An atmospheric perspective on North American carbon dioxide exchange: CarbonTracker

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Communicated by A. R. Ravishankara, National Oceanic and Atmospheric Administration, Boulder, CO, September 27, 2007 (received for review May 23, 2007)

We present an estimate of net CO_2 exchange between the terrestrial biosphere and the atmosphere across North America for every week in the period 2000 through 2005. This estimate is derived from a set of 28,000 CO_2 mole fraction observations in the global atmosphere that are fed into a state-of-the-art data assimilation system for CO_2 called CarbonTracker. By design, the surface fluxes produced in CarbonTracker are consistent with the recent history of CO_2 in the atmosphere and provide constraints on the net carbon flux independent from national inventories derived from accounting efforts. We find the North American terrestrial biosphere to have absorbed −0.65 PgC/yr (1 petagram = 10^{15} g; negative signs are used for carbon sinks) averaged over the period studied, partly offsetting the estimated 1.85 PgC/yr release by fossil fuel burning and cement manufacturing. Uncertainty on this estimate is derived from a set of sensitivity experiments and places the sink within a range of −0.4 to −1.0 PgC/yr. The estimated sink is located mainly in the deciduous forests along the East Coast (32%) and the boreal coniferous forests (22%). Terrestrial uptake fell to −0.32 PgC/yr during the large-scale drought of 2002, suggesting sensitivity of the contemporary carbon sinks to climate extremes. CarbonTracker results are in excellent agreement with a wide collection of carbon inventories that form the basis of the first North American State of the Carbon Cycle Report (SOCCR), to be released in 2007. All CarbonTracker results are freely available at http://carbontracker.noaa.gov.

carbon cycle | greenhouse gases | data assimilation | biogeochemistry | atmospheric composition

Projections of future CO_2 levels in the atmosphere and the associated climate forcing, as well as our ability to control CO_2 levels, depend substantially on our scientific understanding of the natural carbon cycle. Its current capacity to absorb close to half of the carbon released from fossil fuel burning is not guaranteed to grow along with rapidly rising man-made emissions or to even continue at its present-day magnitude. Moreover, natural emissions themselves might increase as a result of already observable rapid warming in parts of the Arctic (1), where large carbon reservoirs are buried beneath the permafrost. Major national and international programs to study the carbon cycle are therefore underway.

The National Oceanic and Atmospheric Administration's (NOAA's) Earth System Research Laboratory (ESRL) monitors CO_2 in the atmosphere as a contribution to the North American Carbon Program (NACP) (2). Mole fractions of CO_2 are determined with an accuracy of 0.1 parts per million (ppm) from surface air samples collected around the globe and from tall towers and small aircraft in North America. These measurements form a record of integrated net CO_2 exchange from multiple processes, geographic areas, and times.

In addition, carbon exchange is monitored locally ($\approx$1 km^2) from a worldwide collection of surface flux measurements in different ecosystems and through periodic inventories of carbon in oceans, forests, and soils. The latter provide long-term constraints on the size of the different carbon pools. Monitoring of the carbon cycle through satellites mostly targets specific processes such as biomass burning, land-use change, or seasonal plant growth. Direct satellite observations of CO_2 are available already for the upper troposphere (3), whereas near-surface CO_2 from space will become available within several years to augment the current efforts.

To integrate this diversity of data into a consistent estimate of surface CO_2 exchange, the NOAA ESRL has built a new data assimilation system called CarbonTracker. It is used to retroactively analyze (reanalyze) the recent flux history of CO_2, using a state-of-the-art atmospheric transport model coupled to an ensemble Kalman filter. Currently, CarbonTracker assimilates only atmospheric CO_2 mole fractions, but efforts to expand it to assimilate observations of other trace gases in the atmosphere ($^{13}CO_2$, $^{14}CO_2$, CH_4) and other observation types (eddy-flux measurements, satellite radiances) are underway. Specifically, such observations could facilitate attribution of carbon fluxes to specific processes such as fossil fuel burning, biomass burning, or agricultural food and biofuel production.

