CarbonTracker - An annual global inversion flux product from the NOAA Earth System Research Laboratory

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Introduction

CarbonTracker is a combined measurement and modeling system that keeps track of the emissions and removal of atmospheric CO_2. Ecosystems in North America appear to have been net sink of -0.7 ± 0.8 PgC/yr during the 2000-2005 period, partially offsetting emissions of 1.9 PgC/yr from the burning of fossil fuels in the U.S., Canada and Mexico combined. Our estimates include sub-continental patterns of sources/sinks coupled to the distribution of dominant ecosystem types across the continent.

The sinks are mainly located in the agricultural regions of the Midwest (35%), deciduous forests along the East Coast (25%), and boreal coniferous forests (14%). There also appears to be substantial interannual variation of the sink, correlated with temperature and moisture variations. Our estimates are optimally consistent with measurements of weekly 14,000 air samples from across the world, ~5,000 daily averages of CO2 around the continent and ~ 5,000 daily averages from tall towers at four locations within the continent.

It is important to note that at this time the uncertainty estimate is itself quite uncertain. It has been derived from the formalism of the data assimilation system, which requires several "educated guesses" for initial uncertainty estimates, and does not take into account several additional factors:

- The calculation is set up for sources/sinks to slowly revert to annual net zero in the absence of observational data, which may produce a bias.
- Due to the sparseness of data, we have had to assume coherence of ecosystem processes over large distances, giving existing observations perhaps an undue amount of weight.
- The simulation sub-model for terrestrial photosynthesis and respiration is very "basic", and will likely be greatly improved for the next release of CarbonTracker.

In upcoming versions of CarbonTracker, the addition of additional measurement sites is expected to lead to significant improvements. This will be especially evident in the specificity of estimated fluxes at smaller spatial scales.

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Methods

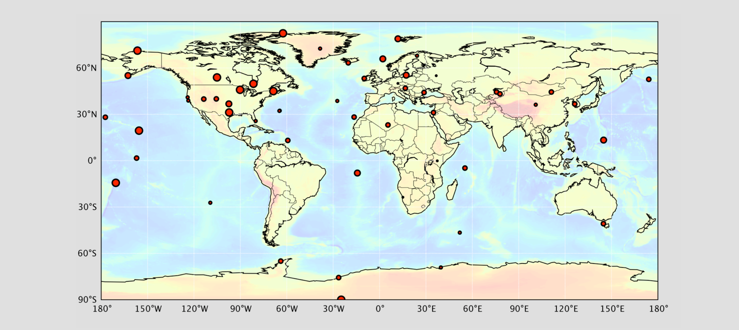
Our Model of Observations

CarbonTracker finds optimal values for scalars λ that multiply high-resolution prior guesses F of net CO_2 fluxes from available process models of the terrestrial biosphere and air-sea exchange. Observations of atmospheric CO_2 mixing ratios at available stations, C_{obs}, are modeled as

$$C_{mod} = \mathcal{T}_{TM5}\left[\lambda_{bio}F_{bio} + \lambda_{ocn}F_{ocn} + F_{ff} + F_{fire}\right],$$

where $\mathcal{T}_{TM5}$ is modeled atmospheric transport working on the sum of fluxes due to the terrestrial biosphere (F_{bio}), the ocean (F_{ocn}), fossil fuel emissions (F_{ff}), and GFEDv2 (van der Werf et al., 2006) direct fire emissions (F_{fire}). Note that only the terrestrial biosphere and ocean fluxes are scaled by the factors λ.

