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Atmospheric Measurement Techniques Discussions

A comparison of in-situ aircraft measurements of carbon dioxide to GOSAT data measured over Railroad Valley playa, Nevada, USA

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Abstract

In this paper we report vertical profiles of CO_2 measured with a cavity ring-down spectrometer (CRDS, Picarro, Inc., 2301-m) on a research aircraft from near ground level to 8 km above mean sea level (a.m.s.l.). The airborne platform employed in this study is an Alpha Jet aircraft operated from NASA Ames Research Center. Flights were undertaken to Railroad Valley, Nevada, USA, to coincide with overpasses of the Greenhouse Gases Observing Satellite (GOSAT). Ground based CO_2 was simultaneously measured using CRDS, also at the time and location of the airborne and satellite measurements. Results of three GOSAT coordinated aircraft profiles and ground based measurements in June 2011 are presented and discussed in this paper. The accuracy of the CO_2 measurements has been determined based upon laboratory calibrations (WMO traceable standard) and pressure/temperature flight simulations in a test chamber. The 2-σ error bars for the CO_2 data presented here are ± 0.4 ppm. Our column CO_2 measurements, which include about 85 % of the tropospheric mass, are extrapolated, using two different techniques, to include the remainder of the tropospheric and stratospheric CO_2. The data are then analyzed using the ACOS (Atmospheric CO_2 observations from space; JPL algorithm used to analyze XCO_2 from GOSAT data) averaging kernels. ACOS version 2.9 is used to interpret the GOSAT data in a collaborative effort between JPL and the GOSAT team. Column averaged CO_2, XCO_2, measured by GOSAT and analyzed from our data ranged from 388.1 to 390.5 ppm. Values of XCO_2 determined from our Alpha Jet measurements and from the GOSAT on three overflight days agree within 1 ppm or better (< 0.3 %).

1 Introduction

Global increases of the two strongest long-lived anthropogenic greenhouse gases carbon dioxide, CO_2, and methane, CH_4, have been well documented (IPCC, 2007; NOAA, 2012). Recently, satellite programs have been developed to measure global

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distributions on continental and smaller scales, enabling the inversion of CO_2 and CH_4 fluxes (Nassar et al., 2011; Bargamaschi et al., 2009). GOSAT (Greenhouse Gases Observing Satellite), is currently monitoring column average mole fractions of CO_2 and CH_4 (Hamazaki et al., 2005); and OCO-2, replacing the original OCO (Orbiting Carbon Observatory) launched by NASA which failed to reach orbit, will soon be launched. For flux inversions, measurement accuracy and potential geospatial biases have to be properly characterized (Miller et al., 2007; Tanaka et al., 2012). Validation of satellite measurements of column CO_2 and other gases is thus very important and is now being carried out using both aircraft profiles and ground based spectrometers (Tanaka et al., 2012; Deutscher et al., 2010; Clerbaux et al., 2008; Morino et al., 2011).

Airborne profiles of CO_2 have previously been carried out on the NASA DC-8 (Vay et al., 1999) and by others (Chen et al., 2010). Measurements reported here are among the first ones to be specifically focused on validating the orbital satellite measurements of XCO_2 being made from space by GOSAT.

We report in this paper vertical, in-situ atmospheric profile measurements of CO_2 and CH_4 made with a wavelength scanned, cavity ring-down spectrometer (CRDS) on an airborne platform. CRDS is a highly sensitive and rapid method for the measurement of CO_2 and CH_4 (Chen et al., 2010). Measurements were made on board an Alpha Jet aircraft on three flights over Railroad Valley (RRV) playa, in Nevada, USA as part of a "vicarious calibration" campaign for the GOSAT satellite in late June of 2011 to coincide with the summer equinox (Kuze et al., 2011).

The RRV campaign was planned and operated by the Jet Propulsion Laboratory (JPL) and the Japan Aerospace Exploration Agency (JAXA) and brought together a number of measurements used to calibrate and validate the results acquired from the GOSAT satellite. The RRV campaign team included members from JPL, JAXA, NIES (the National Institute for Environmental Studies), NASA Ames Research Center, Colorado State University and University of Wisconsin.

