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Increases in early season ecosystem uptake explain recent changes in the seasonal cycle of atmospheric CO_2 at high northern latitudes

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Abstract. We report changes in the seasonal cycle of atmospheric CO_2 at high northern latitudes from 1980 to 1997 based on NOAA/CMDL observation stations. Using a combination of biogeochemical and atmospheric modeling approaches, we show that increases in early season net ecosystem uptake explain the recent trends in the seasonal cycle. A strong year-to-year correlation between spring temperatures and early season uptake further suggests that increased photosynthetic activity is the primary mechanism. At the end of the growing season, a strong correlation between fall temperatures and late season releases provides evidence for a large active pool of decomposing soil carbon. Taken together, our results suggest that the seasonal timing of temperature anomalies may have important consequences for the interannual carbon balance of northern ecosystems.

Introduction

Predicting future levels of atmospheric CO_2 and consequently greenhouse warming over the next century requires that we identify the contribution of a number of proposed mechanisms to recent changes in the annual net flux from terrestrial ecosystems, including a lengthening growing season [*Keeling et al.*, 1996; *Myneni et al.*, 1997], CO_2 fertilization [*Lloyd and Farquhar*, 1996], nitrogen deposition [*Holland et al.*, 1997], and forest regrowth [*Houghton*, 1996]. As many of the proposed mechanisms are likely to have distinctly different impacts on the seasonal cycle of net ecosystem production (NEP), information contained in the seasonal cycle of atmospheric CO_2 may allow us to identify the dominant mechanisms operating within individual biomes or continents.

Here we examine the role of a lengthening growing season on the carbon balance of northern ecosystems by analyzing changes in seasonal cycle of atmospheric CO_2 in regions north of 50°N. We focus on high northern latitudes because large seasonal swings in temperature play a critical role in regulating ecosystem processes, and year-to-year changes in temperature have important consequences for ecosystem carbon balance as measured in tree rings and using eddy covariance techniques.

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Seasonal changes in CO_2: 1980-1997

We analyzed CO_2 data from all of the high northern latitude observation stations in the NOAA/CMDL network [*Conway et al.*, 1994] that had a mostly continuous record from 1980 through 1997. Monthly mean CO_2 concentrations from Mould Bay (76°N), Point Barrow (71°N), Ocean Station M (66°N), and Cold Bay (55°N) were filtered to remove the long-term secular trend using a locally weighted regression procedure [*Cleveland et al.*, 1990]. We then calculated linear rates of change (in units of ppm per year) for each month in the combined time series using techniques described by *Randerson et al.* [1997]. Linear rates of change provide a measure of how the shape of the seasonal cycle has changed through time; positive rates indicate an increase in monthly CO_2 concentrations whereas negative rates indicate a decrease [*Manning*, 1993]. Negative change rates for the combined time series during June, July, August, and September indicate that CO_2 concentrations decreased during summer, while positive rates from November to April indicate CO_2 increased during winter and early spring (Figure 1a).

The monthly rates of change and the mean CO_2 values (Figure 1a) were also used to calculate the peak-to-trough amplitude change [*Randerson et al.*, 1997]. The peak to trough amplitude increase for the combined time series from January 1980 to December 1997 was 0.60%/yr ($p < 0.01$) relative to the mean seasonal cycle for this period. While the pattern of negative summer and positive winter CO_2 change rates was observed at other Northern Hemisphere stations further to the south, including Key Biscayne (25°N), Kumukahi (20°N) and Guam (13°N), the standard errors were much greater and the peak-to-trough amplitude increases were not significant at the $p = 0.05$ level.

Changes in high latitude carbon fluxes

Inferring changes in the seasonality of surface fluxes from the CO_2 observations requires knowledge of lags and mixing processes associated with atmospheric transport. Here we used both forward and inverse modeling approaches with two different atmospheric models to estimate changes in the seasonal cycle of surface fluxes. In a series of forward simulations using the Carnegie-Ames-Stanford Approach (CASA) terrestrial biogeochemistry model [*Potter et al.*, 1993] we imposed increases in net primary production (NPP) during distinct seasonal periods. The seasonal NPP increases generated dynamic time series of NEP that were then used to drive the

