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New constraints on Northern Hemisphere growing season net flux

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[1] Observations of the column-averaged dry molar mixing ratio of CO₂ above both Park Falls, Wisconsin and Kitt Peak, Arizona, together with partial columns derived from aircraft profiles over Eurasia and North America are used to estimate the seasonal integral of net ecosystem exchange (NEE) between the atmosphere and the terrestrial biosphere in the Northern Hemisphere. We find that NEE is ~25% larger than predicted by the Carnegie Ames Stanford Approach (CASA) model. We show that the estimates of NEE may have been biased low by too weak vertical mixing in the transport models used to infer seasonal changes in Northern Hemisphere CO₂ mass from the surface measurements of CO₂ mixing ratio. **Citation:** Yang, Z., R. A. Washenfelder, G. Keppel-Aleks, N. Y. Krakauer, J. T. Randerson, P. P. Tans, C. Sweeney, and P. O. Wennberg (2007), New constraints on Northern Hemisphere growing season net flux, *Geophys. Res. Lett.*, 34, L12807, doi:10.1029/2007GL029742.

1. Introduction

[2] Forecasting CO₂ levels in the atmosphere is needed to predict future climate. Accurate forecasts require an improved understanding of carbon sources and sinks [*Intergovernmental Panel on Climate Change*, 2001]. During the 1990s, fossil fuel combustion and cement production added approximately 6 Pg C yr⁻¹ to the atmosphere. These fluxes are well constrained spatially and temporally [*Andres et al.*, 1996]. From the observed atmospheric increase and the known anthropogenic emissions, the combined ocean and terrestrial biosphere carbon sinks must have been close to 3 Pg C yr⁻¹ [*Intergovernmental Panel on Climate Change*, 2001].

[3] To estimate the spatial and temporal distribution of these carbon sinks, inverse methods have been used to infer carbon fluxes from geographically sparse observations of atmospheric CO₂ mixing ratio, typically measured at the surface [e.g., *Tans et al.*, 1990]. In these methods, surface fluxes are scaled within the framework of an atmospheric

transport model to minimize the difference between the observed and simulated spatial and temporal gradients of atmospheric CO₂ mixing ratio [*Enting et al.*, 1995; *Kaminski et al.*, 1999; *Rayner et al.*, 1999; *Bousquet et al.*, 2000; *Krakauer et al.*, 2004; *Baker et al.*, 2006]. Estimates of both net ecosystem exchange (NEE) and the geographical distribution of fossil fuel carbon sinks vary substantially due in large part to errors in the atmospheric transport models used in these inversions [e.g., *Gurney et al.*, 2004]. This is quite understandable; estimation of fluxes (i.e., mass m⁻² s⁻¹) on large geographical scales requires knowledge of temporal and spatial gradients in CO₂ column abundance (i.e., mass m⁻²) in the atmosphere. These gradients in CO₂ column can be inferred from gradients in the observed mixing ratio at the surface only if the vertical structure of atmospheric CO₂ is well known. Proper simulation of the vertical structure requires accurate simulation of the exchange between the planetary boundary layer (PBL) and the free troposphere: a difficult requirement and an area of active research in the atmospheric dynamics community.

[4] In this study, we use newly available observations of the column and vertical profile dry air CO₂ molar mixing ratios above eight sites (Table 1) to estimate the seasonally-varying carbon flux (NEE) in the northern hemisphere. Because these observations are of the column or partial column abundance, they come close to directly representing a measure of atmospheric CO₂ mass per unit area. As a result, our estimate of NEE are less sensitive to errors in the vertical transport than estimates based solely on surface mixing ratio observations. Our analysis suggests that the seasonally-varying fluxes are substantially larger than the NEE fluxes from the CASA model used in the TransCom 3 studies. We further show, using vertically resolved observations of CO₂ obtained at several sites in Eurasia and North America, that the TransCom models underestimate the seasonally-varying fluxes because they underestimate the efficiency of CO₂ mixing throughout the free troposphere.