One of the main innovations in CarbonTracker is the use of daily CO_2 values derived from continuous observations from a network of tall towers. These data were not available in similar previous studies (4–7) but are potentially highly informative on regional exchange patterns because they represent direct samples of the resulting strong gradients in space and time. The ability to use these data comes from the improved skill of our atmospheric transport model, the efficiency of the ensemble Kalman filter in solving large optimization problems, and the inclusion of subdaily variability in the surface flux models we try to optimize.

In this work, we introduce CarbonTracker and analyze the recent flux history it produces. We compare its regional estimates for North America with an independent "bottom-up" estimate that is part of the State of the Carbon Cycle Report (SOCCR) (8). This document, created as part of the U.S.

Author contributions: P.P.T. designed research; C.S., A.E.A., T.J.C., D.E.J.W., G.R.v.d.W., J.T.R., and P.O.W. contributed data; A.R.J., K.M., J.B.M., L.M.P.B., G.P., A.I.H., and M.C.K. performed research; and W.P. wrote the paper.

The authors declare no conflict of interest.

Freely available online through the PNAS open access option.

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This article contains supporting information online at www.pnas.org/cgi/content/full/0708986104/DC1.

Climate Change Science Program and scheduled for release in the summer of 2007, is exclusively based on inventory data because atmosphere-based estimates were deemed too coarse and uncertain to report. We also assess CarbonTracker's skill in reproducing CO_2 observations from light aircraft not used in the assimilation, as an independent check on the realism of the estimated fluxes and vertical transport. This is specifically relevant for CarbonTracker's role in evaluating column average CO_2 observations that can be obtained from space-based sensors. CarbonTracker demonstrates the feasibility of monitoring the carbon cycle in substantial detail from high-quality atmospheric CO_2 observations.

Assimilating CO_2

The principles behind CarbonTracker are similar to other data assimilation systems. It starts by forecasting atmospheric CO_2 mole fractions around the globe from a combination of CO_2 surface exchange models and an atmospheric transport model driven by meteorological fields from the European Centre for Medium-Range Weather Forecasts (ECMWF). The resulting three-dimensional CO_2 distribution is then sampled at the time and location that observations are available, and the difference between observations and model forecast is minimized. This minimization is achieved by tuning a set of linear scaling factors that control the magnitude of the surface fluxes for larger, but subcontinental, geographical areas. Once the value of each of the scaling factors is determined in many consecutive assimilation cycles, the 6-yr history of surface CO_2 exchange at $1^\circ \times 1^\circ$ can be readily constructed.

In addition to CO_2 mole fractions from all analyzed air samples from the NOAA ESRL Cooperative Air Sampling Network, we use daytime average mole fractions derived from continuous CO_2 time series at five towers [all calibrated against the world CO_2 standard (9)]: (*i*) the 396-m (above ground) level of the WLEF-TV tower near Park Falls, Wisconsin; (*ii*) the 107-m level of a cell phone tower near Argyle, Maine; (*iii*) the 457-m level of the KWKT-TV tower near Moody, Texas; (*iv*) the 40-m level of the tower in Fraserdale, Canada, operated by Environment Canada (EC); and (*v*) the 23-m level of the tower at Candle Lake, Canada, operated by EC. Other daytime average time series used are from the NOAA ESRL observatories at Barrow, Mauna Loa, Samoa, and the South Pole, and the continuous analyzer at Alert, Canada, operated by EC. The continuous data exhibit large variations on synoptic time scales resulting from the fact that changing wind directions bring different CO_2 signals to the sensors. These gradients, together with the modeled wind directions, inform the data assimilation system on regional flux differences. The total number of observations available (≈28,000) is small for data assimilation applications but the largest used in an atmosphere-based CO_2 estimate so far. Details on data treatment and a list of all of the sites is included in supporting information (SI) *Appendix*.

