Lower-tropospheric CO₂ from near-infrared ACOS-GOSAT observations

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Abstract

We present two new products from near-infrared GOSAT observations: LowerMost Tropospheric (LMT, from 0-2.5 km) and Upper troposperic/stratospheric (U, above 2.5 km) carbon dioxide partial column mixing ratios. 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 column mixing ratios significantly improve upon 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 XCO₂; for ocean monthly averages, we find errors of 0.7, 0.5, and 0.5 ppm for retrieved GOSAT LMT, U, and XCO₂. 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 a CO/CO₂ emission factor comparable to 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). LMT is more locally influenced than U, meaning that local fluxes can now be better separated from CO₂ transported from far away.

1 Introduction

44 The Greenhouse Gases Observing Satellite (GOSAT) has been measuring
45 global satellite CO_2 columns since 2009, achieving less than 0.3 ppm
46 variability in regional biases and 1.7 ppm single observation error versus
47 TCCON (Kulawik et al., 2016), where the error is estimated as described in
48 Table 3. The sensitivity of near-infrared radiances to CO_2 varies by altitude
49 differently in the strong and weak bands, resulting in the capability of
50 retrieving multiple pieces of vertical information from near-infrared
51 observations, with 3+ degrees of freedom (i.e. independent pieces of
52 information) for TCCON (Connor et al., 2016; Kuai et al., 2012), 1.6 degrees
53 of freedom for GOSAT (this paper), and 2.0 degrees of freedom for OCO-2
54 (Kulawik, unpublished result). In this paper we use the intermediate
55 retrieved profile from ACOS-GOSAT processing to construct, bias-correct,
56 and validate two partial column mixing ratios from near-infrared GOSAT
57 observations (schematically shown in Fig. 1). The partially correlated errors
58 and sensitivity of these two partial column volume mixing ratios (or mole
59 fractions) are characterized so that they can be used for flux estimation and
60 other science analyses.
61
62 An important goal of carbon cycle research is to improve top-down estimates
63 of CO_2 fluxes, which assimilate data into models to trace the observed
64 variability in the long-lived tracer backwards to sources and sinks.
65 Historically, such top-down flux estimates have relied on surface
66 observations (e.g. Peters et al., 2007; Chevallier et al., 2010), though it was
67 postulated 15 years ago that satellite-based measurements of column CO_2
68 could dramatically reduce top-down based flux uncertainties (Rayner and
69 O'Brien, 2001; O'Brien and Rayner, 2002). Guided by this early work, most
70 GOSAT analyses have focused solely on total column CO_2 (or XCO_2).
71 Separation of XCO_2 into two vertical columns has several advantages over
72 column XCO_2 and surface observations which should improve our ability to
73 accurately estimate fluxes:
74
75 • flux estimates from column measurements rely on observations up to
76   continent-scales away (Liu et al., 2015; Feng et al., 2016); whereas
77   LMT back-trajectories show a more local influence to surface fluxes,
78   making flux estimates more responsive to observations and less
79   susceptible to transport error, a major driver of flux uncertianties
80   (Houweling et al., 2015; Liu et al., 2015; Chevallier et al., 2014; Liu et
81   al., 2011; Prather et al., 2008)
82 • Stephens et al. (2007) show that vertical gradient in mole fraction
83   determined from 2 points in the atmospheric column better constrains
84   model transport and partitioning between northern extratropical land
85   fluxes and land fluxes further south, since vertical transport is an
86   uncertainty in flux estimates (Deng et al., 2015; Lauvaux and Davis,
87   2014; Stephens et al., 2007)

- In majority of cases the LMT covers the entire boundary layer, which partially mitigates one source of flask assimilation error, the boundary layer height (Denning et al., 1996; Gurney et al., 2002; Rayner and O'Brien, 2001); and
- GOSAT provides observations in many areas that are sparsely covered by surface-based measurements.

In this work, we evaulate the precision and comparability of these new LMT and U partial column products derived from GOSAT, with the goal of providing a higher level of 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 column mixing ratios. Section 5.4 shows patterns of the two partial column mixing ratios 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 column mixing ratios. Measurements of CO_2 vertical profiles from aircraft profiles, which extend from the surface to somewhere between 5 and 13 km, can be used to directly validate what is seen with the two GOSAT partial column mixing ratios. The second dataset that is used is CO_2 measurements from remote surface flask sites, which are used to compare to the lower GOSAT partial column, assuming that CO_2 mixing ratios in the lower 0-2.5 km are well mixed at remote sites. The Total Carbon Column Observing Network (TCCON), which currently measures full columns, is used to diagnose discrepancies between aircraft and GOSAT at the sites where both exist. We additionally show the southern hemisphere, which has interesting CO_2 patterns, very little structure in the prior, and no observations used in the bias correction. We show patterns from burning and transport in southern hemisphere from vertically resolved GOSAT, vertically resolved MOPITT CO, and MODIS fire counts. Figure 2 shows aircraft and surface validation locations, along with GOSAT coincidences, with the surface site locations and names shown in Table 1.

2.1 GOSAT

The Greenhouse gases Observing SATellite (GOSAT) takes measurements of reflected sunlight in three near-infrared bands with a circular footprint of approximately 10.5 km diameter at nadir (Kuze et al., 2016; Yokota et al.,

132 2009; Crisp et al., 2012). The Atmospheric CO_2 Observations from Space
133 (ACOS) v3.5 processing of GOSAT XCO_2 observations are used from the Lite
134 products, with quality flag of 0 (good), along with the full CO_2 profile, full
135 CO_2 averaging kernel matrix, and full CO_2 error matrices from ancillary
136 GOSAT files. We use both nadir land observations (looking straight down)
137 and ocean glint observations (sunglint tracking mode), but not medium gain
138 over land, as there is not a sufficient amount of co-located validation data to
139 validate medium gain observations.
140
141 **2.2 Aircraft profiles**
142
143 **2.2.1 ESRL aircraft profiles**
144 Aircraft and ocean measurements taken by NOAA's Earth System Research
145 Laboratory (ESRL) are obtained from an observation package product
146 (GLOBALVIEW-CO2,2013; Sweeney et al., 2015).
147
148 **2.2.2 DOE/LBNL aircraft profiles**
149 Aircraft observations collected over the Southern Great Plains can be
150 obtained from DOE ARM archive (www.arm.gov, search for CO_2 flasks at
151 SGP) under ARM-ACME campaigns and are described in Biraud et al. (2013).
152 Flask-based observations are collected on a bi-weekly basis at altitude
153 ranging from 0.2 to 5km.
154
155 **2.2.3 Aircraft profile extension and errors**
156 Aircraft measurements are extended down to the surface using the lowest
157 measured value, and extended to the tropopause pressure using the aircraft
158 value at the highest altitude. The tropopause pressure is used from the
159 National Centers for Environmental Prediction (NCEP),
160 http://www.esrl.noaa.gov/psd/data/gridded/data.ncep.reanalysis.html. The
161 CarbonTracker model (CT2015, see below) is used to extend the profile
162 through the stratosphere. The aircraft flask measurements themselves have
163 errors, but these are small compared to the other errors in the comparisons
164 (e.g. co-location, extending the aircraft to the top of the atmosphere, etc.)
165
166 **2.3 Remote NOAA/ESRL oceanic surface in situ measurements**
167 Remote surface sites are from the Earth System Research Laboratory
168 Observation Package Data Product surface flask measurements (Conway et
169 al., 1994). The "remote oceanic" locations used in this paper are selected to
170 have at least 97% ocean along a circle with a 5 degrees radius around the
171 location. The locations are shown in Fig. 2 and Table 1. For each station,
172 there can be different options represented by file names (e.g. daytime,
173 nighttime, representative, etc.); in this study "representative" files are used,
174 with outliers removed, if that option is available. Remote ocean sites have
175 been selected because (a) although the vertical airmass observed by GOSAT

176 LMT will not match the vertical airmass observed by the surface site, the
177 long correlation length scales of remote locations should make the
178 comparisons useful; and (b) these sites are not used in development of the
179 bias correction terms (described in Section 3.5 and Appendix A) and so are
180 an independent test of bias correction for observations over ocean.
181
182 2.4 HIPPO aircraft profiles
183 The HIAPER Pole-to-Pole Observations (HIPPO) project samples the
184 atmosphere in a series of profiles from the surface to 9-13 km, from about
185 80N to 60S. The campaigns covered different years as well as different
186 seasons, namely: HIPPO 1: January, 2009, HIPPO 2: November 2009, HIPPO
187 3: March-April, 2010, HIPPO 4: June-July, 2011, and HIPPO 5: August-
188 September, 2011. Frankenberg et al. (2016) recently were successful in
189 evaluating satellite measurements of column CO_2 over ocean (including
190 GOSAT) using HIPPO. In this paper, we look at comparisons between GOSAT
191 and HIPPO 2-5 (HIPPO 1 occurs prior to GOSAT launch) using the HIPPO-
192 identified profiles and the CO2_X field, based on 1s data averaged to 10s,
193 from two (harmonized) sensors: CO2-QCLS and CO2-OMS. Due to the
194 GOSAT glint coverage span of about 40 degrees, and after applying quality
195 screening, many of the comparisons had fairly limited latitudinal spans with
196 the GOSAT improvement over the prior found more in improving the bias
197 rather than improving the standard deviation. The combined campaigns
198 span a wide range of GOSAT latitudes.
199
200 2.5 AJAX aircraft profiles
201 The Alpha Jet Atmospheric eXperiment (AJAX) project
202 (https://earthscience.arc.nasa.gov/ajax) collects in situ CO_2 vertical profiles
203 from the surface to 8 km in several locations, including Railroad Valley, NV;
204 Merced, CA, and other locations in the West Coast. Most of the AJAX Version
205 4 profiles used in this paper were collected to coincide with GOSAT
206 overpasses. Trace gas instruments and the Meteorological Measurement
207 Sensor are housed in an unpressurized sensor pod that is mounted under
208 the wing. A cavity ring-down spectrometer (Picarro Inc. G2301-m) that has
209 been modified for flight conditions is routinely calibrated to NOAA/ESRL gas
210 standards. Calculated 1σ overall uncertainties are 0.16 ppm for CO_2 (Hamill
211 et al. 2016; Tanaka et al., 2016).
212
213 2.6 MOPITT v6 multispectral CO retrieval
214 In section 5, we utilize satellite-based CO observations from MOPITT to
215 understand the spatial variability in LMT and U that may be attributed to
216 fires. The MOPITT instrument on EOS-Terra is in a sun-synchronous orbit
217 with mean local time overpasses of 10:30 and 22:30. It has global coverage
218 in ~3 days with a 22km x 22km horizontal footprint. MOPITT uses gas filter
219 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 lowest 200 hPa of the atmosphere 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 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 that allow each measurement to be split into 2 or 3 vertical columns, the focus of the TCCON project has been on column observations of CO_2 (and columns of other trace gases). Recent work by Kuai et al. (2012), Dohe et al. (2012), and Connor et al. (2016) have explored vertical profile retrievals from TCCON, but there is not yet an operational product.

2.10 AirCore

While the boundary layer and lower free troposphere are relatively well sampled by a network of insitu and flask measurements over the globe, the UT/LS is rarely sampled due to the expense and the difficulty involved in making measurements at these altitudes. The recent advent of the AirCore (Karion et al., 2010; Membrive et al., 2016) has enable more frequent

profiles that sample as high as 30 km, well into the stratosphere. Profiles in this study were dried with MgClO4 and captured in a long stainless steal coated with thin silicate layer (Silconert 1000) and later (within 3 hours of sampling) analyzed for CO_2/CH_4/CO. Given the 3 hour time interval between sampling and analysis of the AirCore and the fact that the average rate of molecular diffusion of CO_2 the resolution of the AirCore is better than 1kPa for the bottom 95% of the atmospheric column. AirCores were used in Appendix A to estimate the error incurred by extending NOAA/ESRL aircraft CO_2 profiles above 6 km.

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 may be chosen to 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, where the GOSAT pressure levels are sigma levels with the 5th level approximately 2.5 km above the surface. The retrieved CO_2 profile averages 1.6 degrees of freedom (DOF) with about 0.8 DOF for levels 16-20 (where level 20 is the surface) and 0.8 DOF for levels 1-15 (where level 1 is at the top of the atmosphere). 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 mixing ratio represented by levels 16-20, which is named LMT_XCO_2 or LMT for short, and the partial column mixing ratio represented by levels 1-15, which is named U_XCO_2 or U for short.   The two partial columns each have about

307 0.8 degrees of freedom, meaning that they will each capture about 80% of
308 the true variability of their partial column.
309
310   The equation for the linear estimate of $\mathbf{x}$, the retrieved CO_2 profile (Connor
311 et al., 2008; Rodgers, 2000) is:
312
313 $\hat{\mathbf{x}} = \mathbf{x}_a + \mathbf{A}_{xx}(\mathbf{x}_{true} - \mathbf{x}_a) + \mathbf{A}_{xv}(\mathbf{v}_a - \mathbf{v}_{true}) + \mathbf{G}_x\varepsilon$ (1)
314
315 Where
316   • $\mathbf{x}$ is the retrieved CO_2 profile, size n_{CO2} (20 for ACOS-GOSAT)
317   • $\mathbf{x_a}$ is the a priori profile, size n_{CO2}
318   • $\mathbf{x}_{true}$ is the true value, size n_{CO2}
319   • $\mathbf{A_{xx}}$ is the n_{CO2} x n_{CO2} CO_2 profile averaging kernel
320   • $\mathbf{A}_{xv}(\mathbf{v}_a - \mathbf{v}_{true})$ is the cross-state error representing the propagation of
321   error from non-CO_2 retrieved parameters, $\mathbf{v}$ (aerosols, albedo, etc.),
322   into retrieved CO_2. This variable is called "$\mathbf{u}$" in Connor et al., 2008.
323   • $\mathbf{v}_a$ is the interferent value (used to generate fit radiances), size n_{interf}.
324   For ACOS-GOSAT n_{interf} is 26(27) for ocean(land)
325   • $\mathbf{v}_{true}$ is the true interferent value, size n_{interf}
326   • $\mathbf{A}_{xv}$ is size n_{CO2} x n_{interf}
327   • $\mathbf{G}_x$ is the gain matrix, size n_{CO2} x n_s, where n_s is the number of spectral
328   points, and
329   • ε is the spectral error, size n_s
330
331 The pressure weighting function, "$\mathbf{h}$" (size n_{CO2}) is used to convert the
332 retrieved CO_2 profile to XCO_2 by tracking each level's contribution to the
333 column quantity.
334
335 $\mathbf{h}_{xco2}{}^T$ = [0.026 0.053 0.053 0.053 … 0.053 0.053 0.053 0.026]   (2a)
336
337 The sensitivity to the top or bottom level is half that of other levels, as these
338 levels contribute to only one layer, rather than two adjacent layers. The
339 GOSAT levels are chosen such that the pressure weighting is very similar for
340 all layers and all observations. However, the pressure weighting is not
341 identical for all layers and all observations and the values used in our
342 analysis are the actual values in the files, with average values shown here,
343 rounded to 2 significant digits.
344
345 The LMT pressure weighting function is obtained by starting with the
346 pressure weighting function for XCO_2, setting levels 1-15 to zero, then
347 normalizing so that the sum of all entries adds to 1. For the U pressure
348 weighting function, levels 16-20 are set to zero, then the vector is
349 normalized so that the sum is 1. The LMT and U pressure weighting
350 functions are:

351

$\mathbf{h_{LMT}}^T = [0\ 0\ 0\ 0\ \dots\ 0\ 0.22\ 0.22\ 0.22\ 0.22\ 0.11]$ (2b)

$\mathbf{h_U}^T = [0.035\ 0.069\ 0.069\ \dots\ 0.069\ 0.069\ 0\ 0\ 0\ 0\ 0]$ (2c)

To calculate XCO_2, the equation is:

$XCO_2 = \mathbf{h_{xco2}}^T \cdot \hat{\mathbf{x}}$ (3)

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

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

$f_{LMT} = 0.235$ (4b)

$f_U = 0.765$ (4c)

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

$$\hat{X C O_2} = XCO_{2_a} + h_{XCO2}{}^T A_{xx}(x_{true} - x_a) + h_{XCO2}{}^T A_{xv}(v_{true} - v_a) + h_{XCO2}{}^T G_x \varepsilon \qquad (5a)$$

$$\hat{X C O_2} = XCO_{2_a} + a_{xx}(x_{true} - x_a) + a_{xv}(v_{true} - v_a) + g_x \varepsilon \qquad (5b)$$

where $\mathbf{a}_{xx}$ is the column averaging kernel, $a_{xx} = h_{XCO2}{}^T A_{xx}$ (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, $\mathbf{h} = [\mathbf{h}_{LMT}, \mathbf{h}_U]$:

$$\begin{pmatrix} \hat{LMT} \\ \hat{U} \end{pmatrix} = \begin{pmatrix} LMT \\ U \end{pmatrix}_a + \mathbf{h}^T A_{xx}(x_{true} - x_a) + \mathbf{h}^T A_{xv}(v_{true} - v_a) + \mathbf{h}^T G_x \varepsilon \qquad (6a)$$

$$\begin{pmatrix} \hat{LMT} \\ \hat{U} \end{pmatrix} = \begin{pmatrix} LMT \\ U \end{pmatrix}_a + a_{xx}(x_{true} - x_a) + a_{xv}(v_{true} - v_a) + g_x \varepsilon \qquad (6b)$$

where now $a_{xx} = [h_{LMT}, h_U]^T A_{xx}$, a (2 x n_{CO2}) matrix, $a_{xv} = [h_{LMT}, h_U]^T A_{xv}$, a 2 by n_{interf} matrix, and $g_x = [h_{LMT}, h_U]^T G_x$, a (2 x n_s) matrix.

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 $\begin{pmatrix} \hat{LMT} \\ \hat{U} \end{pmatrix} - \begin{pmatrix} LMT \\ U \end{pmatrix}_{True}$, a (2 x 2) matrix. 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, $\mathbf{S}_{smoothing} = \mathbf{(I-A)S_a(I-A)^T}$

391   (Rodgers, 2000), with **A** the (n_{CO2} x n_{CO2}) CO_2 profile averaging kernel and
392   **S$_a$** the a priori covariance, both included in the ACOS-GOSAT products.
393
394    $\sigma^2_{[LMT,U]}$ = **h^{T}S**$_{smoothing}$ **h**+ **h^{T}S**$_{interfer}$**h** + **h^{T}S**$_{meas}$**h**   (7a)

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

396    $$= \begin{pmatrix} \sigma_{LMT}{}^2 & c \cdot \sigma_{LMT}\sigma_U \\ c \cdot \sigma_{LMT}\sigma_U & \sigma_U{}^2 \end{pmatrix}$$ (7c)

397

398   Equation 7 estimates the predicted errors for LMT and U, where $\sigma_{[LMT,U]}$ is a
399   (2 x 2) matrix. The diagonals are the square of the predicted error for each
400   parameter, and the off diagonals also depend on the correlated error, c,
401   between these parameters. Table 2 shows the predicted errors for LMT, U,
402   and the error correlation between LMT and U. The predicted errors in Table
403   2 are larger than the actual errors, as seen later in Tables 4 and 5; error for
404   averaged observations is estimated in section 4.1.1. The a priori errors,
405   calculated from σ^2 = **h^{T}S$_a$h** are 34 and 9 ppm for LMT and U, respectively,
406   which are much larger than the posterior errors, indicating that these
407   quantities are largely unconstrained by the retrieval's prior assumption.

408

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

410

411   σ_{XCO_2} = $\mathbf{h}_{XCO\,2}{}^T \mathbf{S}_{smooth} \mathbf{h}_{XCO\,2} + \mathbf{h}_{XCO\,2}{}^T \mathbf{S}_{obs} \mathbf{h}_{XCO\,2}$ (8)

412

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

416

417    $XCO_2 = f_{lmt}LMT\_CO_2 + f_u U\_CO_2$ (9a)

418

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

420

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

422

423   where f$_{LMT}$ and f$_U$ are the air masses for the LMT and U partial columns
424   (0.236, 0.764), respectively, σ_{lmt} is the error for LMT, and *corr* is the error
425   correlation between LMT and U.

426

427   The normalized column averaging kernel is used to see the sensitivity of the
428   column to the true state at different levels, with a value of 1 meaning
429   perfect sensitivity, and a value of 0 meaning no sensitivity. The normalized

430 column averaging kernel is the column averaging kernel, **a**, divided by the
431 pressure weighting function for each layer, **h**$_{XCO_2}$, and multiplied by the
432 fraction of air in the partial column.
433
434 **a_norm**$_{LMT}$[i] = (**h**$_{LMT}$[i] **A**$_{CO_2}$[i,j])/**h**$_{XCO_2}$[j]*f$_{LMT}$ (10a)
435 **a_norm**$_U$[i] = (**h**$_U$[i] **A**$_{CO_2}$[i,j])/**h**$_{XCO_2}$[j]*f$_U$ (10b)
436
437 Figure 3 shows the normalized column averaging kernels for LMT, U, and
438 XCO$_2$ for a land scene. The ocean averaging kernel is very similar. Although
439 the LMT partial column mixing ratio sums the 5 levels within about 2.5 km of
440 the ground, the LMT has some sensitivity to the true state at all 20 levels
441 because the GOSAT radiances are not able to fully resolve between CO$_2$
442 within the surface to 2.5 km versus above this. As expected, the sensitivity
443 for LMT plus U is equal to the sensitivity for XCO$_2$, and the sensitivity for LMT
444 is weighted to the surface whereas the sensitivity for U is weighted to the
445 top of the atmosphere. The negative averaging kernels for LMT in the
446 stratosphere are partially a consequence of the ACOS prior constraint, which
447 does not allow stratospheric variability. Actual stratospheric variability is
448 transferred to the closest levels that are allowed to vary, and the surface
449 compensates for the radiance error induced by this, resulting in a negative
450 sensitivity of the LMT to the true state in the stratosphere. If the
451 stratospheric truth matches that of the *a priori*, then there will be no
452 propagation of error into LMT or U. The averaging kernels shown in Fig. 3
453 are similar to those calculated for TCCON in Fig. 2 of Connor et al. (2016).
454 As seen in Fig. 3, the quantity LMT + U (i.e. XCO$_2$) has a sensitivity of 1
455 between the surface and 600 hPa, with sensitivity dropping off slowly with
456 altitude above 600 hPa. The 0.8 degrees of freedom for LMT indicates the
457 sensitivity of the retrieved LMT to the true LMT. The missing 0.2 degrees of
458 freedom indicates sensitivity to the prior and/or sensitivity to the U part of
459 the true profile. Since the sensitivity of LMT and U together is 1 near the
460 surface, it is mainly sensitivity to the U part of the true profile. Similarly the
461 0.8 degrees of freedom for U indicates some sensitivity to the LMT and some
462 sensitivity to the U prior.
463
464 **3.2 Seasonal behavior of LMT, U, and XCO$_2$ estimated using *only***
465 **aircraft measurements and GOSAT sensitivity (no GOSAT**
466 **observations)**
467 This section answers the following questions:
468   (1) Do U and LMT have unique seasonal signatures?
469   (2) How much of the XCO$_2$ variability is due to LMT versus U
470   variability?
471   (3) How much does the prior influence the LMT and U retrievals?
472

473   This section simulates GOSAT retrievals using the linear estimate given the
474 aircraft in situ profiles at the SGP site (37N, 95W), the GOSAT prior, and the
475 GOSAT averaging kernels. This analysis assumes that the CO_2 profile
476 measured by aircraft at SGP (extended by the CarbonTracker model above
477 5.5 km) is the true CO_2 profile, which is then plugged into Eqs. 5 and 6 to
478 calculate the LMT and U that GOSAT would see at the SGP site, using the
479 GOSAT averaging kernels and priors. The measurement error and
480 interference terms are assumed to be zero for this analysis.
481
482   Using this analysis, the importance of the prior is assessed by using either a
483 prior that is constant in location and time (with only a 2 ppm/year secular
484 increase) or the GOSAT prior, in Eqs. 5 and 6. We assess how much LMT
485 and U contribute to the variations seen in XCO_2 using the variability of the
486 LMT and U partial columns combined with the weighting each has in the full
487 column. The seasonal cycles of each partial column mixing ratio are studied
488 by adjusting all aircraft measurements at SGP (2009 to 2014) to common
489 year (2012) by applying a 2 ppm/year secular trend, and binning all
490 observations by month. This method was used rather than fitting the
491 aircraft observations using the NOAA fitting routine (CCGCRV, described in
492 Thoning et al., 1989) to estimate the seasonal cycle shape because we found
493 that the aircraft observations (matched to GOSAT and within the GOSAT
494 record) are not sufficiently smooth to result in a consistent fit. Figure 4
495 shows the estimates of LMT, U, and XCO_2 using SGP aircraft profiles
496 calculated as described above. There is significant variability in the
497 individual aircraft measurements, seen in panel (a) but this is smoothed out
498 on monthly timescales, seen in the remaining panels. The dashed lines in
499 panel a represent fits using the NOAA fitting software CCGCRV. Single U
500 partial column mixing ratios are rarely more than 1 ppm different from the
501 fit, whereas single LMT mixing ratios can be up to 5 ppm different (e.g. see
502 summer, 2009; January, 2010; Summer, 2011).
503
504   Figure 4 (b) and (c) show the difference between the simulated retrievals
505 with the GOSAT a priori (b) versus a flat a priori (c) for the seasonal cycle.
506 The patterns are very similar, indicating that the signal is primarily coming
507 from the data rather than the prior, with standard deviations of 0.8 ppm for
508 LMT and 0.3 ppm for U (these changes are fully characterized when applying
509 the GOSAT prior to the aircraft true profile with the specified a priori vector).
510
511   Figure 4, panel (d) shows U versus XCO_2. At first glance U and XCO_2 look
512 very similar, but by comparing panel (d) and (b), the XCO_2 deviations move
513 towards LMT relative to the prior. The seasonal variabilities of XCO_2, LMT,
514 and U (maximum minus minimum), are 3.3 ppm, 4.8 ppm, and 3.3 ppm,
515 respectively. Note that the seasonal variations in LMT and U have a 0.56
516 correlation suggesting some independence between these two variables. A

517 straightforward calculation of variation times airfraction (Eq. 4) show that
518 the fraction of variation of XCO_2 resulting from variations in LMT is
519 approximately 30%, and the fraction of the variation in XCO_2 coming from U
520 variation is roughly 70%.   It is expected that U has the much larger impact
521 on XCO_2 due to the fact that the full column is 77% LMT. A similar
522 calculation at Park Falls, where the LMT seasonal cycle is 20 ppm and the U
523 seasonal cycle is 5 ppm finds 45% of the seasonal variability in XCO_2 results
524 from U and 55% from LMT at Park Falls (46N). Here, the high variability in
525 LMT will have a much large impact on XCO_2 despite the fact that it
526 represents a smaller part of the column.
527
528 Figure 4 indicates that LMT and U do have unique seasonal cycles which
529 result from the data rather than the prior.   The LMT partial column, which
530 contributes to 30% of the variations observed in XCO_2, has a much larger
531 seasonal variability than the U partial column or the XCO_2 column, and
532 earlier seasonal cycle maximums and minimums.
533
534 **4.0 Methods**
535 We test the sensitivity of the new products to surface fluxes using back-
536 trajectory footprints in Section 4.1. Section 4.2 discusses how GOSAT is
537 compared to aircraft. Sections 4.3-4.5 describe the bias correction, how the
538 aircraft data is extended to the full atmosphere and the coincidence criteria.
539
540 **4.1 Sensitivity of the LMT and U partial column mixing ratios to**
541 **surface fluxes**
542 To compare LMT and U sensitivity to surface fluxes, we look at 10-day back-
543 trajectory footprints created using Weather Research and Forecasting (WRF)
544 model combined with the Stochastic Time-Inverted Lagrangian Transport
545 (STILT) model (WRF-STILT; Nehrkorn et al., 2010). The "footprint" for an
546 observation is a map of the surface locations to which an observation is
547 sensitive. Footprints are created for each of the 20 GOSAT levels, then
548 convolved with the LMT and U averaging kernels. The averaging kernel
549 estimates the sensitivity of the GOSAT measurement of each quantity to the
550 true state at each level. Footprint maps are created which show the
551 sensitivity of each type of GOSAT observation to sources and sinks. This
552 was done for 10 GOSAT observations in the Amazon. The average distance
553 for the nearest 10% of footprints is 260 km for LMT and 790 km for U. It is
554 likely that there is also a very long tail in the U sensitivity, based on the
555 work of Liu et al. (2015) and Feng at el. (2016).
556
557 **4.2 Comparisons to aircraft**
558 The correct way to validate GOSAT estimates of [LMT, U] is to compare the
559 GOSAT observations to an estimate of what GOSAT should observe, given its
560 sensitivity, when the true atmospheric state is set to the aircraft CO_2 profile

561 using Eq. 6. The agreement should be within the GOSAT observation error,
562 as the smoothing term's effects on the comparison are removed by the
563 application of the GOSAT averaging kernel to the validation data. The
564 aircraft measurements are assumed to be unbiased and have small
565 measurement error compared to the errors in the GOSAT profiles.
566
567 **4.3 GOSAT bias correction**
568 The GOSAT standard XCO_2 product has regional biases and errors which can
569 be partially corrected using jointly retrieved parameters, pre-filters, or
570 radiance properties, e.g. the ratio of the signal in the strong vs. weak band,
571 retrieved albedo slopes or values, retrieved aerosol slopes or values; and
572 through post-processing screening, e.g. removing fits where the difference
573 in the retrieved versus prior surface pressure is greater than 4 hPa. We
574 apply the same techniques to the LMT partial column mixing ratio in
575 Appendix A which is briefly described here. After LMT is corrected, the
576 corrected U partial column mixing ratio is set using Eq. 9a, so that XCO_2 is
577 consistent with LMT and U. The purpose of setting U this way is a) there is a
578 lack of validation data for the U partial column, so bias correction would be a
579 lot less certain, and b) it is useful to have the new products consistent with a
580 current operational column results.
581
582 To correct the LMT partial column mixing ratio, a set of pairs of "true" and
583 "retrieved" values is compiled, using validation data. GOSAT minus true is
584 plotted versus various GOSAT parameters described in Appendix A, and if a
585 slope is found for the GOSAT error versus any parameter, then a correction
586 is applied for that parameter. The robustness of the correction is tested by
587 verifying the correction on data withheld from the fit, as described in
588 Appendix A. Following the initial bias correction, GOSAT LMT is compared for
589 closely occurring ocean and land pairs; a constant bias term is added to the
590 land bias correction so that land and ocean, on average, are consistent.
591
592 **4.4 Coincidence criteria**
593 "Geometric criteria", defined as +-3 degrees latitude, +-5 degrees longitude
594 +-1 week time are used to select coincident GOSAT observations for
595 particular sites. 5 degrees latitude/longitude, 1 hour has previously been
596 used for GOSAT criteria (Kulawik et al., 2016), however this did not yield
597 enough matches for aircraft profiles. With the above criteria, the total
598 matches range from 64 (at Poker Flats, station ID PFA) to 4800 (at the
599 Southern Great Plains, station ID SGP), with median 430, which is
600 approximately 9/month assuming all months are equally well sampled
601 throughout the time series. A tight spatial criteria was selected to best
602 capture the seasonal cycle at a given location, especially for land where
603 spatial variability is large. Because aircraft and surface observations are
604 more infrequent than TCCON, an extended temporal window was used for

