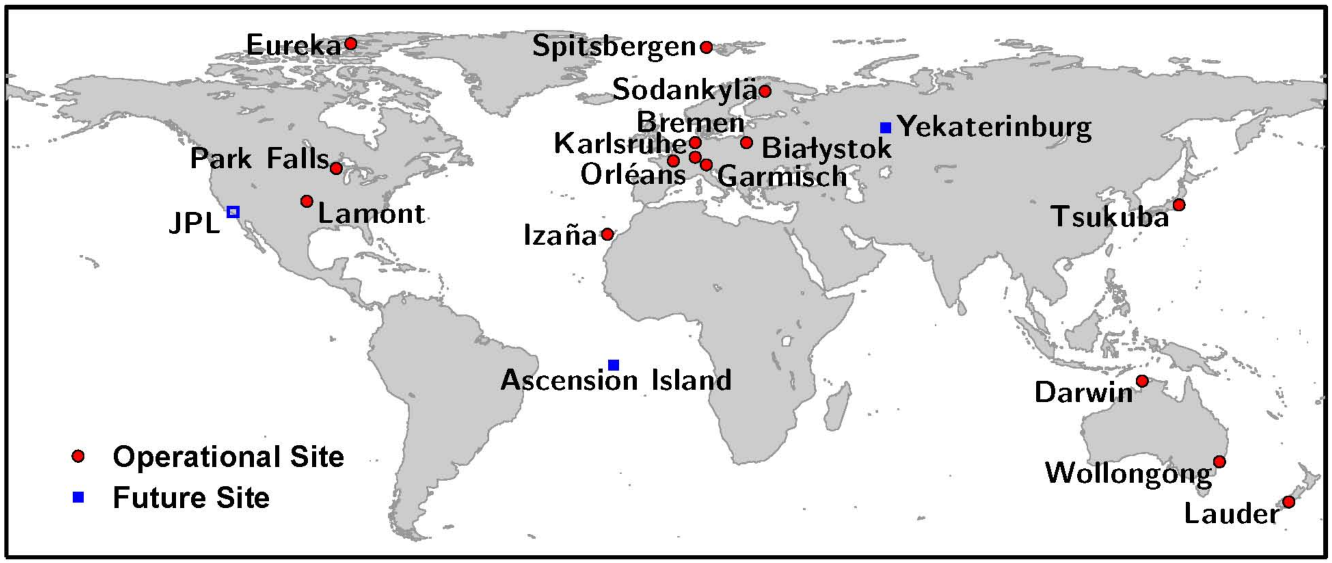
$$\mathrm{column\ dry\ air} =$$

$$\frac{\mathrm{P_s}}{\{g\}_{air}\, m_{air}^{dry}} - \mathrm{column}_{H_2O}\,\frac{m_{H_2O}}{m_{air}^{dry}}$$

$$\mathrm{Xco_2} = 0.2095\,\frac{\mathrm{column}_{\mathrm{CO_2}}}{\mathrm{column}_{\mathrm{O_2}}}$$

The Total Carbon Column Observing Network (TCCON)