Transport of atmospheric CO_2 is simulated by using the global two-way nested transport model TM5. TM5 is an offline model driven by 3- to 6-h meteorological parameters taken from the operational forecast of the ECMWF model (10). In this work, TM5 is run at a global $6^\circ \times 4^\circ$ resolution with nested regions over North America ($3^\circ \times 2^\circ$) and the United States ($1^\circ \times 1^\circ$) (11). The choice of transport model is important in atmospheric CO_2 inverse modeling because the estimated fluxes were shown to be sensitive to vertical and horizontal transport (12). TM5 has been evaluated extensively and consistently performs well in ongoing intercomparisons. Possible biases in its vertical transport are assessed at the end of this article and in *SI Appendix*.

We consider net CO_2 surface exchange from fossil fuel burning, fires, terrestrial biosphere exchange, and exchange with the oceans. Fossil fuel and fire emissions are fixed based on bottom-up estimates of their distribution and magnitude, whereas biospheric and oceanic fluxes are adjusted to match the atmospheric CO_2 record. This choice reflects our faith in inventory-based emissions for fossil fuels and our lack of atmospheric observations to constrain tropical biomass burning CO_2 fluxes in this framework. Details on the applied surface fluxes are included in *SI Appendix*. The four processes considered drive instantaneous CO_2 fluxes in the model according to

$$F(x, y, t) = \lambda_r \cdot F_{\text{bio}}(x, y, t) + \lambda_r \cdot F_{\text{oce}}(x, y, t) + F_{\text{ff}}(x, y, t) + F_{\text{fire}}(x, y, t), \quad [1]$$

where λ_r represents a set of linear scaling factors for each week and each region (r) to be estimated in the assimilation. To create the spatial distribution of regions, the terrestrial biosphere is divided up according to ecosystem type and continent. Nineteen possible ecosystem types summarized in *SI Appendix* are therefore considered in each of 11 global land areas as in Gurney *et al.* (12), yielding a total of 25 ecoregions out of a possible 38 represented in boreal and temperate North America. The 13 ecosystem types not optimized for North America are either not represented (tropical forests in the boreal regions, for instance) or explicitly excluded based on physical considerations (e.g., deserts and polar ice caps were assumed to have zero carbon flux). Similarly, the ocean is divided into 11 large basins encompassing large-scale ocean circulation features. Thus, a total of $r = 135$ scaling factors are optimized globally each week. The ensemble system used to solve for the scalar multiplication factors is similar to that in Peters *et al.* (13). Details of the ensemble Kalman filter design are discussed in *SI Appendix*.

Relatively high temporal and spatial flux variations are represented in the fluxes $F_{\text{bio}}(x, y, t)$ and $F_{\text{oce}}(x, y, t)$ based on prescribed 3-h meteorological variables (e.g., sunlight, temperature, wind speed, surface pressure) and high-resolution input datasets (see *SI Appendix*) and not derived from atmospheric CO_2 observations. This recognizes the limited capacity of our network to sense CO_2 fluxes at the scales of individual counties or even states. Instead, we rely on mechanistic models to provide the high-frequency variations and optimize CO_2 fluxes over broader areas and time scales based on the available observations. The flux patterns at $1^\circ \times 1^\circ$ shown in this work are thus the convolution of optimized parameters λ_r and fluxes $F_{\text{bio}}(x, y, t)$ and $F_{\text{oce}}(x, y, t)$.

A cautionary note is that the high-resolution pattern prescribed to the system will influence the $1^\circ \times 1^\circ$ results we present. Shortcomings in the high-resolution flux modules (such as the distribution of country total fossil fuel emissions by population density instead of using maps of power generation, energy consumption, and traffic density) are therefore also part of our final product. Although we have included specific sensitivity tests in *SI Appendix* to address some of these shortcomings, we caution anyone that the $1^\circ \times 1^\circ$ results should not be interpreted without due consideration of the modeling framework chosen in this study.