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2 Experimental

Airborne and satellite atmospheric measurements of CO_2 were taken above a dry lakebed at Railroad Valley (RRV), Nevada, USA (38°30.234′ N, 115°41.604′ W, elevation 1437 m) on 23, 25 and 26 June 2011. The playa is a flat, high altitude desert site which makes up part of the Great Basin desert of the United States; except for several small oil fields, RRV is an area where local sources and sinks of carbon-species are expected to be minimal. The playa has virtually no vegetation, an overall size of 15 km × 15 km and is approximately 110 km south-west of the nearest city, Ely (elevation: 1962 m, inhabitants: 4000); the location and characteristics of the RRV site are such that it provides an estimate of well-mixed continental air. RRV playa is a radiometrically flat region and has been used to calibrate various satellite radiometers before (Thome, 2001; Tonooka et al., 2005; Kuze et al., 2011).

2.1 Airborne instrument

Cavity ring-down spectroscopy (CRDS) is a technique that has been widely described in the literature (Wheeler et al., 1998; Zalicki and Zare, 1995; Busch and Busch, 1999). For the data presented here we employed a commercial instrument made by Picarro, Inc. (Santa Clara, CA; model 2301-m), a modified airborne version of the basic Picarro CRDS instrument (Crosson, 2008). A pulsed, near infrared laser beam enters an optical cell with highly reflective mirrors. The beam that exits the opposite end of the cell is detected and carries the ring-down signature whose exponential decay time contains information on the absorption of the atmospheric gas flowing through it. CO_2 and CH_4 concentrations are derived from their absorption at selected spectral lines. Simultaneous H_2O measurements are used to correct these concentrations to dry mole fractions.

The Picarro CRDS instrument we used on the Alpha Jet platform has been physically reconfigured to fit the wing-mounted, instrument-pod space on the aircraft. The original instrument case was repacked into two separate boxes, one with electronic

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components and computer parts ("electronic box") and the other one with the cell, valves and other specific components ("analyzer box"). The original thermal management was altered by introduction of the two additional fans for the improved circulation of air in the analyzer box, and by adding an additional insulation blanket. The additional 0.5 micron pore size filter was placed between the inlet and instrument. The instrument cell itself was left intact. In this way a unique instrument was created, placed outside the cabin of the aircraft in the pod and more exposed to environmental conditions (unpressurized environment). The instrument is powered prior to a flight and reaches its operating equilibrium temperature before data taking commences, usually very early in the flight. The in-flight measurements of CO_2, CH_4 and H_2O are continuously logged. The vertical trajectories of the flights are shown in Fig. 2.

CRDS instrument calibration

The Picarro CRDS instrument has been calibrated frequently in our lab employing a NOAA ESRL whole-air standard (416.267 ± 0.07 ppm CO_2, 1985.69 ± 0.3 ppb CH_4). Instrument precision was calculated from the average 1-σ standard deviation during 6 min of the whole-air standard sampling and was better than 0.13 ppm for CO_2 and 1.84 ppb for CH_4. Accuracy was calculated from the offset measured between the (theoretical) NOAA standard and (measured) instrument concentrations of CO_2 and CH_4 and was limited by the accuracy of primary standard. Instrument linearity was assessed using three synthetic standards (Scott Marrin, Inc.) of varying CO_2 and CH_4 concentrations (high: 420 ppm CO_2 and 1.997 ppm CH_4, medium: 396 ppm CO_2 and 1.879 ppm CH_4, low: 328 ppm CO_2 and 1.821 ppm CH_4, all standards are ±1 % NIST).

Instrument calibrations are usually (except in the case of consecutive flights) done before and after each flight to document instrument accuracy and drift. Raw data has been post-processed to correct for the drift and instrument accuracy. Drift was calculated based on applying least-squares linear fit to the measured standard values and was below 0.07 ppm day^{-1} for CO_2 and 0.10 ppb day^{-1} for CH_4. Data was post-corrected for accuracy by multiplying the raw data by the (theoretical/measured) offset.

