Atmos. Chem. Phys. Discuss., doi:10.5194/acp-2016-720, 2016
Manuscript under review for journal Atmos. Chem. Phys.
Published: 7 October 2016
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Atmospheric Chemistry and Physics
Discussions

Lower-tropospheric CO_2 from near-infrared ACOS-GOSAT observations

Susan S. Kulawik[1], Chris O'Dell[2], Vivienne H. Payne[3], Le Kuai[4], Helen M. Worden[5], Sebastien C. Biraud[6], Colm Sweeney[7], Britton Stephens[7], Laura T. Iraci[8], Emma L. Yates[1], Tomoaki Tanaka[8]

(1) Bay Area Environmental Research Institute, Sonoma, CA, USA
(2) Cooperative Institute for Research in the Atmosphere, Colorado State University, Fort Collins, CO, USA
(3) Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA, USA
(4) UCLA Joint Institute for Regional Earth System Science and Engineering (JIFRESSE), Los Angeles, CA, USA
(5) Atmospheric Chemistry Observations & Modeling (ACOM) Laboratory National Center for Atmospheric Research, Boulder CO 80307 USA
(6) Lawrence Berkeley National Laboratory, Earth Science Division, Berkeley, CA, USA
(7) NOAA/ESRL/GMD, Boulder, CO, USA
(8) NASA Ames, Moffett Field, CA, USA

Abstract

We present two new products from near-infrared GOSAT observations: lower tropospheric (LMT, from 0-2.5 km) and upper tropospheric/stratospheric (U, above 2.5 km) carbon dioxide partial columns. We compare these new products to aircraft profiles and remote surface flask measurements and find that the seasonal and year-to-year variations in the new partial columns significantly improve over the ACOS-GOSAT initial guess/a priori, with distinct patterns in the LMT and U seasonal cycles which match validation data. For land monthly averages, we find errors of 1.9, 0.7, and 0.8 ppm for retrieved GOSAT LMT, U, and XCO_2; for ocean monthly averages, we find errors of 0.7, 0.5, and 0.5 ppm for retrieved GOSAT LMT, U, and XCO_2. In the southern hemisphere biomass burning season, the new partial columns show similar patterns to MODIS fire maps and MOPITT multispectral CO for both vertical levels, despite a flat ACOS-GOSAT prior, and CO/CO_2 emission factor consistent with published values. The difference of LMT and U, useful for evaluation of model transport error, has also been validated with monthly average error of 0.8 (1.4) ppm for ocean (land). The new LMT partial column is more locally influenced than the U partial column, meaning that local fluxes can now be separated from CO_2 transported from far away.

1 Introduction

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The Greenhouse Gases Observing Satellite (GOSAT) has been measuring global satellite CO_2 columns since 2009, achieving accuracy to 0.3 ppm in regional biases and 1.7 ppm single observation error (Kulawik et al., 2016). The sensitivity of near-infrared radiances to CO_2 varies by altitude differently in the strong and weak bands, resulting in the capability of retrieving multiple pieces of vertical information from near-infrared observations, with 3+ degrees of freedom (i.e. independent pieces of information) for TCCON (Connor et al., 2015; Kuai et al., 2012), 1.6 degrees of freedom for GOSAT (this paper), and 2.0 degrees of freedom for OCO-2 (Kulawik, unpublished result). In this paper we use the intermediate retrieved profile from ACOS-GOSAT processing to construct, bias-correct, and validate two partial columns from near-infrared GOSAT observations (schematically shown in Fig. 1). The partially correlated errors and sensitivity of these two partial columns are characterized so that they can be used for flux estimation and other science analyses.

An important goal of carbon cycle research is to improve top-down estimates of CO_2 fluxes, which use model assimilation to trace the observed variability in the long-lived tracer backwards to sources and sinks. Historically, such top-down flux estimates have relied on surface observations (e.g. Peters et al., 2007; Chevallier et al., 2010), though it was postulated 15 years ago that satellite-based measurements of column CO_2 could dramatically reduce top-down based flux uncertainties (Rayner and O'Brien, 2001; O'Brien and Rayner, 2002). Guided by this early work, most GOSAT analyses have focused solely on total column CO_2 (or XCO_2). Separation of XCO_2 into two vertical columns has several advantages over column XCO_2 and surface observations which should improve our ability to accurately estimate fluxes:

- flux estimates from column measurements rely on observations up to continent-scales away (Liu et al., 2015; Feng et al., 2016); whereas LMT back-trajectories show a more local influence of surface fluxes versus for XCO_2, making flux estimates more data driven by local measurements rather than relying on model transport, a major driver of flux uncertianties (Houweling et al., 2015; Liu et al., 2015; Chevallier et al., 2014; Liu et al., 2011; Prather et al., 2008)
- Stephens et al. (2007) show that measuring atmospheric values of carbon dioxide at 2 vertical levels better constrains model transport and partitioning between southern hemisphere land and northern mid-latitude land fluxes, since vertical transport is an uncertainty in flux estimates (Deng et al., 2015; Lauvaux and Davis, 2014; Stephens et al., 2007)
- The LMT covers at least the entire boundary layer which partially mitigates one source of flask assimilation error, the boundary layer

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height (Denning et al., 1996; Gurney et al., 2002; Rayner and O'Brien, 2001); and

- GOSAT provides observations in many areas which are sparsely covered by surface-based measurements.

In this work, we evaulate the precision and accuracy of these new LMT and U partial column products derived from GOSAT, with the goal of providing more and better information to the flux inversion estimates than is available from the total column alone. This paper is structured as follows. We introduce the datasets used in Section 2, and the theoretical basis in Section 3. Section 4 describes methodology, e.g. the coincidence criteria and GOSAT bias correction. Section 4.1 uses back-trajectories to estimate the distance to peak sensitivity to surface fluxes for LMT and U. Section 5 shows comparisons to aircraft observations and surface sites, including maps of the two partial columns. Section 5.4 shows patterns of the two partial columns versus MOPITT multi-spectral CO retrievals, and Section 5.5 looks at errors of LMT minus U. Section 6 discusses and summarizes these results.

2. Datasets

There are two datasets used for validation of the new partial columns. Aircraft profiles, which fly from the surface to somewhere between 5 and 13 km, can be used to directly validate what is seen with the two GOSAT partial columns. The second dataset that is used is from remote surface flasks, which are used to compare to the lower GOSAT partial column, assuming that 0-2.5 km is well mixed at remote sites. TCCON, which currently measures full columns, is used to diagnose discrepancies between aircraft and GOSAT at the sites where both exist. Additionally, we compare signals from burning and transport in southern hemisphere land from GOSAT, MOPITT, and MODIS fire counts. Figure 2 shows aircraft and surface validation locations, along with GOSAT coincidences.

2.1 GOSAT

The Greenhouse gases Observing SATellite (GOSAT) takes measurements of reflected sunlight in three shortwave bands with a circular footprint of approximately 10.5 km diameter at nadir (Kuze et al., 2016; Yokota et al., 2009; Crisp et al., 2012). ACOS-GOSAT v3.5 from the lite product with quality flag of 0 are used along with the full profile, profile averaging kernel, and full profile error matrices from ancillary GOSAT files. We use both nadir land observations (looking straight down) and ocean glint observations (sunglint tracking mode), but not medium gain over land, as there is not sufficiently co-located validation data to validate medium gain observations.

2.2 ESRL aircraft profiles

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Aircraft and ocean measurements are obtained from an obspack (co2_1_PROTOTYPE_v1.0.4b_2014-02-13). The measurements are extended down to the surface using the lowest measured value, and extended to the tropopause using the aircraft value at the highest altitude (The Tropopause is from NCEP, http://www.esrl.noaa.gov/psd/data/gridded/data.ncep.reanalysis.html). The CarbonTracker model (CT2015, see below) is used to extend the profile through the stratosphere.

2.3 Remote oceanic surface in situ measurement sites

Remote surface sites are from the Earth System Research Laboratory Observation Package (ObsPack) Data Product surface flask measurements (Conway et al., 1994), which are accurate to 0.1 ppm with excellent coverage in the US and Europe and sparser coverage elsewhere. For each station, there can be different options, represented by file names. The "afternoon" file is preferred, as it best matches the satellite overpass. If "afternoon" is not found, "nighttime" and "marine" (which filters observations by their source) are excluded, and "allvalid", "representative", and "continental" are accepted.

The "remote oceanic" locations used are selected to have at least 97% ocean at a 5 degree radius around the location. The locations are shown in Fig. 2. Although the airmass observed by GOSAT LMT will not match the airmass observed by the surface site, the remote location should result in boundary layer mixing that will make the comparisons useful. Additionally, these sites are not used in development of the bias correction terms (described in Section 3.5 and Appendix A) and are an independent test of bias correction for ocean.

2.4 HIPPO aircraft profiles

The HIAPER Pole-to-Pole Observations (HIPPO) project samples the atmosphere in a series of profiles from the surface to 9-13 km, from about 80N to 60S. The campaigns covered different years as well as different seasons, namely: HIPPO 1: January, 2009, HIPPO 2: November 2009, HIPPO 3: March-April, 2010, HIPPO 4: June-July, 2011, and HIPPO 5: August-September, 2011. Frankenberg et al. (2016) recently were successful in evaluating satellite measurements of column CO_2 over ocean (including GOSAT) using HIPPO. In this paper, we look at comparisons between GOSAT and HIPPO 2-5 (HIPPO 1 occurs prior to GOSAT launch) using the HIPPO-identified profiles and the CO2_X field, based on 1s data averaged to 10s, from two (harmonized) sensors: CO2-QCLS and 15 CO2-OMS. Due to the GOSAT glint coverage span of about 40 degrees with additional screening for the new products, many of the comparisons had fairly limited latitudinal spans with the GOSAT improvement over the prior found more in improving

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the bias rather than improving the standard deviation. The combined campaigns span a wide range of GOSAT latitudes.

2.5 AJAX aircraft profiles

The Alpha Jet Atmospheric eXperiment (AJAX) project collects in situ CO_2 vertical profiles from the surface to 8 km in several locations, including Railroad Valley, NV; Merced, CA, and other locations in the West Coast. Most of the version 4 profiles used in this paper were collected to coincide with GOSAT overpasses. Trace gas instruments and the Meteorological Measurement Sensor are housed in an unpressurized sensor pod that is mounted under the wing. A cavity ring-down spectrometer (Picarro Inc. G2301-m) which has been modified for flight conditions is routinely calibrated to NOAA/ESRL gas standards. Calculated 1σ overall uncertainties are 0.16 ppm for CO_2 (Hamill et al. 2016; Tanaka et al., 2016).

2.6 MOPITT v6 multispectral CO retrieval

In section 5, we utilize satellite-based CO observations from MOPITT to attribute spatial variability in LMT and U. The MOPITT instrument on EOS-Terra is in a sun-synchronous orbit with mean local time overpasses of 10:30 and 22:30. It has global coverage in ~3 days with a 22km x 22km horizontal footprint. MOPITT uses gas filter correlation radiometry (GFCR) to measure atmospheric CO at 4.6 μm (Thermal Infrared) and 2.3 μm (Short-wave Infrared) and is the only satellite instrument capable of simultaneous multispectral retrievals of CO with enhanced sensitivity to near-surface CO for daytime/land observations (Worden et al., 2010). MOPITT CO data have been validated for each retrieval algorithm version using aircraft in situ measurements (Deeter et al., 2014). Here we use daytime only MOPITT V6J (multispectral) data that have been filtered to require cloud free scenes from both MOPITT and MODIS cloud detection. We also use a measure of sensitivity to near-surface CO computed from the trace of the averaging kernel for the bottom 2 pressure levels to select scenes that contain relatively more information from the measurement.

2.7 MODIS fire counts

MODIS fire counts (found at https://lance.modaps.eosdis.nasa.gov/cgi-bin/imagery/firemaps.cgi) are used to identify biomass burning locations. Fire maps are created by Jacques Descloitres with fire detection algorithm developed by Louis Giglio. Blue Marble background image created by Reto Stokli (Giglio et al., 2003; Davies et al., 2004).

2.8 CarbonTracker model

CarbonTracker CT2015, http://carbontracker.noaa.gov, (Peters et al., 2007) is used to extend aircraft profiles from the stratosphere to the top of the

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atmosphere (similarly to in Frankenberg et al., 2016 and Inoue et al., 2013) and to quantify co-location error (similarly to Kulawik et al. (2016).

2.9 TCCON

The Total Carbon Column Observing Network (TCCON) observations, version GGG2014 (Wunch et al., 2011a) at Lamont (Wennberg et al., 2014) and Park Falls (Wennberg et al., 2014), where both aircraft and TCCON observations have co-located measurements, are used to evaluate XCO_2 calculated from the aircraft observations (extended as described by Section 3.7). Although the TCCON observations contain information to split into 2 or 3 vertical columns, the focus of the TCCON project has been on the validation of XCO_2 from OCO-2 and GOSAT. Recent work by Kuai et al. (2012), Dohe et al. (2012), and Connor et al. (2015) have explored vertical profile retrievals from TCCON, but there is not yet an operational product.

3.0 LMT and U theoretical basis

In Section 3.1, equations are presented describing the sensitivity and errors of the new products. In Section 3.2, a simulation is shown of what GOSAT is expected to see from space using the developed equations and aircraft profiles from the Southern Great Plains (SGP) aircraft site.

3.1 Equations describing sensitivity and errors

The ACOS retrievals (O'Dell et al., 2012) utilize an optimal estimation approach with a priori constraints (Rodgers, 2000). It is common practice to represent the state parameter to be retrieved on an altitude grid that is finer than the altitude resolution of the instrument (e.g., Bowman et al., 2006; Deeter et al., 2003; von Clarmann et al., 2003). A major advantage of this approach is that it allows the calculation of diagnostics, such as averaging kernels, which can be used to characterize the sensitivity of the measurement. Constraints (regularization) must be applied in order to stabilize the retrieval (e.g., Rodgers, 2000; Tikhonov, 1963; Twomey, 1963; Steck and von Clarmann, 2001; Kulawik et al., 2006). The constraints include a constraint vector and a constraint matrix, which may be chosen constrain absolute values and/or the shape of the retrieved result.

In the ACOS processing, CO_2 is first retrieved as a 20-level profile, which averages 1.6 degrees of freedom (DOF) with about 0.8 DOF below 2.5 km above the surface (levels 16-20, where level 20 is the surface), and 0.8 DOF above 2.5 km (levels 1-15). This intermediate profile has significant altitude-dependent biases and cannot be used scientifically as-is, but rather this profile is compacted to a single column quantity, XCO_2 as the final step in the ACOS processing. In this work, we post-process the ACOS-GOSAT intermediate profile to calculate and characterize the partial column represented by levels 16-20, which is named LMT_XCO_2 or LMT for short,

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Manuscript under review for journal Atmos. Chem. Phys.
Published: 7 October 2016
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and the partial column represented by levels 1-15, which is named U_XCO_2 or U for short.

The equation for the linear estimate of **x**, the retrieved CO_2 profile (Connor et al., 2008; Rodgers, 2000) is:

$$\hat{\mathbf{x}} = \mathbf{x}_\mathbf{a} + \mathbf{A}_{xx}(\mathbf{x}_{true} - \mathbf{x}_\mathbf{a}) + \mathbf{A}_{xy}(\mathbf{y} - \mathbf{y}_\mathbf{a}) + \mathbf{G}_\mathbf{x}\boldsymbol{\varepsilon} \quad (1)$$

where $\hat{\mathbf{x}}$ is the retrieved CO_2 profile with size n_{CO2} (20 for ACOS-GOSAT), x_{true} is the true value, $\mathbf{A_{xx}}$ is the n_{CO2} x n_{CO2} CO_2 profile averaging kernel, and $\mathbf{A}_{xy}(\mathbf{y} - \mathbf{y}_\mathbf{a})$ is the cross-state error representing the propagation of error from non-CO_2 retrieved parameters **y** (aerosols, albedo, etc., size 26 for ACOS-GOSAT as there are 26 non-CO_2 retrieved parameters) into retrieved CO_2, size n_{interf} x n_{CO2}; and $\mathbf{G}_\mathbf{x}\boldsymbol{\varepsilon}$ is the measurement error.

The pressure weighting function, "**h**" (size n_{CO2}) is used to convert the retrieved CO_2 profile to XCO_2 by tracking each level's contributes to the column quantity.

$$\mathbf{h}_{xco2} = [0.026\ 0.052\ 0.052\ 0.052\ \ldots\ 0.052\ 0.052\ 0.052\ 0.026] \quad (2a)$$

The sensitivity to the top or bottom levels is half other levels, as these levels contribute to only one layer, rather than two adjacent layers. The GOSAT levels are chosen such that the pressure weighting is the same for all layers and the same for all observations.