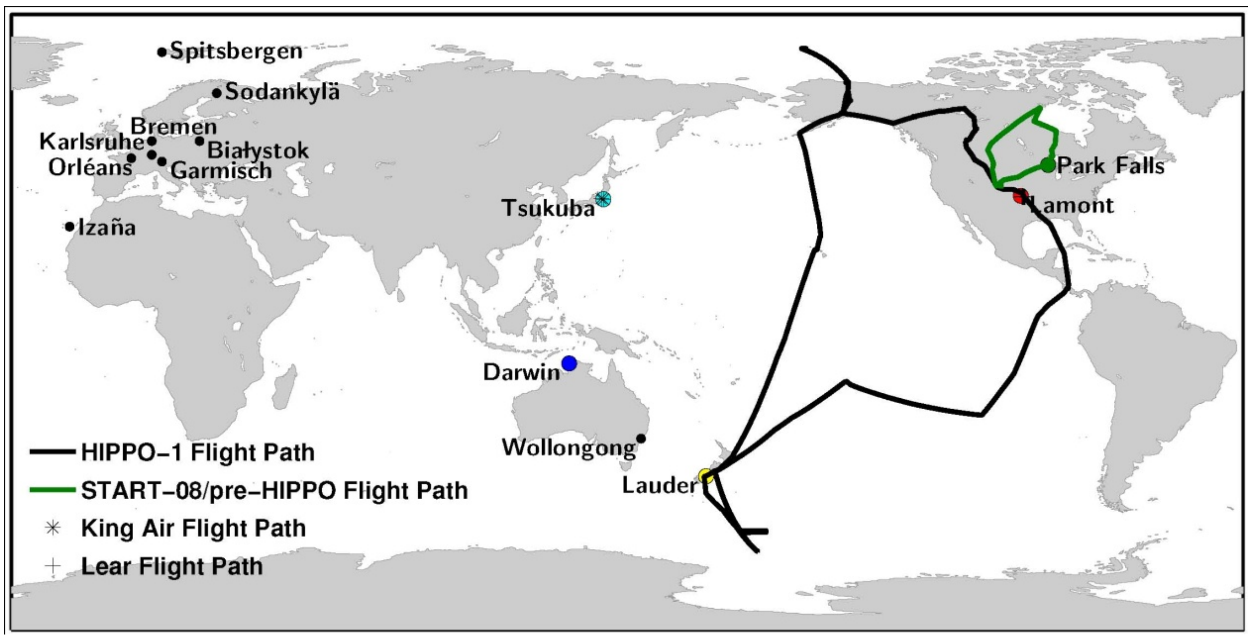
- Global network of ground-based instruments designed to measure the total column amounts of CO_2, CO, CH_4, N_2O and other gases



- To improve our understanding of the carbon cycle
- To provide a transfer standard between the satellite measurements and the ground-based in situ network
- To provide the primary validation dataset for retrievals of X_{CO_2} and X_{CH_4} from space-based instruments

Calibrating the TCCON to WMO Standards

- Cannot use “gas standard” to calibrate TCCON
- TCCON accuracy depends on spectroscopy and other external information about the atmosphere to retrieve total columns
- Unfortunately, current accuracy requirements to determine sources/sinks/fluxes are more stringent than current spectroscopy allows
- Fly in situ instruments tied to WMO scale on aircraft that perform ‘dips’ or spirals over TCCON sites