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Calibration tests were performed in a pressure and temperature controlled environmental chamber using the Scott-Marrin standard gas (420 ppm CO_2 and 1.997 ppm CH_4 ± 1 % NIST) as a source and simulated flight conditions over the pressure range 240–760 Torr, and temperature range 5–20 °C; a typical temperature range observed in the wing-mounted instrument pods during flight. The ascending/descending speeds were selected to be ∼ 300 m min^{-1} with maximum at ∼ 600 m min^{-1} in a few cases. The instrument proved to be robust and its basic data and statistical parameter results did not differ under chamber tests compared to tests at constant pressure and temperature in laboratory calibrations (Table 1 and Fig. 3).

Currently the Picarro instrument is limited to a flight altitude of 9000 m (p = 310 hPa). This altitude limit conforms approximately to the minimum pressure at which Picarro certifies the instrument for operation. The limitation is imposed by the necessity to maintain pressure difference of at least 100 Torr between the ambient pressure and cavity pressure (140 Torr). During the campaign the altitude was limited to 8500 m for the protection of the instrument.

2.2 The Alpha Jet platform

The Alpha Jet, a tactical fighter developed by Dassault-Breguet and Dornier through a German-French NATO collaboration, is owned and operated by H211, LLC, and based at NASA Ames Research Center under a NASA Space Act Agreement. It has a wingspan of 9.1 m, a ceiling of 15.5 km, speed of 76–280 ms^{-1}, a maximum range of 2000 km, and seats for one pilot and one payload operator. Each of two experiment carrying wing pods has an approximate available volume of 0.10 m^3 with a maximum payload weight of 136 kg. The aircraft carries GPS and inertial navigation systems that provide altitude, temperature and position information time stamped with universal time for each research flight.

2.3 GOSAT satellite

2.3.1 Overview

The Greenhouse Gases Observing Satellite (GOSAT) monitors column averaged atmospheric carbon dioxide (XCO_2) and methane (XCH_4) (Kuze et al., 2009).

The Thermal and Near Infrared Sensor for Carbon Observation-Fourier Transform Spectrometer (TANSO-FTS) detects gas absorption spectra of the solar short wave infrared radiation (SWIR) reflected from the Earth's surface and atmosphere, as well as of the thermal infrared radiated from the ground and the atmosphere. TANSO-FTS is capable of detecting three SWIR bands centered at: 0.76, 1.6, and 2.0 µm, as well as a thermal band covering 5.5–14.3 µm with 0.26 cm^{-1} spectral resolution. The TANSO-FTS instantaneous field of view is 15.8 mrad corresponding to a circular nadir footprint of about 10.5 km diameter at sea level. The nominal single-scan data acquisition time is 4 s.

The TANSO Cloud and Aerosol Imager (TANSO-CAI) is an ultraviolet, visible, near infrared, and SWIR radiometer. TANSO-CAI retrieves atmospheric cloud characteristics and aerosol amounts. This information is meant to reject cloudy scenes and to correct for the influence of aerosols on the retrieved XCO_2 and XCH_4 (for the operational GOSAT data-products, information not used in ACOS retrievals O'Dell et al., 2012; Crisp et al., 2012).

GOSAT was launched on 23 January 2009 and was placed in a polar, sun-synchronous orbit at 666 km altitude with an equator crossing at approximately 13:00 LT (local time). The satellite returns to observe the same point on Earth every three days.

2.3.2 Products retrieved from TANSO-FTS

The analysis of the TANSO-FTS spectra is described in detail by Yoshida et al. (2011). From all spectra observed by TANSO-FTS, only those measured without cloud interference are selected for further processing. Briefly, absorption spectra in the three SWIR

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bands are used to retrieve XCO_2 and XCH_4 column abundances. Retrieval uncertainties of the column averages are quoted as 2 ppm for XCO_2 and 8 ppb for XCH_4, or close to 0.5 % for each molecule (Yoshida et al., 2011). Other groups have also independently retrieved XCO_2 and XCH_4 from GOSAT data (Butz et al., 2011; Parker et al., 2011). In this work, we use the ACOS v2.9 XCO_2 data-product retrieved from the Atmospheric Carbon Observation from Space (ACOS) project using GOSAT. The algorithm initially designed for the OCO mission has been applied to GOSAT data. The algorithms as well as latest results are extensively described in O'Dell et al. (2012) and Crisp et al. (2012), respectively. Variations of atmospheric CO_2 are largest near the Earth's surface.