605 the comparisons to obtain sufficient comparison data. Other methods that
606 were tried were dynamic coincidence criteria (Wunch et al., 2011b) which
607 considers a larger area (+- 10 degrees latitude, +- 30 degrees longitude)
608 but also matches atmospheric temperature, and a variant of Basu criteria
609 (Guerlet et al., 2013), which used dynamic coincidences which had model-
610 model differences less than 0.5 ppm. All three criteria gave similar results
611 overall, with different criteria performing better at different stations, but no
612 clear overall best criteria. For HIPPO data, which mainly tests latitude
613 gradients over ocean, the dynamic coincidence approach was used following
614 Frankenberg et al. (2016). Different variations on the dynamic coincidence
615 criteria were tested, e.g. using temperature comparisons at the surface,
616 averaging from the surface to 2.5 km, or weighting temperature differences
617 by the pressure weighting function. The different temperature criteria
618 yielded similar results overall, other than using temperature differences at
619 the surface did not work as well as the other levels. We therefore used the
620 standard dynamic criteria from Wunch et al., (2011b).
621
622 **4.5 Extension of the aircraft profile**
623 The aircraft measurements go from the surface to between 5.5 km to 8 km
624 for most ESRL land to 9-13 km for HIPPO observations. As GOSAT LMT, U,
625 and XCO_2 have sensitivity above 5.5 km and even above 13 km, as seen in
626 the averaging kernel shown in Fig. 3, the aircraft profile needs to be
627 extended from the top measurement to the top of the atmosphere. Four
628 different methods of extension were tested: extending with the GOSAT
629 prior, extending the top aircraft measurement through the tropopause
630 pressure and extending with the GOSAT prior above this, extending with the
631 CT2015 model, and extending the top aircraft measurement through the
632 tropopause pressure and extending with the CT2015 model above this. The
633 different extensions mainly had an effect on the overall LMT, U, and XCO_2
634 biases, rather than the standard deviation, with a spread of 0.4 ppm, as
635 seen in Table A4. The extension that was used in the rest of the paper is
636 extending the top aircraft measurement through the tropopause pressure
637 and extending with the CT2015 model above this. There was no clear
638 winner on the profile extension, and this choice was just a preference.
639
640 **5. GOSAT results**
641 Figure 5 shows GOSAT comparisons for LMT and U versus the aircraft
642 measurements at the SGP site at 37N, 95W which can be compared to the
643 simulated results shown in Fig. 4. The GOSAT LMT and U products show the
644 same seasonal patterns as seen in the aircraft data. Figure 5a shows results
645 without bias correction (though do apply a constant 12 ppm correction to
646 LMT). The GOSAT results show a similar seasonal cycle to the aircraft but
647 with large and temporally correlated errors. Figure 5b shows the results
648 with the bias correction as described in Appendix A. Figure 5c shows

649 CarbonTracker matched to GOSAT (CT@GOSAT) and CarbonTracker
650 matched to the aircraft measurements (CT@aircraft). The difference of
651 CT@GOSAT and CT@aircraft estimates the co-location error. Large
652 differences are seen between CT@GOSAT and CT@aircraft in early 2010,
653 Summer, 2010, and Summer, 2011. In Fig. 5d, the seasonal cycle is shown
654 by transforming all data to lie within 2012 using 2 ppm/year adjustment to
655 CO_2. There are systematic differences seen in the drawdown, which is
656 underestimated by GOSAT. However, when months that have differences of
657 (CT@GOSAT -CT@aircraft) more than 2.5 ppm are removed (removing June,
658 2009; October, 2009; May, 2010; July, 2010; and August, 2010), Figure 5e
659 shows agreement within the GOSAT predicted errors between GOSAT and
660 aircraft. Figure 5f is the same as Figure 5e, but removes all observations
661 that were used to develop the bias correction. There is no significant
662 difference between Fig. 5f and 5e. The authors have some concerns about
663 applying the bias correction to parts of the world where there is not
664 validation data, e.g. the land bias correction was primarily over the U.S..
665 Similarly, the HIPPO observations used for ocean bias correction are in the
666 Pacific Ocean, so the ocean bias correction in the Atlantic Ocean is less
667 certain.
668
669 GOSAT U improves over the a priori for actual observations (Figs. 5d-f) and
670 in simulated (Fig. 4b) results. This is shown by the black (aircraft) vs. blue
671 (GOSAT) in Fig. 5c where there is better agreement in July-November than
672 prior (green) vs. black (aircraft). The bias seen in the U partial column
673 mixing ratio versus the aircraft U estimate is also found in XCO_2 versus the
674 aircraft.
675
676 **5.1 Summary of comparisons to all validation data**
677 GOSAT LMT, U, and XCO_2 are compared to aircraft profiles, where the
678 aircraft profile has the GOSAT averaging kernel applied so that the
679 sensitivity is considered. The comparison locations are shown in Fig. 2.
680 More detailed comparisons, showing results for each location and/or
681 campaign, are shown in Appendix B. Definitions of the quantities calculated
682 and compared are shown in Table 3.
683
684 Table 4 shows the biases with respect to aircraft data and Table 5 shows the
685 standard deviation with respect to aircraft, for single and averaged
686 observations. The bias or standard deviation is calculated for every site (or
687 campaign). The mean represents the average of all site means, and the ±
688 represents the standard deviation for the means averaged by site (or
689 campaign). The variability of the bias by location or time is a key metric in
690 the data quality. Biases that vary by season or location are cannot be
691 corrected for and will be particularly detrimental to the use of satellite data

692 for inverse flux estimates, as the assimilation will attribute these biases to
693 spurious fluxes.
694
695 The co-location error is estimated by comparing CarbonTracker to itself at
696 the satellite location/time and CarbonTracker at the aircraft location/time.
697 For the ocean surface sites, a vertical co-location error is estimated by
698 comparing CarbonTracker with the LMT averaging kernel to CarbonTracker
699 at the surface. In Tables 4-6, the top entry in the ocean surface co-location
700 error is from discrepancies in horizontal location and time. The bottom entry
701 is the co-location error for sampling CarbonTracker for the LMT quantity
702 versus CarbonTracker at the surface.
703

5.1.1 Bias

705 In Table 3, the co-location bias is largest for aircraft land, with an overall
706 bias of -0.6 ppm and bias variability of 0.7 ppm. This gives an approximate
707 best case of what could be achieved by GOSAT-aircraft comparisons. An
708 investigation of the -2 ppm co-location bias in the LMT partial column mixing
709 ratio at CAR in July (during the drawdown) finds that the GOSAT
710 observations are always taken 3-4 hours later than the aircraft. The
711 CarbonTracker model estimates the effect of +3 hours as resulting in a -2
712 ppm change in the LMT partial column mixing ratio. The co-location bias
713 reflects spatial, diurnal, and seasonal co-location errors. Taking out the 5
714 sites that have co-location biases > 0.5 ppm (see Appendix B, Table B1:
715 WBI, BNE, CAR, HIL, and CMA), reduces the co-location bias to -0.2 ± 0.3
716 ppm.
717
718 In Table 4, the "true mean by site/campaign" is the mean true value
719 averaged by location (or campaign). The ± represents the standard
720 deviation of the mean true value by location (or campaign). The GOSAT
721 retrieval must improve on the ± at the very least to provide information on
722 the atmospheric state. The GOSAT prior bias improves over the true
723 variability on land but not for ocean cases for LMT. For U, the a priori minus
724 true variability is the same size as the true variability. The "GOSAT bias"
725 improves over the prior in all entries of the absolute bias, except for XCO_2
726 for ESRL ocean, and U and XCO_2 for AJAX. Issues with both U and XCO_2
727 suggests a possible issue with the profile extension above the aircraft.
728 Improvement over the prior for GOSAT ± bias occurs in all comparisons.
729 Note that for ESRL land, if the 5 stations with large co-location error are
730 taken out, the LMT bias variability decreases from 1.0 ppm to 0.7 ppm.
731
732 The location-dependent bias is important because this bias variability cannot
733 be easily corrected and will be attributed to phantom fluxes. The LMT
734 location dependent bias is no worse than the XCO_2 location dependent bias,
735 whereas the LMT signals are much more variable than XCO_2. The bias

736 variability for XCO_2 and U are possibly too high due to uncertainty of the
737 aircraft profile extension because the bias variability is much larger than the
738 0.3 ppm seen in Kulawik et al. (2016) versus TCCON. Taking out sites with
739 large co-location bias for XCO_2 does not improve the GOSAT XCO_2 bias
740 variability. Taking out the top 4 GOSAT XCO_2 bias outliers results in a
741 GOSAT XCO_2 bias variability of 0.5 ppm for the remaining sites, however
742 these 4 sites are not the same sites where LMT has bias issues, nor are
743 these sites where CarbonTracker shows a large co-location bias.
744
745 **5.1.2 Standard deviation**
746 Table 5 calculates errors versus aircraft data. The co-location error gives an
747 upper bound on how well we could expect GOSAT to compare to the
748 observations. The co-location error is subtracted, in quadrature, from the
749 GOSAT error to estimate the GOSAT errors in the absence of co-location
750 error.
751
752 To reduce the co-location error, a very tight coincidence criteria of 2
753 degrees, 1 hour was applied, yielding 146 matches, of which 89 are at SGP
754 and 39 at HIL. Results for these tight coincidences are compared to the
755 looser coincidence criteria results for these sites. For the tighter
756 coincidences, the LMT co-location error is (0.3,0.7) ppm at (SGP, HIL,
757 respectively), and the GOSAT LMT (n=1) error is (2.6,2.5) ppm. This is
758 compared to the looser coincidence results, where LMT co-location error is
759 (1.8,2.2) ppm and GOSAT LMT error is (3.9,3.8) ppm. This analysis
760 suggests that the co-location error based on CarbonTracker may be
761 underestimated. The GOSAT LMT (n=1) error in Table 5 for ESRL land
762 (which has co-location error subtracted) is 3.4 ppm, whereas the error when
763 the tighter coincidence criteria is applied is actually much less, 2.6 ppm. For
764 U, the GOSAT (n=1) error is (1.0,1.4) whereas it is (1.3,1.2) for the looser
765 criteria, so tight versus loose coincidence criteria did not matter a lot for U
766 comparisons.
767
768 The next row of Table 5 is the predicted error, given by Eqs. 7 and 9, which
769 is on the order of 4.5 ppm for LMT, 1.7 ppm for U, and 0.7 ppm for XCO_2.
770 The actual standard deviation of GOSAT versus aircraft, however, is about
771 half that for LMT and U, and double the predicted error for XCO_2. This is
772 discussed in Section 5.1.5.
773
774 The "true variability" in Table 5 shows how much the different partial
775 column mixing ratios vary by month. The variability of LMT over land is 5.4
776 ppm, about double that of U or XCO_2, and the variability of LMT at remote
777 ocean sites is 1.1 ppm, about 50% larger than U or XCO_2 variability.
778

779 The prior standard deviation (n=15), and GOSAT standard deviation (n=15)
780 look at the error of averaged GOSAT values, which is important for
781 understanding bias that will result from assimilating this data for flux
782 estimates. Kulawik et al. (2016) showed the GOSAT error does not drop off
783 as the inverse square root of the number of observations, like it would if the
784 error were fully random. The error for 15 observation averages is about 0.4
785 times that of 1 observation for land, with a similar factor for XCO_2, LMT, and
786 U; and about 0.5 times that of 1 observation for ocean, similarly for all
787 quantities. Note that the co-location error has been subtracted out (in
788 quadrature) for both the a priori and GOSAT errors.
789
790 The standard deviations for LMT, U, and XCO_2 show improvement over the
791 prior for land cases but improve only marginally or do not improve over
792 ocean. The location-dependent bias, however, does show improvement for
793 LMT and U in Table 4. For surface ocean sites, which are only compared to
794 LMT, the improvement over the prior is much better, mainly because the
795 prior is not very good at these sites.
796
797 **5.1.3 Errors separated into co-location, random, and correlated error**
798 The errors between aircraft and GOSAT observations can be parametrized by
799 the number of GOSAT observations that are averaged. Kulawik et al. (2016)
800 found the form in Eq. 11 matched well to the observed errors.
801

$$error = \sqrt{a^2 + b^2/n} \tag{11}$$

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

804
805 where n are the number of GOSAT observations that are averaged (all of the
806 averaged observations match a single aircraft measurement), a is error that
807 does not reduce with averaging, and b is the random error. a is further split
808 into co-location error, ε_{coloc}, plus a_o, the correlated error in Eq. 12. Correlated
809 error means that no matter how many observations are taken, this error
810 does not reduce, and can be due to interferents or spectroscopy in
811 combination with attributes specific to different locations and times.
812
813 The co-location error is the error resulting from imperfect matching of the
814 aircraft and satellite observations, and is approximated by the standard
815 deviation of the CarbonTracker model at the validation location and time and
816 the model at the satellite observation location and time, and is tabulated in
817 Table 6. This term, as seen in Table 6, is comparable to or even larger than
818 a for LMT land cases. Some co-location schemes (e.g. as implemented by S.
819 Basu described in Guerlet et al. (2013)) use the model-model differences to
820 select the best satellite observations to match validation data. Equation 11
821 is used to determine a and b, and then a_o is calculated from a and ε_{coloc} .