2. Measurements and Models

[5] Measurements of column-averaged dry mixing ratio of CO₂ were obtained at Park Falls, Wisconsin beginning in 2004. Using an automated solar observatory, direct solar spectra were acquired continuously during clear-sky, daytime conditions. These spectra were used to determine vertically integrated CO₂ with high precision (0.1%) and accuracy (0.3%) [*Washenfelder et al.*, 2006]. The 337 days of measurements were taken during May 2004 to November 2006 and have been averaged daily. We also included similar but much infrequent (only 96 days during the two periods: Jan 1979 to Dec 1985 and Mar 1989 to Mar 1995) column measurements obtained at the Kitt Peak solar observatory, Arizona [*Yang et al.*, 2002]. In addition to the ground-

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Table 1. Column and Profile Observation Sites and the CO₂ Seasonal Cycle Amplitude Comparison With Model Simulations

Site Name (Code)	Location	Altitude Range Above Surface, m	Mean Scale Factor A of the 12 Models ^{a,b}	Phase Shift T of 12 Models, days	Scale Factor A for the Mean Response of the 12 Models	RMS in Fitting the Mean Response of the 12 Models, ppm
Poker Flats, AK (PFA)	65.07°N, 147.29°W	1500–7500	1.20 ± 0.11	−16.8 ± 4.5	1.21	0.71
Zotino, Russia (ZOT)	60.75°N, 89.38°E	500–3500	1.44 ± 0.21	−18.4 ± 2.8	1.42	1.70
Estevan Point, Canada (ESP)	49.38°N, 126.55°W	500–5500	1.20 ± 0.12	−16.0 ± 3.2	1.20	0.54
Orleans, France (ORL)	47.80°N, 2.50°E	500–3500	1.39 ± 0.18	−19.6 ± 3.1	1.38	0.43
Park Falls, WI (LEF)	45.93°N, 90.27°W	Total column	1.34 ± 0.14	−7.3 ± 4.0	1.34	0.43
Harvard Forest, MA (HFM)	42.54°N, 72.17°W	500–7500	1.38 ± 0.09	−16.0 ± 2.7	1.38	0.67
Carr, CO (CAR)	40.90°N, 104.80°W	1500–6500	1.20 ± 0.11	−7.6 ± 7.3	1.21	0.56
Kitt Peak, AZ ^c (KTP)	31.90°N, 111.60°W	Total column	1.11 ± 0.07	15.3 ± 4.6	1.12	0.56
Mean			1.28	−14.5 ± 5.0 ^d	1.28	0.70
Mean of 35 surface sites ^e in 30°N~70°N			1.12	−11.9 ± 9.8	1.11	1.07

^aFor LEF and KTP, total CO₂ columns were simulated for the comparison. For the aircraft sites, only partial columns with measurements were simulated. The scale factor A and phase shift T here are described by equation (1).

^bThe names of the models are CSU.gurney, GISS.prather, GISS.prather2, GISS.prather3, JMA-CDTM.maki, MATCH.bruhwieler, MATCH.chen, MATCH.law, RPN.yuen, SKYHL.fan, TM3.heimann, GCTM.baker. For more detail refer to TransCom website (<http://www.purdue.edu/transcom/>) and Gurney *et al.* [2003].

^cThe Kitt Peak observations were taken from Jan 1979 to Mar 1995, for more detail refer to Yang *et al.* [2002].

^dExcluding Kitt Peak due to different observation time period.

^eThese surface sites are part of the *Globalview-CO₂* [2006] network, for a detailed list see auxiliary material.

based total columns, multi-level aircraft CO₂ measurements were available at six sites in North America and Eurasia during 2003–2004 (Table 1). Discrete CO₂ samples were acquired biweekly or monthly during aircraft profiles up to 7500 m above the surface [e.g., Levin *et al.*, 2002]. In our analysis, we used the interpolations of these measurements at fixed temporal (48 per year) and spatial (every 500 m in altitude) intervals [*GLOBALVIEW-CO₂*, 2006].

[6] To compare with the observations, we used the twelve TransCom 3 experiment models that differ in spatial resolution, advection scheme, driving winds, and sub-grid scale parameterizations [Gurney *et al.*, 2003]. Monthly terrestrial biosphere exchange (1° × 1°) was derived from the Carnegie-Ames-Stanford Approach (CASA) terrestrial biosphere model [Randerson *et al.*, 1997], and is annually balanced at each grid cell.