Throughout the rest of this work, we will focus on results for North America (global flux estimates can be found in *SI Appendix*). We adopt the convention that negative fluxes denote a net loss of atmospheric CO_2 and a gain by a surface reservoir, and positive fluxes vice versa. Uncertainties are quoted as the upper and lower limits found in a set of 14 sensitivity experiments conducted to explore the possible outcomes given alternative choices for the main components of the system. This estimate thus addresses systematic modeling errors that were shown to exceed random estimation errors in previous studies (12, 14, 15). Although not quite a full Monte Carlo exploration, we feel that the set we have created forms a plausible range for the best estimate. Where appropriate, the best estimate will be followed by the minimum (subscript) and maximum (superscript) of the

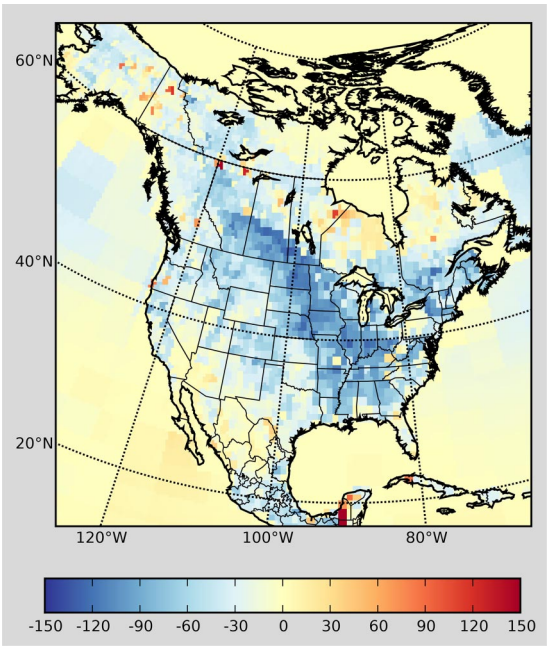

Fig. 1. Mean net terrestrial and oceanic flux (NEP plus fires; no fossil fuel emissions included) for the period 2001–2005 estimated from our system. Units are gC/m^2/yr. Note that the flux patterns at 1° × 1° shown are the combination of 25 parameters optimized against atmospheric observations and 1° × 1° fluxes from mechanistic models. See Eq. **1** and the text for more details.

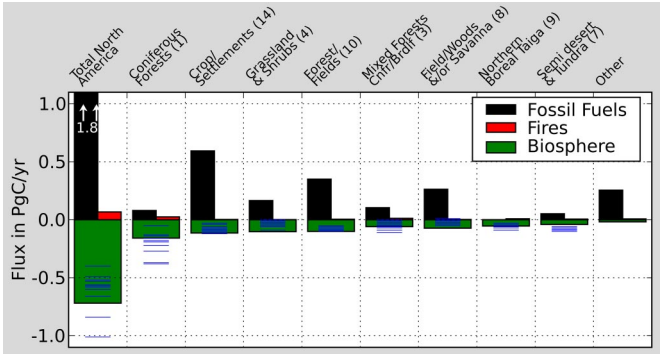

Fig. 2. Annual mean flux per ecoregion within North America for the period 2001–2005 estimated from our system. Black bars are the prescribed fossil fuel fluxes, red bars are the prescribed fire fluxes, and green bars are the estimated biological fluxes. Units are PgC/yr for each ecoregion. Blue horizontal lines denote the range of values found in a set of sensitivity experiments conducted for the year 2001 to determine the uncertainty. The labels refer to ecosystem types according to ref. 16 (http://cdiac.ornl.gov/ftp/ndp017). See text for more details.

sensitivity range. The uncertainty estimate is discussed in more detail in *SI Appendix*.