822
823 The co-location error is subtracted from the correlated error, to try to
824 remove the effect of co-location on the error estimate. This is a statistical
825 subtraction, as no value was found in subtracting the co-location error for
826 individual comparisons (perhaps because the model is not accurate enough
827 to capture the co-location differences case by case). The three quantities
828 from Eq. 12 are shown in Table 6. For LMT the co-location error is about the
829 same size as the correlated error for ocean, and the co-location error is
830 larger than correlated error for land. For U and XCO_2, the correlated errors
831 are larger than the co-location error for ocean, and comparable for land.
832
833 **5.1.4 Comparison of XCO_2 results to previous results**
834 We compare GOSAT XCO_2 comparisons to the previous validations using
835 TCCON (Wunch et al., 2011b; Kulawik et al., 2016) and HIPPO observations
836 (Frankenberg et al., 2016). The GOSAT comparisons to HIPPO in
837 Frankenberg et al. (2016) were for at least 6 averages and did not subtract
838 co-location error (which is only 0.1 ppm over ocean). Using Eq. 12 and
839 Table 6, we find that the XCO_2 error for n=6 is 0.43 ppm, in agreement with
840 0.45 from Frankenberg et al. (2016). Without co-location error, the XCO_2
841 from n=6 is 0.42 ppm. For ESRL land, several quantities in Tables 4-6 can
842 be directly compared to previous GOSAT/TCCON validation: the co-location
843 error (0.8 ppm) is larger than co-location for geometric coincidence (0.4
844 ppm) but smaller than for dynamic coincidence (0.9 ppm) from Kulawik et
845 al. (2016). This makes sense as Kulawik et al. (2016) had a 1 hour
846 coincidence with TCCON whereas 7 days is used in this paper (because
847 aircraft measurements are sparser in time than TCCON observations). a_o
848 and b values of 0.7±0.5 ppm and 1.6±0.2 ppm in this work are consistent
849 with 0.8 ±0.2 ppm and 1.6±0.1 ppm, for a (corrected) and b, respectively,
850 from Kulawik et al. (2016) Table 2. Additionally, the predicted error of
851 0.9±0.1 which is a factor of 1.9 less than the actual error of 1.7±0.4 are
852 identical to the values and relative sizes of predicted versus actual error in
853 Kulawik et al. (2016) at the end of section 3.1.
854
855 As discussed in Section 5.1.1, the location-dependent bias found in Kulawik
856 et al. (2016) versus TCCON sites for XCO_2 was 0.3 (after removing outlying
857 stations north of 60N and locally-influenced stations). In this paper, we find
858 the bias variability for XCO_2 0.9 ppm over land and 0.3 ppm over ocean (see
859 Table 4). One reason for the discrepancy could be from the extension of the
860 profile above the aircraft measurement (about 5-6 km). As seen in
861 Appendix A, different methods for profile extension causes changes on the
862 order of 0.4 ppm. Another possible cause for the discrepancy is that GOSAT
863 has been extensively tested against TCCON and issues that show up at
864 TCCON locations have been previously addressed. This was tested by fitting
865 bias correction factor for U specifically, rather than calculating bias-

866 correction factors for LMT and subtracting the LMT partial column from
867 GOSAT XCO_2 to estimate U. The bias variability for U did not improve when
868 bias correction factors were calculated directly for U. We also compare
869 GOSAT XCO_2 comparisons aircraft and GOSAT XCO_2 comparisons to TCCON
870 at the two sites where both validation data are co-located, Park Falls,
871 Wisconsin (LEF), and Lamont, Oklahoma (SGP). Note that LEF and SGP
872 collect data up to 3.5 and 5 km above the ground, respectively, whereas
873 most sites collect up to 8 km above the ground, so the profile extension
874 error might be higher at these sites. Averaging over these two sites, the
875 GOSAT XCO_2 bias versus aircraft in this work is -0.4 ppm. The GOSAT XCO_2
876 bias versus TCCON in Kulawik et al. (2016) for these two sites is -0.1 ppm.
877 The difference between these comparisons is on the same order as the
878 uncertainty introduced by profile extension discussed in Appendix A.

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

890 The discrepancy between the actual and predicted errors arises from the
891 actual correlation of the LMT and U partial column mixing ratio errors. The
892 predicted error correlation between LMT and U is -0.8. This means that
893 values too low in LMT should be matched with values too high in U, such
894 that the total column has lower relative errors than either partial column
895 separately. The actual error correlation of (LMT-aircraft) and (U-aircraft)
896 averages +0.6, meaning that when LMT is high, U also tends to be high, and
897 XCO_2 does not gain precision when combining LMT and U. So the finding is
898 that the LMT-U error correlation must be changed from the predicted value
899 of -0.8 to the measured value of +0.6. When the diagonal error terms are
900 multiplied by 0.6 and the error correlation between LMT and U is set to 0.6,
901 to match the error correlations observed versus aircraft data, the predicted
902 LMT, U, and XCO_2 errors are consistent with the actual errors. Over ocean,
903 multiplying the diagonal error terms by 0.3 and the error correlation
904 between LMT and U set to 0.6 makes the predicted and actual errors agree.

906 The errors in Table 5 represent the standard deviation of GOSAT minus
907 validation data calculated separately at each validation location. So, the
908 errors in Table 5 do not include the bias errors from Table 4. The persistent
909 regional biases captured in the "GOSAT bias" variability 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 Table 4). 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. This is the first characterization of the effect of bias correction on the actual errors.

In summary, the single-sounding errors of GOSAT LMT and U over land (ocean), based on the ESRL aircraft comparison, and subtracting co-location error, 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 6, and the same LMT-U error 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 (converted to 2012 by subtracting 2 ppm per year secular increase). In February, the lower troposphere has already reached near peak values, whereas the U 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 (Sweeney et al., 2015) 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

954 same pattern of discrepancies are also seen for XCO_2 versus aircraft. At the
955 two sites where aircraft and TCCON are jointly observed, SGP in Oklahoma
956 and LEF in Wisconsin, XCO_2 agrees with TCCON rather than the aircraft.
957 This suggests an issue with the extension of the aircraft profile from the top
958 aircraft measurement (about 6 km) to the top of the atmosphere.
959
960 Figure 7 shows the seasonal cycle at 5 sites arranged west-to-east (a-e) and
961 north-to-south (f-j). The seasonal cycle amplitude in LMT increases for both
962 west-to-east and south-to-north directions. There is also a shift to later in
963 the seasonal cycle minimum going either east to west and north to south, as
964 seen by the slopes in the orange and blue dotted lines. There is a consistent
965 phase lag in the U-prior which is corrected by the GOSAT retrieval, and the
966 LMT prior drawdown is consistently too large in panels i and j, correct for the
967 GOSAT retrieval. The seasonal cycle maximum is harder to quantify for the
968 LMT because LMT CO_2 rises and stays fairly flat between January and April,
969 therefore the maximum can be influenced by small variations in the data, in
970 contrast to U or XCO_2 which rise steadily until April.
971
972 **5.3 Comparisons to remote surface ocean sites**
973 Remote surface sites are useful as comparisons to LMT as these locations
974 are expected to have long vertical length scales of variability near the
975 surface. These comparisons LMT and remote surface ocean sites are not
976 used for estimating errors or bias corrections because there is a mismatch in
977 sampled vertical air mass: to compare validation data and GOSAT LMT
978 properly, validation values are needed at every pressure level at which the
979 GOSAT LMT averaging kernel (as seen in Fig. 3) is not zero. Since there is
980 only validation data at the surface, the only option is to directly compare the
981 surface site value to the GOSAT LMT result, rather than integrating
982 validation results over the pressure range where GOSAT LMT is sensitive.
983 The vertical co-location error is estimated by comparing CarbonTracker LMT
984 (estimated with Eq 6b, where $\mathbf{x}_{true}$ is set to the CarbonTracker value, $\mathbf{x}_a$ is
985 the GOSAT prior, and cross-state error and measurement error are set to
986 zero) versus CarbonTracker surface values. The GOSAT LMT a priori is
987 significantly worse for remote ocean sites as compared to North America,
988 and this allows the GOSAT product to show what is in the data versus the
989 prior. In Table 6, the co-location error for surface ocean sites is higher than
990 for ocean aircraft comparisons (1.0 ppm vs. 0.3 ppm, respectively), and the
991 GOSAT bias versus ocean surface sites in Table 4 is also higher (1.1 ppm vs.
992 0.1 ppm, respectively). Because of the limited GOSAT ocean coverage,
993 there are typically only about 4 consecutive months for each station, but this
994 is adequate to evaluate the performance. Figure 8 shows an average over
995 all locations, and the 4 sites with the highest number of matches, arranged
996 from north to south. Note the improvement of GOSAT (red) over the a priori
997 (green) when comparing to the surface site measurements (pink).

998   Unsurprisingly, the performance of XCO$_2$ (blue) shows that surface site
999   observations are not suitable for XCO$_2$ validation. GOSAT LMT improves
1000 over the prior in terms of the overall bias, the bias variability, and the
1001 standard deviation over the prior even without averaging; the error reduces
1002 further with averaging.
1003 Table 6. Estimated co-location, correlated, and random errors using Eq. 12.
1004 The co-location errors are taken from Table 4.
1005
1006 **5.4 Source versus outflow in biomass burning with comparisons to**
1007 **MOPITT CO and MODIS fire counts**
1008 The SH region is of particular interest for validation as the GOSAT prior is
1009 nearly spatially and vertically constant, varying primarily by month. Figures
1010 9 and 10 compare GOSAT LMT and U partial column mixing ratios,
1011 respectively, to MOPITT multispectral CO retrievals and MODIS fire counts,
1012 to see how much fires in this part of the world are responsible for the
1013 patterns seen in the GOSAT partial columns. The GOSAT prior, in the left
1014 columns of Figs. 9 and 10, is nearly constant in the southern hemisphere.
1015 The scale needed to span the seasonal range is about 13 ppm, about half
1016 that needed to capture the seasonal variability in the U.S.
1017
1018 The pattern seen in LMT matches MODIS fire count images, shown in the
1019 right column, and matches MOPITT near-surface CO shown in the third
1020 column. Because of the different overpass time and the different coverage
1021 due to cloudiness between these satellites, an exact match should not be
1022 expected. In February, sub-Saharan Africa has fires and south-central Africa
1023 does not, whereas the situation is reversed in August. This pattern is seen
1024 in GOSAT LMT, MOPITT near-surface, and MODIS fire counts. The main
1025 differences between GOSAT and MOPITT are seen in October, where GOSAT
1026 LMT shows outflow over the Atlantic and MOPITT near-surface CO does not.
1027 This may be because the multi-spectral CO has little surface sensitivity over
1028 the ocean.
1029
1030 In the mid-troposphere, MOPITT CO shows enhancement in sub-Saharan
1031 Africa in February, central Africa in August, and outflow in October, and
1032 GOSAT retrieved U shows the same patterns as MOPITT. Interestingly, both
1033 MOPITT and GOSAT show no enhancement in South America in August,
1034 whereas the surface shows very strong enhancements in both. MOPITT
1035 shows very little outflow in September, but strong outflow in October.
1036 GOSAT does not have ocean coverage in this region for September, but
1037 GOSAT U shows strong outflow in October.
1038
1039 The LMT signal in the Amazon region is clearly visible by May (not shown),
1040 whereas the CO signal seen from MOPITT
1041 (http://www.acom.ucar.edu/mopitt/MOPITT/data/plots6j/maps_mon.html)

1042 seems to ramp up starting in August. We look at the quantitative values for
1043 the enhancements and background values for surface CO and LMT CO_2 in
1044 Table 7 and use this to estimate $\Delta CO/\Delta CO_2$ emission ratios for May and
1045 August.
1046
1047 The GOSAT LMT degrees of freedom are about 0.8 and do not vary
1048 significantly, mainly because only clear-sky observations (with
1049 aerosols/clouds < 0.3 optical depth) are used. The MOPITT degrees of
1050 freedom for the near-surface varies significantly. MOPITT enhancement for
1051 different degrees of freedom cutoffs are shown in different columns of Table
1052 7. To account for the degrees of freedom, note that if a retrieved variable
1053 has degrees of freedom 0.2, it will capture about 20% of the true variability;
1054 if a retrieved variable has degrees of freedom 0.4, it will capture about 40%
1055 of the true variability. So, an estimate of the emission ratio which considers
1056 the degrees of freedom is:
1057
1058 $$emission\ ratio = \frac{CO - \quad background\ (ppb)}{CO_2 - C\ _2\ background\ (ppb)} * \frac{CO_2\ degrees\ of\ freedom}{CO\ degrees\ of\ freedom} \qquad (13)$$
1059
1060 Without utilizing a model as a transfer function, the exact ratio cannot be
1061 estimated, due to the varying sensitivities with altitude and different
1062 observation locations and times.
1063
1064 The emission ratio is estimated using Eq. 13 with the information shown in
1065 Table 7. The emission ratio estimate ranges from 6-7% in May and 10-15%
1066 in August, for the different MOPITT sensitivity groupings. The emission ratio
1067 seen by the MOPITT and GOSAT LMT products are compared to those
1068 estimated from aircraft observations over tropical forests by Akagi et al.
1069 (2011, Table 1), which is 8.8%. The MOPITT/GOSAT ratio is similar to Akagi
1070 et al. (2011), but 2-3% lower in May, and 1-6% higher in August.
1071
1072 **5.5 Differences between LMT and U**
1073 The difference between CO_2 in the free troposphere and boundary layer can
1074 be used to evaluate model transport. One previous finding is that surface
1075 assimilation estimates of northern extra-tropical and southern hemisphere
1076 land flux differences are correlated with the gradients between CO_2 at 4 km
1077 and 1 km in the assimilated model. When the model-based vertical
1078 gradients of CO_2 are larger than aircraft observations, models tend to predict
1079 too large northern hemisphere sinks and too large southern hemisphere
1080 sources (Stephens et al., 2007). Aircraft observations of CO_2 at 4 km and 1
1081 km are taken at only a few sites worldwide, primarily in the U.S. Therefore,
1082 global measurements of the difference between CO_2 in the free troposphere
1083 and boundary layer are of great interest. In this section we calculate the
1084 errors for LMT-U compared to aircraft profiles and show this difference for

1085 GOSAT and CarbonTracker in the U.S. and the southern hemisphere in two
1086 different months.

1087

1088 The error estimate for LMT-U is calculated using Eq. 14. Note that a positive
1089 correlation in the errors for LMT and U results in a smaller error for the
1090 quantity (LMT – U) than the sum of the squares of LMT and U.

1091

1092 $\sigma_{(LMT-U)} = \sqrt{\sigma_{lmt}^2 + \sigma_u^2 - 2 \cdot \sigma_{lmt}\sigma_u c}$ (14)

1093

1094 Table 8a-c give the bias, standard deviation, and error with averaging for
1095 LMT – U. In Table 8a, the GOSAT bias and bias variability of (LMT – U)
1096 improves over the prior for all cases. The bias variability of 0.3, 0.9 and 0.8
1097 ppm of (LMT – U) for HIPPO ocean, ESRL ocean, and ESRL land,
1098 respectively, is comparable to the LMT bias variability of 0.3, 1.0, and 1.0 for
1099 the same categories. In Table 8b, the 15-observation average standard
1100 deviation for GOSAT LMT-U is 0.6 (1.2) ppm for ocean (land), 0.2 ppm
1101 higher for ocean and 0.7 ppm lower for land than LMT. In Table 8c, the
1102 correlated error is 0.5 (0.9) ppm for ocean (land), which is 0.2 ppm higher
1103 for ocean and 0.8 ppm lower for land. The land standard deviation for LMT-
1104 U is 2.3 ppm before subtracting off the 2.1 ppm co-location error. The
1105 difference between the land error for LMT and LMT-U is due to the estimated
1106 size of the co-location error.

1107

1108 Figure 11 shows the seasonal cycle of LMT-U for 3 sites. The differences
1109 between GOSAT and aircraft values at the CAR site in Colorado and LEF in
1110 Wisconsin during the drawdown can be explained by co-location error. The
1111 dotted lines shows CarbonTracker matched to GOSAT (red dotted) or aircraft
1112 (pink dotted) locations/times. The difference between the red dotted and
1113 pink dotted lines estimate the co-location error. If GOSAT were corrected by
1114 this difference, the agreement with aircraft would be much better. The co-
1115 location bias and standard deviation are estimated in Tables 7a and 7b, and
1116 are large compared to the observed GOSAT errors. The error estimates for
1117 GOSAT are corrected by the co-location error. Note that the CAR aircraft
1118 measurements also did not sample down to the boundary layer during this
1119 time period.

