# Airborne Continuous $CO_2$ in the US Southern Great Plains

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## ABSTRACT

We report on 10 years of airborne measurements of atmospheric $CO_2$ mole fraction from continuous and flask systems, collected between 2002 and 2012 over the Atmospheric Radiation Measurement Program Climate Research Facility in the US Southern Great Plains (SGP). These observations were designed to quantify trends and variability in atmospheric mole fraction of $CO_2$ and other greenhouse gases with the precision and accuracy needed to evaluate ground-based and satellite-based column $CO_2$ estimates, test forward and inverse models, and help with the interpretation of ground-based $CO_2$ mole fraction measurements. During flights, we measured $CO_2$ and meteorological data continuously and collected flasks for a rich suite of additional gases: $CO_2$, CO, $CH_4$, $N_2O$, $^{13}CO_2$, carbonyl sulfide (COS), and trace hydrocarbon species. These measurements were collected approximately twice per week by small aircraft (Cessna 172 first, then Cessna 206) on a series of horizontal legs ranging in altitude from 460 m to 5,500 m (AMSL). Since the beginning of the program, more than 400 continuous $CO_2$ vertical profiles have been collected (2007-2012), along with about 330 profiles from NOAA/ESRL 12-flask (2006-2012) and 284 from NOAA/ESRL 2-flask (2002-2006) packages for carbon cycle gases and isotopes. Averaged over the entire record, there were no systematic differences between the continuous and flask $CO_2$ observations when they were sampling the same air, i.e., over the one-minute flask-sampling time. Using multiple technologies (a flask sampler and two continuous analyzers), we documented a mean difference of <0.2 ppm between instruments. However, flask data were not equivalent in all regards; horizontal variability in $CO_2$ mole fraction within the 5-10 minute legs sometimes resulted in significant differences between flask and continuous measurement values for those legs, and the information contained in fine-scale variability about atmospheric transport was not captured by flask-based observations. The $CO_2$ mole fraction trend at 3000 m (AMSL) was 1.91 ppm $y^{-1}$ between 2008 and 2010, very close to the concurrent trend at Mauna Loa of 1.95 ppm $y^{-1}$. The seasonal amplitude of $CO_2$ mole fraction in the free troposphere (FT) was half that in the planetary boundary layer (PBL) (~15 ppm vs. ~30 ppm) and twice that at Mauna Loa (approximately 8 ppm). The $CO_2$ horizontal variability was up to 10 ppm in the PBL and less than 1 ppm at the top of the vertical profiles in the FT.

## INSTRUMENT DESCRIPTION & FLIGHT MISSION

The first continuous analyzer (RM0) was installed on the aircraft (Figure 1) in June 2007 and the second analyzer (RM12) was installed in March 2011.

The typical flight pattern consists of 12 level legs at standard altitudes from 5,500 m to 300 m. Level legs are 5 minutes and 10 minutes long above and below 2,000 m respectively. (Figure 2a) and are oriented perpendicular to wind direction in order to minimize engine contamination (Figure 2b). The end-points of the legs are curved in a daisy pattern. Total flight time is ~3 hours. Note that flight days are biased towards cloud-free conditions.