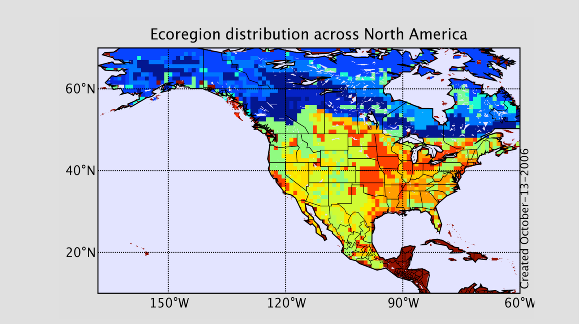
An optimization technique (a fixed-lag ensemble Kalman smoother implemented within the TM5 atmospheric transport model) is used to find the unique values of λ that yield the smallest RMS difference between observed and modeled valued CO_2 mixing ratios.



CarbonTracker 2006 observational network

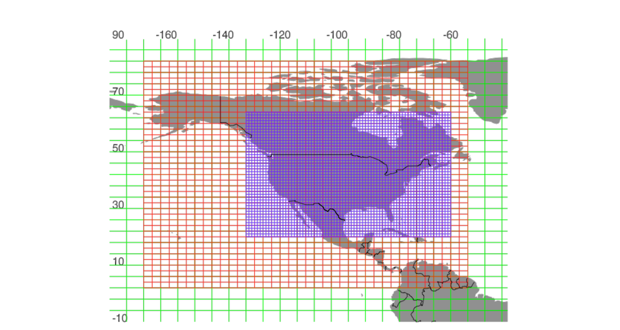
Optimization at the Ecosystem Scale

We optimize for land fluxes at sub-continental scales by dividing 11 large (TransCom) regions into independent ecoregions. For CarbonTracker 2006, we use 19 global ecosystems derived from version 1.3 of the Olson (1992) ecoregion product. Not all ecosystems are present in each TransCom region, and between the two North American (temperate and boreal) regions there are 24 independent ecoregions for which fluxes are optimized (see figure at right).



The 24 ecoregions in North America

Modeled Atmospheric Transport



Nested grids of the TM5 transport model

The TM5 transport model features 2-way grid nesting for high-resolution transport over selected regions. CarbonTracker 2006 is configured to use a global 6° x 4° grid (green lines at left) and a 1° x 1° grid (blue) over most of North America. A 3° x 2° transitional grid (red) is used to facilitate the nesting.

ECMWF operational forecast model output is used to drive TM5 over the period 2000-2006.

The Role of Process Models

A persistent challenge in inverse modeling of atmospheric carbon dioxide mixing ratios is that the upwind footprint of a point observation is small relative to continental scales. CarbonTracker uses detailed process models to solve the problem of spreading the influence of observations beyond an observation's immediate footprint. For land regions, this is partly accomplished by optimizing fluxes for entire ecosystems (see box at left for details). We use a terrestrial biosphere model--currently, a CASA variant that incorporates GFEDv2 fires--to make high-resolution first-guess predictions of flux across an ecosystem. Over the next *N* weeks of the optimization window, this first guess flux is continually refined by available observations. For CarbonTracker 2006, the optimization window is *N*=5 weeks long.

The optimized factors λ scale the process model's predicted net flux over the whole ecosystem for each week. We rely on the process model to give the high-resolution spatial and temporal distribution of flux, whereas the inversion is focused on constraining the magnitude of the net flux.

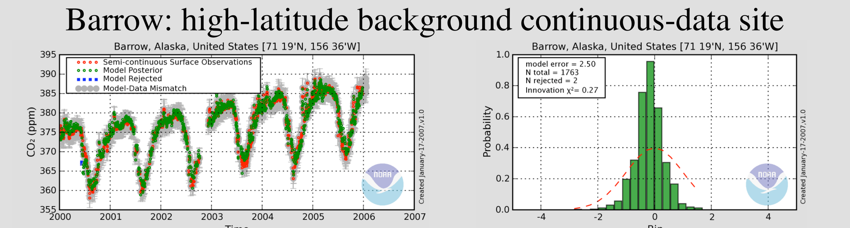
For CarbonTracker 2006, we start with monthly-mean CASA NPP and heterotrophic respiration fluxes. We distribute these according to analyzed 3-hourly incident surface solar radiation and temperature, following the scheme outlined in Olsen and Randerson (2004).

