New constraints on Northern Hemisphere growing season net flux

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[1] Observations of the column-averaged dry molar mixing ratio of CO_2 above both Park Falls, Wisconsin and Kitt Peak, Arizona, together with partial columns derived from six 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 earlier 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 CO_2 mass from the surface measurements of CO_2 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*, LXXXXX, doi:10.1029/2007GL029742.

1. Introduction

[2] Forecasting future CO_2 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 CO_2 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 CO_2 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 significantly, 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 CO_2 column abundance (i.e., mass m^{-2}) in the atmosphere. These gradients in CO_2 column can be inferred from gradients in the observed mixing ratio at the surface only if the vertical structure of atmospheric CO_2 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 CO_2 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 representing directly a measure of atmospheric CO_2 mass per unit area. As a result, our estimate of NEE is significantly 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 CO_2 obtained at several sites in Eurasia and North America, that the TransCom models underestimate the seasonally-varying fluxes because they underestimate the efficiency of mixing of CO_2 throughout the free troposphere.

2. Measurements and Models

[5] Measurements of column-averaged dry CO_2 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 CO_2 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 measure-

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Table 1. Column and Profile Observation Sites and the CO_2 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

[a]For LEF and KTP, total CO_2 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).

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

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

[d]Excluding Kitt Peak due to different observation time period.

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

ments obtained at the Kitt Peak solar observatory, Arizona [*Yang et al.*, 2002]. In addition to the ground-based total columns, multi-level aircraft CO_2 measurements were available at six sites in North America and Eurasia during 2003–2004 (Table 1). Discrete CO_2 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 CO_2 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 CO_2 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 square fit, assuming the observed seasonal cycle $S(\mathrm{t})$ can be expressed as a function of the simulated CASA biosphere model response $S_0(\mathrm{t})$, adjusted by scale A, time delay T, and offset B:

$$S(\mathrm{t}) = A \times S_0(\mathrm{t} - T) + B \qquad (1)$$

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

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

[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 CO_2 is 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 CO_2 seasonal cycle of column-averaged observation and the TransCom simulations is shown in Figure 1. The observed seasonal CO_2 cycle amplitude is larger than any model simulation. A best fit was obtained by increasing the CASA fluxes by 34%. Models also underestimated the CO_2 seasonal cycle at Kitt Peak and 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 significant fraction of the northern hemisphere landmass, they provide a measure of CO_2 variations that is not highly sensitive to error in the transport fields. As a group, the seasonal cycle in column CO_2 is most sensitive to the seasonal fluxes themselves. This is sup-

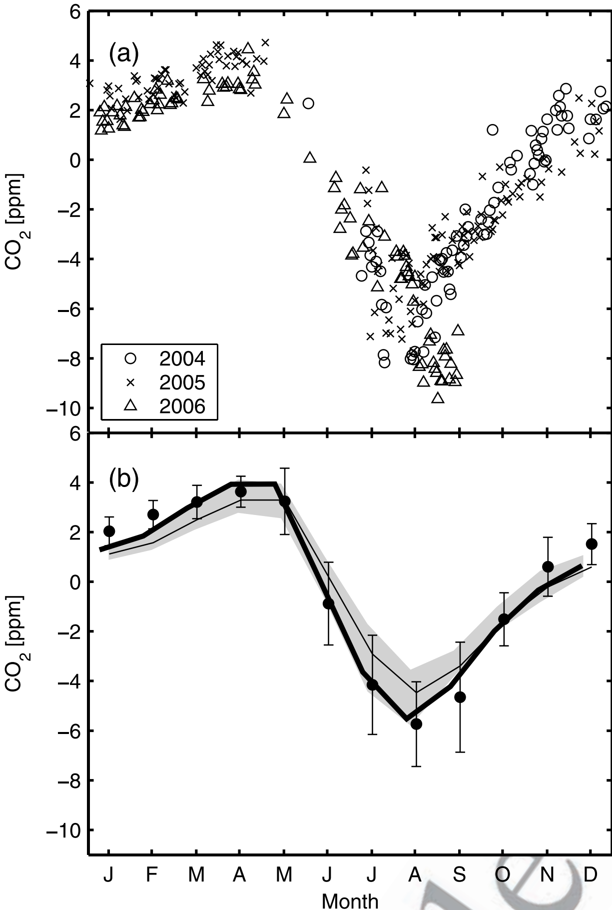

Figure 1. (a) Atmospheric column-average CO_2 mole fractions at Park Falls for May 2004–March 2006. (b) The monthly mean of observations (closed circles) compared with the TransCom simulations (grey shade shows range of 12-model predictions; thin solid line represents average). Each of the 12 models 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).

ported by the relatively small variation in the model simulations of the columns illustrated for Park Falls in Figure 1 and for the other sites in the accompanying auxiliary material[1]. 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% 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 CO_2 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 amplitude of the CO_2 seasonal cycle. In addition, the phase analysis of CO_2 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 CO_2.