The LMT pressure weighting function is obtained by starting with the pressure weighting function for XCO_2, setting levels 1-15 to zero, then normalizing so that the sum of all entries adds to 1. For the U pressure weighting function, levels 16-20 are set to zero, then the vector is normalized so that the sum is 1. The LMT and U pressure weighting functions are:

$$\mathbf{h}_{LMT} = [0\ 0\ 0\ 0\ \ldots\ 0\ 0.22\ 0.22\ 0.22\ 0.22\ 0.11] \quad (2b)$$
$$\mathbf{h}_{U} = [0.035\ 0.069\ 0.069\ \ldots\ 0.069\ 0.069\ 0\ 0\ 0\ 0\ 0] \quad (2c)$$

To calculate XCO_2, the equation is:

$$XCO_2 = \mathbf{h}_{xco2} \cdot \hat{\mathbf{x}} \quad (3)$$

The fraction of total air in each of the partial columns are:

$$f_{XCO2} = 1 \quad (4a)$$

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$f_{LMT} = 0.23446$ (4b)
$f_U = 0.76554$ (4c)

Combining Eqs. 1, 2a, and 3, the XCO_2 estimate is:

$$(X\hat{C}O_2) = (XCO_2)_a + \mathbf{h}_{XCO2}\mathbf{A}_{xx}(\mathbf{x}_{true} - \mathbf{x}_\mathbf{a}) + \mathbf{h}_{XCO2}\mathbf{A}_{xy}(\mathbf{y} - \mathbf{y}_\mathbf{a}) + \mathbf{h}_{XCO2}\mathbf{G}_\mathbf{x} \quad (5a)$$

$$(X\hat{C}O_2) = (XCO_2)_a + \mathbf{a}_{xx}(\mathbf{x}_{true} - \mathbf{x}_\mathbf{a}) + \mathbf{a}_{xy}(\mathbf{y} - \mathbf{y}_\mathbf{a}) + \mathbf{g}_\mathbf{x}\boldsymbol{\varepsilon} \quad (5b)$$

where $\mathbf{a}_{xx}$ is the column averaging kernel, $\mathbf{a}_{xx} = \mathbf{h}_{XCO2}{}^T\mathbf{A}_{xx}$ (see Appendix A of Connor, 2008).

Similarly, to calculate the linear estimate for the 2-vector [LMT, U], Equation 1 is multiplied by the 2 x n_{CO2} pressure weighting function, $\mathbf{h} = [\mathbf{h}_{LMT}, \mathbf{h}_U]$:

$$\begin{pmatrix} L\hat{M}T \\ \hat{U} \end{pmatrix} = \begin{pmatrix} LMT \\ U \end{pmatrix}_\mathbf{a} + \mathbf{h}\mathbf{A}_{xx}(\mathbf{x}_{true} - \mathbf{x}_\mathbf{a}) + \mathbf{h}\mathbf{A}_{xy}(\mathbf{y} - \mathbf{y}_\mathbf{a}) + \mathbf{h}\mathbf{G}_\mathbf{x}\boldsymbol{\varepsilon} \quad (6a)$$

$$\begin{pmatrix} L\hat{M}T \\ \hat{U} \end{pmatrix} = \begin{pmatrix} LMT \\ U \end{pmatrix}_\mathbf{a} + \mathbf{a}_{xx}(\mathbf{x}_{true} - \mathbf{x}_\mathbf{a}) + \mathbf{a}_{xy}(\mathbf{y} - \mathbf{y}_\mathbf{a}) + \mathbf{g}_\mathbf{x}\boldsymbol{\varepsilon} \quad (6b)$$

where now $\mathbf{a}_{xx} = [\mathbf{h}_{LMT}, \mathbf{h}_U]\mathbf{A}_{xx}$, a 2 x n_{CO2} matrix, $\mathbf{a}_{xy} = [\mathbf{h}_{LMT},\mathbf{h}_U]\mathbf{A}_{xy}$, a 2x n_{interf} matrix, and $\mathbf{g}_x = [\mathbf{h}_{LMT}, \mathbf{h}_U]\mathbf{G}_x$, a 2x$n_s$ matrix, where n_s are the number of spectral points.

The last two terms in Eq. 6 represent the cross-state and measurement error, respectively, and are often jointly called the observation error (Worden et al., 2004). The error in [LMT, U] is estimated by taking the covariance of $\begin{pmatrix} L\hat{M}T \\ \hat{U} \end{pmatrix} - \begin{pmatrix} LMT \\ U \end{pmatrix}_{True}$. The errors can be calculated either from taking the covariance (6a) or from (6b). The covariance of (6a) has a fairly simple form, in terms of the standard definitions of the error covariances for the full profile, $\mathbf{S}_{interf}$, and $\mathbf{S}_{meas}$, which are included in the ACOS-GOSAT ancillary products, and $\mathbf{S}_{smoothing}$ can be calculated from the standard equation, $\mathbf{S}_{smoothing} = \mathbf{(I\text{-}A)S_a(I\text{-}A)^T}$ (Rodgers, 2000), with $\mathbf{A}$ the n_{CO2} x n_{CO2} CO_2 profile averaging kernel and $\mathbf{S_a}$ the a priori covariance, both included in the ACOS-GOSAT products.

$$\sigma_{[LMT,U]} = \mathbf{hS_{smoothing}h^T + hS_{interfer}h^T + hS_{meas}h^T} \quad (7a)$$

$$= \begin{pmatrix} \mathbf{h}_{lmt}{}^T\mathbf{S}_{smooth}\mathbf{h}_{lmt} & \mathbf{h}_{lmt}{}^T\mathbf{S}_{smooth}\mathbf{h}_U \\ \mathbf{h}_U{}^T\mathbf{S}_{smooth}\mathbf{h}_{lmt} & \mathbf{h}_U{}^T\mathbf{S}_{smooth}\mathbf{h}_U \end{pmatrix} + \begin{pmatrix} \mathbf{h}_{lmt}{}^T\mathbf{S}_{obs}\mathbf{h}_{lmt} & \mathbf{h}_{lmt}{}^T\mathbf{S}_{obs}\mathbf{h}_U \\ \mathbf{h}_U{}^T\mathbf{S}_{obs}\mathbf{h}_{lmt} & \mathbf{h}_u{}^T\mathbf{S}_{obs}\mathbf{h}_U \end{pmatrix} \quad (7b)$$

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Manuscript under review for journal Atmos. Chem. Phys.
Published: 7 October 2016
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$$= \begin{pmatrix} \sigma_{LMT}^{2} & \sigma_{LMT}\sigma_{U} corr \\ \sigma_{LMT}\sigma_{U} corr & \sigma_{U}^{2} \end{pmatrix} \tag{7c}$$

The resulting error covariance $\sigma_{[LMT,U]}$ is a 2x2 matrix, where the diagonals are the square of the predicted error for each parameter, and the off diagonals also depend on the correlated errors between these parameters. Table 1 shows the predicted errors for LMT, U, and the error correlation between LMT and U. The predicted errors in Table 1 are larger than the actual errors, seen in Tables 2 and 3; and the error for averaged observations is estimated in section 4.1.1. It is worth noting that the *a priori* errors are much larger for LMT and U, at 34 and 9 ppm, respectively, than the posterior errors, indicating that these quantities are largely unconstrained by the retrieval's prior assumption.

Through the same process as Eqs 6-7, the XCO_2 error is:

$$\sigma_{XCO_2} = \mathbf{h}_{XCO2}^{T}\mathbf{S}_{smooth}\mathbf{h}_{XCO2} + \mathbf{h}_{XCO2}^{T}\mathbf{S}_{obs}\mathbf{h}_{XCO2} \tag{8}$$

XCO_2 can also be calculated as a function of LMT and U, and the XCO_2 errors can be calculated as a function of the errors in [LMT, U]. These are shown in Eq. 9.

$$XCO_2 = f_{lmt}LMT\_CO_2 + f_u U\_CO_2 \tag{9a}$$

$$\sigma_{XCO_2} = \sqrt{(f_{lmt} \quad f_u)\begin{pmatrix} \sigma_{lmt}^{2} & \sigma_{lmt}\sigma_u corr \\ \sigma_{lmt}\sigma_u corr & \sigma_u^{2} \end{pmatrix}\begin{pmatrix} f_{lmt} \\ f_u \end{pmatrix}} \tag{9b}$$

$$\sigma_{XCO_2} = \sqrt{0.23^2\sigma_{lmt}^{2} + \sigma_u^{2}0.77^2 + 2 * 0.77 * 0.23\sigma_{lmt}\sigma_u corr} \tag{9c}$$

where f_{LMT} and f_U are the air masses for the LMT and U partial columns (0.236, 0.764), respectively, σ_{lmt} is the error for LMT, and *corr* is the error correlation between LMT and U.

The normalized column averaging kernel is used to see the sensitivity of the column to the true state at different levels, with a value of 1 meaning perfect sensitivity, and a value of 0 meaning no sensitivity. The normalized column averaging kernel is the column averaging kernel, **a**, divided by the pressure weighting function for each layer, $\mathbf{h}_{XCO2}$, and multiplied by the fraction of air in the partial column.

$$\mathbf{a\_norm}_{LMT} = (\mathbf{h}_{LMT}\,\mathbf{A}_{CO2})/\mathbf{h}_{XCO2} * f_{LMT} \tag{10a}$$
$$\mathbf{a\_norm}_{U} = (\mathbf{h}_{U}\,\mathbf{A}_{CO2})/\mathbf{h}_{XCO2} * f_{U} \tag{10b}$$

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Figure 3 shows the normalized column averaging kernels for LMT, U, and XCO_2 for land and ocean scenes. Although the LMT partial column sums the 5 levels within about 2.5 km of the ground, the LMT has some sensitivity to the true state at all 20 levels because the GOSAT radiances are not able to fully resolve between CO_2 within the surface to 2.5 km versus above this. As expected, the sensitivity for LMT plus U is equal to the sensitivity for XCO_2, and the sensitivity for LMT is weighted to the surface whereas the sensitivity for U is weighted to the top of the atmosphere. The negative averaging kernels for LMT in the stratosphere are partially a consequence of the ACOS prior constraint, which allows no stratospheric variability. Actual stratospheric variability is transferred to the closest levels that are allowed to vary, and the surface compensates for the radiance error induced by this, resulting in a negative sensitivity of the LMT to the true state in the stratosphere. If the stratospheric truth matches that of the *a priori*, then there will be no propagation of error into LMT or U. The averaging kernels shown in Fig. 3 are similar to those calculated for TCCON in Figure 2 of Connor et al. (2015).

3.2 Seasonal behavior of LMT, U, and XCO_2 estimated using *only* aircraft measurements and GOSAT sensitivity (no GOSAT observations)

This section answers the following questions: (1) Do U and LMT have unique seasonal signatures? (2) How much of the XCO_2 variability is due to LMT versus U variability (3) How much does the prior influence the LMT and U retrievals?

This section uses simulated GOSAT retrievals using the linear estimate, Eqs. 5 and 6, given the aircraft in situ profiles at the SGP site (37N, 95W), the GOSAT prior, and the GOSAT averaging kernels. Using this analysis, the importance of the prior is assessed by using either a flat prior or the GOSAT prior in Eqs. 5 and 6. We assess how much LMT and U contribute to the variations seen in XCO_2 using the variability of the LMT and U partial columns combined with the weighting each has in the full column. The seasonal cycles of each partial column are studied by converting all aircraft measurements to lie between 2012 and 2013 by applying a 2 ppm/year secular trend, and averaging by month. This method was used rather than fitting the aircraft observations using the NOAA CCGCRV to estimate the seasonal cycle shape because the aircraft observations are not sufficiently smooth to result in a consistent fit.
Figure 4 shows the estimates of LMT, U, and XCO_2 using SGP aircraft profiles calculated as described above. There is significant variability in the individual aircraft measurements, seen in panel (a) but this is smoothed out on monthly timescales, seen in the remaining panels. The dashed lines in

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panel a represent fits using the NOAA fitting software CCGCRV. The U partial column is rarely more than 1 ppm different from the fit, whereas LMT can be up to 5 ppm different (e.g. see summer, 2009; January, 2010; Summer, 2011).

Figure 4 (b) and (c) show the difference between simulated retrievals with the GOSAT a priori (b) versus a flat a priori (c). The patterns are very similar, indicating that the signal is primarily coming from the data rather than the prior, with standard deviations of 0.8 ppm for LMT and 0.3 ppm for U (these changes are fully characterized when applying the GOSAT prior to the aircraft true profile with the specified a priori vector).

Figure 4, panel (d) shows U versus XCO2. At first glance these look the same, but by comparing panel (d) and (b), the XCO_2 deviations from U are towards LMT. The seasonal variabilities of XCO_2, LMT, and U (maximum minus minimum), are 3.3 ppm, 4.8 ppm, and 3.3 ppm, respectively. Note that the seasonal variations in LMT and U have a 0.56 correlation. A straightforward calculation of variation * airfraction (Eq. 4) show that the fraction of variation of XCO_2 resulting from variations in LMT is approximately 30%, and the fraction of the variation in XCO_2 coming from U variation is roughly 70%. So even though LMT has more variability, U has the much larger impact on XCO_2 due to the fact that the full column is 77% LMT. A similar calculation at Park Falls, where the LMT seasonal cycle is 20 ppm and the U seasonal cycle is 5 ppm finds 45% of the seasonal variability in XCO_2 results from U and 55% from LMT at Park Falls (46N).

Figure 4 indicates that LMT and U do have unique seasonal cycles which result from the data rather than the prior. The LMT partial column, which contributes to 30% of the variations observed in XCO_2, has a much larger seasonal variability than the U partial column or the XCO_2 column, and earlier seasonal cycle maximums and minimums.

4.0 Methods

We test the sensitivity of the new products to surface fluxes using back-trajectory footprints in Section 4.1. Section 4.2 discusses how GOSAT is compared to aircraft. Sections 4.3-5.6 describe the bias correction, how the aircraft data is extended to the full atmosphere and the coincidence criteria.

4.1 Sensitivity of the LMT and U partial columns to surface fluxes

To compare LMT and U sensitivity to surface fluxes, we look at 10-day back-trajectory footprints created using WRF-STILT (Nehrkorn et al., 2010). The "footprint" for an observation is a map of the surface locations to which an observation is sensitive. Footprints are created for each of the 20 GOSAT levels, then convolved with the LMT and U averaging kernels. The averaging

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kernel estimates the sensitivity of the GOSAT measurement of each quantity to the true state at each level. Footprint maps are created which show the sensitivity of each type of GOSAT observation to sources and sinks. This was done for 10 GOSAT observations in the Amazon. The distance for the nearest 10% of footprints is 260 km for LMT and 790 km for U. It is likely that there is also a very long tail in the U sensitivity, based on the work of Liu et al. (2015) and Feng at el. (2016).

4.2 Comparisons to aircraft

The correct way to validate GOSAT estimates of [LMT, U] is to compare the GOSAT observations to an estimate of what GOSAT should observe, given its sensitivity, when the true atmospheric state is set to the aircraft CO_2 profile using Eq. 6. The agreement should be within the GOSAT observation error, as the smoothing term's effects on the comparison are removed by the application of the GOSAT averaging kernel to the validation data.

4.3 GOSAT bias correction

The GOSAT standard XCO_2 product has regional biases and errors which can be partially corrected using jointly retrieved parameters, pre-filters, or radiance properties, e.g. the ratio of the signal in the strong vs. weak band, retrieved albedo slopes or values, retrieved aerosol slopes or values; and through post-processing screening, e.g. removing fits where the difference in the retrieved versus prior surface pressure is greater than 4 hPa (). We apply the same techniques to the LMT partial column in Appendix A which is briefly described here. After LMT is corrected, the corrected U partial column is set using Eq. 9a, so that XCO_2 is consistent with LMT and U.

To correct the LMT partial column, a set of pairs of "true" and "retrieved" values is compiled, using validation data. GOSAT minus true is plotted versus various GOSAT parameters described in Appendix A, and if a slope is found for GOSAT error versus a parameter, a correction is applied. The robustness of the correction is tested by applying the correction on data withheld from the fit, as described in Appendix A. Following the initial bias correction, GOSAT LMT is compared for closely occurring ocean and land pairs; the a constant bias term is added to the land bias correction so that land and ocean, on average, are consistent.

4.4 Coincidence criteria

"Geometric criteria", defined as +-3 degrees latitude, +-5 degrees longitude +-1 week time are used to select coincident GOSAT observations for particular sites. 5 degrees latitude/longitude, 1 hour has previously be used for GOSAT criteria (Kulawik et al., 2016), however this did not yield enough matches for aircraft profiles. With the above criteria, the total matches range from 64 (PFA) to 4800 (SGP), with median 430, which is

Atmos. Chem. Phys. Discuss., doi:10.5194/acp-2016-720, 2016
Manuscript under review for journal Atmos. Chem. Phys.
Published: 7 October 2016
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Atmospheric Chemistry and Physics Discussions

approximately 9/month. A tight spatial criteria was selected to best capture the seasonal cycle at a given location, especially for land where spatial variability is large. Because aircraft and surface observations are more infrequent than TCCON, extended time was used for the comparisons to obtain sufficient comparison data. Other methods that were tried were dynamic coincidence criteria (Wunch et al., 2011b) which considers a larger area (+- 10 degrees latitude, +- 30 degrees longitude) but also matches atmospheric temperature, and a variant of Basu criteria (Guerlet et al., 2013), which used dynamic coincidences which had model-model differences less than 0.5 ppm. All three criteria gave similar results overall, with different criteria performing better at different stations, but no clear overall best criteria. For HIPPO data, which mainly tests latitude gradients over ocean, the dynamic coincidence approach was used following Frankenberg et al. (2016)

4.5 Extension of the aircraft profile

The aircraft measurements go from the surface to between 5.5 km to 8 km for most ESRL land to 9-13 km for HIPPO observations. As GOSAT LMT, U, and XCO_2 have sensitivity above 5.5 km and even above 13 km, as seen in the averaging kernel shown in Fig. 3, the aircraft profile needs to be extended from the top measurement to the top of the atmosphere. Four different methods of extension were tested: extending with the GOSAT prior, extending the top aircraft measurement through the tropopause and extending with the GOSAT prior above this, extending with the CT2015 model, and extending the top aircraft measurement through the tropopause and extending with the CT2015 model above this. The different extensions mainly had an effect on the overall LMT, U, and XCO_2 biases, rather than the standard deviation, with a spread of 0.4 ppm, as seen in Table A4. The extension that was used in the rest of the paper is extending the top aircraft measurement through the tropopause and extending with the CT2015 model above this.