Annual Mean Fluxes

The 5-yr annual mean pattern of Net Ecosystem Production (NEP) derived from CarbonTracker is shown in Fig. 1. This represents the terrestrial part of the carbon cycle including fires but without the large fossil fuel emissions. The pattern of uptake is consistent with previous estimates of the North American carbon fluxes. Several factors influence the terrestrial CO_2 sink, but land-use history has been identified as the major determinant of regional terrestrial uptake (17–20). Large sinks can be found, for instance, in forests recovering from logging in the past century, as well as on abandoned agricultural lands recovering from past carbon losses. Increased fire suppression and changes in agricultural methods have also led to increased carbon storage in the soils and biosphere. These factors combined may be the cause of the strong uptake we calculate over the East Coast of the United States, in the Canadian coniferous forests, and across the grass and croplands of the Midwest.

A quantitative breakdown of this map by ecosystem type is shown in Fig. 2. We estimate total uptake in North America at $-0.65^{-0.40}_{-1.01}$ PgC/yr (1 petagram = 10^{15} g), with the majority of the sink in regions dominated by forest–field complexes ($-0.23^{-0.10}_{-0.33}$ PgC/yr), coniferous forests ($-0.16^{-0.05}_{-0.38}$ PgC/yr), croplands ($-0.11^{-0.03}_{-0.12}$ PgC/yr), and grasslands and shrubs ($-0.10^{0.0}_{-0.10}$ PgC/yr). These estimates compare well with the SOCCR totals of −0.681 PgC/yr of absorption by the biosphere, of which −0.383 PgC/yr occurs in forests. Uncertainty on the SOCCR estimates is also close to 50%, making the good correspondence of the means somewhat fortuitous. A sink of −0.120 PgC/yr in the SOCCR inventory due to woody encroachment (described as invasion of woody plants into abandoned grass land or forests into shrub land) is not readily compared with any of our ecosystems, but the −0.10 PgC/yr sink found over grassland and shrubs might be part of this. However, more detailed comparisons with woody encroachment estimates are needed to complete this picture.

Large net uptake seen in areas dominated by croplands (−0.11 PgC/yr) may be due to the "atmospheric view" we take with CarbonTracker. Over agricultural lands, our system sees strong CO_2 uptake during the growing season but a much smaller return flux from respiration during the non-growing season. The difference can be explained by harvesting of crops and their subsequent transport, which is a substantial term in the carbon budget (21). The harvested crops are returned to the atmosphere after consumption spread across the country as a much smaller source per unit area. Because CarbonTracker was not built to keep track of lateral transport, this source is most likely assigned to regions with large population densities, whereas croplands remain annual mean net absorbers of carbon in the Midwest even though the soil carbon accumulation over these areas is thought to be small (22).

Similarly, it can be argued that lateral transport of wood-derived products and agricultural products for the international market, and carbon dissolved in river streams should be subtracted from the estimated net-absorption to yield the net CO_2 sink of North America. Although this carbon [total of ≈0.16 PgC/yr (19, 23, 24)] is removed from the atmosphere over North America and stored in other reservoirs, the longer-term stability of such reservoirs is hard to estimate and therefore questionable as a continental carbon sink.

Year-to-Year Variations

Year-to-year variations in the terrestrial carbon budget depend on climate variations that alter growing season length, regional temperatures, and moisture conditions (19, 25, 26). Through such mechanisms, a widespread drought over Europe in 2003 appears to have caused a reduction in CO_2 uptake of nearly 0.5 PgC/yr (27). As markets develop for the trading of CO_2 emissions, such anomalies represent multiple billions of dollars change in the continent's carbon budget; hence the need to monitor them closely.