In the ocean, we use Takahashi *et al*. (2002) monthly climatological fields of air-sea CO_2 partial pressure difference coupled with gas transfer and barometric relationships to distribute the flux in time. These relationships use the analyzed ECMWF meteorology to impose temporal variability on the climatological ΔpCO2 fields. Spatial resolution is currently maintained at the coarse TransCom eleven ocean regions.

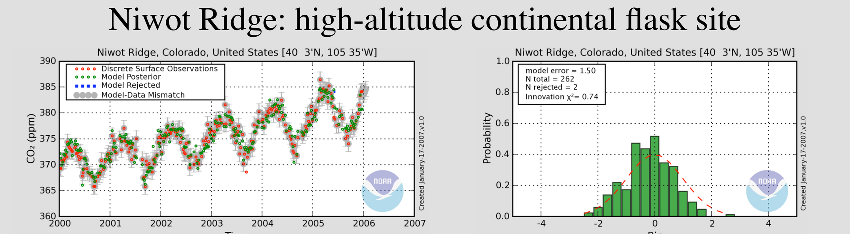
Evaluation: Match to Observations

CarbonTracker modeled mixing ratios generally match observations, in terms of long-term trend, the magnitude and timing of seasonal cycles, and interannual variability. Mixing ratio time series (left panels) and model-data mismatch normalized by assumed error (the χ-statistic, right panels) are presented for four representative sites.

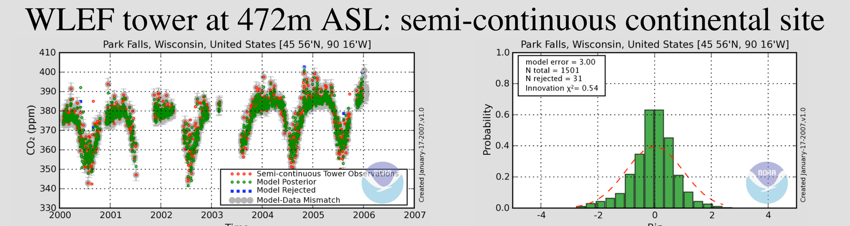
Barrow: high-latitude background continuous-data site



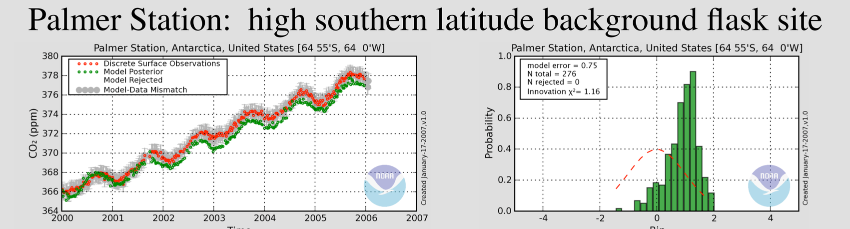
Niwot Ridge: high-altitude continental flask site



WLEF tower at 472m ASL: semi-continuous continental site



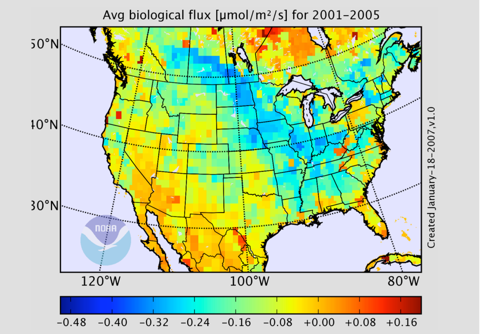
Palmer Station: high southern latitude background flask site



The persistent bias at high southern latitudes (above) is consistent with an emerging consensus that the Southern Ocean is a smaller sink than previously thought.