3 Data analysis/results

Vertical profiles of CO_2 measured on the Alpha Jet platform with CRDS on 23, 25 and 26 June, as described above, currently extend to an upper altitude limit of ~8500 m. These profiles are shown in Fig. 5. The precision (given as 1-σ over 6 min periods), calibrated accuracy and empirically determined drift and repeatability of these measurements are shown in Table 1. The total flight time is approximately 2 h, with actual profile measurements over RRV lasting up to 25 min, which introduced maximal uncertainty due to the drift of 0.14 ppm.

In order to compare aircraft results with GOSAT, a column averaged mixing ratio has to be reconstructed from the profile measurements. As measurements were only taken up to about 8500 m altitudes, measured vertical profiles must be extrapolated up to the tropopause and into the stratosphere. Extrapolation to the ground level is less crucial: Alpha Jet data were acquired to within a few tens meters of the ground. Elevation of the RRV playa is 1437 m, and minimal altitudes for the three days ranged from 1452 to 1591 m (Table 2), with uncertainty in GPS altitude measurements of 20–40 m. A Picarro (model 1301) CRDS instrument was deployed at the RRV site and the ground data taken simultaneously with GOSAT overpasses is plotted as a ground level

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point in Fig. 5 and given as ~20 min averages (the duration of the flight in the spiral). Agreement of ground data with the lowest altitude CRDS measurements indicates that no extrapolation is required at the lowest altitudes.

3.1 Calculation of XCO_2 estimates from aircraft profiles

3.1.1 Extrapolation of aircraft profiles

Above 330 hPa, the aircraft CO_2 profiles have to be extrapolated. Given a surface pressure at RRV of 850 hPa, about 15 % of the atmospheric mass constituting XCO_2 resides above the 330 hPa level. We pursued two simple but very different extrapolation techniques in order compute XCO_2 and obtain a first order estimate of the uncertainty induced by the extrapolation. The first approach (method 1, AJAX 1) simply extrapolated the CO_2 profile linearly between the highest aircraft measurement to the 1 hPa level, fixed at the ACOS CO_2 a priori concentration. The second approach (method 2, AJAX 2) assumed a 140 hPa tropopause height (estimated from coincident radiosonde measurements from RRV), extrapolated the profile to a constant 388 ppm mixing ratio at this level and maintained the a priori stratospheric profile shape above this level (though shifted as the a priori values appeared somewhat too high). Both approaches are shown in Fig. 6. The 388 ppm tropopause value is based on an informed guess, assuming that the profile taken on 25 June 2011 – showing the lowest mixing ratios at high altitudes – is most representative for tropopause mixing ratios.

3.1.2 Computation of XCO_2

Using the high resolution and extrapolated aircraft profiles, the mean XCO_2 can be easily derived by a (dry-) mass-weighted average of the profiles. For a quantitative comparison with satellite retrievals, the column averaging kernels have to be taken into account. As the averaging kernels are provided at a coarse pressure grid, we first smoothed the aircraft profiles with a ±25 hPa box-filter (equivalent to an average

ACOS retrieval layer thickness) and then interpolated to the ACOS retrieval levels. The averaging kernel corrected XCO_2 is shown in Table 2 and and in Fig. 5.

4 Discussion

The calculated mean values of XCO_2 from GOSAT and values derived from in-situ aircraft measurements are shown in Table 2 and in Figs. 5 and 6. The Fig. 5 shows CO_2 data from vertical profiles taken on three days. Overlaid on each day's plot are 3 vertical lines: red color (long dash), is Alpha Jet data "filed in" by method 1 and derived using the ACOS algorithm; red color (short dash), is similar but "filled in" by method 2; blue color is the ACOS analyzed GOSAT overpass data for each day. There is very close agreement of the two analyzed results for method 1 and method 2 "fill in". The results from Alpha Jet measurements differ from each other ±0.5 ppm using different data "fill in" techniques. From 23 June to 25 June, XCO_2 changed by about 1.5 ppm (based on all methods), providing some variance to the observations and thus not only enabling validation of the overall XCO_2 accuracy but also the capability to retrieve synoptic variability. Measured data up to 8500 a.m.s.l. dominate the resulting mean mixing ratio but care has to be taken as the extrapolation method can induce biases of about 0.5 ppm. Agreement of the results from the aircraft and satellite are very good ±0.5 ppm and they compare well within stated uncertainties of the two methods of arriving at mean column mixing ratios. Very assuring is the fact that GOSAT also observes the change in XCO_2 during the campaign, despite its overall small magnitude (1.5 ppm).