1120

1121 The predicted error for LMT-U over land in Table 8b is 2.7 ppm, whereas the
1122 actual error is 2.3 ppm. If LMT and U had zero correlation, the predicted
1123 error (using Eq. 14) would be 3.6 ppm. This is another corroboration of the
1124 positive correlation between the LMT and U errors.

1125

1126 Figure 12 shows LMT – U for February and July in the U.S. averaged over
1127 2010-2014 for February and 2009-2013 for July. LMT – U diagnoses model
1128 vertical transport (Stephens, 2007) and transport of outflow (Deeter, 2013).

1129 Aircraft values for LMT – U are shown as squares. The aircraft patterns are
1130 captured by GOSAT, with discrepancies in July for BNE, CAR, SCA, and SGP
1131 due to co-location error (see CAR plot in Fig. 11). The CarbonTracker model
1132 captures the aircraft patterns very well. The main differences between
1133 GOSAT and CarbonTracker are seen in the southwestern U.S. in July (where
1134 there are no aircraft measurements). Figure 12c-d shows LMT – U for
1135 February and October in the southern hemisphere. The only aircraft site in
1136 this region is Rarotonga, where Fig. 11 shows good agreement for both
1137 CarbonTracker and GOSAT. The patterns in the southern hemisphere show
1138 more differences between CarbonTracker and GOSAT. In February, GOSAT
1139 shows a high gradient in the eastern Pacific and northern South America not
1140 seen in CarbonTracker, and more negative gradient in central and southern
1141 Africa. In October large gradients are seen by GOSAT in South America and
1142 Africa with outflow into the Atlantic, with little seen in CarbonTracker.

1144 LMT-U is predominantly positive in this southern hemisphere region in
1145 October. Vertical transport from the northern hemisphere would
1146 predominantly show up in the U partial column, whereas flux from land or
1147 ocean would predominantly show up in the LMT partial column. An overall
1148 positive value for LMT – U could either suggest that the overall flux is
1149 positive in this month, or that transport from the northern hemisphere was
1150 negative, though the blank space in the Amazon due to cloudy conditions,
1151 where LMT-U is expected to be negative from plant uptake, creates
1152 uncertainty both in this crude estimate and in the formal assimilated results
1153 from GOSAT data.

1155 **6.0 Discussion and conclusions**
1156 GOSAT near-infrared observations provide information to retrieve two partial
1157 column mixing ratios, one from the surface to about 2.5 km (LMT_XCO_2),
1158 and the second above about 2.5 km (U_XCO_2). The two partial columns
1159 have distinct seasonal cycles, with peaks and troughs earlier for the LMT
1160 partial column, and later for the U partial column, as compared to XCO_2
1161 similar to those observed from the NOAA aircraft (e.g. Sweeney et al.,
1162 2015). After bias correction, shown in detail in Appendix A, and following
1163 the same process as the bias correction for ACOS-GOSAT XCO_2, both partial
1164 column mixing ratios show agreement with aircraft, LMT shows agreement
1165 with remote surface observations, and both show improvement over the
1166 GOSAT prior. Single observations for land have observation errors of 3.4,
1167 1.3, and 1.7 ppm for LMT, U, and XCO_2, respectively, and single
1168 observations for ocean have observation errors of 1.5, 0.8, and 0.9 ppm for
1169 LMT, U, and XCO_2, respectively. These errors are significantly reduced with
1170 averaging, though some systematic errors, generally below 1 ppm, remain.
1171 The co-location errors from mismatch of GOSAT versus validation data, as
1172 quantified by CarbonTracker, makes the errors on LMT challenging to

validate, and extension of validation data to the top of the atmosphere with modeled CO2 adds uncertainty on the order of 0.4 ppm on the LMT bias. 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 with MOPITT multispectral CO and emission ratios are compared to Akagi et al. (2011), with our emission ratio 2-3% lower in May and 1-6% higher in August. The LMT-U difference, which can be used to evaluate model transport error (e.g. Stephens et al., 2007), has also been evaluated with monthly average error of 0.8 (1.4) ppm for ocean (land). The new LMT partial column mixing ratio allows the local boundary air to be distinguished from the free troposphere, captured in the U partial column mixing ratio, better disentangling local versus remotely influenced signals.

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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. Land nadir mode ("land") and ocean glint mode ("ocean") are bias corrected separately for LMT. 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. This is done because the XCO_2 bias correction has been checked against TCCON which has sensitivity throughout the entire column, and because there is uncertainty in the "true" U used for validation, which is calculated from aircraft extended with the CarbonTracker model above about 5 km, composing a large part of the U partial column.

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 in either land or ocean groups 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), u_dofs (degrees of freedom for U), 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

1539 ocean and 0.310 for land soundings. This indicates that, for ocean,
1540 approximately 40% of the CO_2 attributed to the surface should be moved
1541 from LMT to U, indicating that possibly (a) the troposphere is constrained
1542 too much relative to the surface, (b) an issue with the forward model, such
1543 as systematic errors in spectroscopy, or (c) some other retrieval artefact.
1544 The bias correction coefficient for delta_grad_CO_2 for simulated OCO-2 land
1545 data is 0.29, very similar to the value of 0.31 for actual GOSAT data
1546 (Kulawik, unpublished result). The simulated runs have no spectroscopic
1547 error or other forward model errors, so the need for delta_grad_CO2
1548 correction is likely not driven by forward model errors, but could be a
1549 consequence of way the CO_2 profile is constrained in the retrieval through
1550 the constraint matrix, which allows a lot of variability near the surface and
1551 damps variability in the mid-troposphere. This could prejudice the retrieval
1552 system to attribute radiance variations to CO_2 variations at the surface
1553 rather than elsewhere in the profile, with the delta_grad_CO2 correction
1554 factor undoing this tendency. This relationship should be explored further
1555 using a simulated system with different constraint matrices.
1556
1557 The filtering cutoffs and bias terms are shown in Table A1. The errors
1558 calculated by the bootstrap method (Rubin, 1981). The effects of the cutoffs
1559 and bias corrections from Table A1 on biases and standard deviations is
1560 shown in Table A2.
1561
1562 The overall land bias is not zero because the land bias constant correction
1563 undergoes a final step to harmonize land and ocean observations by
1564 matching GOSAT values for pairs of close land and ocean observations. The
1565 results (using the final bias correction) for different matching criteria are: 1
1566 degree and 1 hour (25 matches, bias -0.54 ppm in LMT and -0.96 ppm in
1567 XCO_2), 2 degrees and 24 hours (295 matches, 0.17 ppm in LMT and -0.61
1568 ppm in XCO_2), 4 degrees and 48 hours (4095 matches, 1.17 ppm in LMT and
1569 -0.09 ppm in XCO_2), and using dynamic coincidence criteria (422,542
1570 matches, 0.29 ppm in LMT, -0.42 in XCO_2). Using the assumption that there
1571 is no bias in XCO_2, the 4 degree, 48 hours result is used, and 1.17 ppm is
1572 added to the LMT constant bias for land. This constant bias is subtracted
1573 from LMT, then the LMT partial column is subtracted from XCO_2 to generate
1574 the corrected U partial column. The 1.2 ppm change in the land bias to
1575 match ocean results gives an idea of the size of the uncertainty in the bias.
1576
1577 As seen from Tables A3a and A3b, all bias corrections are superior to the
1578 uncorrected dataset, and all correction tests perform similarly in the bias
1579 standard deviation and mean standard deviation, but with variability in the
1580 overall bias, depending on the development set that is used. The overall
1581 bias has some uncertainty on the order of 0.5 ppm.
1582

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 pressure with the GOSAT prior above this, (3) the CT2015 model, and (4) extending the top aircraft measurement to the tropopause pressure 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 0.4 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.

Table A5 compares the extension with AirCore versus CarbonTracker. AirCore measures from the surface up to as high as 13 hPa, meaning that all but the top GOSAT pressure level is measured. 8 AirCore observations are found to matches aircraft and GOSAT observations within 3 degrees longitude, 5 degrees latitude, and 7 days. 6 of the matches are at SGP and 2 are at CAR. For these matches, the aircraft observations are extended either with AirCore (using CarbonTracker at only the top pressure level) or CarbonTracker. The finding is similar to the finding from Table A4, that there is uncertainty in the overall bias of 0.4 ppm, but that the standard deviation is not affected by which extension is used. The reason for 0.4 ppm bias is that the CarbonTracker stratosphere is high compared to AirCore for these 8 observations. This propagates into a high bias in the "true" U and a low bias in the "true" LMT, through the averaging kernel. Because there is uncertainty in the true value of the stratosphere that is used to extend the aircraft profiles, there is some uncertainty in the overall bias of GOSAT LMT and U on the order of 0.4 ppm.

There were several 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 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. (4) Comparisons were made, taking out observations used in the bias correction

1626 at SGP, where there are plenty of matches. These comparisons were as
1627 good as the full set.

1628

1629 The mean and standard deviation of the bias correction is -11.4±7.6,
1630 2.7±2.7 ppm for LMT and U land, respectively and -1.0±3.1 ppm, -1.7±0.9
1631 ppm for LMT and U ocean, respectively. The mean and standard deviations
1632 of the bias correction for XCO_2 are: -0.6±1.0 ppm for land and -0.6±0.6 for
1633 ocean. The bias corrections are larger for the partial columns than for XCO_2;
1634 the size and variability of the bias correction is an indication of its
1635 importance.

1636

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1638

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.

1647 Table 1. Sites used for validation in this paper

Type	Site	Site name	Country	Latitude	Longitude	match
aircraft	AOA	Aircraft Observation of Atmospheric trace gases, JMA	Japan	28.8N	148.4E	77
aircraft	BNE	Beaver Crossing, Nebraska	USA	40.8N	97.2W	452
aircraft	CAR	Briggsdale, Colorado	USA	40.4N	104.3W	1599
aircraft	CMA	Cape May, New Jersey	USA	38.8N	74.3W	536
aircraft	DND	Dahlen, North Dakota	USA	47.5N	99.2W	415
aircraft	ESP	Estevan Point, British Columbia	Canada	49.4N	126.5W	142
aircraft	ETL	East Trout Lake, Saskatchewan	Canada	54.4N	104.9W	237
aircraft	HIL	Homer, Illinois	USA	40.1N	87.9W	1039
aircraft	LEF	Park Falls, Wisconsin	USA	45.9N	90.3W	717
aircraft	NHA	Worcester, Massachusetts	USA	42.9N	70.5W	430
aircraft	PFA	Poker Flats, Alaska	USA	65.1N	147.3W	107
aircraft	RTA	Rarotonga	Cook Is.	21.3S	159.8W	228
aircraft	SCA	Charleston, South Carolina	USA	32.8N	79.6W	764
aircraft	SGP	Southern Great Plains, Oklahoma	USA	36.6N	97.5W	6066
aircraft	TGC	Sinton, Texas	USA	27.7N	96.9W	941
aircraft	THD	Trinidad Head, California	USA	41.1N	124.2W	226
aircraft	WBI	West Branch, Iowa	USA	41.7N	91.4W	602
Surface	MNM	Minamitorishima	Japan	24.3N	154.0E	66,732
Surface	MLO	Mauna Loa, Hawaii	USA	19.5N	155.6W	940
Surface	KUM	Cape Kumukahi, Hawaii	USA	19.5N	154.8W	876
Surface	GMI	Mariana Islands	Guam	13.4N	144.6E	1043
Surface	CHR	Christmas Island	Kiribati	1.7N	157.2W	1038
Surface	ASC	Ascension Island	U.K.	8.0S	14.4W	2125
Surface	SMO	Tutuila	American Samoa	14.2S	170.6W	4267
Surface	EIC	Easter Island	Chile	27.2S	109.4W	432
Surface	SEY	Mahe Island	Seychelles	4.7S	55.5E	679
Aircraft	HIPPO 2S	November, 2009, Pacific Ocean		0-39S	161-178W	156
Aircraft	HIPPO 2N	November, 2009, Pacific Ocean		6-41S	151-179E	277
Aircraft	HIPPO 3S	April, 2010, Pacific Ocean		16S-14N	160-170W	68
Aircraft	HIPPO 3N	April, 2010, Pacific Ocean		16S-8N	161-170W	71
Aircraft	HIPPO 4S	June, 2011, Pacific Ocean		5-15N	160-164W	13

Aircraft	HIPPO 4N	July, 2011, Pacific Ocean		4-44N	134E-172W	1054
Aircraft	HIPPO 5S	August, 2011		3S-15N	160-166W	20
Aircraft	HIPPO 5N	September, 2011		18S-21N	156-169W	363
Aircraft	AJAX	California/Nevada	USA	37.3-38.5N	116-121W	35

1648
1649
1650 Table 2
1651 Predicted errors and degrees of freedom for LMT and U. As seen in Table 3,
1652 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

1653
1654
1655 Table 3. Definition of comparison terms

1656 Co-location bias: The mean difference of CarbonTracker matched to the
1657   satellite minus CarbonTracker matched to the aircraft. A persistent
1658   co-location bias indicates sampling differences. For example, a
1659   seasonal co-location error was found to result from time-of-day
1660   difference between validation data collection time and the GOSAT
1661   overpass (see Fig. 11). For ocean flasks, where the validation data is
1662   only at the surface, vertical co-location bias of 0.3 ppm results from
1663   sampling difference between the model sampled with the LMT
1664   averaging kernel and the model at the surface (see Table 4).
1665 Co-location error, ε_{coloc} : The standard deviation of CarbonTracker matched
1666   to the satellite minus CarbonTracker matched to the aircraft or surface
1667   flask. This represents error introduced by the satellite not observing
1668   at the exact time and location of the validation data. The surface
1669   flasks have an additional term, the standard deviation of
1670   CarbonTracker sampled with the LMT averaging kernel and
1671   CarbonTracker sampled at the surface.
1672 Correlated error: Correlated error is the component of the standard
1673   deviation which does not reduce when additional GOSAT observations
1674   are averaged. Think of this quantity as a regional, daily (or a bit
1675   longer) bias. See Eq. 11.

1676 Random error: Random error is the component of the standard deviation
1677   that reduces when more GOSAT observations are averaged. See Eq.
1678   11.
1679 GOSAT bias: The mean of GOSAT minus the validation data. The bias is
1680   calculated by latitude, season, and time. Different biases at different
1681   locations can cause phantom fluxes.
1682 GOSAT error: The standard deviation of GOSAT minus the validation data
1683 Predicted error: The error predicted by the GOSAT optimal estimation
1684   retrieval system.
1685 Prior bias: The mean of the GOSAT prior minus the validation data
1686 True mean: The mean of all validation data at that site. For stations, the
1687   mean is averaged over time, and for each HIPPO campaign, it is
1688   averaged over latitude/longitude.
1689 True variability: The standard deviation of the validation data for each
1690   station or campaign. The true variability is higher over land than
1691   ocean, or for the LMT versus U. Observations with larger error will be
1692   more useful at locations where there is higher true variability.
1693 (n=1), (n=15): This specifies how many GOSAT observation are averaged
1694   prior to the calculation of bias or error. All GOSAT observations that
1695   are averaged match the same validation data point. The size of n
1696   matters for errors, with larger numbers averaged resulting in smaller
1697   errors (but not reducing as fast as the square root of n).