5. GOSAT results

Figure 5 shows GOSAT comparisons for LMT and U versus the aircraft measurements at the SGP site at 37N, 95W which can be compared to the simulated results shown in Fig. 4. The GOSAT LMT and U products show the same seasonal patterns as seen in the aircraft data. Figure 5b shows CarbonTracker matched to GOSAT (CT@GOSAT) and CarbonTracker matched to the aircraft measurements (CT@aircraft). The difference of CT@GOSAT and CT@aircraft estimates the co-location error. Large differences are seen between CT@GOSAT and CT@aircraft in early 2010, Summer, 2010, and Summer, 2011. In Fig. 5c, the seasonal cycle is shown by transforming all data to lie within 2012 using 2 ppm/year adjustment to CO_2. There are systematic differences seen in the drawdown, which is

Atmos. Chem. Phys. Discuss., doi:10.5194/acp-2016-720, 2016
Manuscript under review for journal Atmos. Chem. Phys.
Published: 7 October 2016
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underestimated by GOSAT. However, when months that have differences of (CT@GOSAT -CT@aircraft) more than 2.5 ppm are removed, Figure 5d shows agreement within the GOSAT predicted errors between GOSAT and aircraft.

GOSAT U improves over the a priori for real (Figs. 5c-d) and in simulated (Fig. 4b) results. The black (aircraft) vs. blue (GOSAT) in Fig. 5c shows much better agreement in July-November than prior (green) vs. black (aircraft). The bias seen in the U partial column versus the aircraft U estimate is also found in XCO_2 versus the aircraft.

5.1 Summary of comparisons to all validation data

GOSAT LMT, U, and XCO_2 are compared to aircraft profiles, where the aircraft profile has the GOSAT averaging kernel applied so that the sensitivity is considered. The comparison locations are shown in Fig. 2. More detailed comparisons, showing results for each location and/or campaign, are shown in Appendix B.

Table 2 shows the biases with respect to aircraft data and Table 3 shows the standard deviation with respect to aircraft, for single and averaged observations. The bias or standard deviation is calculated for every site (or campaign). The mean represents the average of all site means, and the ± represents the standard deviation of all the sites (or campaigns). The variability of the bias by location or time is a key metric in the data quality. Biases that vary by season or location are the biggest detriment of use of satellite data (or any other type), as the assimilation will attribute these biases to spurious fluxes.

The co-location error is estimated by comparing CarbonTracker to itself at the satellite location/time and CarbonTracker at the aircraft location/time. For the ocean surface sites, a vertical co-location error is estimated by comparing CarbonTracker with the LMT averaging kernel to CarbonTracker at the surface. In Tables 2-4, the top entry in the ocean surface ct_ct difference is from discrepancies in horizontal location and time. The bottom entry is the ct_ct difference between the CarbonTracker LMT quantity and CarbonTracker at the surface.

5.1.1 Bias

In Table 2, the "ct_ct bias" is the estimate of the co-location bias; it is the mean difference between CarbonTracker at the satellite location/time and CarbonTracker at the aircraft location/time. The ct_ct bias is largest for aircraft land, with an overall bias of -0.6 ppm and bias variability of 0.7 ppm. This gives an approximate best case of what could be achieved by GOSAT-AIRCRAFT comparisons. An investigation of the -2 ppm ct_ct bias at CAR in

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July, during the drawdown finds that the GOSAT observations are always taken 3-4 hours later than the aircraft in July. The CarbonTracker model estimates the effect of +3 hours as resulting in a -2 ppm change. The ct_ct bias reflects spatial, diurnal, and seasonal co-location errors. Taking out the 5 sites that have errors > 0.5 ppm (see Appendix B, table b): WBI, BNE, CAR, HIL, and CMA, reduces the ct_ct bias to -0.2 ± 0.3 ppm.

In Table 2, the "true mean by site/campaign" is the mean value averaged by location (or campaign number). The ± represents the standard deviation of the mean by location (or campaign number). The GOSAT retrieval must improve on the ± at the very least to provide information on the atmospheric state. The GOSAT a priori bias represents how well the GOSAT prior does. The GOSAT prior improves over the true variability on land but not for ocean cases for LMT. For U, the a priori variability to true is the same size as the true variability. The "GOSAT bias" is the bias of the retrieved GOSAT values. Comparing to the GOSAT prior, there is improvement in all entries of the absolute bias, except XCO_2 for ESRL ocean, and U, XCO_2 for AJAX. Issues with both U and XCO_2 suggests a possible issue with the profile extension above the aircraft. The improvement in the GOSAT ± bias occurs in all ocean comparisons and in LMT land. For ESRL land, GOSAT LMT has an overall bias of -0.3 ppm and bias variability of 1.0 ppm. If the 5 stations with large ct_ct variability are taken out, the bias decreases to -0.3 ± 0.7 ppm.

The location-dependent bias is important because this bias variability will be attributed to phantom fluxes. The bias variability is 0.5 (1.0) ppm for GOSAT LMT, 0.2 (0.9) ppm for U, and 0.4 (0.9) for XCO_2 ocean (land). The LMT location dependent bias is no worse than the XCO_2 location dependent bias, whereas the LMT signals are much more variable than XCO_2. The bias variability for XCO_2 and U are possibly too high due to uncertainty of the aircraft profile extension because the bias variability is much larger than the 0.3 ppm seen in Kulawik et al. (2016) versus TCCON. The variability of the LMT ct_ct bias is 0.7 ppm, and when the 5 sites with ct_ct co-location error larger than 0.5 ppm are taken out, the GOSAT LMT bias variability drops to 0.7 ppm. Taking out sites with large ct_ct biases for XCO_2 does not improve the GOSAT XCO_2 bias variability. Taking out the top 4 GOSAT bias outliers results in a GOSAT bias variability of 0.5 ppm for the remaining sites, however these 4 sites are not the same sites where LMT has bias issues, nor are they sites where ct_ct XCO_2 shows a large bias.

5.1.2 Standard deviation

Table 3 shows standard deviations of key quantities versus aircraft data. The co-location standard deviation, which is estimated using the standard deviation of CarbonTracker at the satellite location/time minus

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CarbonTracker at the aircraft location/time, is less than 0.3 ppm for aircraft ocean, 2.1 ppm for LMT land, 0.5 ppm for U land, and 0.8 ppm for XCO_2 land. The surface ocean has 1.0 ppm co-location error, also including the vertical co-location. The AJAX comparisons, which are primarily from GOSAT underflights, has a co-location error half that of the ESRL land matches, which have coincidence criteria of 7 days, and 3-5 degrees.

The next entry is the predicted error, given by Eqs. 7 and 9, which is on the order of 4.5 ppm for LMT, 1.7 ppm for U, and 0.7 ppm for XCO_2. The actual standard deviation of GOSAT versus aircraft, however, is about half that for LMT and U, and double the predicted error for XCO_2. This is discussed in Section 5.1.5.

The next entry, "true variability" shows how much the different partial columns vary seasonally. The variability of LMT for land, at 5.4 ppm, is about double that of U or XCO_2 (at 2.0 and 2.5 ppm, respectively), and the variability for ESRL ocean, at 1.1 ppm, about 50% larger than U, XCO2 at 0.8 ppm.

The prior standard deviation (n=15), and GOSAT standard deviation (n=15) look at the error of averaged GOSAT values, which is important for assimilation. Similarly to Kulawik et al. (2016), the GOSAT error does not drop off as the inverse square root of the number of observations, like it would if the error were fully random. The error for 15 observation averages is about 0.4 times that of 1 observation for land, with a similar factor for all quantities; and about 0.5 times that of 1 observation for ocean, similarly for all quantities. Note that the co-location error has been subtracted out (in quadrature) for both the a priori and GOSAT errors.

The standard deviations for LMT, U, and XCO_2 improve over the prior for land cases but improve only marginally or do not improve over ocean. The location-dependent bias, however, does show improvement for LMT and U in Table 2. For surface ocean sites, which are only compared to LMT, the improvement over the prior is much better, mainly because the prior is not very good at these sites.

5.1.3 Errors separated into co-location, random, and correlated error

The errors between aircraft and GOSAT observations can be parametrized by the number of GOSAT observations that are averaged. Kulawik et al. (2016) found the form in Eq. 11 matched well to the observed errors.

$$error = \sqrt{(a^2 + b^2 / n} \qquad (11)$$

$$error = \sqrt{(\varepsilon_{coloc}{}^2 + a_o{}^2 + b^2 / n} \qquad (12)$$

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where *n* are the number of GOSAT observations that are averaged (all of the averaged observations match a single aircraft measurement), *a* is error that does not reduce with averaging, and *b* is the random error. *a* is further split into co-location error, ε_{coloc}, plus a_o, the correlated error in Eq. 12. Correlated error means that no matter how many observations are taken, this error does not reduce, and can be due to interferents or spectroscopy in combination with attributes specific to different locations and times.

The co-location error is the error resulting from imperfect matching of the aircraft and satellite observations, and is approximated by the standard deviation of the CarbonTracker model at the validation location and time and the model at the satellite observation location and time, and is tabulated in Table 4. This term, as seen in Table 4, is comparable to or even larger than *a* for LMT land cases. Some co-location schemes (e.g. as implemented by S. Basu described in Guerlet et al. (2013)) use the model-model differences to select the best satellite observations to match validation data. Equation 11 is used to determine a and b, and then a_o is calculated from *a* and ε_{coloc}.

The co-location error is subtracted from the correlated error, to try to remove the effect of co-location on the error estimate. The three quantities from Eq. 12 are shown in Table 4. For LMT the co-location error is about the same size as the correlated error for ocean, and the co-location error is larger than correlated error for land. For U and XCO_2, the correlated errors are larger than the co-location error for ocean, and comparable for land.

5.1.4 Comparison of XCO_2 results to previous results

We compare GOSAT XCO_2 comparisons to the previous validations using TCCON (Wunch et al., 2011b; Kulawik et al., 2016) and HIPPO observations (Frankenberg et al., 2016). The GOSAT comparisons to HIPPO in Frankenberg et al. (2016) were for at least 6 averages and did not subtract co-location error (which is only 0.1 ppm over ocean). Using Eq. 12 and Table 4, we find that the XCO_2 error for n=6 is 0.43 ppm, in agreement with 0.45 from Frankenberg et al. (2016). We would expect the same result, as we are comparing to the same dataset with the same coincidence criteria. Without co-location error, the XCO_2 from n=6 is 0.42 ppm. For ESRL land, several quantities in Tables 2-4 can be directly compared to previous GOSAT/TCCON validation: the co-location error (0.8 ppm) is larger than co-location for geometric coincidence (0.4 ppm) but smaller than for dynamic coincidence (0.9 ppm) from Kulawik et al. (2016). This makes sense as Kulawik et al. (2016) had a 1 hour coincidence with TCCON whereas 7 days is used in this paper, since aircraft measurements are sparser in time than TCCON observations. a_o and b values of 0.7±0.5 ppm and 1.6±0.2 ppm in

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this work are consistent with 0.8 ±0.2 ppm and 1.6±0.1 ppm, for a (corrected) and b, respectively, from Kulawik et al. (2016) Table 2. Additionally, the predicted error of 0.9±0.1 which is a factor of 1.9 less than the actual error of 1.7±0.4 are identical to the values and relative sizes of predicted versus actual error in Kulawik et al. (2016) at the end of section 3.1. Kulawik et al. (2016) estimated that the XCO2 location-dependent bias was 0.3 (after removing outlying stations north of 50N and locally-influenced stations).

As discussed in Section 5.1.1, the location-dependent bias found in Kulawik et al. (2016) versus TCCON sites was 0.3 (after removing outlying stations north of 60N and locally-influenced stations). In this paper, we find this variability to be 1.0 ppm. One reason for the discrepancy could be from the extension of the profile above the aircraft measurement (about 5-6 km). However, as seen in Table A4, extension of the aircraft profile by 4 different methods did not make more than 0.1 ppm difference in the bias variability of U. Another possible cause for the discrepancy is that GOSAT has been extensively tested against TCCON and issues that show up at TCCON locations have been previously addressed. This was tested by fitting bias correction factor for U specifically, rather than calculating bias-correction factors for LMT and subtracting the LMT partial column from GOSAT XCO_2 to estimate U. The bias variability for U did not improve when bias correction factors were calculated directly for U. In Section 4.2, discrepancies between the XCO_2 calculated from the aircraft and TCCON XCO_2 are seen in locations where both measurements are co-located, so this does point towards the reason being the profile extension.

5.1.5 Predicted and actual error correlations

One surprising finding is that LMT and U actual errors are less than the predicted errors whereas the actual XCO_2 errors are larger than predicted, even though all three errors are calculated from the same error covariance (see Eqs. 7-8). Equation 9c relates the errors in LMT, U, and XCO_2. For land, the XCO_2 predicted error of 0.9 ppm is consistent with LMT predicted error of 4.6 ppm, U error of 1.8 ppm, and error correlation of -0.8. The XCO_2 actual error (1.7 ppm) is much *larger* than the predicted error whereas the LMT and U errors are *smaller* than predicted.

The discrepancy between the actual and predicted errors arises from the actual correlation of the LMT and U partial column errors. The predicted error correlation between LMT and U is -0.8. This means that values too low in LMT should be matched with values too high in U, such that the total column should have lower relative errors than either partial column separately. The actual error correlation of (LMT-aircraft) and (U-aircraft) average +0.6, meaning that when LMT is high, U also tends to be high, and

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XCO_2 does not gain precision when combining LMT and U. So the finding is that the LMT-U error correlation must be changed from the predicted value of -0.8 to the measured value of +0.6. When this error correlation is changed and all error terms multiplied by approximately *0.6, the predicted and actual errors of LMT, U, and XCO_2 are consistent. Over ocean, the error correlation is the same, but the multiplication factor is

The errors in Table 3 are the standard deviation with respect to validation data at one location. The persistent regional biases captured in the "GOSAT bias" standard deviation also reflect errors in the GOSAT measurement and should somehow be combined into the full error. These regional biases likely result from persistent interferent errors, such as due to aerosols, or an interaction between spectroscopic errors and local conditions. Some but not all of the bias, particularly for LMT land, can be attributed to co-location error (see bias ct_ct (ppm) in Table 3). The correlation of the LMT and U location-dependent biases (using biases separated by location from Table B1) is also positive, 0.6, similar to the correlation of the individual errors in LMT and U, so this would not account for the discrepancy between the predicted correlation of -0.8 and actual correlation of 0.6 between the LMT and U errors. Another possible reason for the positive error correlation in LMT and U is that it is a consequence of the bias correction. The error correlation on the uncorrected data was found to be -0.8, which supports that the bias correction modifies the error correlation between U and LMT.

In summary, the single-sounding errors of GOSAT LMT and U over land (ocean), based on the ESRL aircraft comparison, are 3.4 and 1.3 ppm (1.5 and 0.8 ppm) respectively, with a positive correlation of 0.6. This is consistent with the XCO_2 error of 1.8 (1.0) ppm for land (ocean), using Eq. 9c. To find the error of averaged LMT and U, the single-sounding errors can be replaced by Eq 11, with a and b values given in Table 4, and the same LMT-U correlation of 0.6.

5.2 Variability within the U.S.

The CarbonTracker model identifies 19 eco-regions within North America (http://www.esrl.noaa.gov/gmd/ccgg/carbontracker/CT2011_oi/documentation_assim.html). The ESRL aircraft stations can be broadly grouped into conifer forest: pfa, etl, esp, thd; grass/shrub: car, bne; crops: hil, wbi, sgp; forest/field: dnd, lef, nha, cma, sca; and mixed: tgc. The variability at these sites is a combination of the local activity at the site, latitude of the site, and transport into/out of the site.

Maps of GOSAT LMT, U, and XCO_2 along with aircraft, surface, tower, and TCCON observations for February and July are shown in Fig. 6. In February, the lower troposphere has already reached near peak values, whereas the U

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partial column is continuing to increase through April. In July, there is a large gradient in the LMT, primarily west to east, but also north to south, seen also in the stations shown in Fig. 6. The LMT pattern agrees with aircraft and tower patterns, showing that GOSAT LMT is able to see variations in the summertime CO_2 depletion near the surface due to biospheric processes. The U partial column shows more discrepancies with aircraft than LMT which is in general agreement, and the same pattern of discrepancies are also seen for XCO_2 versus aircraft. At the two sites where aircraft and TCCON are jointly observed, SGP in Oklahoma and LEF in Wisconsin, XCO_2 agrees with TCCON rather than the aircraft. This indicates an issue with the extension of the aircraft profile from the top aircraft measurement (about 6 km) to the top of the atmosphere.

Figure 7 shows the seasonal cycle at 5 sites arranged west-to-east (a-e) and north-to-south (f-j). The seasonal cycle amplitude in LMT increases traversing the region in both west-to-east and south-to-north directions. There is also a shift to later in the seasonal cycle minimum going either west to east and north to south. The seasonal cycle maximum is harder to quantify for the LMT. The LMT CO_2 rises and stays fairly flat from January to April, therefore the maximum can be influenced by small temporal variations in the data, in contrast to U or XCO_2 which rises steadily until April.