In our 5-yr estimate, 2002 stands out as a particularly low net uptake year (−0.32 PgC/yr) in North America, with only about half of the sink of the other years (Fig. 3). This phenomenon is apparent in both the temperate (−0.32 PgC/yr) and boreal (0.0 PgC/yr) zones and seems unrelated to emissions from fires in 2002 [≈0.065 PgC across North America (28)]. This suggests that the balance of

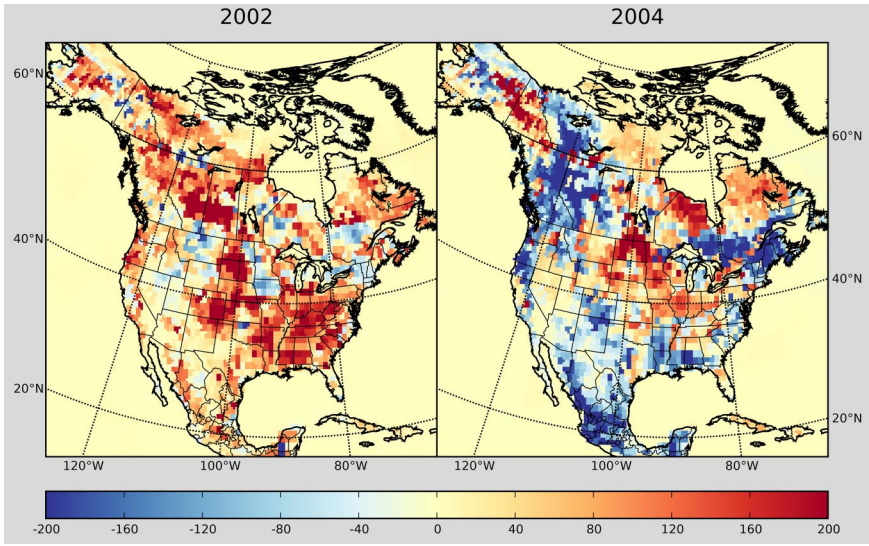

Fig. 3. Net terrestrial summer flux (NEP plus fires for weeks 20–34) anomaly for the 2 extreme years of our estimate. 2002 had a strong positive summer flux anomaly due to droughts. In contrast, 2004 showed high uptake during the summer. The parameter estimates for 25 ecoregions have been projected to 1° × 1° to create this map. Units are gC/m^2/yr.

photosynthesis and respiration was modified this year, likely driven by drought. In 2002, North America experienced one of the largest droughts in over a century with conditions over nearly 45% of the United States classified as "Extreme" or "Exceptional" [Palmer Drought Stress Index (PDSI): below −4] in the U.S. Drought Monitor (http://drought.unl.edu/dm). Corroborating evidence of reduced growing season uptake in 2002 comes from multiple AmeriFlux eddy-covariance sites (AmeriFlux Data Server, http://public.ornl.gov/ameriflux), reduced crop yields (National Agricultural Statistics Service, www.nass.usda.gov/Data_and_Statistics/index.asp), and independent modeling efforts (29).

In contrast to this continentwide effect, lower-than-average uptake in temperate North America in 2001 (−0.40 PgC/yr) was compensated by higher-than-average uptake in the boreal regions that year (−0.27 PgC/yr). In 2004, strong uptake in the boreal biosphere was accompanied by a very active boreal North American fire season (0.09 PgC/yr), specifically in Alaska. At the same time, an unusually wet late-summer/fall in the temperate regions (PDSI: >3) apparently led to increased uptake in the United States (−0.66 PgC/yr) to give 2004 the largest continental total terrestrial sink in this 6-yr period (Fig. 3).

CarbonTracker Evaluation

Recently, Stephens *et al.* (30) and Yang *et al.* (31) showed that a large set of atmospheric inverse model results (12) were inconsistent with free tropospheric (FT) CO_2 mole fractions as a result of an incorrect combination of vertical transport and surface fluxes in the underlying models. Transport biases are one of the largest unknown sources of error in flux inversions (15) and can be revealed by confronting the results with independent observations.