1698
1699
1700 Table 4. Biases versus validation data. See Table 3 for terminology used in
1701 this table. Note that all data is averaged by location or campaign. The ±
1702 represents the variability of the bias by location or campaign, a key metric in
1703 the data quality.

	Type	Ocean surface (ppm)	HIPPO Ocean (ppm)	ESRL Ocean (ppm)	ESRL Land (ppm)	AJAX Land (ppm)
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	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

1705 Table 5. Standard deviations versus validation data. See Table 3 for
1706 definitions of terms. The co-location errors have been subtracted out from
1707 the GOSAT errors.

	Type	Ocean surface (ppm)	HIPPO Ocean (ppm)	ESRL Ocean (ppm)	ESRL Land (ppm)	AJAX Land (ppm)
Co-location error	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
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 error (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 error (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 error (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	**-**

1709 Table 6. Estimated co-location, correlated, and random errors using Eq. 12.
1710 The co-location errors are taken from Table 4.

	Type	Ocean surface (ppm)	HIPPO Ocean (ppm)	ESRL Ocean (ppm)	ESRL Land (ppm)
Co-location error	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

1712 Table 7. Enhancements in CO and CO$_2$ for May and August, 2010. The
1713 target box is 11 to 18S, 60 to 56W for May, and 13-17S, 55-60W, for
1714 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. The different CO target columns are for different
cutoffs for the degrees of freedom between the surface and 200 hPa above
the surface for MOPITT.

		CO					GOSAT LMT CO₂	
		backgrnd (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±2.5
	N	1502	2023	1556	500	215		26
	DOFs		0.21	0.24	0.32	0.39		0.85
	Δvalue	-	54	55	88	114	-	3.2
	Em. ratio		6%	6%	7%	7%	-	-
August, 2010	Mean	91±22	305±171	311±180	336±200	372±221	387.4	393.1±4.8
	N	2989	3881	3227	1887	1231		49
	Δvalue (ppb)	-	213.7	219.3	244.8	281.1	-	5.7
	Em. ratio		15%	13%	11%	10%		

Table 8a. Bias terms for LMT – U. Compare to Table 4.

	HIPPO Ocean (ppm)	ESRL Ocean (ppm)	ESRL Land (ppm)
Co-location 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 8b. Standard deviations for LMT – U. Compare to Table 5. 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)
Co-location error	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 error (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 error (n=15)	0.5± 0.2	0.8±0.1	1.4±0.8
GOSAT error (n=15)	0.5± 0.2	0.7±0.1	1.2±0.8

Table 8c. Error fits for LMT – U. Compare to Table 6.

	HIPPO Ocean (ppm)	ESRL Ocean (ppm)	ESRL Land (ppm)
Co-location error	0.3±0.1	0.3±0.1	2.1±0.7

Correlated error (a)	0.4±0.2	0.6±0.0	0.9±0.9
Random error (b)	1.4±0.4	1.1±0.1	2.1±0.7

Table A.1 Filtering and Bias corrections. Note observations over land and ocean are corrected separately.

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	-
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: Bias correction robustness test for LMT observations over ocean. 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

Table A3b: Bias correction robustness test for LMT observations over land. 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 A5: Effect of profile extension, part 2. Extension of the aircraft with CarbonTracker versus extension with AirCore

Profile extension	LMT bias	LMT std	U bias	U std
(a) CT2015	0.3	3.1	-0.2	1.0
(b) AirCore	0.0	3.1	0.2	1.0

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1764 Table B1. Actual and predictions of errors by station/campaign. See Table 3

1765 for definitions of the quantities calculated in Table B1.

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location	latitude, longitude	Co-location error	a corr. error	b rand. error	GOSAT prior bias (n=1)	GOSAT error (n=1)	pred. Error (n=1)	Co-location bias	true mean	prior bias	GOSAT bias	true stdev (n=1)	prior error (n=15)	GOSA erro (n=1
		(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
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	1.0	1.5	2.6	1.8	4.3	-0.3	391.3	-1.2	0.7	1.3	2.3	1.1
		±0.2	±0.3	±0.2	±0.8	±0.3	±0.2	±0.3	±1.6	±1.5	±1.0	±0.5	±0.9	±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	2.5	3.0	3.2	4.0	4.6	-0.5	392.2	-1.0	-0.8	5.4	3.0	2.7
		±0.6	±1.2	±0.7	±0.6	±0.7	±0.3	±0.7	±3.1	±1.2	±1.0	±1.8	±1.0	±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**	**0.7**	**1.2**	**1.1**	**1.4**	**1.8**	**0.0**	**391.2**	**0.6**	**0.3**	**2.0**	**1.0**	**0.8**
		±0.3	±0.4	±0.1	±0.4	±0.3	±0.0	±0.2	±0.6	±0.6	±0.9	±0.2	±0.2	±0.4
	ave. land, corrected		0.6		0.5	1.3				0.6	0.3	2.0	0.9	0.5
			±0.4		±0.0	±0.3				±0.6	±0.9	±0.2	±0.2	±0.4
AOA, RTA	**average ocean**	**0.2**	**0.6**	**0.6**	**1.0**	**0.8**	**1.7**	**-0.1**	**391.3**	**-1.2**	**0.7**	**0.8**	**0.5**	**0.6**
		±0.0	±0.1	±0.2	±0.4	±0.0	±0.0	±0.1	±1.6	±1.6	±0.1	±0.8	±0.0	±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
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**	**1.0**	**1.6**	**1.5**	**1.9**	**0.9**	**-0.1**	**391.5**	**-0.3**	**-0.0**	**2.5**	**1.3**	**1.1**
		±0.3	±0.5	±0.2	±0.4	±0.4	±0.1	±0.3	±1.1	±0.6	±0.9	±0.6	±0.6	±0.5
	ave. land, corrected		0.7		0.5	1.7				-0.2	0.1		1.1±0.6	0.6
			±0.5		±0.0	±0.4				±0.6	±0.9			±0.5
AOA, RTA	**average ocean**	**0.2**	**0.4**	**0.7**	**1.1**	**0.9**	**0.7**	**-0.1**	**391.4**	**0.4**	**0.6**	**0.8**	**0.5**	**0.5**
		±0.1	±0.1	±0.1	±0.4	±0.1	±0.1	±0.1	±1.5	±2.3	±0.4	±0.8	±0.1	±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**	**0.4**	**1.6**	**0.8**	**1.7**	**4.3**	**-0.3**	**392.2**	**-0.2**	**-0.2**	**0.6**	**0.6**	**0.6**
		±0.1	±0.2	±0.3	±0.4	±0.3	±0.3	±0.2	±1.6	±2.4	±0.3	±0.3	±0.3	±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**	**0.3**	**0.8**	**0.3**	**0.8**	**1.7**	**0.1**	**391.1**	**0.3**	**0.2**	**0.4**	**0.3**	**0.4**
		±0.1	±0.2	±0.1	±0.1	±0.1	±0.1	±0.1	±1.2	±1.1	±0.3	±0.3	±0.1	±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**	**0.9**	**0.4**	**0.9**	**0.6**	**0.0**	**391.4**	**0.9**	**0.1**	**0.4**	**0.3**	**0.3**
		±0.2	**±0.2**	**±0.1**	**±0.2**	**±0.1**	**±0.1**	**±0.1**	**±1.3**	**±1.4**	**±0.2**	**±0.3**	**±0.1**	**±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	-	-

1767 *AJAX profiles are co-located within 1 hour and 1 degree and therefore do not have multiple GOSAT

1768 matches to average.

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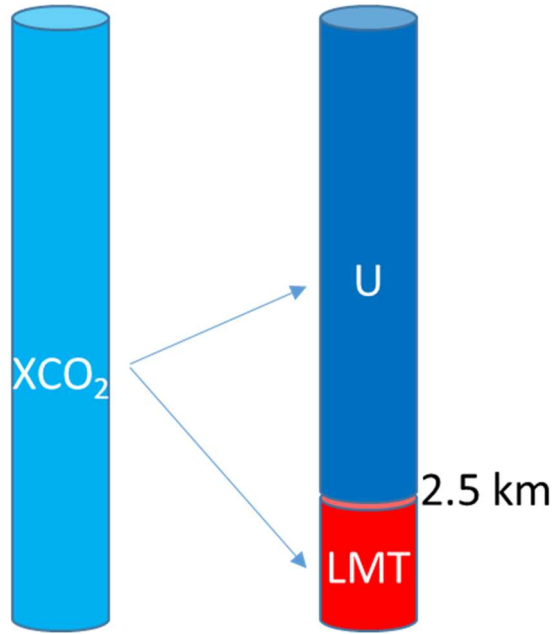
Figure 1. XCO_2 full column measurement (left) and the two partial columns that we introduce (right): the lowermost troposphere (LMT), a partial column from the surface to approximately 2.5 km, and the partial column above 2.5 km (U).
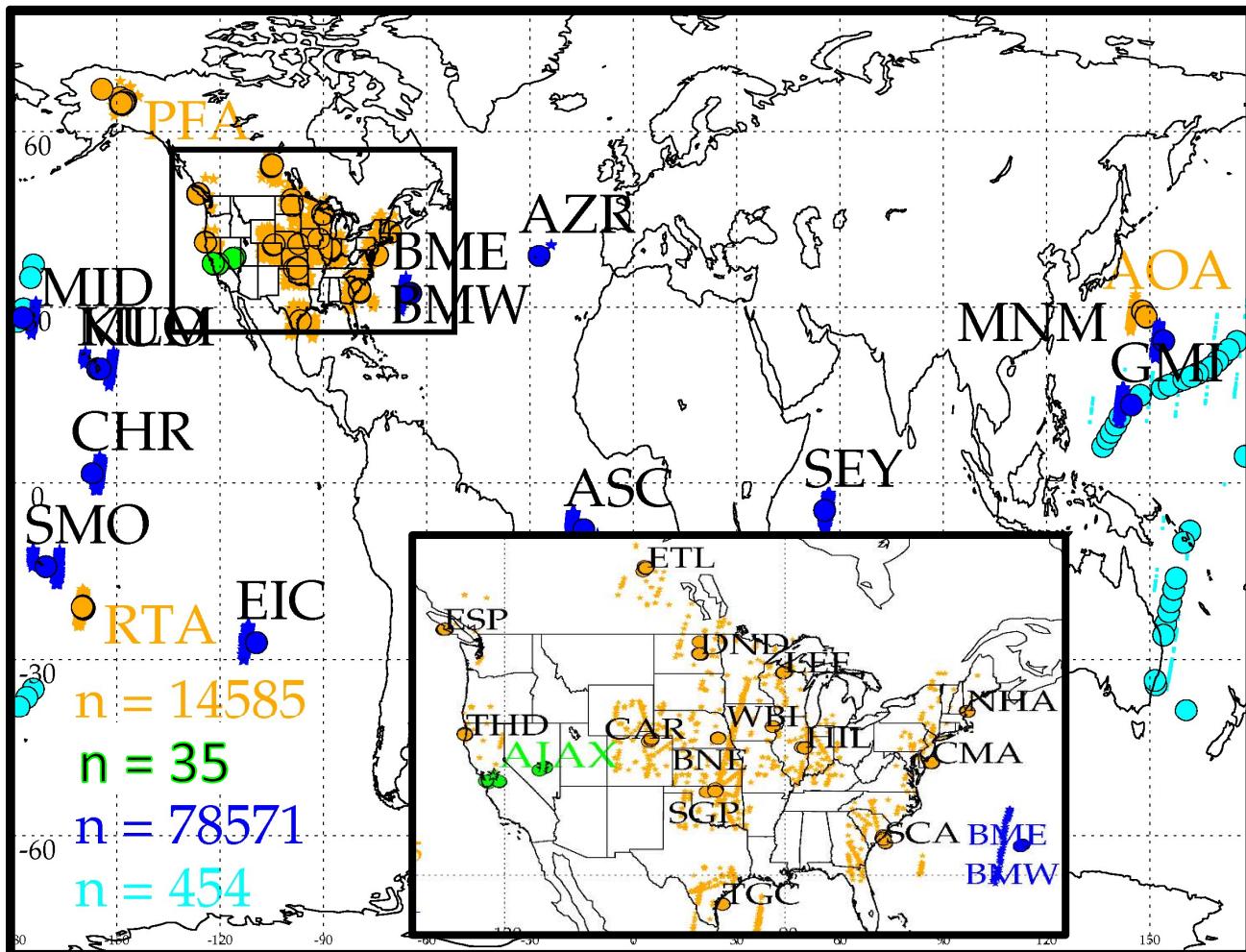
Figure 2. Validation locations. The 4 sets of validation data shown here are: ESRL aircraft profiles (orange), which occur over land (in the US) and ocean (RTA, Rarotonga, and AOA), AJAX aircraft data (green) in the western U.S., the HIPPO aircraft profiles (light blue), and remote ocean surface sites (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.
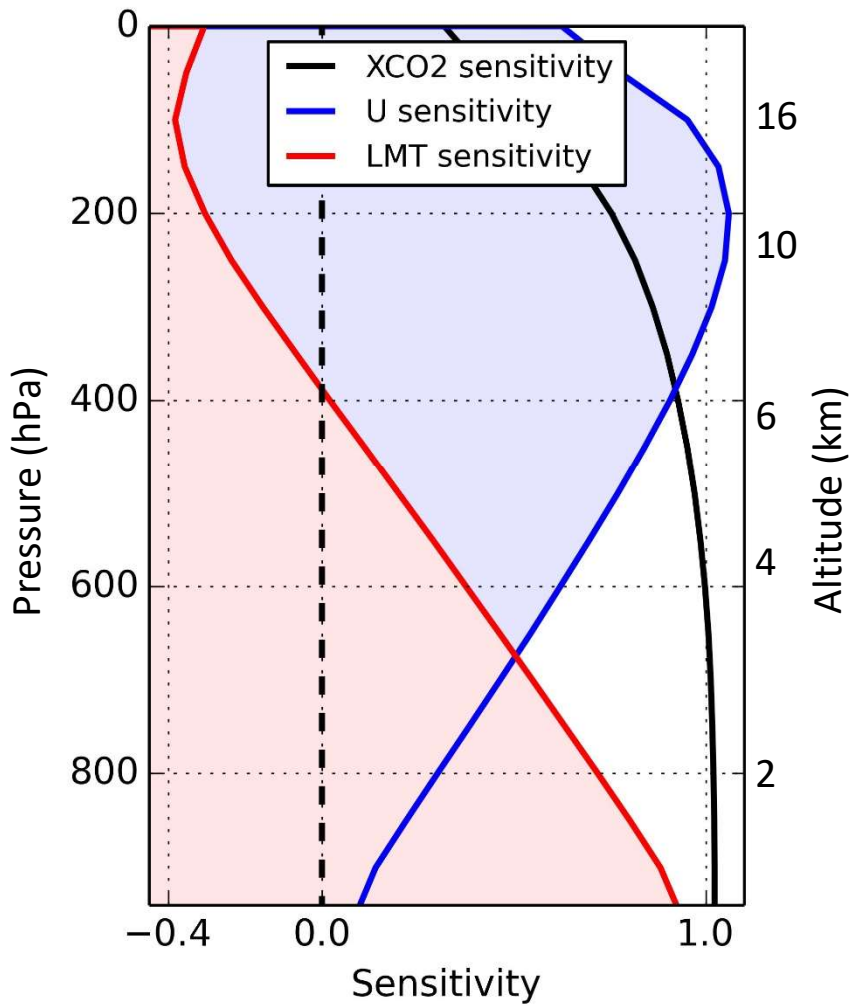
Figure 3. Sensitivity of XCO_2 (black), partitioned into the LMT (red) and U (blue) partial columns for an average land averaging kernel. The LMT sensitivity is approximately 1 near the surface and drops off steadily with decreasing pressure.
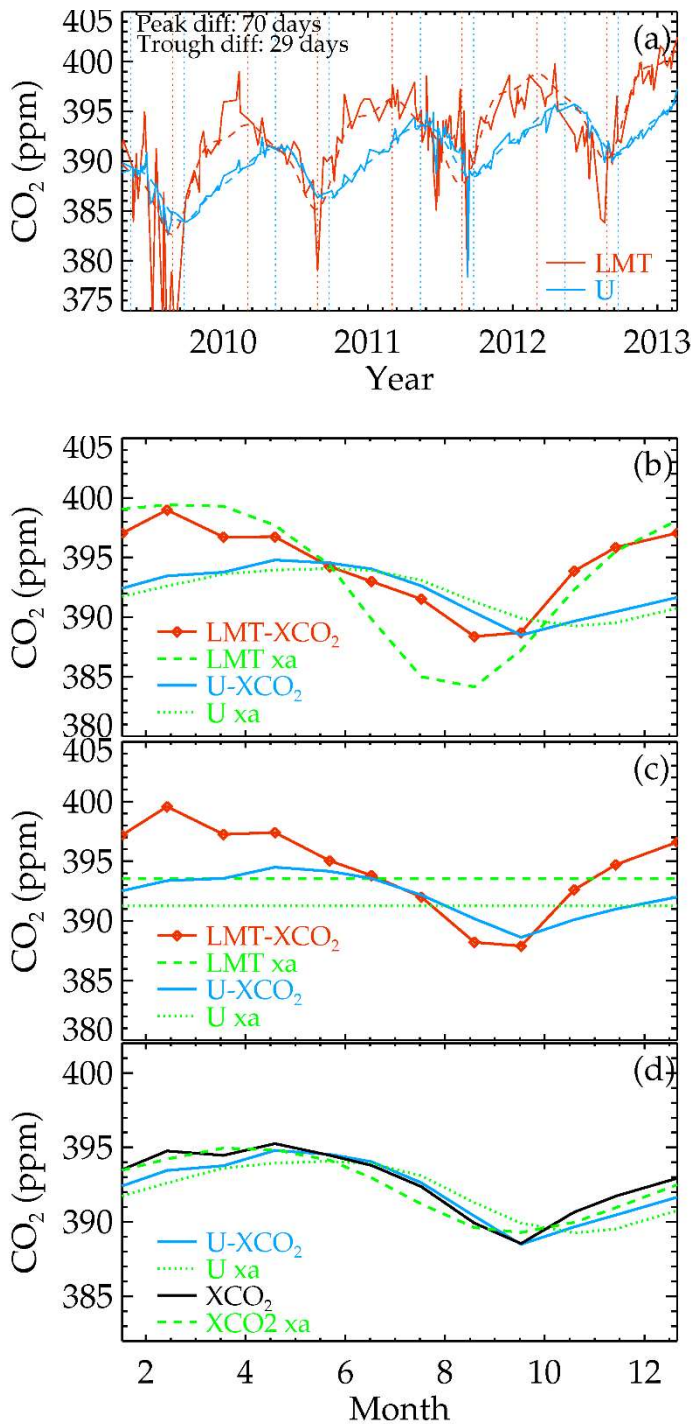
Figure 4. Simulated GOSAT retrievals from SGP aircraft profiles, Eqs. 5-6, and the GOSAT averaging kernels. (a) Time series of LMT (red) and U (blue) with monthly averages of LMT (red dashed) and U (blue dashed); (b) seasonal cycle, averaging in 1-month increments. Green dotted and dashed lines are the initial guess/a priori (xa). (c) same as (b) except that the prior is set to a constant, showing that LMT and U results are not strongly influenced by the prior. (d) Same as (b) but showing U (blue) and XCO_2 (black).