5.3 Comparisons to remote ocean sites

Remote surface sites are useful as comparisons to LMT as these locations are expected to be fairly well mixed in the boundary layer. These comparisons are not used for estimating errors or bias corrections because there could be a mismatch in airmass. Comparisons to surface sites are direct comparisons without the averaging kernel applied, as there is no profile information at these sites. The vertical co-location error is estimated by comparing CarbonTracker LMT versus CarbonTracker surface values in Tables 2 and 3. The GOSAT LMT a priori is significantly worse for these locations as compared to North America, and this allows the GOSAT product to show what is in the data versus the prior. In Table 4, the correlated error for surface sites is higher than for ocean aircraft comparisons (1.0 ppm vs. 0.3 ppm, respectively), and the mean bias is also higher (0.7 ppm vs. 0.1 ppm, respectively). Because of the GOSAT ocean coverage, there are typically only about 4 consecutive months for each station, but this is adequate to evaluate the performance. Figure 8 shows an average over all locations, and the 4 sites with the highest number of matches, arranged from north to south. Note the improvement of GOSAT (red) over the a priori (green) when comparing to the surface site measurements (pink). Unsurprisingly, the performance of XCO_2 (blue) shows that surface site observations are not suitable for XCO_2 validation. GOSAT LMT improves over the prior in terms of the overall bias, the bias variability, and the standard deviation over the prior even without averaging; the error reduces further with averaging.

5.4 Source versus outflow in biomass burning with comparisons to MOPITT CO

The SH region is of particular interest for validation as the GOSAT prior is nearly spatially and vertically constant, varying primarily by month. GOSAT LMT and U partial columns are compared to MOPITT multispectral CO retrievals and MODIS fire counts for February, August, and September, 2010 in Figs. 9 and 10. The GOSAT prior (left column in Figs 9-10) is nearly constant in the southern hemisphere. The scale needed to span the seasonal range is about 13 ppm, about half that needed for the variability in the U.S. The pattern seen in LMT matches MODIS fire count images, shown in the right column, and matches MOPITT near-surface CO shown in the middle column. Because of the different overpass time and the different coverage due to cloudiness between these satellites, an exact match should not be expected. Also, note that multi-spectral CO does not have surface sensitivity over ocean. In February, sub-Saharan Africa has fires and south-central Africa does not, whereas the situation is reversed in August. This pattern is seen in GOSAT LMT, MOPITT near-surface, and MODIS fire counts.

In the mid-troposphere, MOPITT CO shows enhancement in sub-Saharan Africa in February, central Africa in August, and outflow in October, and GOSAT retrieved U shows the same patterns as MOPITT. Interestingly, both MOPITT and GOSAT show no enhancement in South America in August, whereas the surface has very strong enhancements in both.

The LMT signal in the Amazon region is clearly visible by May (not shown), whereas the CO signal seen from MOPITT (http://www.acom.ucar.edu/mopitt/MOPITT/data/plots6j/maps_mon.html) seems to ramp up starting in August. We look at the $\Delta CO/\Delta CO_2$ emission ratio in May and August to check the enhancements seen in LMT relative to MOPITT in these two months has a similar ratio is seen both months. The enhancements and background values for surface CO and LMT CO_2 are shown in Table 5.

The emission ratio estimate is calculated by taking the ratio of MOPITT multispectral CO divided by GOSAT LMT, each with their background subtracted. The raw emission ratio (which does not consider the sensitivity) is 4.7% for May, 2010 and 5.8% for August, 2010, using the degrees of freedom (DOFs) > 0.3 data. If "all MOPITT" data is used, the raw emission ratio for May and August, 2010 is 2.2% and 2.3%, respectively. The ratio dropping to half makes sense because the average MOPITT DOFs drops by half between these two categories. Based on the relative DOFs between

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MOPITT and GOSAT, the emission ratios are likely about 10%, however, the dropoff of the vertical sensitivity would also need to be taken into account. Without utilizing a model as a transfer function, the exact ratio cannot be estimated, due to the varying sensitivities with altitude and observation locations and times. The emission ratio seen by the MOPITT and GOSAT LMT products are consistent with those estimated from aircraft observations over tropical forests by Akagi et al. (2011, Table 1), which is 8.8%. The ratio is consistent (within 2%) between May and August, and the ratio is consistent with aircraft observations. If, instead, the emission ratio were calculated from column XCO_2 and CO, the free troposphere and stratospheric variations in CO and CO_2 would need be either zero or solely from locally influenced fires.

5.5 Differences between LMT and U

The difference between CO_2 in the free troposphere and boundary layer can be used to evaluate model transport. One previous finding is that surface assimilation estimates of northern minus southern hemisphere land flux are correlated with the difference between CO_2 at 4 km and 1 km in the assimilated model. When the vertical difference of CO_2 is larger than aircraft observations, models tend to predict too large northern hemisphere sinks and too large southern hemisphere sources (Stephens et al., 2007). Measurements CO_2 and 4 km and 1 km are performed only at a few sites worldwide, primarily in the U.S. Therefore, global measurements of the difference between CO_2 in the free troposphere and boundary layer are of great interest. In this section we calculate the errors for LMT-U compared to aircraft profiles and show this difference for GOSAT and CarbonTracker in the U.S. and the southern hemisphere in two different months.

The error estimate for LMT-U is calculated using Eq. 13. Note that a positive correlation in the errors for LMT and U results in a smaller error for the quantity (LMT – U).

$$\sigma_{(LMT-U)} = \sqrt{\sigma_{lmt}{}^2 + \sigma_u{}^2 - 2 * \sigma_{lmt}\sigma_u corr} \qquad (13)$$

Table 5a-c give the bias, standard deviation, and error with averaging for LMT – U. In Table 5a, the GOSAT bias and bias variability of (LMT – U) improves over the prior for all cases. The bias variability of 0.3, 0.9 and 0.8 ppm of (LMT – U) for HIPPO ocean, ESRL ocean, and ESRL land, respectively, is comparable to the LMT bias variability of 0.3, 1.0, and 1.0 for the same categories. In Table 5b, the 15-observation average standard deviation for GOSAT LMT-U is 0.6 (1.2) ppm for ocean (land), 0.2 ppm higher for ocean and 0.7 ppm lower for land than LMT. In Table 5c, the correlated error is 0.5 (0.9) ppm for ocean (land), which is 0.2 ppm higher for ocean and 0.8 ppm lower for land. The land standard deviation for LMT-

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U is 2.3 ppm before subtracting off the 2.1 ppm co-location error. The difference between the land error for LMT and LMT-U is due to the estimated size of the co-location error.

Figure 11 shows the seasonal cycle of LMT-U for 3 sites. The differences between GOSAT and aircraft values at the CAR site in Colorado and LEF in Wisconsin during the drawdown can be explained by co-location error. The dotted lines shows CarbonTracker matched to GOSAT (red dotted) or aircraft (pink dotted) locations/times. The difference between the red dotted and pink dotted lines estimate the co-location error. If GOSAT were corrected by this difference, the agreement with aircraft would be much better. The co-location bias and standard deviation are estimated in Tables 6a and 6b, and are large compared to the observed GOSAT errors. The error estimates for GOSAT are corrected by the co-location error.

The predicted error for land in Table 6b is 2.7 ppm, whereas the actual error is 2.3 ppm. If LMT and U had zero correlation, the predicted error (using Eq. 13) would be 3.6 ppm. This is another corroboration of the positive correlation between the LMT and U errors.

Figure 12 shows LMT – U for February and July in the U.S. averaged over 2010-2014 for February and 2009-2013 for July. Aircraft values for LMT – U are shown as squares. The aircraft patterns are captured by GOSAT, with discrepancies in July for CAR, SGP, and SCA due to co-location error (e.g. see CAR plot in Fig. 11). The CarbonTracker model captures the aircraft patterns very well. The two maps show differences in the southwestern U.S. in July, where there are no aircraft measurements. Figure 12c-d shows LMT – U for February and October in the southern hemisphere. The only aircraft site in this region is Rarotonga, where Fig. 11 shows good agreement for CarbonTracker and GOSAT. The patterns in the southern hemisphere show some differences between CarbonTracker and GOSAT. In February, GOSAT shows a high gradient in the eastern Pacific and northern South America not seen in CarbonTracker, and more negative gradient in central and southern Africa. In October large gradients are seen by GOSAT in South America and Africa with outflow into the Atlantic, with little seen in CarbonTracker.

LMT-U is predominantly positive in this southern hemisphere region in October. Vertical transport from the northern hemisphere would predominantly show up in the U partial column, whereas flux from land or ocean would predominantly show up in the LMT partial column. An overall positive value for LMT – U could either suggest that the overall flux is positive in this month, or that transport from the northern hemisphere was negative, though the blank space in the Amazon due to cloudy conditions, where LMT-U is expected to be negative from plant uptake, creates

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uncertainty both in this crude estimate and in the formal assimilated results from GOSAT data.

6.0 Discussion and conclusions

GOSAT near-infrared observations provide information to retrieve two partial columns, one from the surface to about 2.5 km (LMT_XCO_2), and the second above about 2.5 km (U_XCO_2). The LMT partial column is sensitive near the surface, whereas the U partial column is sensitive to the free troposphere and above; the two partial columns have distinct seasonal cycles, with peaks and troughs earlier for the LMT partial column, and later for the U partial column, as compared to XCO_2. After bias correction, both partial columns show agreement with aircraft, LMT shows agreement with remote surface observations, and both show improvement over the GOSAT prior. Single observations for land have observation errors of 3.4, 1.3, and 1.7 ppm for LMT, U, and XCO_2, respectively, and single observations for ocean have observation errors of 1.5, 0.8, and 0.9 ppm for LMT, U, and XCO_2, respectively. These errors are significantly reduced with averaging, though some systematic errors, generally below 1 ppm, remain. The co-location errors from mismatch of GOSAT versus validation data, as quantified by CarbonTracker, makes the errors on LMT challenging to validate. The value of observing two partial columns can be seen in Fig. 8, where the GOSAT LMT agrees with remote surface sites whereas neither the prior nor XCO_2 agree with the surface site, and Figs. 9-10, where surface versus tropospheric CO_2 are distinguished for source and outflow of African biomass burning emissions in August and October. The observed LMT CO_2 enhancements are consistent with MOPITT multispectral CO and emission ratios in Akagi et al. (2011). The LMT-U difference, which can be used to evaluate model transport error (e.g. Stephens et al., 2007), has also been validated with monthly average error of 0.8 (1.4) ppm for ocean (land). The new LMT partial column allows the local boundary air to be distinguished from the free troposphere, captured in the U partial column, disentangling local versus remotely influenced signals.

Funding Acknowledgements:

This research was funded by NASA and performed under BAER Institute's ARC-CREST cooperative agreement.

The AJAX team recognizes the support and partnership of H211 L. L. C. and the NASA Postdoctoral Program; funding for instrumentation and aircraft integration is gratefully acknowledged from Ames Research Center Director's funds.

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CarbonTracker CT2015 results provided by NOAA ESRL, Boulder, Colorado, USA from the website at http://carbontracker.noaa.gov.

Part of this work was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with NASA.

TCCON at Lamont and Park Falls are funded by NASA grants NNX14AI60G, NNX11AG01G, NAG5-12247, NNG05-GD07G, and NASA Orbiting Carbon Observatory Program, with the DOE ARM program providing technical support in Lamont and Jeff Ayers providing technical support in Park Falls.

Atmos. Chem. Phys. Discuss., doi:10.5194/acp-2016-720, 2016
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Appendix A. Bias Correction

The ACOS-GOSAT XCO_2 product undergoes bias correction (Wunch et al., 2011) which significantly improves the errors (Kulawik, 2016). We apply this same technique to correct the LMT product. Following the LMT correction, U is corrected by subtracting the LMT partial column from ACOS-GOSAT corrected XCO_2, thus maintaining consistency between the [LMT,U] partial columns and the total XCO_2 column after bias-correction.

To determine the LMT bias correction, GOSAT and aircraft data are matched using dynamic coincidence criteria (Wunch, 2011), and the difference between GOSAT LMT and aircraft LMT is calculated for all pairs versus each potential parameter. In order to identify the critical bias-predicting parameters, for those cases for which this difference has a clear slope, a bias correction is applied iteratively, where the strongest parameter dependence is corrected before the next parameters are tested. At the end all parameters are fit simultaneously. Filters are applied to flag the data as bad when the bias is significant even after correction. The parameters considered for bias correction are: delta_grad_co2, albedo_1, albedo_2, albedo_3, albedo_slope_1, albedo_slope_2, albedo_slope_3, aod_dust, aod_ice, aod_total, b1offset, ice_height, surfacePressure_xa, surfacePressureDiff, co2_ratio, dp_cld, h2o_ratio, s32, xco2_error, LMT_dofs (degrees of freedom for LMT partial column), U_dofs (degrees of freedom for U partial column), xco2_dofs, asza, lza, and delta_grad_co2_prime. These parameters are described in the ACOS-GOSAT v3.5 user's guide with the exception of delta_grad_co2_prime which is defined as delta_grad_co2 with the value set to 50 when it is greater than 50 for land, and the value set to -10 when it is greater than -10 for ocean. Two figures of merit were considered for the cutoffs and bias fits, (1) bias variability by location and season and (2) the single-observation standard deviation. The former is the standard deviation of the biases calculated in 4 seasons and for each location/campaign. For both of these figures of merit, smaller is better.

By far the strongest bias is related to delta_grad_CO2. This parameter is the difference between the retrieved CO_2 and a priori dry-air molefraction between the surface and vertical level 13 (approximately 630 hPa for soundings near sea level), and represents the slope of the retrieved CO_2 profile in the troposphere The resulting coefficient for this term is 0.396 for ocean and 0.310 for land soundings. This indicates that, for ocean, approximately 40% of the CO_2 attributed to the surface should be moved from LMT to U, indicating that possibly (a) the troposphere is constrained too much relative to the surface, (b) an issue with spectroscopy, or (c) some other retrieval artefact. As the bias correction for simulated OCO-2 data is very similar factor (Kulawik, unpublished result), with simulations run with no spectroscopic error, it is likely a consequence of the constraint, or some other aspect of the retrieval.

The filtering cutoffs and bias terms are shown in Table A1. The errors calculated by the bootstrap method (Rubin, 1981). The effects of the cutoffs and bias corrections from Table A1 on biases and standard deviations is shown in Table A2.

The overall land bias is not zero because the land bias constant correction undergoes a final step to harmonize land and ocean observations by matching GOSAT values for pairs of close land and ocean observations. The results for different matching criteria are: 1 degree and 1 hour (25 matches, bias -0.54 ppm in LMT and -0.96 ppm in XCO_2), 2 degrees and 24 hours (295 matches, 0.17 ppm in LMT and -0.61 ppm in XCO_2), 4 degrees and 48 hours (4095 matches, 1.17 ppm in LMT and -0.09 ppm in XCO_2), and using dynamic coincidence criteria (422,542 matches, 0.29 ppm in LMT, -0.42 in XCO_2). Using the assumption that there is no bias in XCO_2, the 4 degree, 48 hours result is used, and 1.17 ppm is added to the LMT constant bias for land. This constant bias is subtracted from LMT, then the LMT partial column is subtracted from XCO_2 to generate the corrected U partial column.

As seen from Tables A3a and A3b, all bias corrections are superior to the uncorrected dataset, and all correction tests perform similarly in the bias standard deviation and mean standard deviation, but with variability in the overall bias, depending on the development set that is used. The overall bias has some uncertainty on the order of 0.5 ppm.

Another potential error source that is quantified is the effect of different profile extension schemes above aircraft observations. The ESRL aircraft measurements go up to 5-8 km above ground, and the HIPPO observations go up to 9-13 km above ground. 4 different profile extension methods are tried above the aircraft: using (1) the GOSAT a priori profile, (2) extending the top aircraft measurement to the tropopause with the GOSAT prior above this, (3) the CT2015 model, and (4) extending the top aircraft measurement to the tropopause with the CT2015 model above this. Table A4 shows the land and ocean characteristics with each of the profile extension type. The main effect is on the overall bias (up to 0.3 ppm) in the comparisons. One issue is likely in the top 4 levels, from which a difference between a priori and the true profile would propagate as a bias.

There were two ways that the developed bias correction was insulated from the validation: (1) the bias correction uses dynamic coincidence criteria (Wunch, 2011), whereas the comparisons to validation data use geometric coincidence criteria (±5 degrees latitude and longitude, and ±1 week). The

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overlap between these two sets is about 50%. (2) remote ocean surface sites were not used to develop the bias correction. These locations are expected to have good mixing between the surface and 2.5 km, but since we do not have profiles at these locations, these observations are not used for direct validation. These comparisons between GOSAT and remote surface sites show excellent improvement over the GOSAT prior. (3) No data over the southern hemisphere biomass burning is used in the bias correction, and GOSAT compares very well to MOPITT in this region.

The mean and standard deviation of the bias correction is -11.4±7.6, 2.7±2.7 ppm for LMT and U land, respectively and -1.0±3.1 ppm, -1.7±0.9 ppm for LMT and U ocean, respectively. The mean and standard deviations of the bias correction for XCO_2 are: -0.6±1.0 ppm for land and -0.6±0.6 for ocean. The bias corrections are larger for the partial columns than for XCO_2; the size and variability of the bias correction is an indication of its importance.