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5 Summary/conclusions

Atmospheric vertical profile measurements of CO_2 mixing ratios were carried out over Railroad Valley, Nevada during June 2011 to coincide with GOSAT overpasses. The mean atmospheric values of CO_2 dry air mole fractions were derived from the data using the GOSAT averaging kernel and the JPL ACOS data reduction algorithm. Agreement of the satellite and aircraft CO_2 mixing ratios as well as ground measurements fall within the uncertainties of the methods employed to acquire these numbers.

These results provide a preliminary assessment of the validation of GOSAT, future objectives are to support future measurements of XCO_2 and XCH_4 by NASA's OCO-2 mission and by GOSAT by performing coincident aircraft and satellite measurements at different locations and times of year, with the aim of better validating satellite observations under different operating conditions.

Appendix A

Methane profiles

Methane (CH_4) and water vapor measurements were also recorded simultaneously with CO_2. However, direct comparisons with satellite retrievals were not possible due to the fact that the algorhitms are still under development/evaluation. We present results of airborne and ground measurements of CH_4 in Fig. A1. H_2O measurements are used internally by the instrument to calculate dry mixing ratios of CO_2 and CH_4, and cannot be calibrated, thus we decided not to present this data.

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Table 1. Empirically determined accuracy, precision, drift and repeatability of the measurements.

Parameter	CO_2	CH_4
Accuracy	0.07 ppm*	0.003 ppm*
Precision (1-sigma over 6 min)	< 0.13 ppm	< 0.00184 ppm
Drift (ppm h^{-1})	< 0.070	< 0.0001 ppm
Repeatability (ppm day^{-1})	< 0.062	< 0.001 ppm

* Accuracy is limited by the accuracy of primary standards.

Table 2. CO_2 column average values derived from Alpha Jet measurements using two different extrapolation approaches (AJAX 1 and AJAX 2), and GOSAT (reported using the ACOS algorithm v. 2.9) and maximum and minimum Alpha Jet altitudes during each coincident flight and GOSAT overpass. The surface elevation at RRV is 1427 m a.m.s.l.

Date	AJAX 1 (ppm)	AJAX 2 (ppm)	GOSAT (ppm)	Altitude max (m)	Altitude min (m)
23 June 2011	390.5	390.1	390.02	8228	1591
25 June 2011	388.9	388.6	388.13	8584	1524
26 June 2011	388.8	388.5	388.89	8648	1452

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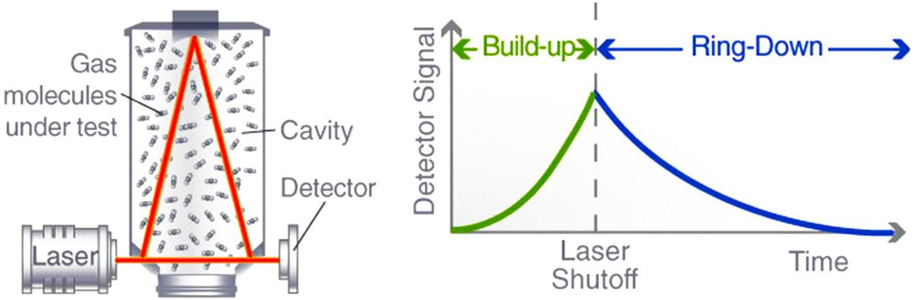

Fig. 1. Schematic representation of the cavity ring-down cell and decaying signal after laser shutoff.