(a) No bias correction n = 4580

GOSAT LMT
Aircraft LMT_AK
GOSAT U-XCO$_2$
Aircraft U-XCO$_2$_AK

(b) With bias correction n = 4580

GOSAT LMT
Aircraft LMT_AK
GOSAT U-XCO$_2$
Aircraft U-XCO$_2$_AK

(c) Quantifying co-location error n = 4580

GOSAT LMT
Aircraft LMT_AK
CT LMT @GOSAT
CT LMT @airplane

(d) All data Seasonal cycle n = 4580

GOSAT LMT
airplane LMT
prior LMT
GOSAT U-XCO$_2$
airplane U-XCO$_2$
prior U-XCO$_2$

(e) Remove co-location error Seasonal cycle n = 4267

GOSAT LMT
airplane LMT
prior LMT
GOSAT U-XCO$_2$
airplane U-XCO$_2$
prior U-XCO$_2$

(f) Only observations not used in bias corr. Seasonal cycle n = 2607

GOSAT LMT
airplane LMT
prior LMT
GOSAT U-XCO$_2$
airplane U-XCO$_2$
prior U-XCO$_2$

Figure 5. GOSAT versus aircraft data at the SGP site (37N, 95W). (a,b,c) Aircraft LMT (pink) and U (blue) versus GOSAT LMT (red) and U (black) for monthly averages of GOSAT/airplane matches. (a) using no bias correction, (b) using bias correction factors derived in Appendix A (c) also showing CarbonTracker matched to GOSAT (red dotted) and CarbonTracker matched to aircraft (pink dotted) for LMT. (d) Seasonal cycle of GOSAT and airplane, same colors as top panels, and adding the priors in green. (e) Seasonal cycle, but removing months where the CarbonTracker differences seen in (b) are larger than 2.5 ppm. (f) Same as (e) but with observations used in the bias correction removed from the comparison
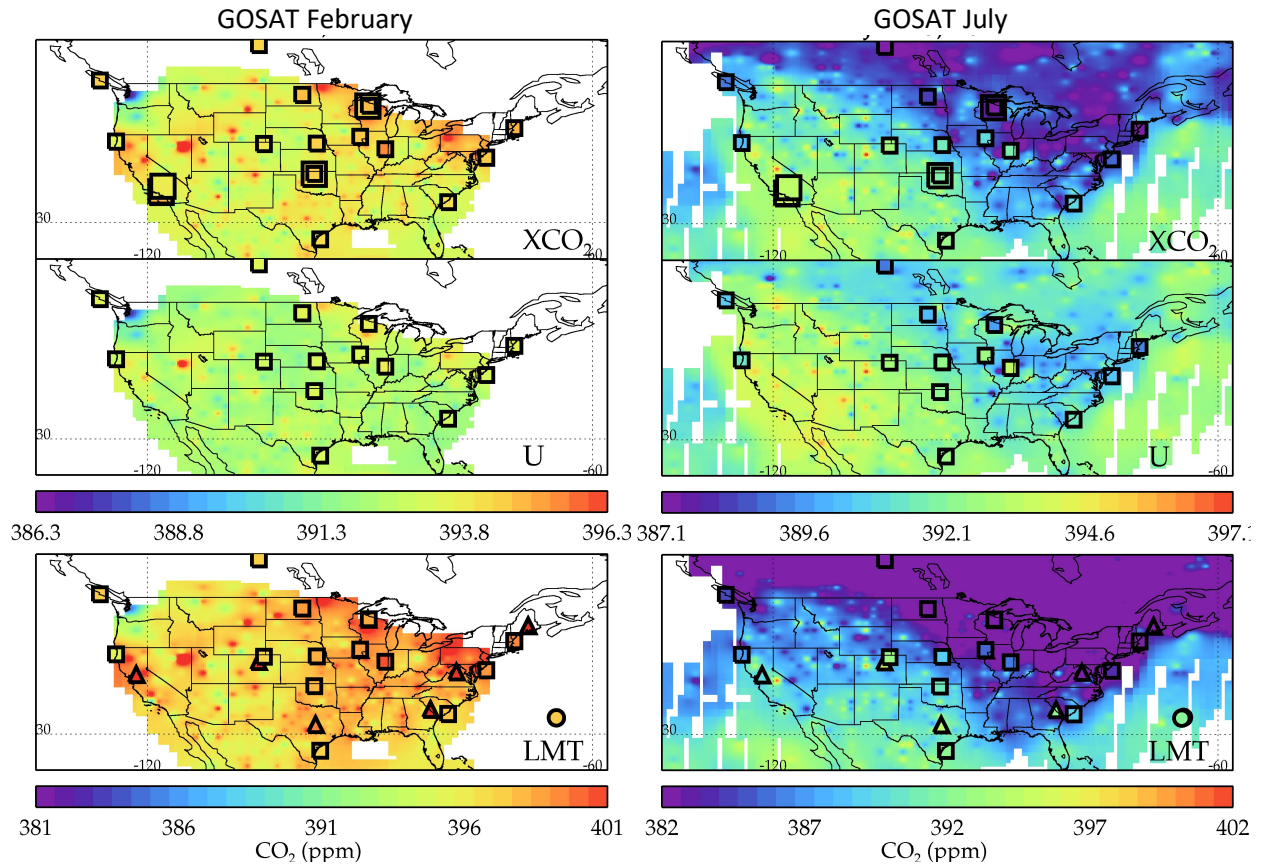
Figure 6. GOSAT XCO_2 (top), U (middle), and LMT (bottom) in February (left) and July (right). Aircraft with GOSAT averaging kernels are small squares, towers are triangles, remote ocean surface sites are circles, and TCCON are large squares (only shown on XCO_2 panels). Data is averaged over the GOSAT record.
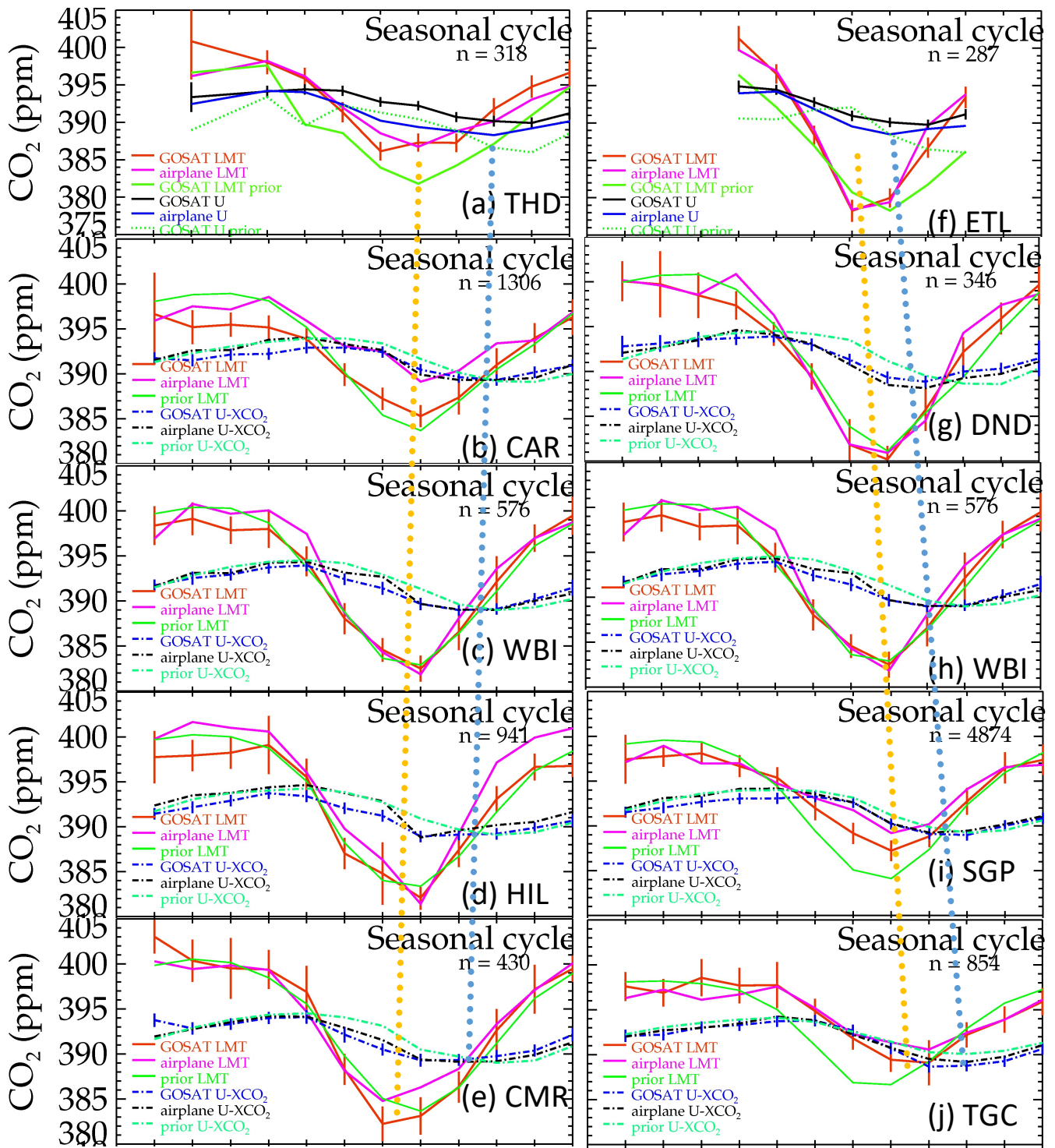