Atmos. Chem. Phys. Discuss., doi:10.5194/acp-2016-720, 2016
Manuscript under review for journal Atmos. Chem. Phys.
Published: 7 October 2016
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Appendix B. Detailed comparisons by site and campaign

In addition to the averaged results provided previously, Table B1 below breaks down the validation results for each individual station. This table could be useful for diagnosing outliers in the comparisons, looking at correlations of site-to-site biases or standard deviations in LMT and U.

Atmos. Chem. Phys. Discuss., doi:10.5194/acp-2016-720, 2016
Manuscript under review for journal Atmos. Chem. Phys.
Published: 7 October 2016
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Table 1
Predicted errors and degrees of freedom for LMT and U. As seen in Table 2, the predicted errors are much larger than the actual errors.

	land	ocean
LMT error (ppm)	4.3 ppm	4.4 ppm
U error (ppm)	1.7 ppm	1.7 ppm
U,LMT pred. error correlation	-0.72	-0.78
LMT DOFs	0.86	0.86
U DOFs	0.84	0.83

Table 2. Biases versus aircraft. The top entries are the co-location biases. The second row is the mean and variability of the true state. The 3rd row are the prior bias, and the fourth set are the GOSAT bias (prior and GOSAT bias have co-location bias subtracted). All data is first averaged by location or campaign. The ± represents the variability of the bias by location or campaign, a key metric in the data quality.

	Type	**Ocean surface (ppm)**	**HIPPO Ocean (ppm)**	**ESRL Ocean (ppm)**	**ESRL Land (ppm)**	**AJAX Land (ppm)**
CT_CT bias (estimate of co-location bias)	LMT	-0.3±0.3 -0.3±0.8	-0.3±0.2	-0.3±0.4	-0.6±0.7	-0.6
	U		0.1±0.1	-0.1±0.1	0.0±0.2	0.0
	XCO_2		0.0±0.1	-0.1±0.1	-0.1±0.3	-0.1
true mean by site/campaign	LMT	391.3±1.6	392.2±1.6	391.7±1.1	392.2±3.1	393.6
	U		391.1±1.2	391.3±1.6	391.2±0.6	392.2
	XCO_2		391.4±1.3	391.4±1.5	391.5±1.1	392.4
prior bias	LMT	-0.8±1.5	0.1±2.4	-1.5±4.5	-0.4±1.2	-1.4
	U		1.2±0.1	-1.2±1.6	0.6±0.6	0.4
	XCO_2		0.9±1.4	0.4±2.3	-0.2±0.6	-0.1
GOSAT bias	LMT	1.1±1.1	0.1±0.3	0.3±0.7	-0.2±1.0	0.4
	U		0.1±0.3	0.7±0.1	0.3±0.9	1.0
	XCO_2		0.1±0.2	0.6±0.4	0.1±0.9	0.7

Table 3. Standard deviations versus aircraft showing the errors resulting from imperfect co-location, GOSAT predicted error, and GOSAT error (for single observations). The next sets are the true variability, 15-observation averages of prior error and GOSAT error. The GOSAT and prior standard deviation have the co-location error subtracted.

	Type	**Ocean surface (ppm)**	**HIPPO Ocean (ppm)**	**ESRL Ocean (ppm)**	**ESRL Land (ppm)**	**AJAX Land (ppm)**
colocation standard deviation	LMT	0.5±0.2 0.9±0.4	0.3±0.1	0.3±0.1	2.1±0.7	1.1
	U		0.1±0.1	0.2±0.0	0.5±0.3	0.1
	XCO_2		0.1±0.2	0.2±0.1	0.8±0.3	0.2

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predicted error (n=1)	LMT	4.3±0.2	4.3±0.3	4.3±0.1	4.6±0.3	4.1
	U		1.7±0.1	1.7±0.0	1.8±0.0	1.7
	XCO_2		0.6±0.1	0.7±0.1	0.9±0.1	0.8
GOSAT standard deviation (n=1)	LMT	1.7±0.4	1.7±0.3	1.5±0.1	3.4±0.7	2.9
	U		0.8±0.1	0.8±0.0	1.3±0.3	1.1
	XCO_2		0.9±0.1	0.8±0.1	1.7±0.4	0.9
true variability	LMT	1.3±0.8	0.6± 0.2	0.9±0.6	5.5±2.0	2.8
	U		0.4±0.3	0.8±0.8	2.0±0.2	2.0
	XCO_2		0.3±0.3	0.8±0.8	2.5±0.6	2.4
prior standard deviation (n=15)	LMT	2.2±0.9	0.5± 0.3	0.7±0.2	2.1±1.0	-
	U		0.3±0.1	0.5±0.0	0.9±0.2	-
	XCO_2		0.3±0.1	0.5±0.1	1.1±0.6	-
GOSAT standard deviation (n=15)	LMT	0.4±0.3	0.5± 0.1	0.4±0.1	1.9±1.1	-
	U		0.4±0.1	0.6±0.1	0.7±0.4	-
	XCO_2		0.3±0.1	0.4±0.1	0.8±0.5	-

Table 4. Estimated co-location, correlated, and random errors. The co-location errors are the same as in Table 3.

	Type	Ocean surface (ppm)	HIPPO Ocean (ppm)	ESRL Ocean (ppm)	ESRL Land (ppm)
colocation standard deviation	LMT	1.0±0.4	0.3±0.1	0.3±0.1	2.1±0.7
	U		0.1±0.1	0.2±0.0	0.5±0.3
	XCO_2		0.1±0.1	0.1±0.1	0.8±0.3
correlated error (a_o)	LMT	0.4±0.3	0.3±0.2	0.3±0.2	1.7±1.3
	U		0.3±0.2	0.5±0.1	0.6±0.4
	XCO_2		0.2±0.2	0.4±0.1	1.1±0.6
random error (b)	LMT	1.6±0.4	1.6±0.3	1.4±0.2	3.0±0.6
	U		0.8±0.1	0.6±0.1	1.2±0.1
	XCO_2		0.9±0.1	0.4±0.1	0.8±0.3

Table 5. Enhancements in CO and CO_2 for May and August, 2010. The target box is 11 to 18S, 60 to 56W for May, and 55-60S, 13-17W for August. The CO background box is 11 to 18S, 40 to 44W for May and 157.8-161.8W, 19-23S for August. Rarotonga aircraft measurements are used for CO_2 background.

		CO					**GOSAT LMT CO_2**	
		backg rnd (ppb)	Target all (ppb)	Target DOFs > 0.15) (ppb)	Target (DOFs > 0.25) (ppb)	Target (DOFs > 0.30) (ppb)	backgrnd from RTA (ppm)	Target (DOFs = 0.8) (ppm)
May, 2010	Mean	68±9	122±49	123±54	146±77	182±96	386.4	389.6±2.3
	N	1502	2023	1556	500	215		13
	DOFs		0.21	0.24	0.32	0.39		0.85
	ΔCO or ΔCO_2	-	54	55	88	114	-	3.2

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August, 2010	Mean	91±22	305±171	311±180	336±200	372±221	387.4	392.2±6.7
	N	2989	3881	3227	1887	1231		5
	ΔCO or ΔCO_2	-	213.7	219.3	244.8	281.1	-	4.8

Table 6a. Bias terms for LMT – U. Compare to Table 2.

	HIPPO Ocean (ppm)	ESRL Ocean (ppm)	ESRL Land (ppm)
colocation bias	-0.4±0.2	-0.2±0.3	-0.6±0.5
true mean	1.1±0.8	0.4±0.5	1.0±2.7
prior bias	-1.0±1.3	-2.8±2.9	-1.0±1.2
GOSAT bias	0.0±0.4	-0.5±0.9	-0.5±0.8

Table 6b. Standard deviations for LMT – U. Compare to Table 3. The predicted errors in the table use the errors given at the end of Section 5.1.5.

	HIPPO Ocean (ppm)	ESRL Ocean (ppm)	ESRL Land (ppm)
colocation stdev	0.3±0.1	0.3±0.1	2.1±0.7
predicted error (n=1)	1.2±0.0	1.2±0.0	2.7±0.0
GOSAT stdev (n=1)	1.5±0.4	1.3±0.1	2.3±0.5
true variability	0.5± 0.2	0.8±0.1	4.8±1.5
prior stdev (n=15)	0.5± 0.2	0.8±0.1	1.4±0.8
GOSAT stdev (n=15)	0.5± 0.2	0.7±0.1	1.2±0.8

Table 6c. Error fits for LMT – U. Compare to Table 4.

	HIPPO Ocean (ppm)	ESRL Ocean (ppm)	ESRL Land (ppm)
colocation stdev	0.3±0.1	0.3±0.1	2.1±0.7
correlated (a)	0.4±0.2	0.6±0.0	0.9±0.9
random (b)	1.4±0.4	1.1±0.1	2.1±0.7

Table A.1 Filtering and Bias corrections

parameter	ocean filtering	ocean bias correction	land filtering	land bias correction
albedo_2	0.0215< val <0.024	-1272.02 ± 50	-	-
albedo_slope_2	val < 8e-6	-	-	-
aod_dust	val < 0.01	-	-	-36.03 ± 1
aod_total	val < 0.25	-	-	-
h2o_ratio	0.96 < val < 1.02	-	-	-
co2_grad_delta	-40 < val < 17	0.396330 ± 0.004	-	0.310 ± 0.003
constant	-	52.674 ± 6	-	0.01259 ± 0.4
b1_offset	-	-1.25204 ± 0.05	-	-
surfacepressure_xa	-	-0.0381105 ± 0.006	-	-
s32	-	17.0742 ± 3	-	-
surfacepressurediff	-	0.869280 ± 0.05	-	-
albedo_1	-	144.458 ± 9	-	-
co2_grad_delta_prime	-	-0.171350 ± 0.01	-	-0.027 ± 0.005
dofs_LMT	-	-	val > 0.68	-

Atmos. Chem. Phys. Discuss., doi:10.5194/acp-2016-720, 2016
Manuscript under review for journal Atmos. Chem. Phys.
Published: 7 October 2016
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xco2_error	-	-	val < 1.4	6.02 ± 0.3
albedo_slope_3	-	-	-1.5e-4 < val <2.0e-4	-
xco2_dofs	-	-	val > 1.3	-
ice_height	-	-	val > -0.1	-
surfacePressureDiff	-	-	-4 < val < 2	-
albedo_3	-	-	-	-11.66 ± 0.7
dp_cld	-	-	-	0.219 ± 0.01

* parameters also used in ACOS-GOSAT XCO_2 bias correction

Table A2a. Effects of bias corrections and quality flags on land comparisons (ESRL aircraft land observations)

	n	lmt bias (ppm)	lmt bias var. (ppm)	lmt stdev (ppm)	u bias var. (ppm)	u stdev (ppm)
original (XCO_2 flags)	15143	13.54	2.79	7.70	1.61	3.05
all quality flags (see appendix A)	12714	13.37	2.30	7.55	1.27	2.98
bias correction (see appendix A)	12714	-1.18	1.43	3.47	0.79	1.36
fit U separately	11978	-	-	-	0.70	1.43

Table A2b. Effects of bias corrections and quality flags on ocean comparisons (HIPPO and ESLR ocean dataset stations/campaigns: tgc, rta, aoa, 2S, 2N, 3S, 3N, 4S, 4N, 5S, 5N)

	n	lmt bias (ppm)	lmt bias var. (ppm)	lmt stdev (ppm)	u bias var. (ppm)	u stdev (ppm)
original (XCO_2 flags)	9836	1.73	3.46	3.77	0.78	0.85
with cutoffs (see Appendix A)	6143	1.47	1.92	3.18	0.63	0.69
bias correction (see Appendix A)	6143	0.04	0.68	1.60	0.38	0.79
fit U separately	6143	-	-	-	0.35	0.60

The fit parameters are tested for robustness by using a subset of the dataset to determine the fit and then testing the fit on the independent subset. For the ocean data, HIPPO campaigns 2N, 3S, 4, and 5 are used to develop bias correction, and HIPPO 2S and 3N are used for testing. For land data, stations bne, car, cma, dnd, esp, etl, hil, hip, are used for development, and stations lef, nha, pfa, sca, sgp, tgc, thd, wbi are used for testing.

Table A3a: Ocean bias correction robustness test. Comparisons to aircraft data are tested using (a) no bias correction, (b) bias correction using the test dataset, (c) an independent dataset, and (d) the entire dataset

Bias correction testing	Mean bias	Bias std	mean std
no correction	0.69	0.69	2.97
subset tested on itself	-0.04	0.33	1.47
independent subset	-0.26	0.46	1.58
all data used	-0.14	0.49	1.54

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Table A3b: Land bias correction robustness test. Same as Table A3a but for land.

Bias correction testing	**Mean bias**	**Bias std**	**mean std**
no correction	13.00	2.47	7.54
subset tested on itself	0.16	1.55	3.68
independent subset	1.05	1.24	3.67
all data used	0.50	1.51	3.65

Table A4: Effect of profile extension. GOSAT corrected as described in Table A1 and compared to aircraft data with profile extended 4 different ways: (a) using the GOSAT prior, (b) extending the aircraft to the tropopause pressure, with the GOSAT prior above this, (c) using the CT2015 model, and (d) extending the aircraft to the tropopause pressure, with the CT2015 above this

Profile extension	**LMT bias**	**LMT Bias std**	**LMT std**	**U bias**	**U Bias std**	**U std**
(a) prior	-0.90	1.37	3.46	-0.38	0.70	1.25
(b) extend+prior	-0.99	1.44	3.47	-0.20	0.79	1.35
(c) CT2015	-1.20	1.39	3.47	-0.02	0.66	1.26
(d) extend+CT2015	-1.18	1.43	3.47	-0.05	0.79	1.36

Table B1. Actual and predictions of errors by station/campaign. Columns *a* and *b* are the fits to actual errors when averaging using Eq. 11a; ε_{coloc} is the standard deviation of CT2015 at the observation vs. validation data. The predicted error is the error calculated from the ACOS full error covariance for each type of quantity. Bias ct_ct is difference between CT2015 at the satellite and validation locations. True mean is the average validation value at each location; prior and GOSAT biases are difference between the prior and retrieved GOSAT minus validation data. The last three columns are the standard deviation of the true, prior minus true, and GOSAT retrieved minus true for 15 observation averages.

location	latitude, longitude	ε_{coloc} ct_ct stdev	a corr. error	b rand. error	GOSAT prior (n=1)	GOSAT stdev (n=1)	pred. Error (n=1)	bias ct_ct	true mean	prior bias	GOSAT bias	true stdev (n=1)	prior stdev (n=15)	GOSAT stdev (n=15)
		(ppm)	(ppm)	(ppm)	(ppm)	(ppm)	(ppm)	(ppm)	(ppm)	(ppm)	(ppm)	(ppm)	(ppm)	(ppm)
a) LMT vs. surface ocean flasks at remote sites														
bmw	32N,65W	0.4	0.9	2.5	4.6	2.6	4.2	-0.8	391.8	-3.0	-1.4	3.3	2.8	1.1
mid	28N,177W	0.8	1.5	1.8	4.2	2.3	4.3	0.1	389.9	-2.4	-0.2	2.2	4.5	1.5
mnm	24N,154E	0.3	0.8	1.6	3.8	1.8	4.2	0.2	393.2	-3.8	-0.6	1.6	2.8	0.9
mlo	20N,156W	0.8	1.0	1.4	2.6	1.7	4.5	-0.6	390.9	-2.1	-0.3	1.7	2.2	1.0
kum	20N,155W	0.7	1.5	1.2	2.6	1.9	4.5	-0.6	390.0	-1.1	0.7	1.7	2.5	1.5
gmi	13N,145E	0.5	0.7	1.6	2.8	1.8	4.4	0.0	394.8	-2.9	0.9	1.2	1.9	0.8
chr	2N,157W	0.3	0.8	1.4	1.6	1.6	4.4	-0.2	392.1	-0.8	0.4	1.1	1.9	0.9
sey	5S,56E	0.4	1.3	1.8	2.2	2.2	4.0	-0.3	391.4	-0.2	0.7	1.3	0.8	1.3
asc	8S,14W	0.3	1.0	1.5	1.7	1.8	4.4	-0.4	390.4	0.1	1.5	0.7	2.5	1.1
smo	14S,171W	0.5	0.5	1.7	2.2	1.8	4.2	-0.5	390.6	0.0	0.6	0.5	2.2	0.7