3. Methods

[7] In our analysis, we compare the observed amplitude and phase of the atmospheric CO₂ seasonal cycles to simulations obtained from propagating seasonal surface fluxes from a terrestrial biosphere model (CASA) with annually-balanced fluxes through the twelve different transport models. Since the same fluxes are used, differences in the simulated atmospheric CO₂ seasonal cycles at different altitudes and locations result only from the differences in transport in the models. To quantify the differences between the observations and the simulations, we use a simple least squares fit, assuming the observed seasonal cycle $S(t)$ can be expressed as a function of the simulated CASA biosphere model response $S_0(t)$, adjusted by scale factor A , time delay T , and offset B :

$$S(t) = A \times S_0(t - T) + B \quad (1)$$

[8] Focusing on the shape of seasonal cycle, we report A and T but not offset B . The A and T parameters can also be thought of as two spatially uniform adjustments to all CASA surface fluxes because of the linear relationship between these fluxes and $S(t)$. Besides the simulations from the twelve models, the mean of all these models' simula-

tions is considered as our “best” estimate and included in the comparison. The fitting rms (σ) for the all-model mean simulation is reported to measure the goodness of the fit, and to derive a weighted mean CASA scale factor (but not time delay) for n different sites:

$$\bar{A} = \frac{\sum_{i=1}^n A_i / \sigma_i^2}{\sum_{i=1}^n 1 / \sigma_i^2} \quad (2)$$

[9] To compare the observations with the neutral biosphere simulations, the measurements were detrended and offset by the annual mean value. The interannual trend for the Park Falls column CO₂ was empirically determined as 1.80 ppm yr^{−1} during 2004 to 2006. For Kitt Peak, the trends were 1.41 ppm yr^{−1} during 1979 to 1985 and 0.83 ppm yr^{−1} during 1989 to 1995. For the temporally evenly spaced GlobalView assimilations, their seasonal cycles were directly decomposed using the empirical mode decomposition method [Huang *et al.*, 1998] and folded into one year.

4. Results and Discussion

[10] The comparison between the Park Falls CO₂ seasonal cycle of column-averaged observation and the TransCom simulations is shown in Figure 1. The observed seasonal CO₂ cycle amplitude is larger than any model simulation. A best fit was obtained by increasing the CASA fluxes by 34%. Models also underestimated the CO₂ seasonal cycle at Kitt Peak and at all the other six aircraft sites. The average difference across all the column and partial column sites was 28% (Table 1). Because these vertically-integrated observations sample a substantial fraction of the northern hemisphere landmass, they provide a measure of CO₂ variations that is not highly sensitive to error in the transport fields. As a group, the seasonal cycle in column CO₂ is most sensitive to the seasonal fluxes themselves. This is supported by the relatively small variation in the model simulations of the columns illustrated for Park Falls in

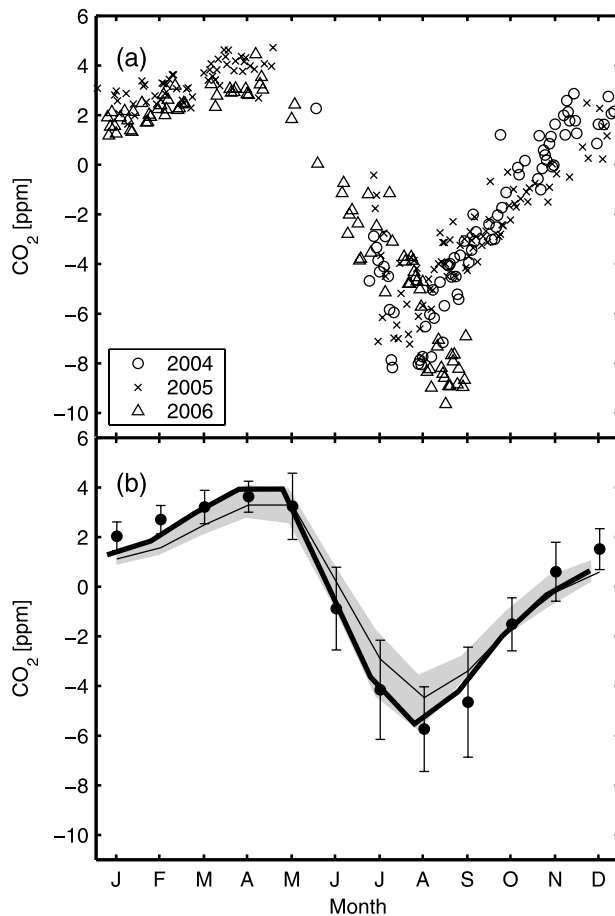


Figure 1. (a) Atmospheric column-average CO₂ mole fractions at Park Falls for May 2004–March 2006. (b) The monthly mean of observations (closed circles) compared with the TransCom simulations (grey shade shows range of 12-model predictions; thin solid line represents average). Each of the 12 models underpredicts the seasonal cycle observed in the column measurements. The best match to the observations is achieved by scale the model-mean simulations by 1.34 and shift them 7 days earlier (thick solid line).

