The changing carbon cycle at Mauna Loa Observatory

Wolfgang Buermann*†, Benjamin R. Lintner‡§, Charles D. Koven*, Alon Angert*¶, Jorge E. Pinzon‖, Compton J. Tucker‖, and Inez Y. Fung*,**

*Berkeley Atmospheric Sciences Center and ‡Department of Geography, University of California, Berkeley, CA 94720; and ‖National Aeronautics and Space Administration/Goddard Space Flight Center, Greenbelt, MD 20771

Contributed by Inez Y. Fung, December 29, 2006 (sent for review July 6, 2006)

The amplitude of the CO_2 seasonal cycle at the Mauna Loa Observatory (MLO) increased from the early 1970s to the early 1990s but decreased thereafter despite continued warming over northern continents. Because of its location relative to the large-scale atmospheric circulation, the MLO receives mainly Eurasian air masses in the northern hemisphere (NH) winter but relatively more North American air masses in NH summer. Consistent with this seasonal footprint, our findings indicate that the MLO amplitude registers North American net carbon uptake during the warm season and Eurasian net carbon release as well as anomalies in atmospheric circulation during the cold season. From the early 1970s to the early 1990s, our analysis was consistent with that of Keeling *et al.* [Keeling CD, Chin JFS, Whorf TP (1996) *Nature* 382:146–149], suggesting that the increase in the MLO CO_2 amplitude is dominated by enhanced photosynthetic drawdown in North America and enhanced respiration in Eurasia. In contrast, the recent decline in the CO_2 amplitude is attributed to reductions in carbon sequestration over North America associated with severe droughts from 1998 to 2003 and changes in atmospheric circulation leading to decreased influence of Eurasian air masses. With the return of rains to the U.S. in 2004, both the normalized difference vegetation index and the MLO amplitude sharply increased, suggesting a return of the North American carbon sink to more normal levels. These findings indicate that atmospheric CO_2 measurements at remote sites can continue to play an important role in documenting changes in land carbon flux, including those related to widespread drought, which may continue to worsen as a result of global warming.

atmospheric circulation | atmospheric CO_2 seasonal cycle | terrestrial carbon sinks | continental droughts

The time series of CO_2 at Mauna Loa Observatory (MLO) located on the Island of Hawaii is unique not only because of its accuracy and length but also because it was designed and has been repeatedly demonstrated to capture the globally averaged secular trend in atmospheric CO_2. The seasonal cycle of atmospheric CO_2 at the MLO, with a maximum at the beginning of the growing season (May) and a minimum at the end of the growing season (September/October), records the "breathing" of the northern hemisphere (NH) biosphere, that is, the seasonal asynchrony between photosynthetic drawdown and respiratory release of CO_2 by terrestrial ecosystems (e.g., refs. 1–3).

During the course of a year, the MLO experiences marked shifts in large-scale atmospheric circulation. In the NH cold season, air masses from Eurasia dominate transport to the MLO as a result of a deepening of the Aleutian Low and intensified midlatitude westerly flow (4). In the NH warm season, the dominant subtropical North Pacific high-pressure system located to the northeast of the MLO leads to short-range transport of air masses to the MLO that originate over or near the North American continent (4). During this season, the MLO receives an approximately equal mix of air masses from both continents with relatively more North American contributions at the peak of the NH growing season (July/August). The MLO is also located in the vicinity of the subsiding branch of the Hadley circulation, rendering it sensitive to interhemispheric mixing.

Several studies have analyzed variability in the MLO CO_2 seasonal cycle to infer the sensitivity of ecosystem dynamics to climate perturbations. The increasing trends in the seasonal amplitude of CO_2 at the MLO and Point Barrow, AK, from the early 1970s to the early 1990s are postulated to be evidence of a temperature-related lengthening of the boreal growing season (1). Reports of a greening trend in the satellite-derived normalized difference vegetation index (NDVI) throughout the 1980s at northern high latitudes consistent with springtime warming provided additional support for this hypothesis (5). The warming trend at northern high latitudes stimulated wintertime respiration as well as summertime photosynthesis, with both contributing to the observed CO_2 amplitude increases (6). In addition to these temperature-based analyses, positive trends in precipitation from 1950 to 1993 over the continental United States have also contributed to higher rates of carbon sequestration (7), consistent with the CO_2 record.