Atmos. Chem. Phys. Discuss., doi:10.5194/acp-2016-720, 2016
Manuscript under review for journal Atmos. Chem. Phys.
Published: 7 October 2016
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eic	27S,109W	0.5	0.8	1.2	2.1	1.4	4.2	-0.4	389.7	0.7	2.7	0.7	1.9	0.8
	average	**0.5** ±0.2	**1.0** ±0.3	**1.5** ±0.2	**2.6** ±0.8	**1.8** ±0.3	**4.3** ±0.2	**-0.3** ±0.3	**391.3** ±1.6	**-1.2** ±1.5	**0.7** ±1.0	**1.3** ±0.5	**2.3** ±0.9	**1.1** ±0.3
b) LMT vs. ESRL aircraft														
pfa	66N,147W	1.6	5.0	1.6	2.1	5.3	5.1	0.1	388.0	1.9	0.3	8.2	1.5	5.0
etl	54N,105W	2.2	2.6	2.6	3.6	3.7	4.8	-0.3	388.7	-1.0	-0.6	6.9	3.5	2.7
esp	49N,126W	3.2	3.2	4.6	4.1	5.6	5.0	0.0	386.1	-2.4	-0.2	4.4	3.6	3.4
dnd	47N,99W	1.4	2.9	2.4	3.8	3.8	4.5	-0.1	390.0	-0.6	-0.7	7.8	5.0	3.0
lef	46N,90W	2.6	3.5	2.2	3.7	4.1	4.7	-0.3	392.1	-0.9	-1.4	6.8	4.5	3.5
nha	43N,71W	1.6	1.9	3.5	2.8	4.0	4.8	-0.3	393.3	-0.1	0.1	7.7	2.6	2.1
wbi	42N,91W	2.8	1.9	2.9	2.6	3.5	4.5	-1.5	393.3	-0.7	-0.9	5.1	2.3	2.1
thd	41N,124W	2.2	2.7	3.5	2.5	4.4	4.6	0.3	389.5	-1.5	0.9	3.9	2.5	2.8
bne	41N,97W	2.1	2.4	3.0	3.3	3.9	4.4	-1.3	393.2	-2.5	-2.2	5.0	3.1	2.5
car	41N,104W	2.7	2.7	3.3	3.6	4.2	4.2	-2.2	393.0	-2.7	-2.6	3.5	3.3	2.8
hil	40N,88W	2.2	2.2	3.0	3.4	3.8	4.5	-0.9	396.3	-2.0	-2.4	5.7	3.1	2.4
cma	39N,74W	1.8	1.8	3.7	3.0	4.1	4.8	-0.6	394.9	-0.7	-0.5	6.1	2.3	2.0
sgp	37N,98W	1.8	2.7	2.9	4.1	3.9	4.3	-0.5	394.3	-1.5	-0.7	4.2	3.7	2.8
sca	33N,79W	1.0	1.1	3.2	2.3	3.3	4.8	-0.5	395.6	0.3	-1.3	2.9	1.8	1.3
aoa	29N,148E	0.4	0.7	1.2	1.1	1.4	4.2	-0.5	392.4	-5.0	-0.8	1.5	0.9	0.8
tgc	28N,97W	1.1	1.5	2.5	2.7	2.9	4.2	-0.1	394.9	-0.2	0.0	2.7	2.3	1.7
rta	21S,160W	0.4	0.2	1.6	1.0	1.6	4.3	0.0	390.9	1.3	0.7	0.7	0.7	0.5
	average land	**2.0** ±0.6	**2.5** ±1.2	**3.0** ±0.7	**3.2** ±0.6	**4.0** ±0.7	**4.6** ±0.3	**-0.5** ±0.7	**392.2** ±3.1	**-1.0** ±1.2	**-0.8** ±1.0	**5.4** ±1.8	**3.0** ±1.0	**2.7** ±0.9
	ave. land, corrected		**1.5** ±1.2		**2.4** ±0.6	**3.4** ±0.7				**-0.5** ±01.2	**-0.3** ±1.0		**2.2** ±1.0	**1.7** ±0.9
aoa, rta	**average ocean**	**0.4** ±0.0	**0.4** ±0.5	**1.4** ±0.3	**1.1** ±0.1	**1.5** ±0.1	**4.3** ±0.1	**-0.3** ±0.4	**391.7** ±1.1	**-1.9** ±04.5	**-0.1** ±1.1	**1.1** ±0.6	**0.8** ±0.1	**0.7** ±0.2
c) U vs. ESRL aircraft														
pfa	66N,147W	0.5	1.3	1.1	1.3	1.7	1.8	0.1	392.0	1.8	1.5	2.4	1.0	1.3
etl	54N,105W	0.4	1.0	1.2	1.6	1.6	1.8	0.1	390.8	1.3	0.9	1.8	1.7	1.1
esp	49N,126W	1.2	2.0	1.1	1.6	2.3	1.8	0.4	389.9	1.7	2.2	2.1	1.9	2.0
dnd	47N,99W	0.6	0.7	1.3	1.6	1.5	1.8	0.2	390.5	0.8	0.4	2.2	1.8	0.8
lef	46N,90W	0.5	0.5	1.2	1.4	1.3	1.8	0.0	391.3	0.4	0.1	2.1	1.5	0.6
nha	43N,71W	0.5	0.8	1.2	1.3	1.5	1.8	0.0	391.5	0.4	0.3	2.5	0.9	0.8
wbi	42N,91W	0.4	0.6	1.1	0.8	1.2	1.8	-0.2	391.2	0.3	-0.2	2.1	0.6	0.7
thd	41N,124W	0.9	1.0	1.2	1.2	1.6	1.8	0.4	390.5	1.4	1.8	1.9	0.8	1.1
bne	41N,97W	0.4	0.6	1.2	1.1	1.3	1.7	-0.1	391.2	0.4	-0.4	2.0	1.1	0.7
car	41N,104W	0.6	0.8	1.3	1.0	1.5	1.7	-0.2	391.1	0.4	0.0	2.0	1.0	0.8
hil	40N,88W	0.5	0.7	1.1	1.1	1.3	1.8	-0.1	392.1	-0.4	-0.9	2.0	0.9	0.8
cma	39N,74W	0.3	0.5	1.4	0.9	1.5	1.8	-0.1	391.5	0.3	0.1	2.1	0.5	0.6
sgp	37N,98W	0.4	0.5	1.1	0.8	1.2	1.7	0.0	391.4	0.0	-0.4	1.7	0.7	0.6
sca	33N,79W	0.2	0.4	1.1	0.5	1.2	1.8	-0.1	391.8	0.2	-0.8	1.6	0.3	0.5
aoa	29N,148E	0.2	0.6	0.4	0.5	0.8	1.7	-0.1	392.4	0.0	0.6	1.4	0.5	0.6
tgc	28N,97W	0.2	0.3	1.0	0.5	1.1	1.7	0.0	391.6	0.4	-0.3	1.9	0.5	0.4
rta	21S,160W	0.2	0.5	0.7	0.5	0.8	1.7	0.0	390.1	2.3	0.8	0.2	0.5	0.5
	average land	**0.5** ±0.3	**0.7** ±0.4	**1.2** ±0.1	**1.1** ±0.4	**1.4** ±0.3	**1.8** ±0.0	**0.0** ±0.2	**391.2** ±0.6	**0.6** ±0.6	**0.3** ±0.9	**2.0** ±0.2	**1.0** ±0.2	**0.8** ±0.4
	ave. land, corrected		**0.6** ±0.4		**0.5** ±0.0	**1.3** ±0.3				**0.6** ±0.6	**0.3** ±0.9	**2.0** ±0.2	**0.9** ±0.2	**0.5** ±0.4
aoa, rta	**average ocean**	**0.2** ±0.0	**0.6** ±0.1	**0.6** ±0.2	**1.0** ±0.4	**0.8** ±0.0	**1.7** ±0.0	**-0.1** ±0.1	**391.3** ±1.6	**-1.2** ±1.6	**0.7** ±0.1	**0.8** ±0.8	**0.5** ±0.0	**0.6** ±0.1
d) XCO_2 vs. ESRL aircraft														
pfa	66N,147W	0.7	2.1	1.2	1.4	2.4	1.3	0.2	391.1	1.8	1.2	3.8	1.0	2.1
etl	54N,105W	0.7	1.3	1.5	1.9	2.0	0.9	0.0	390.3	0.7	0.6	2.8	2.1	1.4
esp	49N,126W	1.5	2.2	2.0	1.9	2.9	0.9	0.4	389.0	0.8	1.6	2.4	2.1	2.2
dnd	47N,99W	0.7	1.0	1.6	2.0	1.9	0.9	0.1	390.4	0.5	0.2	3.1	2.4	1.1
lef	46N,90W	0.9	1.1	1.5	1.7	1.8	1.0	0.0	391.4	0.1	-0.3	2.7	2.0	1.2
nha	43N,71W	0.7	0.9	1.7	1.5	1.9	1.0	-0.1	391.9	0.3	0.3	3.5	1.2	1.0
wbi	42N,91W	0.9	0.8	1.4	1.0	1.6	0.8	-0.5	391.7	0.0	-0.3	2.3	0.8	0.9
thd	41N,124W	1.1	1.2	1.7	1.1	2.1	0.9	0.4	390.3	0.7	1.6	2.2	1.0	1.3
bne	41N,97W	0.6	0.8	1.5	1.2	1.7	0.7	-0.4	391.7	-0.3	-0.8	2.2	1.3	0.9
car	41N,104W	1.0	1.0	1.7	1.1	2.0	0.8	-0.6	391.5	-0.3	-0.7	2.1	1.2	1.1
hil	40N,88W	0.8	1.0	1.5	1.6	1.8	0.9	-0.3	393.1	-0.7	-1.3	2.4	1.3	1.0
cma	39N,74W	0.6	0.6	1.9	1.2	2.0	0.9	-0.2	392.3	0.0	0.0	2.8	0.8	0.8
sgp	37N,98W	0.7	0.9	1.4	1.2	1.7	0.8	-0.1	392.1	-0.3	-0.5	1.9	1.1	1.0

Atmos. Chem. Phys. Discuss., doi:10.5194/acp-2016-720, 2016
Manuscript under review for journal Atmos. Chem. Phys.
Published: 7 October 2016
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sca	33N,79W	0.3	0.3	1.5	0.7	1.6	0.9	-0.2	392.7	0.2	-0.9	1.7	0.6	0.5
aoa	29N,148E	0.2	0.5	0.6	0.5	0.8	0.6	-0.2	392.4	-1.2	0.3	1.4	0.5	0.6
tgc	28N,97W	0.4	0.5	1.2	0.9	1.4	0.7	0.0	392.3	0.3	-0.3	1.9	0.9	0.6
rta	21S,160W	0.1	0.3	0.8	0.5	0.9	0.7	0.0	390.3	2.0	0.8	0.2	0.4	0.4
	average land	**0.8 ±0.3**	**1.0 ±0.5**	**1.6 ±0.2**	**1.5 ±0.4**	**1.9 ±0.4**	**0.9 ±0.1**	**-0.1 ±0.3**	**391.5 ±1.1**	**-0.3 ±0.6**	**-0.0 ±0.9**	**2.5 ±0.6**	**1.3 ±0.6**	**1.1 ±0.5**
	ave. land, corrected		**0.7 ±0.5**		**0.5 ±0.0**	**1.7 ±0.4**				**-0.2 ±0.6**	**0.1 ±0.9**		**1.1±0.6**	**0.6 ±0.5**
aoa, rta	**average ocean**	**0.2 ±0.1**	**0.4 ±0.1**	**0.7 ±0.1**	**1.1 ±0.4**	**0.9 ±0.1**	**0.7 ±0.1**	**-0.1 ±0.1**	**391.4 ±1.5**	**0.4 ±2.3**	**0.6 ±0.4**	**0.8 ±0.8**	**0.5 ±0.1**	**0.5 ±0.1**
e) LMT GOSAT HIPPO ocean														
2S	30S-0S	0.3	0.3	1.5	0.5	1.5	4.0	-0.1	390.9	2.0	-0.4	0.5	0.4	0.5
2N	15S-5S	0.4	0.3	1.6	0.5	1.6	4.1	-0.1	390.7	2.2	-0.2	0.4	0.5	0.5
3S	10S-10N	0.2	0.0	2.4	0.7	2.4	4.3	-0.4	393.5	-0.1	0.0	1.2	0.3	0.6
3N	5S-10N	0.5	0.3	1.9	0.5	1.9	3.9	-0.4	393.4	-0.1	-0.4	0.6	0.4	0.6
4S	10N	0.1	0.5	1.5	0.5	1.6	4.6	-0.5	394.5	-3.0	0.2	0.3	0.4	0.6
4N	15-30N	0.3	0.4	1.5	1.2	1.5	4.2	-0.3	393.4	-4.2	-0.5	0.5	0.8	0.5
5S	0-20N	0.4	0.6	1.5	1.4	1.6	4.5	-0.2	390.7	-0.1	-0.4	0.6	1.0	0.7
5N	10S-20N	0.5	0.5	1.3	1.1	1.4	4.5	-0.3	390.6	2.0	0.3	0.7	0.8	0.6
	average	**0.3 ±0.1**	**0.4 ±0.2**	**1.6 ±0.3**	**0.8 ±0.4**	**1.7 ±0.3**	**4.3 ±0.3**	**-0.3 ±0.2**	**392.2 ±1.6**	**-0.2 ±2.4**	**-0.2 ±0.3**	**0.6 ±0.3**	**0.6 ±0.3**	**0.6 ±0.6**
f) U GOSAT HIPPO ocean														
2S	30S-0S	0.1	0.6	0.8	0.4	1.0	1.6	0.1	390	2.6	0.1	0.3	0.4	0.7
2N	15S-5S	0.2	0.2	0.7	0.2	0.7	1.6	0.1	390.1	2.6	0.7	0.2	0.2	0.2
3S	10S-10N	0.1	0.3	0.9	0.6	1.0	1.7	0.0	391.6	0.9	0.3	1.0	0.6	0.4
3N	5S-10N	0.3	0.1	0.8	0.4	0.8	1.6	0.1	391.1	1.3	0.4	0.4	0.3	0.2
4S	10N	0.1	0.2	0.8	0.2	0.8	1.8	0.3	392.8	-0.2	0.2	0.2	0.2	0.3
4N	15-30N	0.1	0.2	0.7	0.3	0.7	1.6	-0.1	392.9	-0.3	0.2	0.2	0.2	0.3
5S	0-20N	0.1	0.3	0.8	0.3	0.9	1.8	0.1	390.4	1.2	-0.2	0.2	0.2	0.4
5N	10S-20N	0.2	0.3	0.7	0.3	0.8	1.8	0.1	390.2	1.8	0.0	0.3	0.2	0.4
	average	**0.1 ±0.1**	**0.3 ±0.2**	**0.8 ±0.1**	**0.3 ±0.1**	**0.8 ±0.1**	**1.7 ±0.1**	**0.1 ±0.1**	**391.1 ±1.2**	**0.3 ±1.1**	**0.2 ±0.3**	**0.4 ±0.3**	**0.3 ±0.1**	**0.4 ±0.1**
g) XCO_2 GOSAT HIPPO ocean														
2S	30S-0S	0.1	0.4	0.8	0.2	0.9	0.5	0.0	390.2	2.5	0.0	0.2	0.2	0.5
2N	15S-5S	0.1	0.0	0.7	0.2	0.7	0.5	0.0	390.2	2.5	0.5	0.2	0.2	0.2
3S	10S-10N	0.1	0.2	1.1	0.6	1.1	0.7	-0.1	392.0	0.6	0.2	1.1	0.5	0.3
3N	5S-10N	0.3	0.0	0.9	0.4	0.9	0.5	0.0	391.6	1.0	0.2	0.5	0.2	0.2
4S	10N	0.1	0.3	0.9	0.2	0.9	0.8	0.1	393.2	-0.9	0.2	0.2	0.2	0.4
4N	15-30N	0.1	0.1	0.7	0.3	0.8	0.6	-0.1	393.1	-1.2	0.0	0.2	0.1	0.2
5S	0-20N	0.1	0.3	0.9	0.5	1.0	0.7	0.0	390.5	0.9	-0.2	0.3	0.3	0.4
5N	10S-20N	0.2	0.3	0.8	0.5	0.8	0.8	0.0	390.3	1.8	0.0	0.3	0.3	0.4
	average	**0.1 ±0.2**	**0.2 ±0.2**	**0.9 ±0.1**	**0.4 ±0.2**	**0.9 ±0.1**	**0.6 ±0.1**	**0.0 ±0.1**	**391.4 ±1.3**	**0.9 ±1.4**	**0.1 ±0.2**	**0.4 ±0.3**	**0.3 ±0.1**	**0.3 ±0.1**
h) AJAX														
LMT		1.1			2.2	3.1	4.1	-0.6	393.6	-2.0	-0.2	2.8		
LMT, corrected*					1.9	2.9				-1.4	+0.4			
U		0.1			0.9	1.1	1.7	0.0	392.2	0.4	1.0	2.0		
XCO_2		0.2			0.6	0.9	0.8	-0.1	392.4	-0.1	0.7	2.4	-	-

*AJAX profiles are co-located within 1 hour and 1 degree and therefore do not have multiple GOSAT matches to average.

Atmos. Chem. Phys. Discuss., doi:10.5194/acp-2016-720, 2016
Manuscript under review for journal Atmos. Chem. Phys.
Published: 7 October 2016
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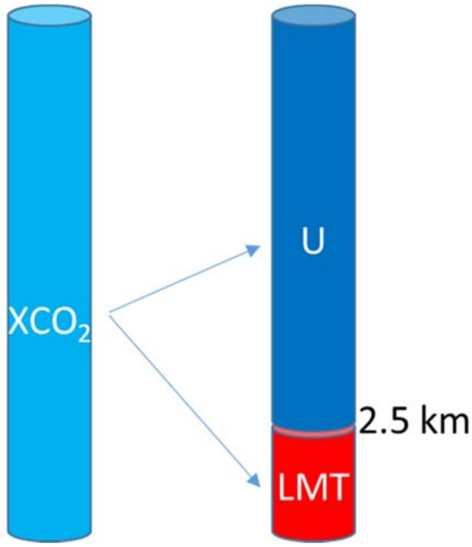

Figure 1. XCO_2 full column measurement (left) and the two partial columns that we introduce (right): the lowermost troposphere (LMT), a partial column from the surface to approximately 2.5 km, and the partial column above 2.5 km (U).