Figure 1 and for the other sites in the accompanying auxiliary material¹. Our column-based optimization implies that the true growing season net flux (GSNF) in the northern hemisphere is approximately 28% greater than that predicted by CASA. North of 30°N, this corresponds to a GSNF of 7.9 Pg C/yr.

[11] The results shown here are not sensitive to the seasonally-varying fossil fuel fluxes. We repeated our analysis to investigate the impact of seasonally-varying fossil fuel emissions (in 1995) estimated by A. L. Brenkert (Carbon dioxide emission estimates from fossil-fuel burning, hydraulic cement production, and gas flaring for 1995 on a one degree grid cell basis, 1998 (data available at <http://cdiac.esd.ornl.gov/epubs/ndp/ndp058a/ndp058a.html>)) on our estimate of the seasonal cycle of carbon dioxide due to terrestrial processes. Including this estimate of fossil fuel

emissions increases our estimate of the terrestrial fluxes obtained from the column data by ~1% in average and decreases the estimate obtained from the surface observations by a similar amount (see auxiliary material).

[12] The NEE from CASA was derived from 1990 satellite observations, and so the observed 0.66% yr⁻¹ increase rate of CO₂ seasonal-signal amplitude between 1981 to 1995 [Randerson *et al.*, 1997] may explain some, but clearly not all, of the differences between the observations and simulations of the CO₂ seasonal cycle amplitude. In addition, the phase analysis of CO₂ seasonal cycles shown in Table 1 shows that for all sites except Kitt Peak, CASA fluxes needed to be shifted earlier by one to three weeks, which may, in part, be explained by advances in the timing of spring thaw since 1988 [Smith *et al.*, 2004]. More generally, although changes in the seasonality of terrestrial fluxes and the annual mean flux are probably linked by means of long-term trends in photosynthesis and respiration, this relationship is complex and not necessarily predictable without more information about the underlying drivers [Randerson *et al.*, 1999]. For example, if the 2.3 Pg C/yr Northern Hemisphere terrestrial sink inferred by Gurney *et al.* [2002] were caused by long-term gains in carbon during spring or fall, it might cause the seasonal cycle of atmospheric carbon dioxide to decrease, whereas gains during mid-summer may have the opposite effect. Further, relatively large carbon sinks may be sustained by very small long-term increases in net primary production (much less than 1% yr⁻¹) [Friedlingstein *et al.*, 1995] that would have a small influence on the observed season cycle of CO₂.

[13] In contrast to the column results, comparison of the simulations of the seasonal cycle with CO₂ observations obtained at the surface (GLOBALVIEW-CO₂ flasks) between 30°N to 70°N shows a much smaller underestimation of seasonal cycle (~12%, Table 1) and a smaller phase delay ($T_{\text{surface}} = -11.9$ days; $T_{\text{column}} = -14.5$ days). Both the amplitude and phase differences between the estimates from surface and column observations suggest that the TransCom models as a group do not mix the surface fluxes into the free troposphere quickly enough.

[14] The vertical propagation of the seasonal cycle of CO₂ from its source at the surface into the interior of the atmosphere is sensitive to the efficiency of vertical exchange. To investigate the accuracy of the TRANSCOM model simulations of this propagation, we analyzed the CO₂ vertical profiles at the six sites sampled by the aircraft. Directly comparing the simulations and observations for these sites using the same analysis method as described above was, however, hampered by large differences in the shape of the CO₂ seasonal cycle at some sites (e.g., ZOT in Figure 2). (The results of such an analysis are shown in the online supplement¹; the retrieved CASA scale factors increase with altitude, but the increase is not statistically significant.) To minimize the impact of this mismatch, we analyzed the simulations (using the a priori CASA fluxes) and the atmospheric observation separately. At each site, we defined a reference height (3500 m) and fit the seasonal cycles $S_H(t)$ at all other heights (H) in both the observations and simulations by:

$$S_H(t) = A_H \times S_{3500}(t - T_H) + B \quad (3)$$

¹Auxiliary material data sets are available at <ftp://ftp.agu.org/apend/gl/2007gl029742>. Other auxiliary material files are in the HTML.