An updated analysis of CO_2 and climate time series reveals a different picture for the recent decade. Even with some interannual fluctuations, the trend in the Mauna Loa seasonal amplitude since the early 1990s has been negative despite the continued warming over northern latitudes (Fig. 1). In addition, prolonged and spatially extensive midlatitude continental droughts (8) and declines in plant growth (9) were observed from 1998 to 2003. An analysis of the CO_2, NDVI, temperature, and precipitation records averaged for the NH shows that since 1994, NH CO_2 uptake in the springtime has been accelerating as a result of warming, whereas net CO_2 uptake in the summer is lower than in the previous decade because of droughts (10). Because there are no continental-scale observations of respiration, the respiratory release of CO_2 is modeled as a function of ambient temperature, soil moisture, and the amount of refractory carbon in litter and soils. Thus, estimates of the net carbon flux (or carbon source/sink) are model-dependent and only weakly constrain explanations of variability and trends in the CO_2 amplitude.

Here we analyze the CO_2 record at a single station, the MLO, to focus on interannual and quasidecadal changes in carbon

Author contributions: W.B. and I.Y.F. designed research; W.B., B.R.L., C.D.K., and A.A. performed research; W.B., J.E.P., and C.J.T. analyzed data; W.B. and I.Y.F. wrote the paper; and J.E.P. and C.J.T. contributed NDVI data.

The authors declare no conflict of interest.

Freely available online through the PNAS open access option.

Abbreviations: MLO, Mauna Loa Observatory; NH, northern hemisphere; NDVI, normalized difference vegetation index; SPI, standardized precipitation index; PDSI, Palmer drought-severity index.

†To whom correspondence may be sent at the present address: Center for Tropical Research, UCLA Institute of the Environment, P.O. Box 951496, Los Angeles, CA 90025-1496. E-mail: buermann@ucla.edu.

§Present address: Department of Atmospheric and Oceanic Sciences and Institute of Geophysics and Planetary Physics, University of California, Los Angeles, CA 90095.

¶Present address: Department of Environmental Sciences and Energy Research, Weizmann Institute of Science, Rehovot 76100, Israel.

**To whom correspondence may be addressed. E-mail: ifung@uclick.berkeley.edu.

This article contains supporting information online at www.pnas.org/cgi/content/full/0611224104/DC1.

© 2007 by The National Academy of Sciences of the USA

ENVIRONMENTAL SCIENCES

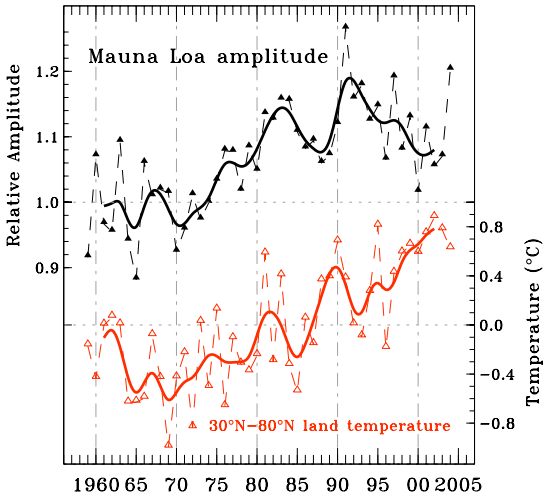

Fig. 1. Time series of the relative amplitude of the seasonal cycle of atmospheric CO_2 at the MLO (black) and anomalies in observed annual land temperatures (red) for the latitudinal band from 30°N to 80°N (except Greenland). Plotted are both annual means (triangles connected by dashed lines) and a smoothed time series based on a five-point binomial filter (thick solid curves). The relative amplitudes are in respect to the mean amplitude of the first 5 yr of CO_2 record (1959–1963). Temperature anomalies are relative to the 1959–2004 study period. For both time series, annual values correspond to the annual tick marks on the time axis.

sources/sinks in North America versus those in Eurasia. The analysis takes advantage of the MLO's changing seasonal footprint from relatively more North American contributions during the NH growing season (May to October) to more Eurasian contributions during the NH cold season (November to April). We present evidence that the observed decline in the MLO seasonal amplitude since the early 1990s is indicative of a slowing North American carbon sink in the growing season as well as changing footprints of atmospheric transport in the cold season. To examine these hypotheses, we analyzed spatial and temporal correlation patterns of the MLO seasonal amplitude time series with gridded fields of the satellite NDVI, land surface temperature, and indices that represent drought as well as outputs from a recent integration of an atmospheric transport model.