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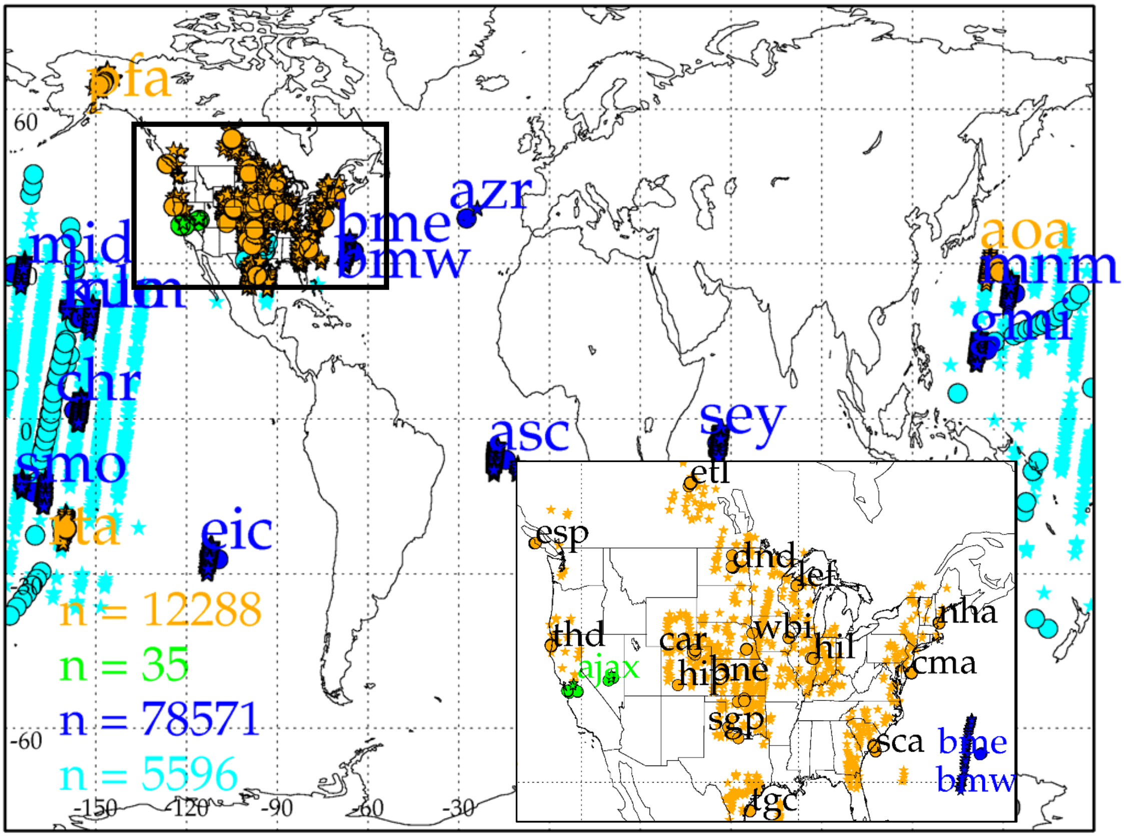

Figure 2. Validation locations. The 4 sets of validation data shown here are: ESRL aircraft (orange), which has both land (in the US) and ocean (RTA and AOA), AJAX aircraft data (green) in the western U.S., the HIPPO aircraft campaign (light blue), and remote ocean surface sites (dark blue). The matching GOSAT locations are shown as stars and the validation locations are shown as outlined circles. The number of GOSAT observations in each set are shown as the "n = " number in the lower left of the plot.

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Published: 7 October 2016
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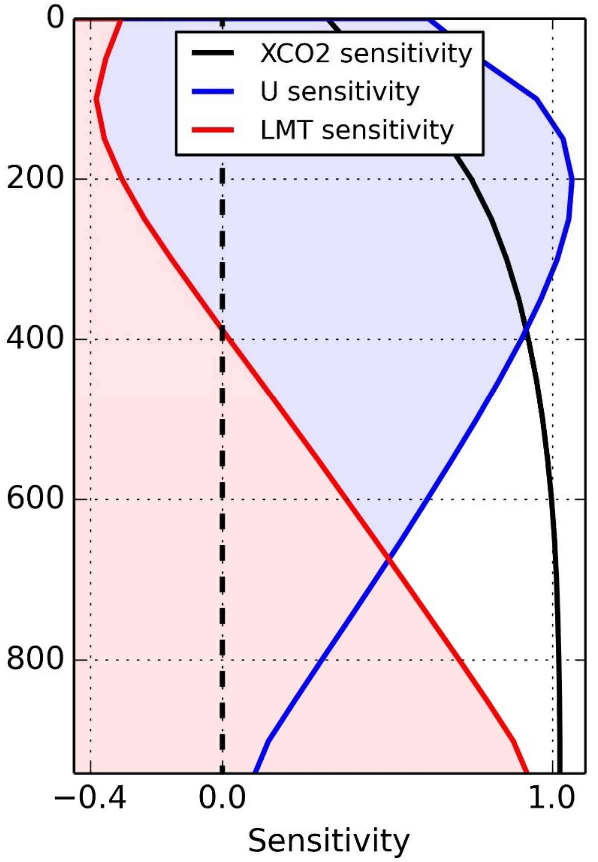

Figure 3. Sensitivity of XCO_2 (black), partitioned into the LMT (red) and U (blue) partial columns for an average land averaging kernel. The LMT sensitivity is approximately 1 near the surface and drops off steadily with decreasing pressure. The ocean averaging kernel is very similar.

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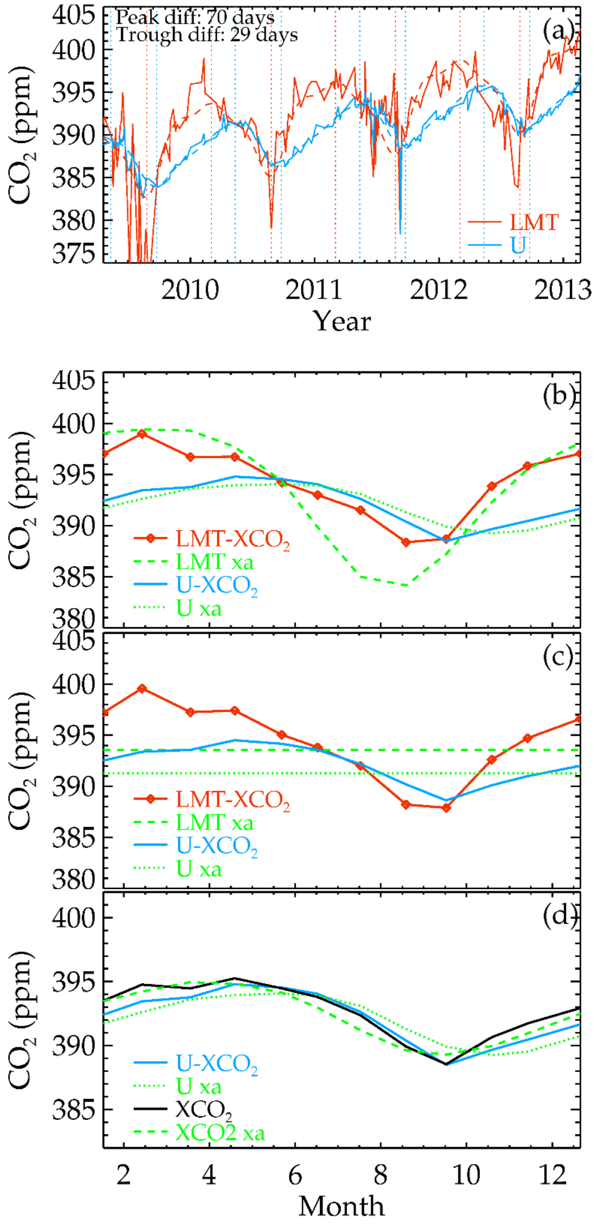

Figure 4. Simulated GOSAT retrievals from SGP aircraft profiles, Eqs. 5-6, and the GOSAT averaging kernels. (a) Time series of LMT (red) and U (blue) with dashed lines the monthly averages; (b) seasonal cycle (created by moving all measurements to be in 2012 by offsetting CO_2 by 2 ppm per year), averaging in 1-month increments. Dotted and dashed lines are initial guess/a priori. (c) same as (b) except that the prior is set to a constant (with 2 ppm/year secular increase), showing that LMT and U results are not strongly influenced by the prior. (d) Same as (b) but showing U (blue) vs. XCO_2 (black) which shows that XCO_2 estimates look most similar to the U partial column. Analysis in Section 3.3 shows that 70% of XCO_2 variations result from variations in the U partial column.

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Manuscript under review for journal Atmos. Chem. Phys.
Published: 7 October 2016
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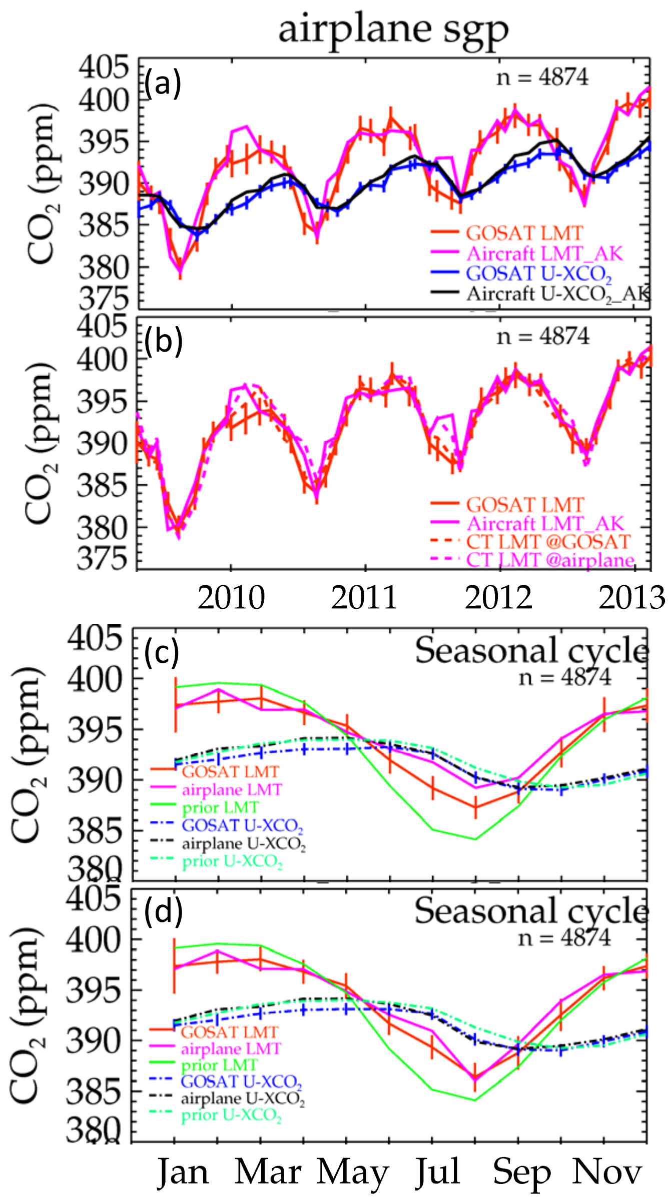

Figure 5. GOSAT versus aircraft data at the SGP site (37N, 95W). (a) aircraft LMT (pink) and U (blue) versus GOSAT LMT (red) and U (black) for monthly averages of GOSAT/airplane matches. (b) same as (a) but also showing CarbonTracker matched to GOSAT (red dotted) and CarbonTracker matched to aircraft (pink dotted) for LMT. (c) Seasonal cycle of GOSAT and airplane, same colors as top panel, and adding the priors in green. (d) Same as (c) but removing months where the CarbonTracker difference from (b) is larger than 2.5 ppm (removing months 6/9, 10/9, 5/10, 7/10, 8/10). This shows that the systematic monthly differences in panel (c) result from co-location error. In (c) and (d), the GOSAT prior overestimates the high and overestimates the drawdown. For all metrics except for the U bias, GOSAT LMT and U improve over the prior estimates.

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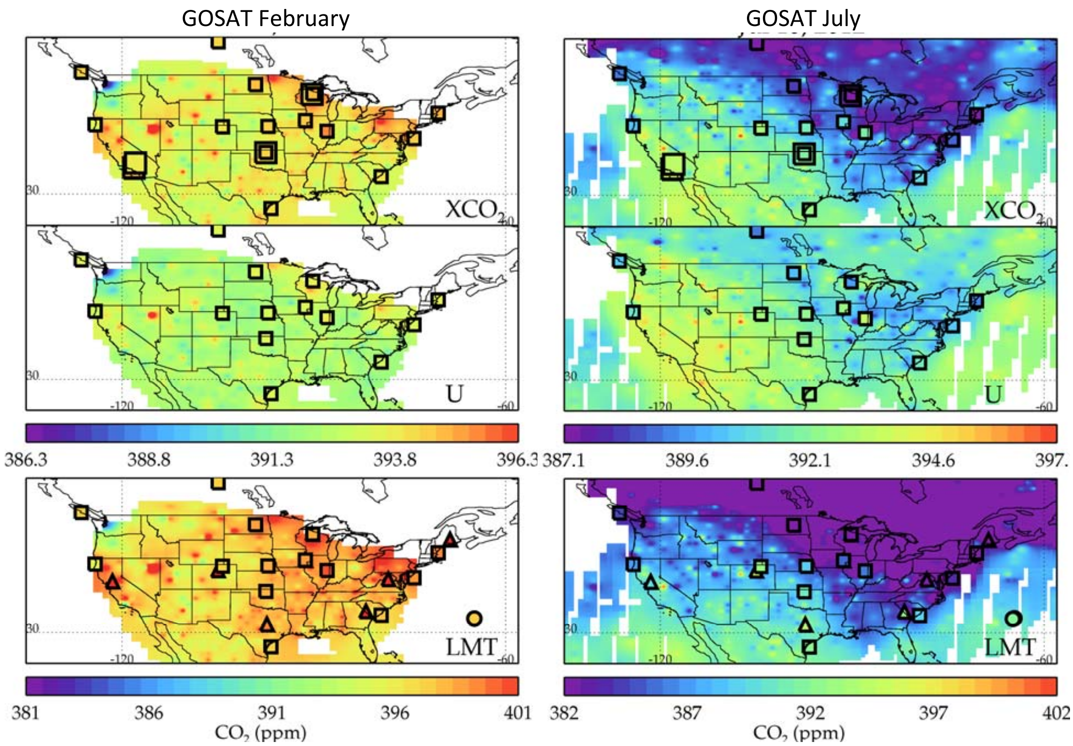

Figure 6. GOSAT XCO_2 (top), U (middle), and LMT (bottom) in February (left) and July (right). Aircraft with GOSAT averaging kernels are small squares, towers are triangles, remote ocean surface sites are circles, and TCCON are large squares (only shown on XCO_2 panels). Data is averaged over the GOSAT record (converted to 2012 by adding/subtracting 2 ppm per year).

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Manuscript under review for journal Atmos. Chem. Phys.
Published: 7 October 2016
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Atmospheric Chemistry and Physics
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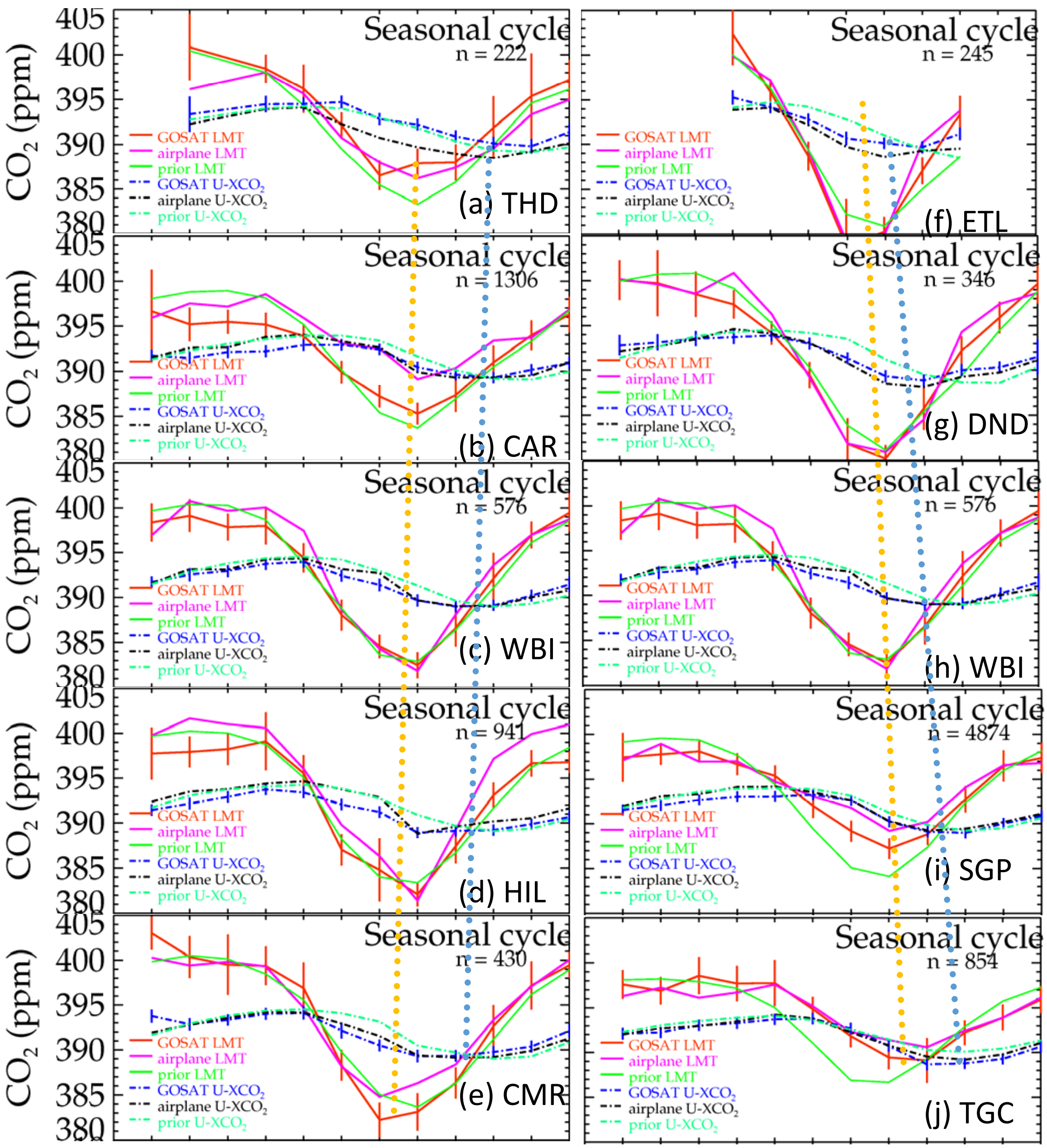

Figure 7. Seasonal cycle at 5 sites arranged from north to south (a-e) and west to east (f-j). The seasonal cycle minimum is marked for LMT (orange) and U (blue). The seasonal cycle shifts forward going west and backwards going north, for both LMT and U. There is a consistent delay in the drawdown for the U prior for (b-j) which is corrected by the retrieval. The LMT prior is consistently too large for (i-j) with a phase shift in (j) which is corrected by the GOSAT retrieval.