Figure 7. Seasonal cycle at 5 sites arranged from west to east (a-e) and north to south (f-j), for GOSAT LMT (red), aircraft LMT (pink), GOSAT LMT prior (green), GOSAT U (blue dashed), aircraft U (black dashed) and GOSAT U prior (green dashed). The seasonal cycle minimum is marked for LMT (orange dotted) and U (blue dotted).
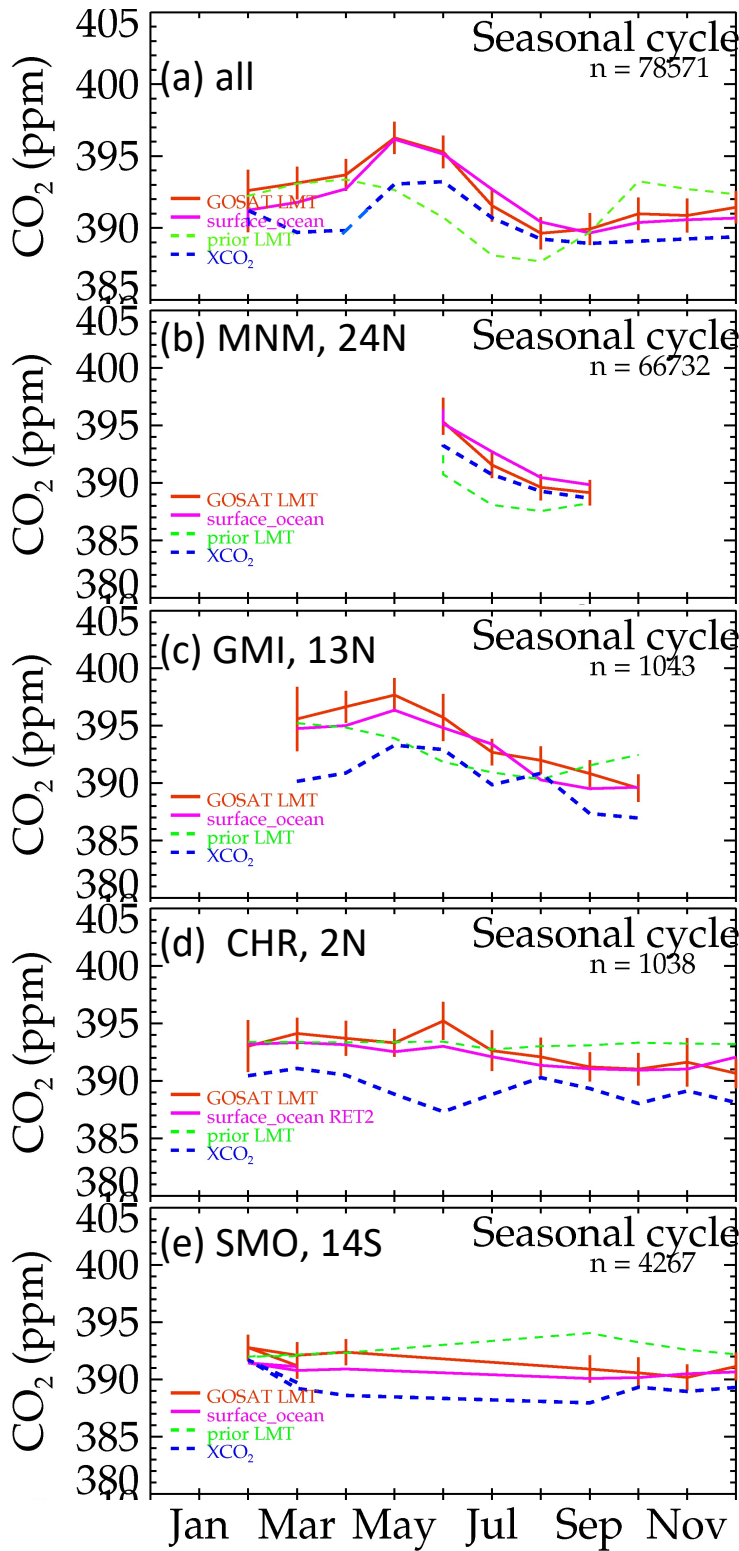
Figure 8. GOSAT LMT compared with remote ocean surface sites. GOSAT (red) improves over the prior (green dashed) versus surface sites (pink) for the average over all sites (a) and at the four sites with the most matches (b-e). XCO_2 values are shown for comparison (blue dashed).
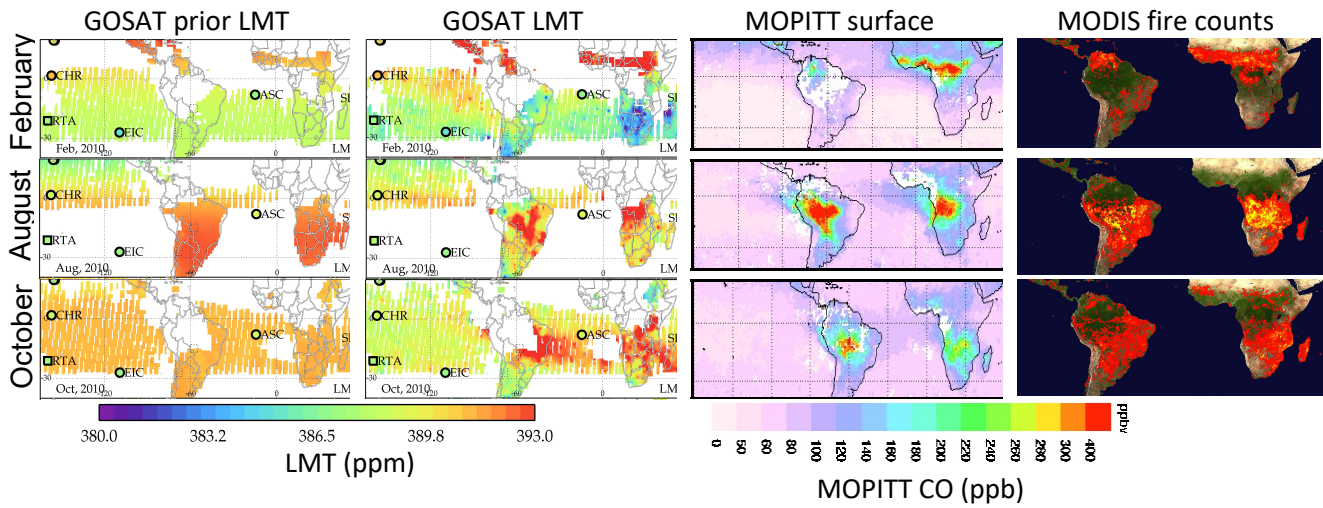
Figure 9. GOSAT LMT versus MOPITT and MODIS fire counts in for February, August, and October, 2010. GOSAT prior (left) and retrieved (second column) LMT compared with MOPITT multispectral CO (third column) and MODIS fire counts (right).
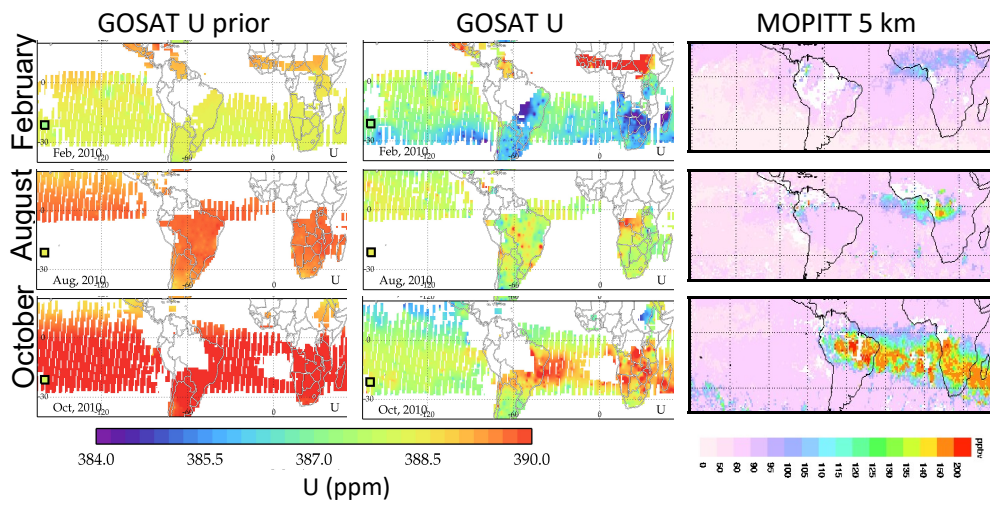
Figure 10. GOSAT U versus MOPITT for February, August, and October, 2010. GOSAT prior (left) and retrieved (middle) compared with MOPITT multispectral CO (right) at 5 km. Note the biomass burning outflow see in October for both MOPITT and GOSAT.
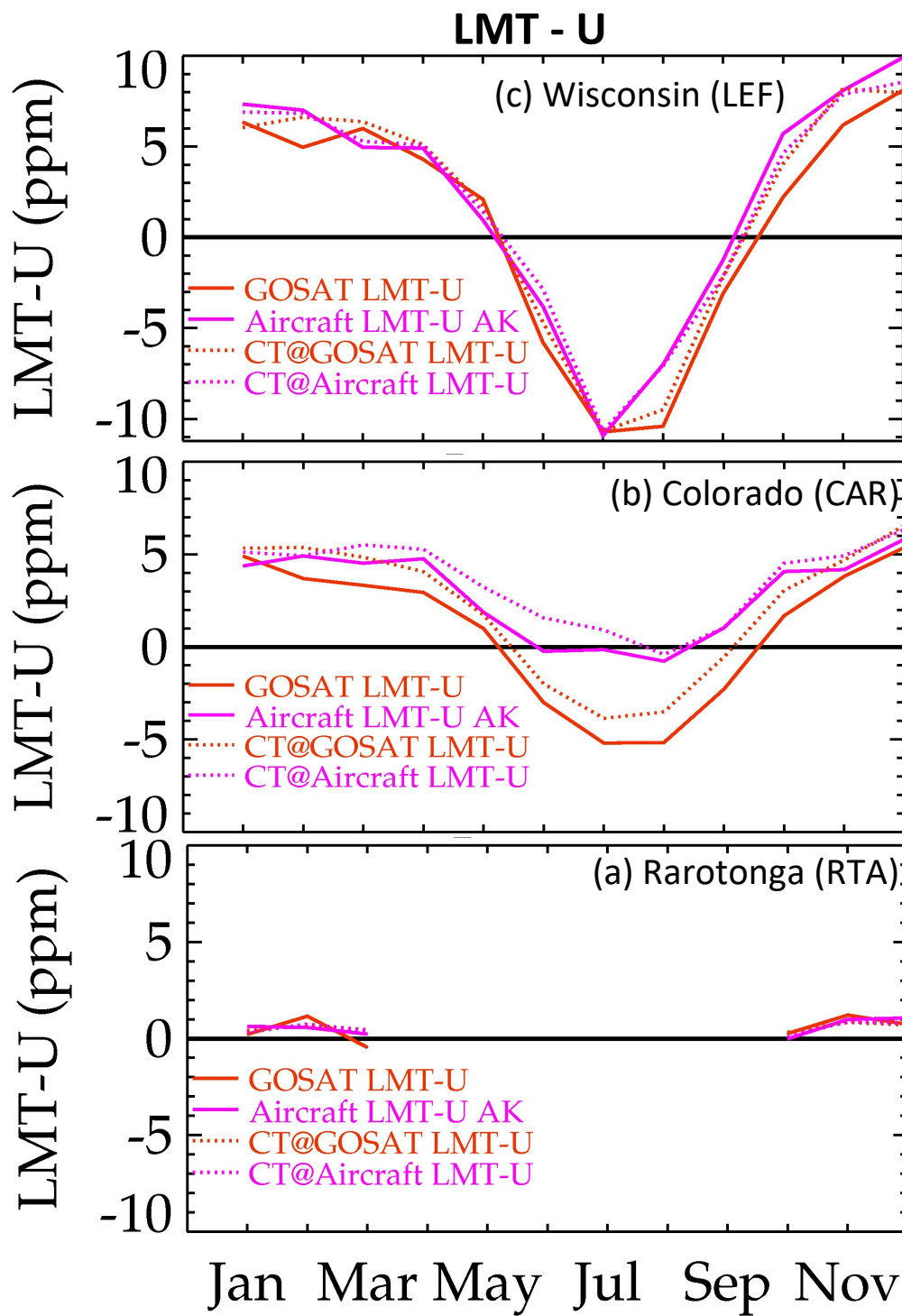
Figure 11. GOSAT LMT - U (red) versus aircraft (pink) at 3 sites. The dotted line show CarbonTracker matched to GOSAT (red dotted) or aircraft (pink dotted). Co-location error explains the discrepancies in the drawdown at CAR and LEF. At CAR the discrepancies are due to mismatch in the time of day the data is collected.
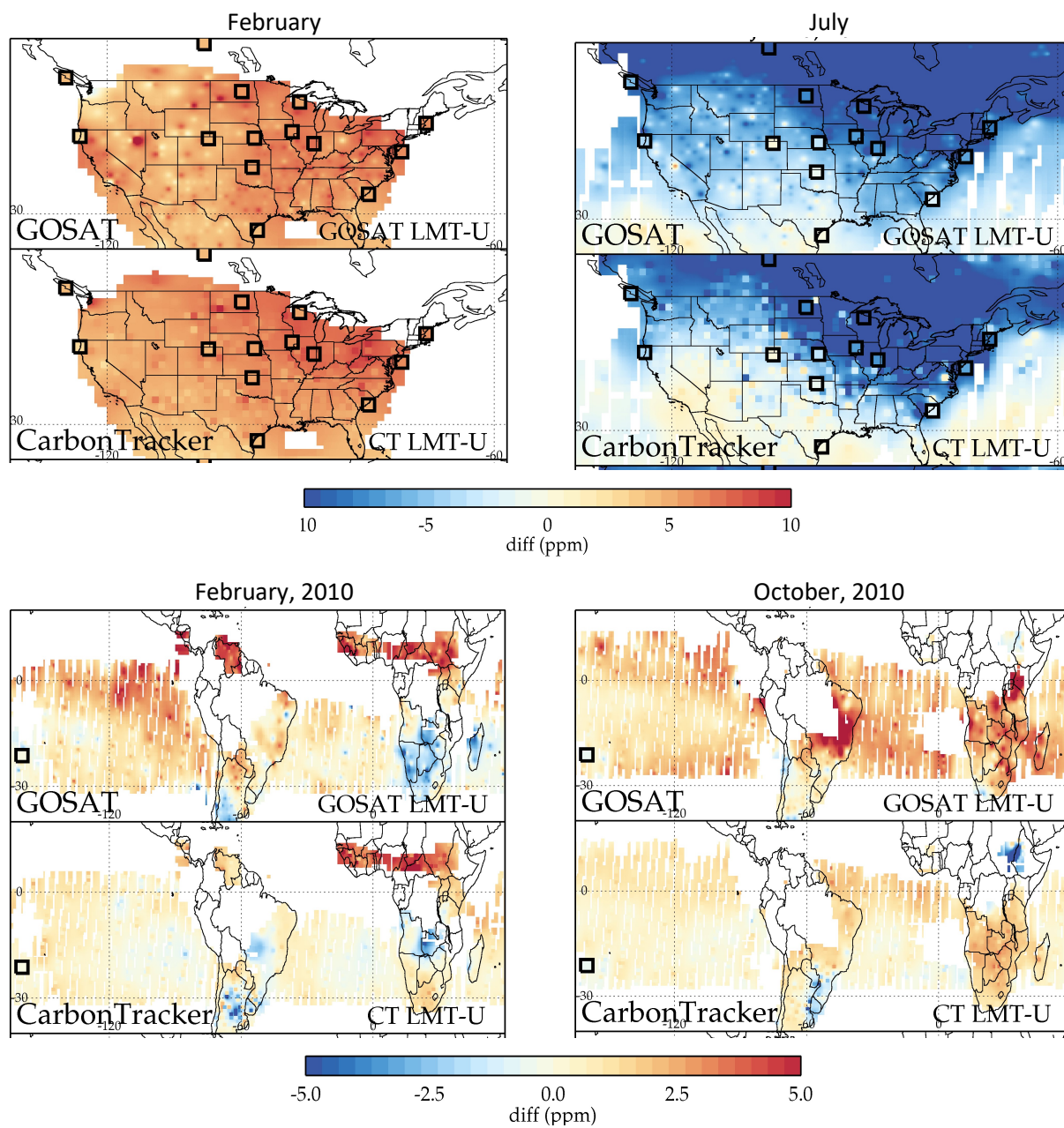
Figure 12. LMT – U differences. Results shown for the U.S. (top) and South America/Africa (bottom) for two different months, with GOSAT on the top and CarbonTracker on the bottom. Aircraft LMT – U differences are shown in the squares. There is agreement in the U.S. other than southwestern U.S. in July, with more differences in the southern hemisphere.