Results

North American fluxes

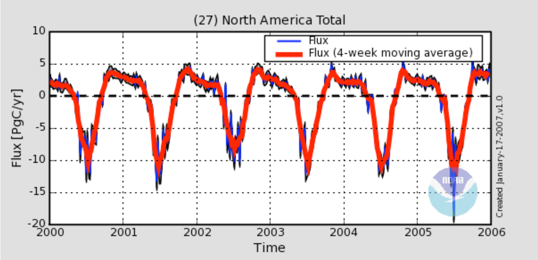


CT06 2001-2005 average biological flux

North American ecosystems appear to be a sink, with a net flux to the atmosphere of about -0.7 ± 0.8 PgC/yr. This is less than half the emissions due to fossil fuel use. Year after year, North America is a greater sink than that predicted by the first-guess terrestrial carbon model.

CarbonTracker 2006 North American carbon dioxide flux estimates (PgC/yr)					
	Biological flux				
	First Guess	Final Estimate	Fire emissions	Fossil fuel emissions	Total
2000	-0.1 ± 1.2	-0.6 ± 0.8	0.04	1.7	1.1 ± 0.8
2001	-0.2 ± 1.2	-0.7 ± 0.8	0.03	1.8	1.1 ± 0.8
2002	0.0 ± 1.2	-0.4 ± 0.8	0.07	1.8	1.5 ± 0.8
2003	-0.3 ± 1.2	-0.8 ± 0.7	0.07	1.9	1.2 ± 0.7
2004	-0.1 ± 1.2	-0.9 ± 0.6	0.10	1.9	1.1 ± 0.6
2005	-0.2 ± 1.2	-0.8 ± 0.8	0.06	1.9	1.2 ± 0.8
mean	-0.2 ± 1.2	-0.7 ± 0.8	0.06	1.8	1.2 ± 0.8

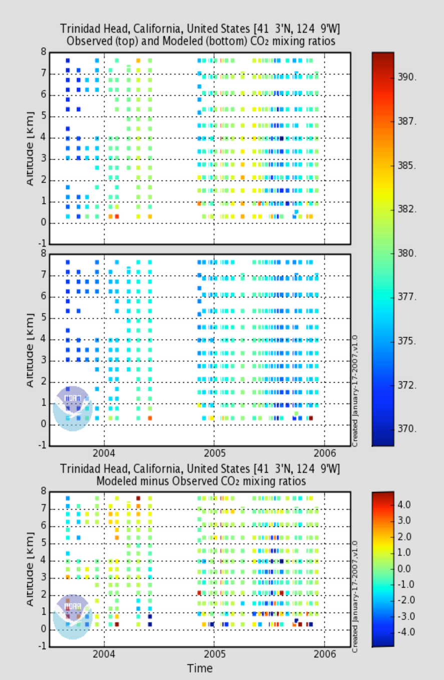
The continental-scale drought in 2002 is clearly manifested in CarbonTracker results. While the first-guess process model predicted a reduction in the sink by about 0.2 PgC/yr, CarbonTracker detected a change of about twice that size.



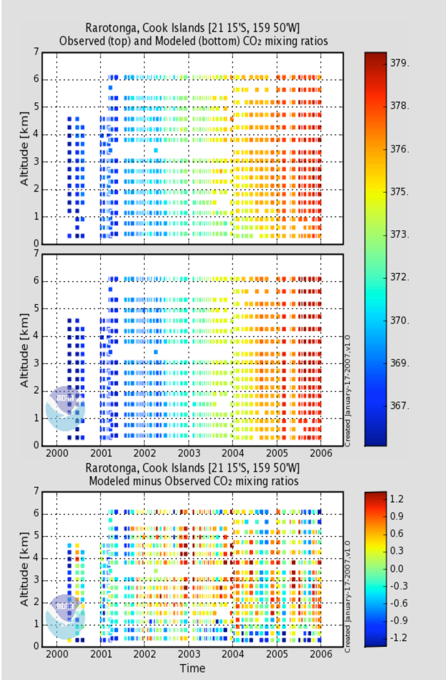
CT06 North American flux time series

Evaluation: Comparison with Aircraft Data (reserved from optimization)