[13] In contrast to the column results, comparison of the simulations of the seasonal cycle with CO_2 observations obtained at the surface (GLOBALVIEW-CO_2 flasks) between 30°N to 70°N shows a much smaller underestimation of seasonal cycle (~12%, Table 1) and a smaller phase delay ($T_{surface} = -11.9$ days; $T_{column} = -14.5$ 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 season cycle of CO_2 from its source at the surface into the interior of the atmosphere is sensitive to the size of the fluxes and the efficiency of vertical exchange. To investigate the accuracy of the TRANSCOM model simulations of this propagation, we analyzed the CO_2 vertical profiles at the six sites interrogated 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 CO_2 seasonal cycle at some sites (e.g., ZOT in Figure 2). (The results of such an analysis are shown in the online supplement[1]; 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 simulations and observations by:

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

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

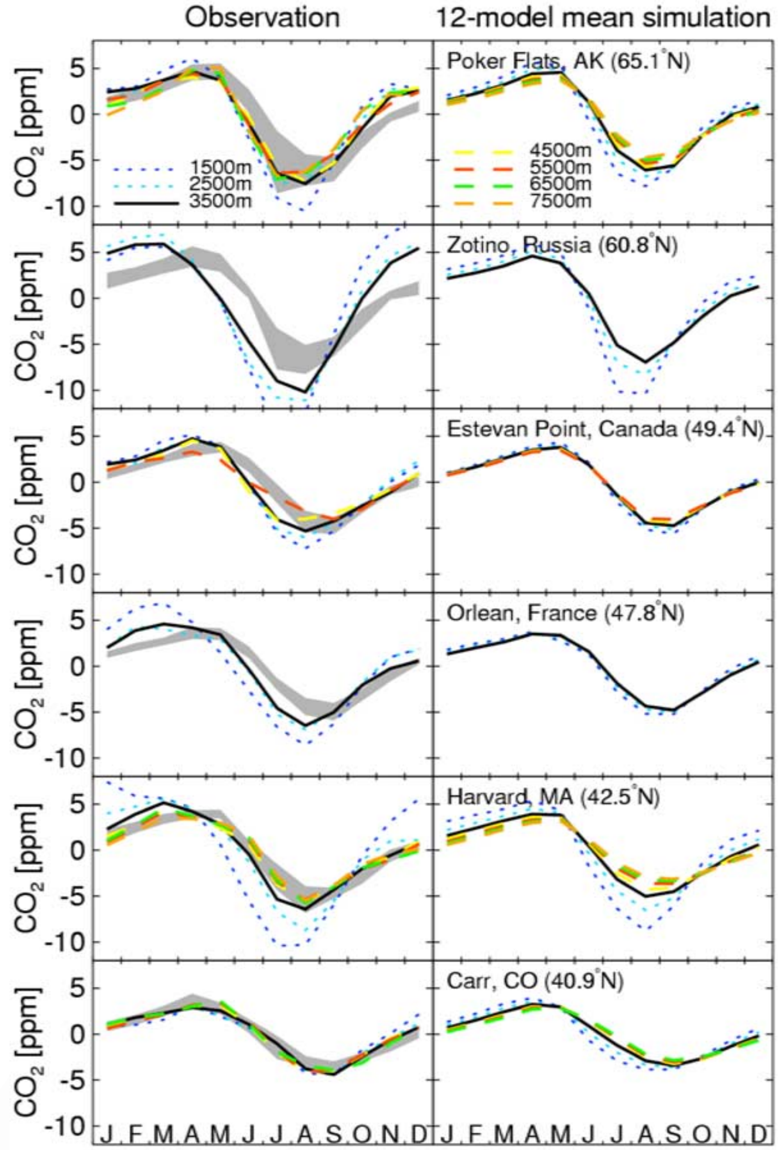

Figure 2. Comparison of the CO_2 seasonal cycles at different levels, for both (left) the aircraft observations and (right) the TransCom 12-model mean simulation. Each altitude level is represented by a different line and each row represents one site respectively. The range of model simulations for 3500 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 slower 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 CO_2 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 CO_2 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 CO_2 Change for Best Matching the Other Levels (Equation (3))[a]

	Optimal Values for Scale Factor A_H											
	PFA		ZOT		ESP		ORL		HFM		CAR	
Altitude	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
	Optimal Values for Time Delay T_H, days											
Altitude	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

[a]For 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 CO_2 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 CO_2 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 CO_2 from aircraft. In addition, the total column measurements allow a more continuous record of CO_2 mass. The Total Carbon Column Observing Network (TCCON) is being established to expand the number of sites where CO_2 columns are measured (data available at http://www.tccon.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 CO_2 mass between the 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 their simulations publicly available. This work was supported by a NASA grant NNG05GD07G. N. Y. Krakauer was supported by Graduate Fellowships from both NASA Earth and Space Science and the Betty and Gordon Moore Foundation. Column CO_2 data from the Park Falls installation are available at www.tccon.caltech.edu.

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