Discussion and Summary

The unique location of the MLO in the context of seasonally varying atmospheric circulation allows the separate identification of the variations in North American versus Eurasian carbon sources and sinks. Our analysis of the increasing trend in the MLO amplitude from the early 1970s to the early 1990s extends the analysis of Keeling *et al.* (1) by attributing the photosynthetic drawdown to North America and enhanced cold-season respiration to Eurasia. The time series of the MLO amplitude beyond the early 1990s shows behavior and controls very different from the earlier two decades. Our analysis suggests that throughout the last two decades, the MLO CO_2 seasonal amplitude has recorded a changing North American carbon sink that is dominated by shifts in the North American hydrologic regime rather than by temperature trends. The decline in the MLO amplitude since the early 1990s captures the effects of North American droughts, especially those of 1998–2003, on growing-season carbon uptake on the continent. The amplitude decline is also

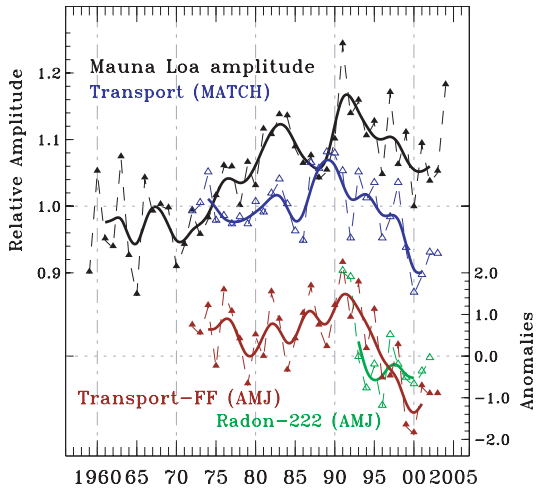

Fig. 5. Time series of observed (black) and simulated (blue) relative amplitude of the seasonal cycle of atmospheric CO_2 at the MLO, and standardized anomalies in mean springtime (April to June) simulated fossil fuel (FF) only (dark red) and observed radon-222 (green) concentrations. Plotted are both annual (dashed) and 5-yr running (thick line) means. Following ref. 4, simulated monthly CO_2 concentrations from the transport-model (MATCH) output correspond to three vertical and nine horizontal grid-point averages centered at the MLO station (155°W, 19°N). For consistency, the seasonal cycle from the monthly MATCH record was extracted with the same curve-fitting algorithm that was used for the observed record (see *Methods*). The observed and simulated relative amplitudes are in respect to the corresponding mean amplitude of the first 5 yr of simulations (1972–1976). Simulated FF and radon anomalies are relative to the 1992–2002 radon record.

attributed to reduced cold-season CO_2 transport from Eurasia in the early 1990s arising from changes in large-scale atmospheric circulation, especially in the NH spring.

Inversion and ecosystem models have inferred significant and variable Eurasian and North American carbon sinks for the past two decades (e.g., refs. 10, 19, and 20). The analysis of the MLO amplitude variations here supports the inversion result of a stronger North American net carbon uptake during 1991–1995 compared with 1988–1990. The MLO amplitude provides little constraint on the inferred Eurasian carbon sink because the MLO does not capture a strong signature of Eurasian net photosynthesis, given that Eurasian-originating air masses arriving at the MLO dominate in the cold season but not the growing season.

With the return of rains to the US in 2004, the MLO amplitude sharply increased, suggesting a return of the North American carbon sink to more normal levels. The latter emphasizes the exquisite sensitivity of the North American terrestrial carbon sink to changes in the hydrologic regime. This work suggests that time-series measurements of atmospheric CO_2 at remote sites can continue to play an important role in documenting changes in land-carbon flux, including those related to widespread drought, which future projections (e.g., refs. 21 and 22) show may continue to worsen as a result of global warming.