To this purpose, we have compared the optimized three-dimensional CO_2 mole fraction distribution produced by CarbonTracker to a set of ≈13,000 independent (i.e., nonassimilated) flask samples of CO_2 taken in the free troposphere as part of the NOAA ESRL Aircraft Program between 2000 and 2006. Fig. 4 shows the distribution of the residuals (simulated-minus-observed mole fractions) for all samples by month. The annual mean and standard deviation of the distribution is 0.07 ± 1.91 ppm. This bias is somewhat larger when assessed by season with a mean model overestimate of FT mole fractions of 0.27 ± 2.67 ppm in summer (June/July/August) and a model underestimate of FT mole fractions by 0.15 ± 1.47 ppm in winter (November/December/January). We note, though, that analysis of simulated-minus-observed mole fractions for surface data that were not reserved but assimilated showed a similar bias (see *SI Appendix* for more detailed discussion of the remaining biases), suggesting that part of the difference is in the phase or amplitude of the seasonally varying fluxes and not in vertical transport. Overall, the agreement with FT data at the level of a few tenths of a ppm is quite satisfactory and shows no evidence of large biases in the combined fluxes and transport in CarbonTracker, at least over North America.

In addition, column average mole fractions of CO_2 are measured by a Fourier transform spectrometer (FTS) deployed at Park Falls, Wisconsin (32, 33). Fig. 5 shows the comparison with CarbonTracker after cosampling in time and space, and applying a simple FTS averaging kernel (33). Differences between CarbonTracker and FTS observations are small (Δ = 0.5 ± 0.9 ppm) and their correlation is high (linear correlation R^2 of 0.93), as is

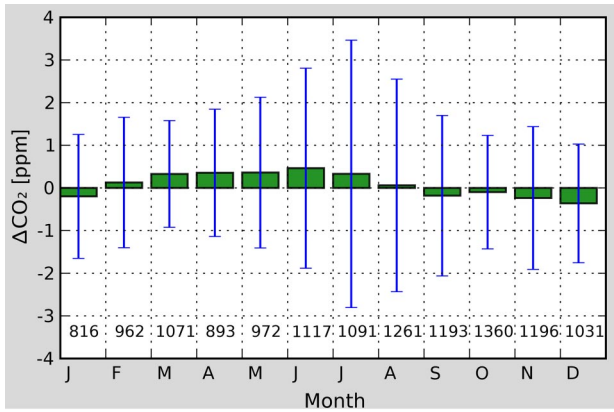

Fig. 4. Modeled-minus-observed CO_2 for a set of 13,000 observations in the free troposphere. The differences are averaged by month (green bar), and the range (blue) indicates the standard deviation. The number below each bar denotes the number of observations used in the statistic. Note that all data collected through NOAA's Aircraft Program were not used in the assimilation and are thus an independent check on the estimated fluxes as well as vertical transport in the TM5 model. Units are mole fraction expressed as ppm.

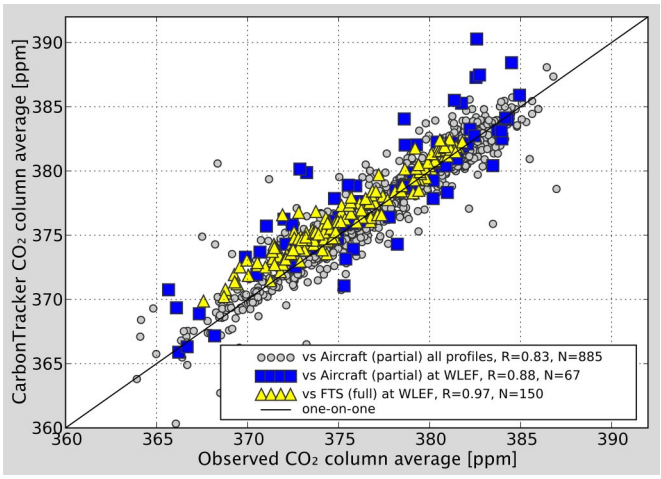

Fig. 5. Comparison between column average CO_2 from observations and from our assimilated CO_2 distribution. Included are full column averages from FTS observations (yellow), partial column averages from aircraft samples at Parks Falls, Wisconsin (blue), and partial column averages from all NOAA ESRL aircraft observations (gray). Shown is the general good agreement between modeled CO_2 columns and independent (nonassimilated) observations. Linear correlation coefficients are given in the key. Units are mole fraction expressed as ppm.