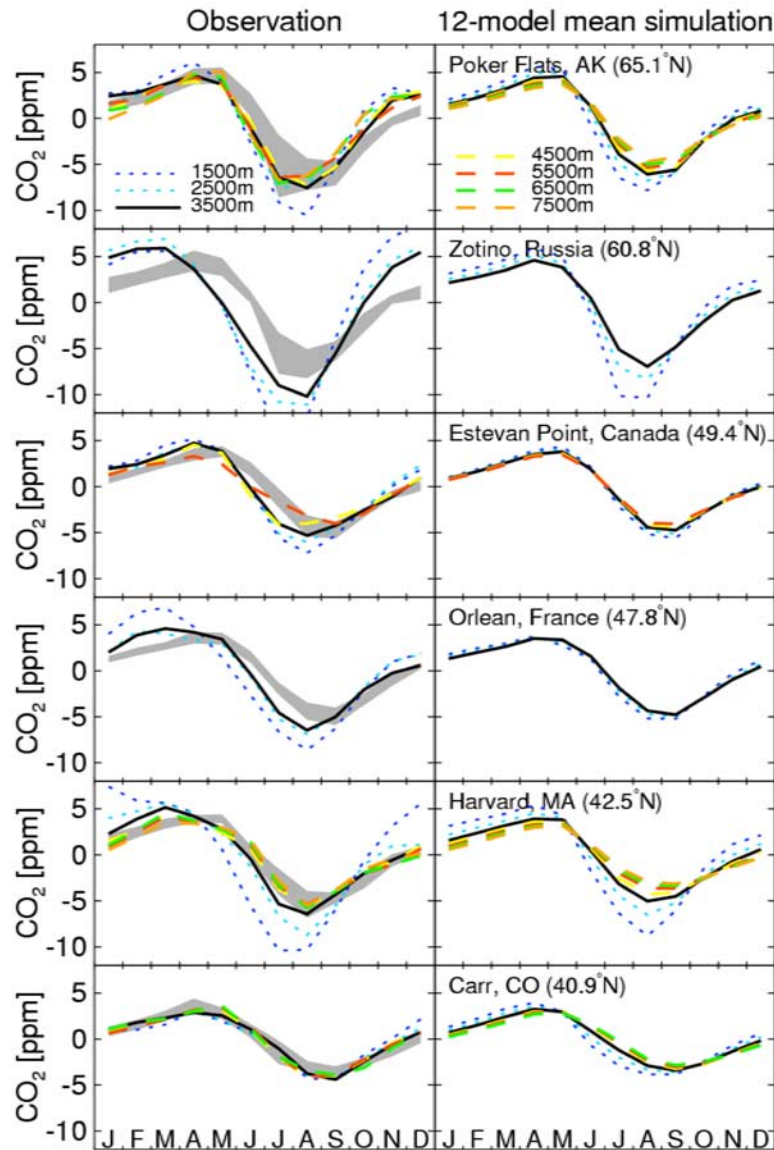


Figure 2. Comparison of the CO₂ seasonal cycles at different levels, for both (left) the aircraft observations and (right) the TransCom 12-model mean simulation. Each altitude level is represented by a different line and each row represents one site respectively. The range of model simulations for 3500 meters altitude is also shown in the left panel as the shaded area.

where T_H represents the time delay, A_H is the scaled amplitude and B is a seasonally-invariant offset. The comparison for each site is shown in Figure 2 and the retrieved values of A_H and T_H are listed in Table 2. In the model simulations, the scale factors monotonically decrease with altitude at all sites, while the time delays monotonically increase. In contrast, in the observations at or above 2500 m, all sites except ESP showed smaller decreases or even increases in the amplitude scale factor with altitude as well as shorter delay, and even advance (at PFA) in the seasonal cycle phase. For levels below 2500 m, the observations showed mixed trends from site to site, again possibly influenced by strong PBL variation. The observation-model differences above 2500 m strongly suggest that the atmospheric vertical and/or meridional

mixing within the free troposphere is faster than the TransCom simulations.