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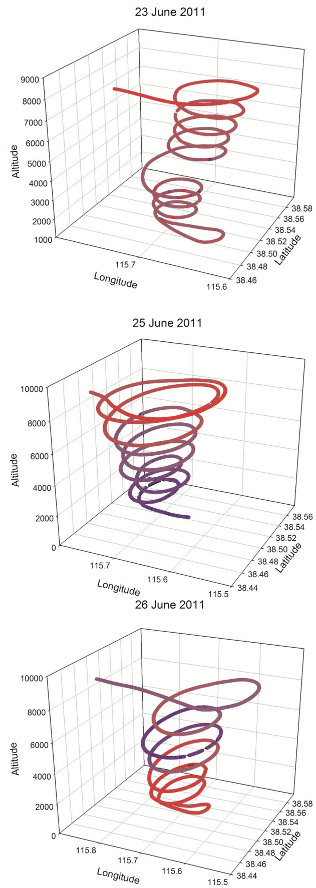

Fig. 2. Trajectories of the three flights taken at Railroad Valley, Nevada, USA on 23, 25 and 26 June 2011 (colors qualitatively represent the values in the observed range of concentrations, red – min, blue – max, see Fig. 5).

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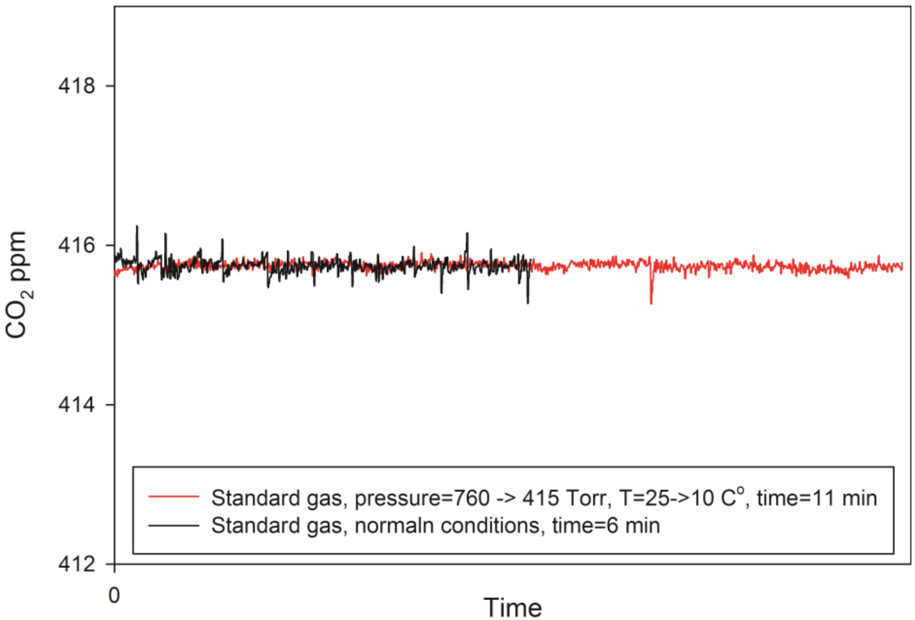

Fig. 3. A comparison between laboratory calibration and the calibration done in the pressure/temperature chamber under changing conditions (both pressure and temperature were changed simulating ascending maneuver).

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Fig. 4. Alpha Jet aircraft.

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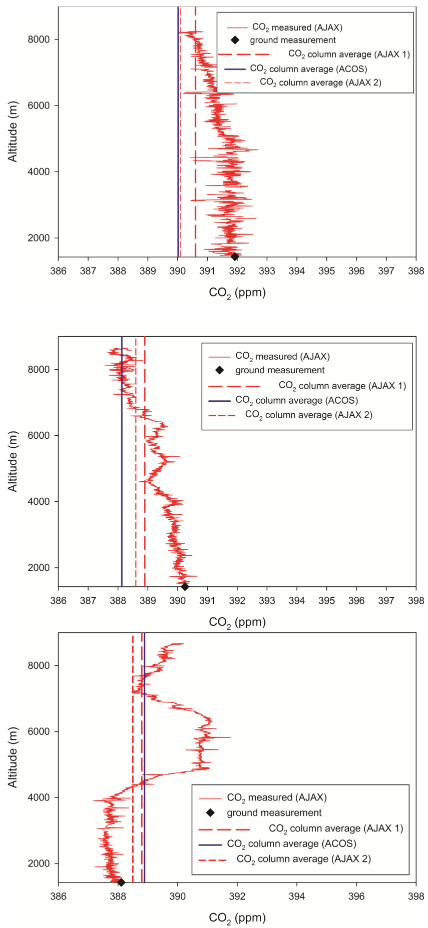

Fig. 5. In situ CO_2 profiles measured by CDRS and derived XCO_2 using two different methods (AJAX 1 and AJAX 2) along with GOSAT XCO_2 measurements for 23, 25 and 26 June.