the agreement on day-to-day variations and the amplitude of the seasonal cycle (see *SI Appendix*). This suggests that our model represents column average CO_2 well, at least at this location. For 22 other locations, we have integrated discrete samples from the NOAA ESRL Aircraft Program to give partial column average values for each flight (885 in total) and again cosampled our model to make a partial CO_2 column value. The excellent agreement ($\Delta = 0.05 \pm 2.7$ ppm, $R^2 = 0.83$) for this much larger domain (mostly North America and the eastern Pacific) and time span (2000–2006) is also shown in Fig. 5. For reference, partial columns for the WLEF-TV tower are included separately. Again, the comparison with independent data reveals no large biases in CarbonTracker fluxes and vertical transport as argued in more detail in *SI Appendix*.

The favorable comparison of our product to aircraft-derived column CO_2 and FTS-derived values shows a high level of consistency among all three. It also suggests that, at least over North America and the Northern Pacific, our three-dimensional CO_2 fields are a useful assimilation of sparse observational data that could be used to quantitatively assess satellite-derived CO_2 columns. In 2008, two dedicated missions called the Orbiting Carbon Observatory (OCO; National Aeronautics and Space Administration) and GoSat (Japanese Space Agency) will be launched for this purpose. Currently, the Atmospheric Infrared Sounder (AIRS) and the Scanning Imaging Absorption Spectrometer for Atmospheric Chartography (SCIAMACHY) already deliver experimental column average CO_2 products. Demands on the precision and accuracy of satellite-observed CO_2 are high (34, 35), and it is currently unclear whether the existing and planned satellite sensors can provide unbiased information on net carbon exchange. Our first analysis here suggests that flux and transport biases in CarbonTracker are small enough to evaluate such products quantitatively even at many locations where independent observations are not available.

Discussion

The first release of CarbonTracker marks a significant step in our ability to monitor month-by-month surface sources and sinks of CO_2. In addition to overcoming many technical hurdles, the system introduces a novel ensemble assimilation method and a large number of other innovations to model atmospheric CO_2 mole fractions accurately. CarbonTracker's ability to derive trustworthy surface fluxes depends strongly on the careful observations made by dedicated researchers all over the world. Expansion of the monitoring efforts to sparsely sampled regions of the world, and to collect more high-frequency time series across North America, should therefore have the highest priority. Moreover, independent monitoring of the isotopic fraction of $^{14}CO_2$ in the atmosphere would allow independent verification of the fossil fuel fluxes by tuning for parameters in models describing those fluxes. Such estimates have great value for climate change mitigation policies. In addition, they would improve estimates of other fluxes because in the current version of CarbonTracker, relatively small errors in the fossil fuel emissions inventories may be aliased into relatively larger errors in other fluxes.

We stress that CarbonTracker currently is a framework on which to expand in future updates. Public release of new reanalyses incorporating both new data and innovations in the system itself are scheduled for October of each year starting in 2007. We welcome any contribution to CarbonTracker, and cooperation with those interested in the effort as CarbonTracker is intended to be a tool for the carbon cycle scientific community. In addition, we intend to improve and develop CarbonTracker further into a tool that is useful to policymakers from the national to the regional level. Therefore, all results, data, code, and other tools used in this study are freely available from NOAA ESRL's CarbonTracker web site, http://carbontracker.noaa.gov.

We thank Taro Takahashi, Greg Marland, T. J. Blasing, Tris West, Jerry Olson, and the EDGAR consortium for contributing data sets used to complete this study. Development of the GFED2 fire emissions was supported by National Aeronautics and Space Administration Grant NNG04GK496. The column CO_2 observations at Park Falls were obtained with support from National Aeronautics and Space Administration Grant NNG05GD07G. CarbonTracker is a National Oceanic and Atmospheric Administration contribution to the North American Carbon Program.

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