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- Slope:
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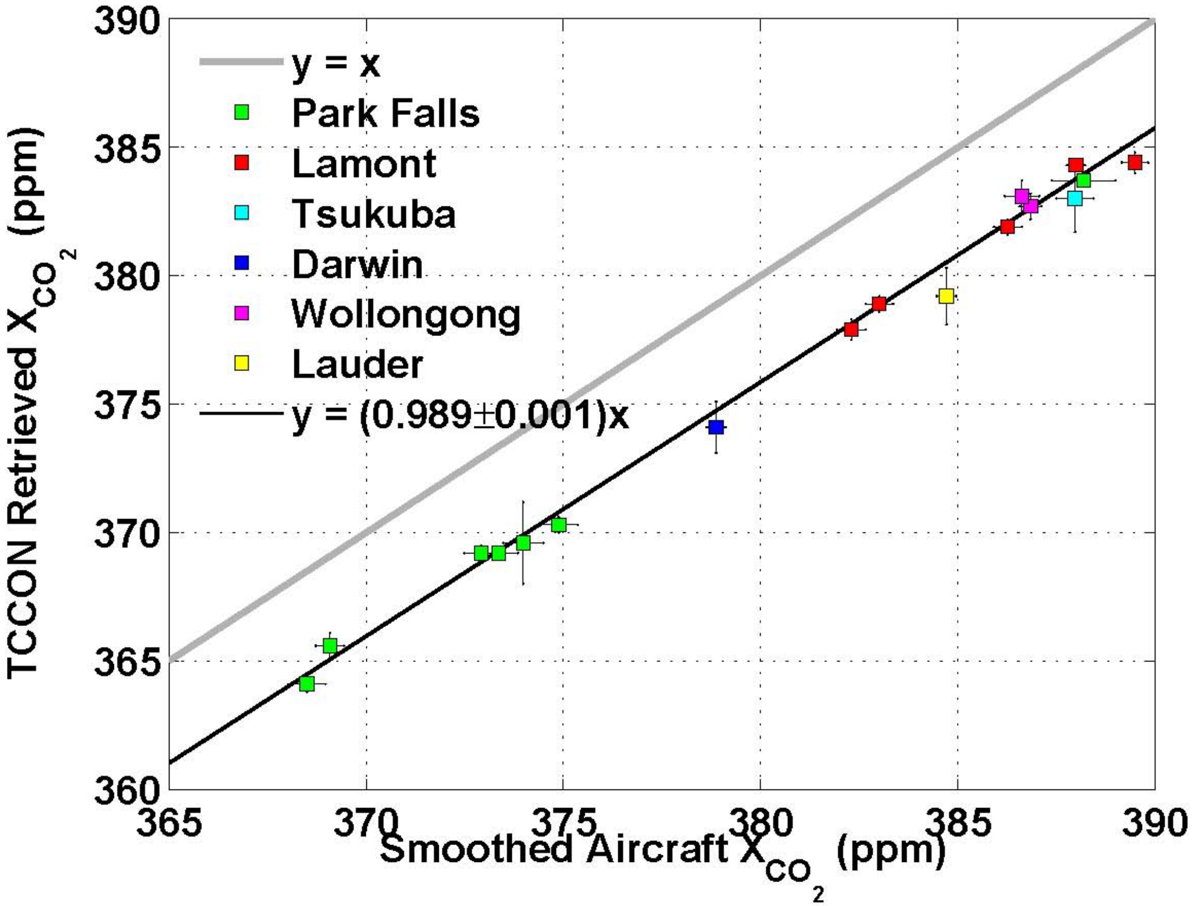
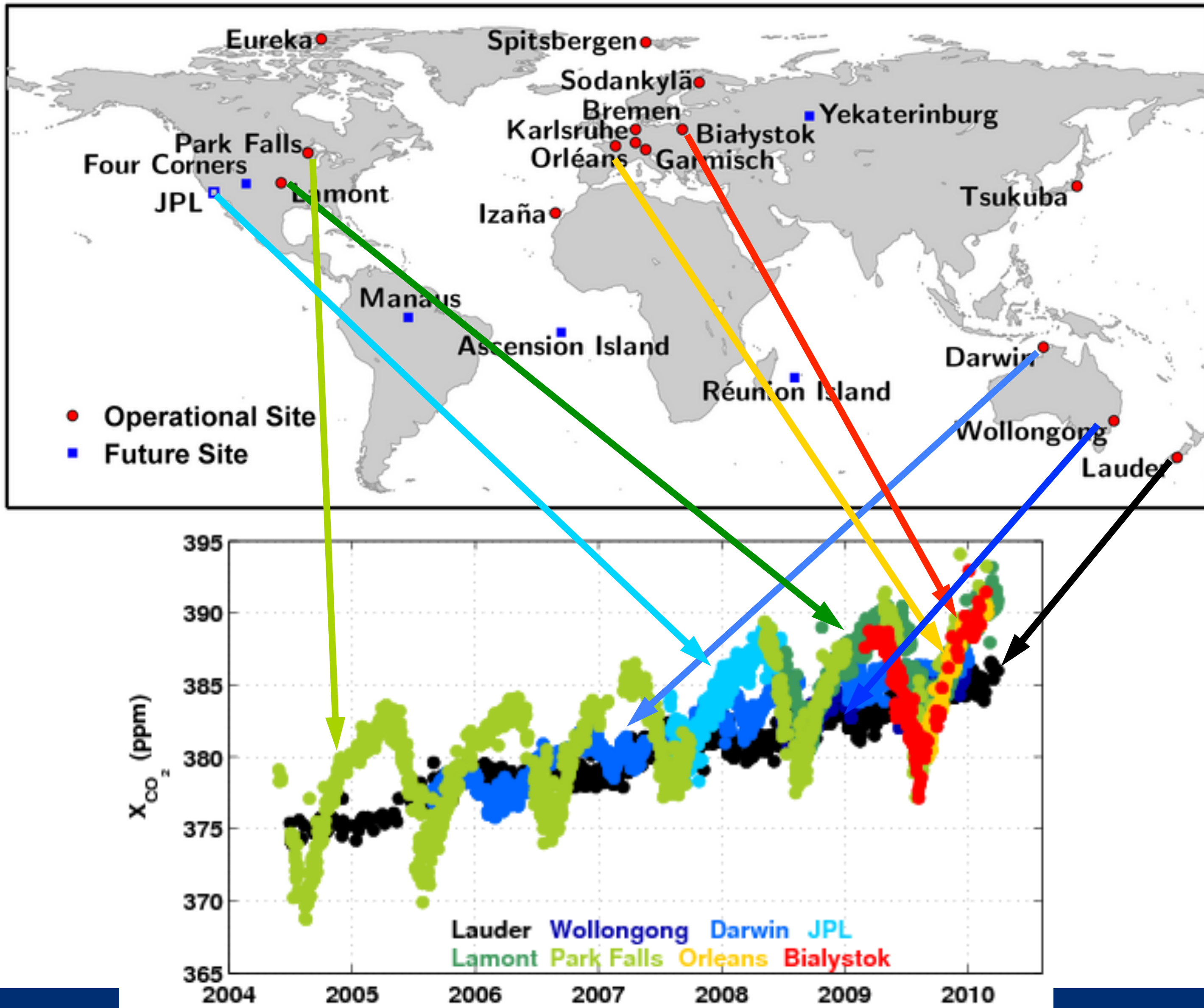
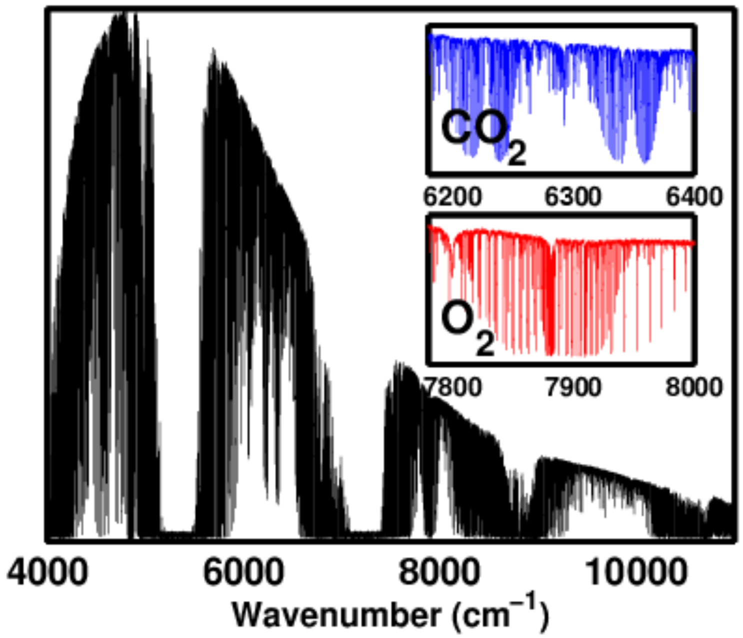


TCCON Measurements



TCCON Instrumentation and Analysis

- Main instrument: Bruker 125HR Fourier transform spectrometer
  - Measures ~0.02 cm^{-1} resolution
  - Solar absorption measurements
  - Covers 3900 – 15500 cm^{-1}
- Spectral fitting and data processing by the GFIT nonlinear least squares profile scaling algorithm
- Requires good knowledge of spectroscopic line strengths and widths
  - Only good to ~1% accuracy
  - Insufficient for carbon cycle flux estimate needs



- Requires good knowledge of the atmospheric state (T, P, Z, H_2O)
  - NCEP/NCAR analysis
- Requires good a priori knowledge of the shape of the profile of interest (i.e. CO_2, CO, CH_4, N_2O)
  - ACE-FTS, MkIV, GLOBALVIEW, Andrews et al. (2001) CO_2 stratosphere