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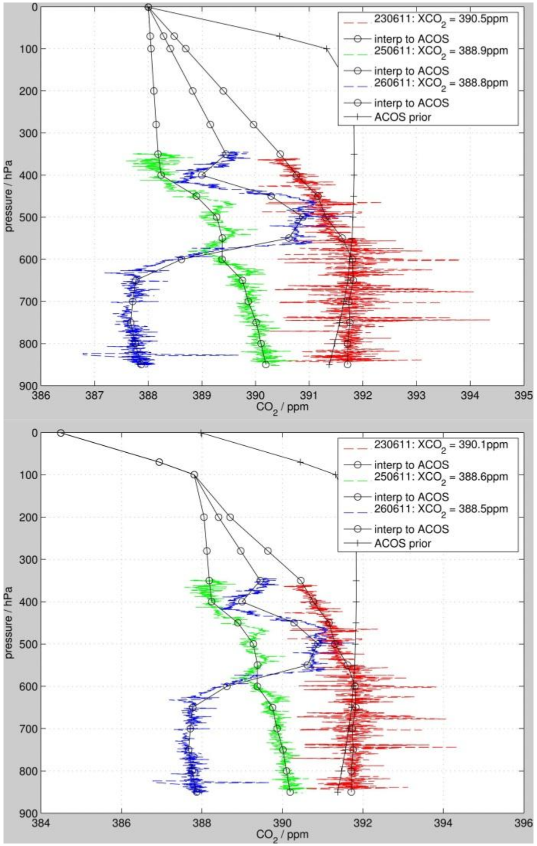

Fig. 6. Two different methods of extrapolation of the CO_2 aircraft data to the stratosphere, AJAX1 and AJAX2, respectively. The first method (top panel, AJAX1) extrapolates linearly the highest aircraft measurement to 1 hPa level. The second method (bottom panel, AJAX2) extrapolates linearly the highest measured value to 140 hPa (tropopause height) and 388 ppm of CO_2 mixing ratio at this level, and maintains the a priori stratospheric CO_2 profile above.

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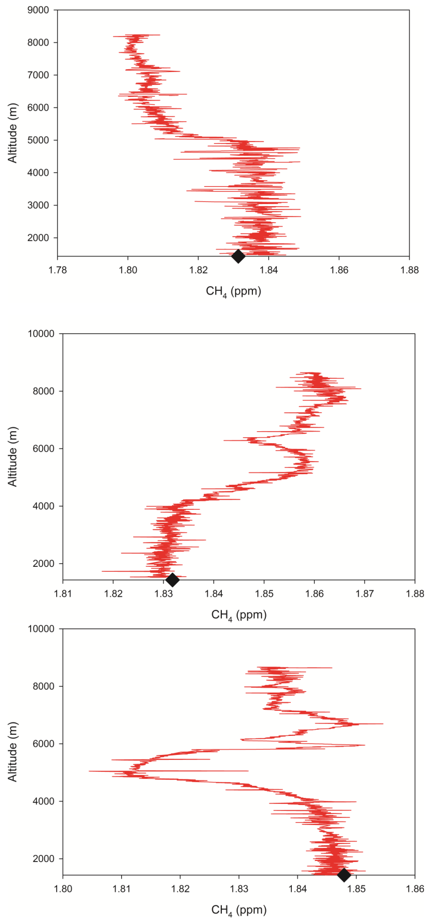

Fig. A1. In situ airborne CH_4 profiles and ground measurements (diamond shaped symbols) simultaneously recorded by two instruments for 23, 25 and 26 June, respectively.

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