A "byproduct" of the data assimilation system, once sources and sinks have been estimated, is that the mole fraction of CO_2 is calculated everywhere in the model domain, including higher altitudes, over the entire 2001-2005 time period. As a check on model transport properties, calculated CO_2 mole fractions can be compared with measurements of ~9,000 air samples taken by aircraft over North America, which have not been used in the estimation of sources/sinks. Column averages of the CO_2 mole fraction have been calculated as well, and they can be compared to satellite measurements of the same quantity when the averaging is done in the same way as for the satellite results



West coast vertical profiles are critical for establishing the free tropospheric input to North America. Our model has a bias towards high mixing ratios at altitude.



Tropical vertical profiles at background locations principally manifest the global CO_2 growth rate. Aircraft data will hopefully lead to a refinement of vertical exchange in TM5.

Collaborative Opportunities

Putting Your Ecosystem Model in CarbonTracker

CarbonTracker is designed to be used to with multiple process models. It is modular in design and components can be easily changed. Once the flux output from a process model is prepared for a CarbonTracker forward run, no further manipulations are needed to run CarbonTracker in inverse mode with those first-guess fluxes.

Types of data currently sampled from the model include surface, tall tower, and aircraft flask sampling, afternoon averages at sites operating continuous CO_2 analyzers, full column averages at specified local times (to coincide with satellite overpasses), and hourly-averaged fluxes for comparison with eddy covariance flux measurements. Other types of sampling are also possible. Simulated data derived from un-optimized process model fluxes can thus be directly compared to available atmospheric mixing ratio and flux measurements.

CarbonTracker reads fluxes from process models. It can be used in forward mode to produce simulated data at the times and places and with the same averaging characteristics as actual observations, and in inverse mode to make process model predictions more consistent with observations. Researchers can thus receive information on the consistency of fluxes from their models with available CO_2 observations, and time- and space-dependent scaling factors required to bring those fluxes into agreement with observations.

Our Goals for Collaboration

More data. Currently, CarbonTracker uses mixing ratio observations from the NOAA observational network and the Canadian Meteorological Service. Our estimates will grow more reliable as the number of data processed by the inversion is increased. Please contact us to contribute data.

Better flux estimates. CarbonTracker is designed to make use of a fully built-out observation network, and is capable of assimilating large amounts of data. As more data become available, we hope this will allow us to explore uncertainties and biases due to process model and transport errors.

Better knowledge of mechanisms. One end goal of our efforts is to better understand the processes underlying surface exchange of carbon dioxide. Better knowledge of mechanisms means better predictive power.

Better fossil fuel emissions. Another end goal is to measure the magnitude of fossil fuel CO_2 fluxes in support of emissions reductions policies. We need to know this large term in the carbon cycle in order to make inferences about biological fluxes.

To make progress on persistent problems. Tracer concentrations in the atmosphere result from transport acting on fluxes. By using multiple species and vertical profiles, we hope to bring more prior knowledge to the table, both about transport and about emissions.

For More Information

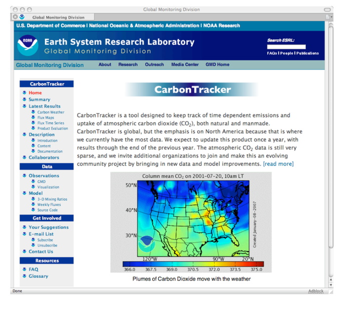
Documentation, references, results and further information are all available at the CarbonTracker web site:

http://www.cmdl.noaa.gov/ccgg/carbontracker

We welcome suggestions, comments, and proposals for collaborative activities.

Reach us by email at

CarbonTracker.team@noaa.gov



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