**Figure 1**. Cessna 206, taking off from Ponca City airport, 20 miles northwest of ACRF 60 m tower.

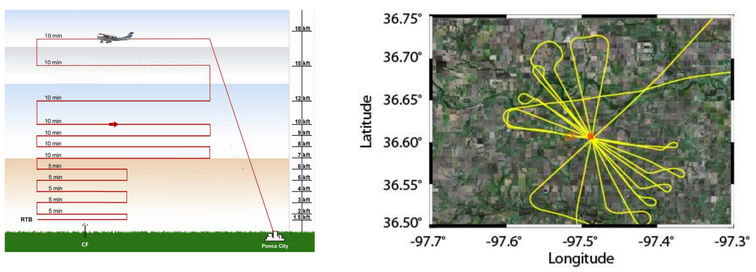


**Figure 2**. Vertical flight pattern and horizontal flight path over the ACRF 60m Tower (July 12, 2010).

Each analyzer (Figure 3) has non-imaging optics and negligible sensitivity to motion of platform. The NDIR analyzer has a functional frequency response of 8 Hz. It operates differentially with a pair of identical optical benches. Radiation is collimated by non-imaging optics from the light source and then through the measurement cell containing the sample gas. Light is transmitted through the measurement cell and concentrated onto the photo-detector. A pair of identical radiation filters, fore and aft of the measurement cell, isolates radiation to the targeted molecular band centered at 4.26 µm. Attenuation of the transmitted radiation serves as the needed measure of $CO_2$ Dry Mole Fraction. Accuracy, including bias, is approximately 0.1 ppm at 1 Hz (Figure 5).

**Figure 3**. Continuous $CO_2$ (RM0 and RM12) and $O_3$ analyzers.

**Figure 4**. Compressor and 12-flask packages (built by High Precision Devices, Inc.)

A 12-flask package (Figure 4) was installed on the aircraft in March 2006 in collaboration with NOAA-ESRL. This package provides a rich suite of additional trace gases observations including $CO_2$, CO, $CH_4$, $N_2O$, $^{13}CO_2$, $^{14}CO_2$, carbonyl sulfide (COS), and many trace hydrocarbon species. This package is also used to cross-validate our continuous $CO_2$ observations (Figure 6).

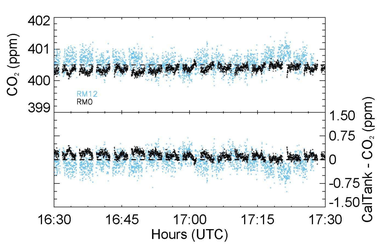


**Figure 5**. Instrument accuracy and precision from a known tank connected to the RM0 & RM12 instruments inlet.

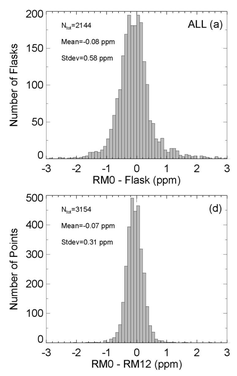


**Figure 6**. Comparison of (a) flask-based and continuous measurements, and (b) continuous measurements from two analyzers (RM0 and RM12). This graph shows no systematic bias.

The addition of RM12 analyzer allows a validation of observations collected on the aircraft using multiple technologies. An example of the agreement between the two continuous systems and the flask package is shown on Figure 7. The difference between the two analyzers is -0.06 ppm.

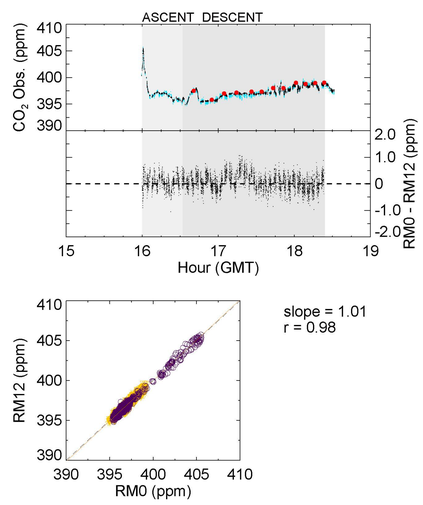


**Figure 7**. Validation of $CO_2$ concentrations collected on April 28, 2011.

Figure 7 gives an example of observations collected using all three systems (RM0, RM12, and PFP) during an April 28, 2011 flight. The mean and standard deviation of the difference between RM0 and RM12 was 0.06 ppm and 0.3 ppm, respectively. Noise in the difference between observations from the pair of analyzers should equal the square root of the sum of the square of the accuracy of each analyzer. For thirty-seven flights between March 16, 2011 and July 30, 2011, comparisons made in the same manner gave a mean RM0–RM12 difference of -0.08 ppm and a standard deviation of the difference of 0.31 ppm.