Atmos. Chem. Phys. Discuss., doi:10.5194/acp-2016-720, 2016
Manuscript under review for journal Atmos. Chem. Phys.
Published: 7 October 2016
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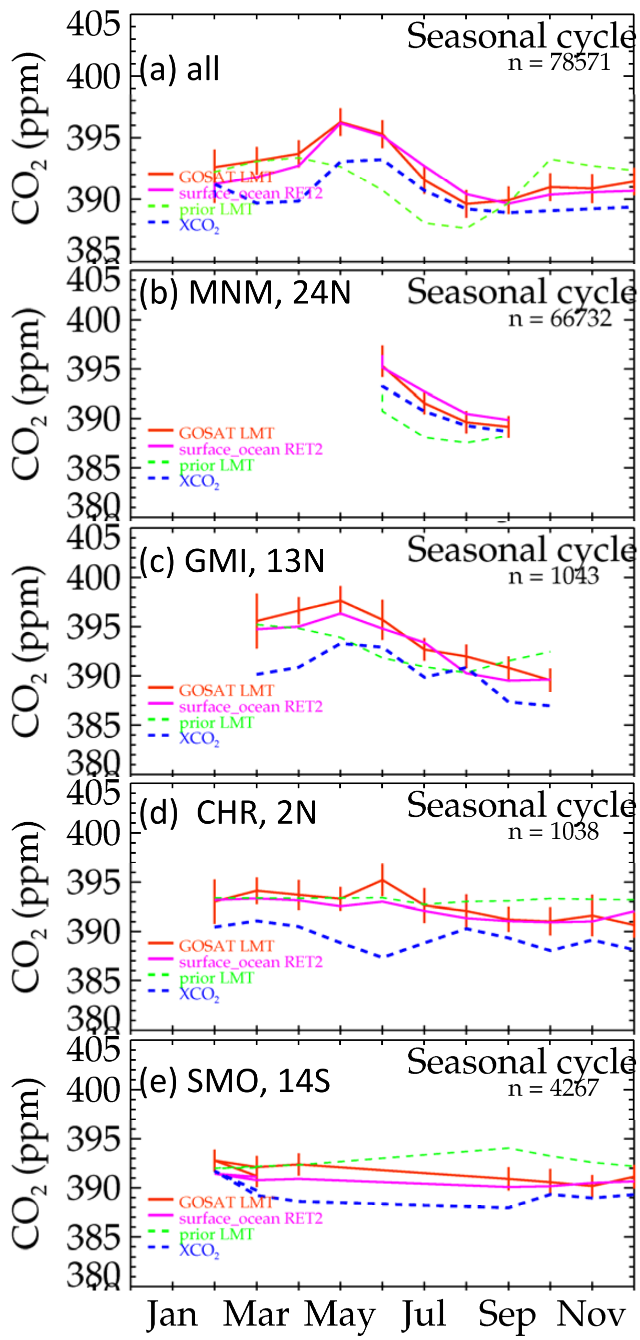

Figure 8. GOSAT LMT compared with remote ocean surface sites for different sites. GOSAT (red) compares well with surface site (pink) for the average of all sites (a) and at the four (of twelve) sites with the most matches (b-e). There is marked improvement over the prior (green). XCO_2 values are shown for comparison (blue dashed).

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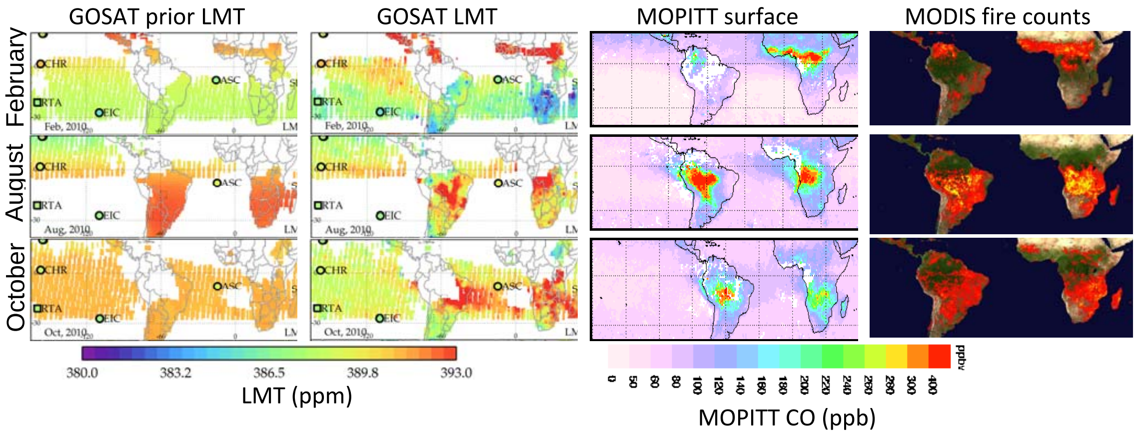

Figure 9. GOSAT LMT versus MOPITT and MODIS fire counts in for February, August, and October, 2010. GOSAT prior (left) and retrieved (second column) LMT compared with MOPITT multispectral CO (third column) and MODIS fire counts (right). The GOSAT prior is approximately constant in the southern hemisphere on monthly timescales. GOSAT LMT shows the pattern of biomass burning in South America and Africa seen by MOPITT and MODIS and reduces from the prior in the Pacific, matching surface and aircraft observations. Note that multi-spectral MOPITT retrievals have little surface sensitivity over ocean, but the outflow seen in October is seen in mid-tropospheric MOPITT.

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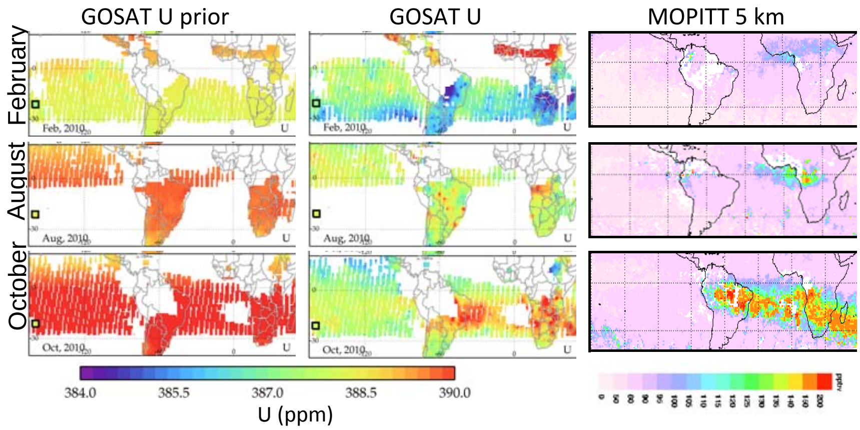

Figure 10. GOSAT U versus MOPITT for February, August, and October, 2010. GOSAT prior (left) and retrieved (middle) compared with MOPITT multispectral CO (right) at 5 km. The GOSAT prior is approximately constant in the southern hemisphere on monthly timescales. GOSAT U shows low CO_2 from the growing season for the Amazon and southern Africa in February. In August, GOSAT U shows little enhancement in South America, but enhancement in southern Africa, in agreement with MOPITT. In October, GOSAT U shows enhancement over the burning regions and outflow similar to MOPITT.

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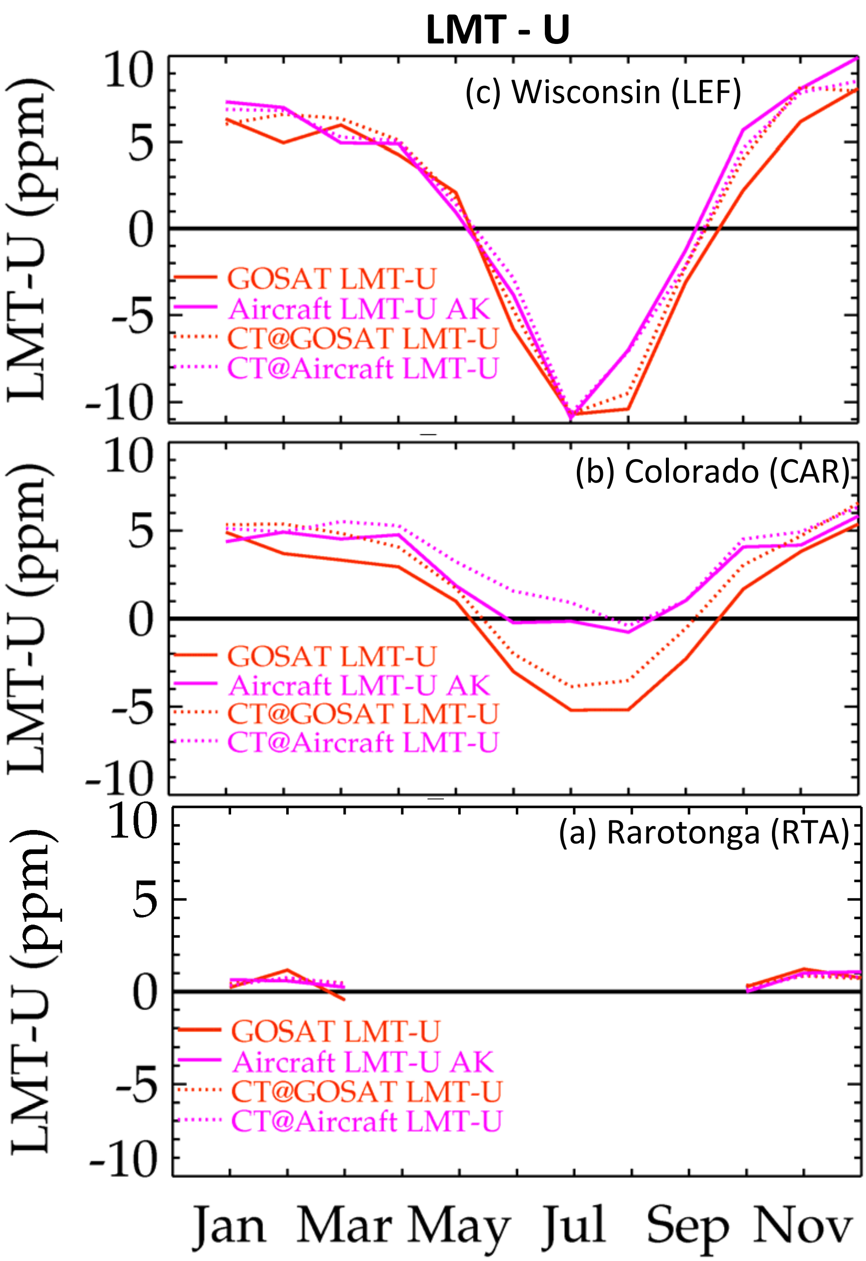

Figure 11. GOSAT LMT - U (red) versus aircraft (pink) at 3 sites. The dotted line show CarbonTracker matched to GOSAT (red dotted) or aircraft (pink dotted). Co-location error explains the discrepancies in the drawdown at CAR and LEF. At CAR the discrepancies are due to mismatch in the time of day the data is collected.

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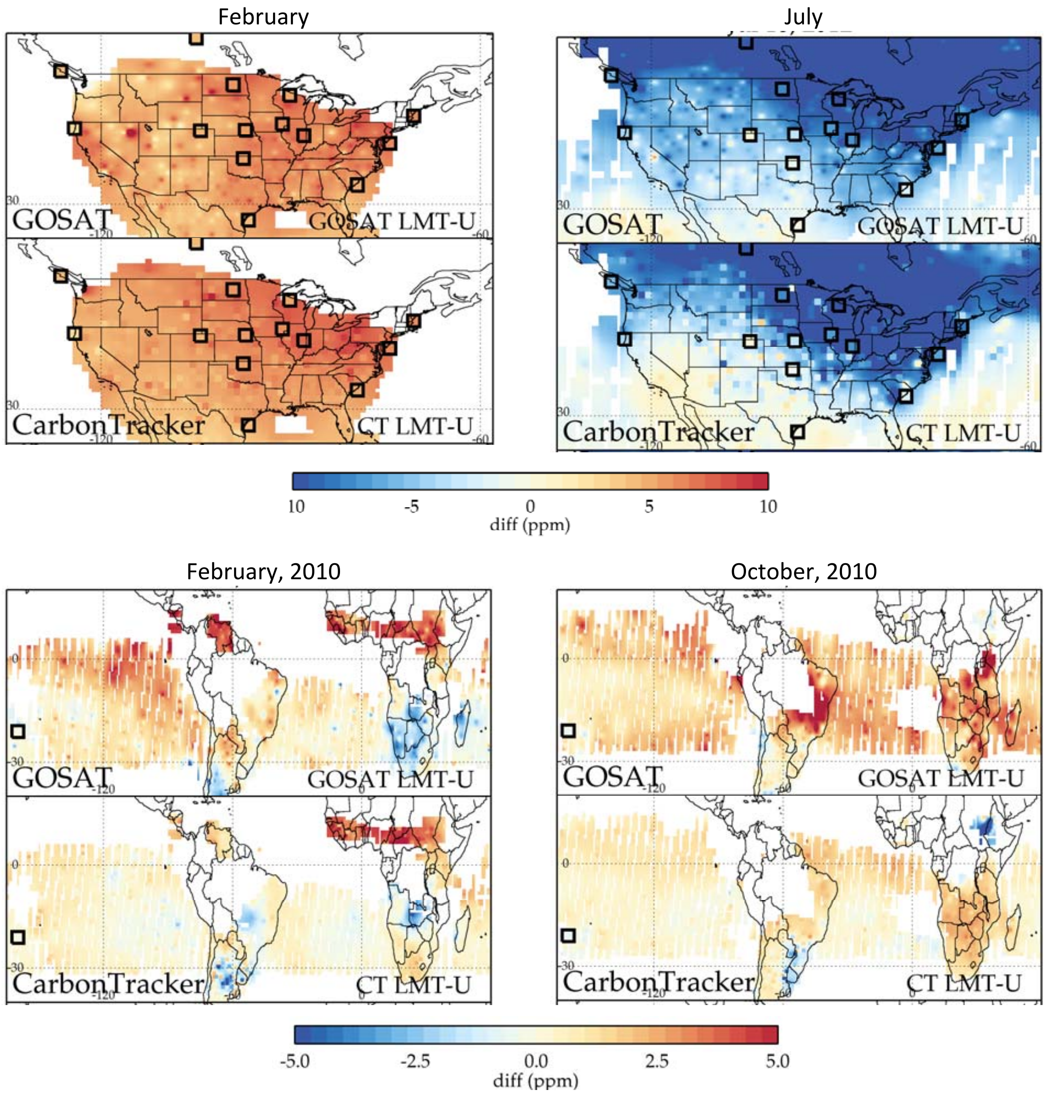

Figure 12. LMT – U differences. LMT – U diagnoses model vertical transport (Stephens, 2007) and transport of outflow (Deeter, 2013). Results shown for the U.S. (top) and South America/Africa (bottom) for two different months. GOSAT is shown on the top and CarbonTracker on the bottom. Aircraft LMT – U differences are shown in the squares. There is agreement in the U.S. where there is a lot of surface-based data to ingest into CarbonTracker, but disagreement in southern Africa during the growing season in February, the Amazon region in the biomass burning season in October, and in the outflow from Africa and South America in October.