5. Summary and Implications

[15] Comparison of the column-averaged CO₂ dry volume mixing ratio measurements and the TransCom models implies that GSNF north of 30°N is ~ 7.9 Pg C/yr, approximately 28% larger than that predicted by CASA. Using multi-level observed CO₂ from the Northern hemisphere to diagnose the model performance at different altitudes, we identify substantial underestimation of free troposphere vertical mixing rates by TransCom models. While the mixing between the PBL and the free troposphere has been a major focus of carbon flux inversion experiments (i.e. TransCom), this analysis suggests that equally large

Table 2. Optimal Values of Scale Factor, A_H , and Time Delay in Days, T_H , Applied to 3500-m-Level Seasonal CO₂ Cycle for Best Matching the Other Levels (Equation (3))^a

Altitude	Optimal Values for Scale Factor A_H											
	PFA		ZOT		ESP		ORL		HFM		CAR	
	Obs.	Mod.	Obs.	Mod.	Obs.	Mod.	Obs.	Mod.	Obs.	Mod.	Obs.	Mod.
7500 m	0.88	0.80							0.78	0.74		
6500 m	0.93	0.85							0.87	0.78	1.05	0.90
5500 m	0.89	0.90			0.74	0.91			0.83	0.84	1.00	0.94
4500 m	0.92	0.95			0.89	0.95			0.85	0.91	1.05	0.98
3500 m	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
2500 m	1.03	1.12	1.18	1.20	1.07	1.07	1.03	1.06	1.25	1.23	0.98	1.12
1500 m	1.33	1.30	1.32	1.51	1.24	1.16	1.41	1.12	1.67	1.57	0.96	1.26
Altitude	Optimal Values for Time Delay T_H , days											
	Obs.	Mod.	Obs.	Mod.	Obs.	Mod.	Obs.	Mod.	Obs.	Mod.	Obs.	Mod.
	7500 m	-2.0	7.0							13.0	13.0	
6500 m	-4.0	6.0							11.0	10.0	3.0	12.0
5500 m	-1.0	4.0			8.0	1.0			10.0	8.0	-2.0	10.0
4500 m	0.0	2.0			-3.0	1.0			6.0	4.0	-4.0	8.0
3500 m	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
2500 m	-5.0	-4.0	-4.0	-5.0	-4.0	-1.0	-5.0	-3.0	-6.0	-6.0	-4.0	-8.0
1500 m	-7.0	-10.0	-10.0	-10.0	-4.0	-2.0	-12.0	-7.0	-21.0	-13.0	-4.0	-16.0

^aFor each site, the left column is for the observations and the right column is for the 12-model mean simulations.

errors exist in the rate of vertical mixing throughout the free troposphere.

[16] The weak vertical exchange of the TransCom models will have impacts beyond the estimation of seasonal CO₂ exchange between the biosphere and atmosphere. Gurney *et al.* [2004] have shown, for example, that the inferred uptake of fossil fuel carbon by land in the Northern Hemisphere by the various TransCom models (from 0.0 to 4.0 Pg C/yr depending on which transport model is used) is correlated with their estimate of the CO₂ seasonal cycle produced by the biosphere fluxes. Gurney *et al.* suggest that this correlation is consistent with errors in parameterization of the seasonal mixing efficiency between the planetary boundary layer (PBL) and the free troposphere (FT), which co-varies in time with the surface carbon exchange direction and strength [Denning *et al.*, 1995]. Our finding suggests that as a group, the TransCom models may have too little vertical mixing in the free troposphere and so may overestimate the size of the Northern Hemisphere land sink. The validity of this inference, however, depends in part on the how the transport errors vary seasonally, something this study has not addressed.

[17] The analysis described in this letter illustrates the utility of having information about the vertical distribution of CO₂ from aircraft. In addition, the total column measurements allow a more continuous record of CO₂ mass. The Total Carbon Column Observing Network (TCCON) is being established to expand the number of sites where CO₂ columns are measured (data available at <http://www.tcon.caltech.edu>). TCCON will include a number of sites in both the Northern and Southern Hemispheres. These observations should provide an improved measure of the gradient in CO₂ mass between two hemispheres. Based on the findings of this study, we expect that the N–S gradient will be larger than predicted by the TransCom inversions tied to surface observations.

[18] **Acknowledgments.** We thank the TransCom 3 modeling community (K. Gurney, M. Prather, T. Maki, L. Bruhwiler, Y. Chen, R. Law, C. Yuen, S. Fan, M. Heimann, and D. Baker) for making the results of

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