The standard deviation of the difference was largely controlled by the electro-optical noise of RM12

## OBSERVATIONS

Figure 8 shows four years of $CO_2$ vertical profiles. Lower concentrations are observed during the growing season and large vertical gradients in the winter. Combining these observations with our surface NEE estimates (Riley et al. 2009) on diurnal, synoptic, and seasonal time scales will facilitate improvement of regional (e.g., WRF-STILT) and global (i.e., CarbonTracker) atmospheric inversion estimates of surface C and energy exchanges.

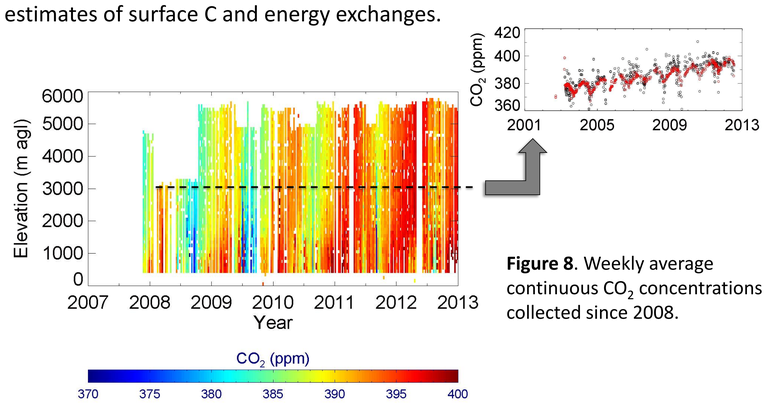


**Figure 8**. Weekly average continuous $CO_2$ concentrations collected since 2008.

Figure 9 shows a climatology of all vertical profiles collected between 2007 and 2010, shown as an anomaly relative to mole fraction at Mauna Loa (Mauna data not yet available in 2011). $CO_2$ observations at the Mauna Loa observatory have been interpolated on a weekly basis to normalize flight profiles. $CO_2$ observations are binned into 100m altitude pixel and weekly flight profiles. Each quadrant of the graph corresponds to a 3-month average climatological vertical profile (JFM: January-February-March, ...). The solid black line shows the mean vertical profile calculated across each 3-month average, and the yellow shaded area shows one standard deviation around the average value.

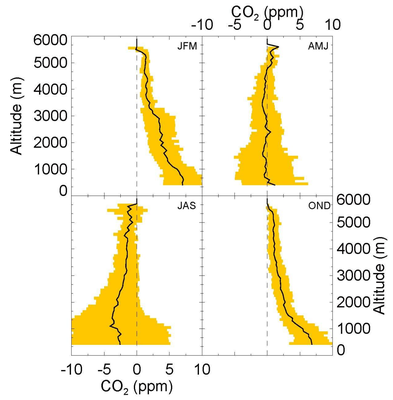


**Figure 9.** Climatology of all vertical profiles collected between 2007 and 2010

## CONCLUSIONS

- Ten years of atmospheric $CO_2$ profiles presented here show the strong influence of land surface fluxes on PBL-FT gradients and how they vary seasonally, and the continental influence on the amplitude of seasonal variability in mole fraction.
- The secular increase in FT atmospheric $CO_2$ mole fraction at SGP was consistent with the trend at Mauna Loa of 1.95 ppm $y^{-1}$.
- There was substantial variability in $CO_2$ mole fraction over the 5-10 minute horizontal legs, generally largest within the PBL and smaller in the FT. A better understanding of the source of this fine-scale variability would give insight into controls on vertical transport mechanisms for atmospheric $CO_2$ and improve atmospheric inversions.
- To test whether comparability goals have been met, for example the WMO/GAW target of ≤0.1 ppm, we recommend that multiple technologies be deployed on each airborne platform.

## REFERENCE

Biraud S.C. , M.S. Torn, J.R. Smith, C. Sweeney, W.J. Riley, and P. P. Tans. A Multi-Year Record of Airborne CO2 observations in the U.S. Southern Great Plains. Atmos. Meas. Tech., 6, 751–763, doi:10.5194/amt-6-751-2013., 2013.

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