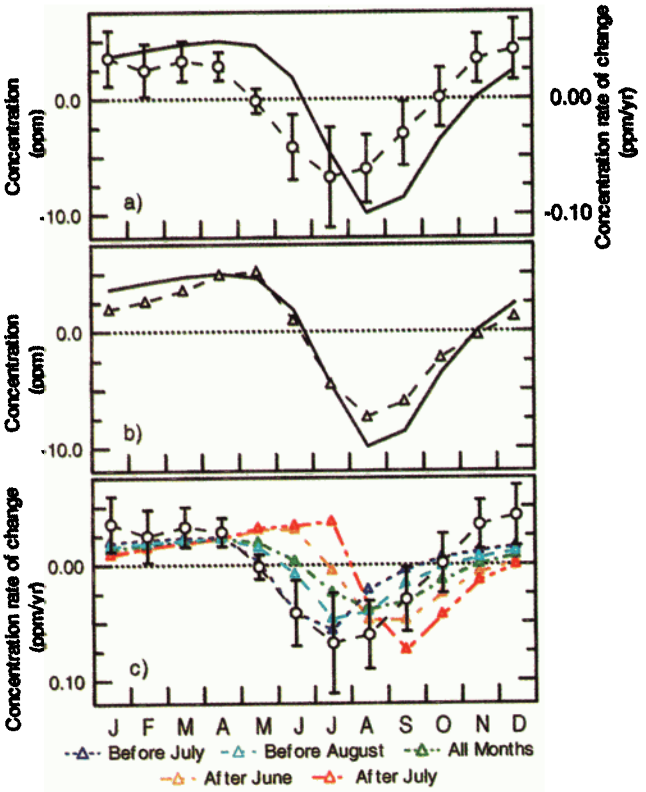

Figure 1. a) The filtered seasonal cycle of CO_2 from 1980 to 1997 averaged for Mould Bay, Point Barrow, Ocean Station M, and Cold Bay stations in the NOAA/CMDL flask network (solid line, left axis). Negative rates of change during the summer and positive rates during the winter and early spring indicate that the peak-to-trough amplitude increased and that the shape of the seasonal cycle changed from 1980 to 1997 (dashed line with circles and standard error bars, right axis). b) Modeled and observed seasonal cycles of atmospheric CO_2 averaged for the high latitude stations described in Figure 1a. The modeled concentrations (dashed line) are from the GISS model driven by NEP fluxes from the control run and ocean exchange, biomass burning, and fossil fuel emissions as described by *Randerson et al.* [1997]. The observed seasonal cycle is the same as Figure 1a (solid line). c) Simulated and observed monthly CO_2 change rates from January 1980 to December 1997 for the high latitude stations described in Figure 1a. Simulated CO_2 change rates from the GISS model are shown for the five CASA model runs in which NPP increased before July (dark blue), before August (light blue), during all months (green), after June (brown), and after July (red). Observations are denoted by the black dashed line with circles and standard error bars (same as Figure 1a).

3-D Goddard Institute for Space Studies (GISS) atmospheric tracer model [*Fung et al.*, 1991]. We compared simulated monthly CO_2 change rates from the GISS model with the observations shown in Figure 1a. Our goal was to identify the time of the year that changing surface fluxes from terrestrial ecosystems most closely reproduced the atmospheric observations.

In four CASA model runs, NPP increases were confined to months before July, before August, after June, and after July (Table 1). Within each of the seasonal periods, NPP increases were distributed monthly in proportion to the steady state seasonal cycle of NPP. In a fifth model run, NPP increased in all months by an amount proportional to the steady state seasonal

Table 1. Summary of the 6 CASA-GISS Model Runs

Model run: Timing of NPP increases	CASA: Linear increase in NPP[1] (r) from 1980 to 1997	CASA: Terrestrial sink in 1997 North of 50°N (Pg C yr^{-1})	GISS: Peak-to-trough CO_2 amplitude increase[2] (% yr^{-1})
Control:	0.00	0.01	0.00
All months:	0.60	0.47	0.47
Before August:	0.60	0.47	0.45
Before July:	0.60	0.47	0.21
After June:	0.60	0.48	0.63
After July:	0.60	0.48	0.56

[1]Annual NPP north of 50°N in each simulated year, t, is described by the following equation: $NPP(t) = NPP_0(1 + rt)$ where NPP_0 is the initial steady state annual NPP at each cell.

[2]NPP increases before July generated the smallest peak-to-trough amplitude increase because the enhanced early season uptake decreased peak CO_2 concentrations during April and May.

cycle of NPP. For the 1980 to 1997 period, we prescribed linear increases in annual NPP at a rate of 0.60%/yr in regions north of 50°N (see Table 1 for the exact equation). All of the simulations had the same increase in annual NPP - we manipulated only the seasonal distribution. In a control simulation, NPP was held constant at 60 Pg C/yr. Each simulation started with carbon pools and carbon fluxes in steady state in 1980 using input data sets described by *Randerson et al* [1997].

At high northern latitudes, the combination of the GISS tracer model and the steady state CASA NEP fluxes captured the phasing of the mean seasonal cycle of CO_2 but underestimated the magnitude by approximately 20% (Figure 1b). In these regions, almost all of the mean seasonal cycle can be attributed to exchange with northern terrestrial ecosystems; contributions from ocean exchange, fossil fuel emissions, and tropical biomass burning are small [*Heimann et al.*, 1998, *Erickson et al.*, 1996].

To reproduce the rapid decrease in monthly CO_2 change rates between April and July observed at the high northern latitude stations, increases in ecosystem uptake are required early in the growing season (Figures 1c). The best fit between observed and modeled change rates occurred when NPP (and ecosystem uptake) increased before the month of July. When NPP increased during the entire year in proportion to the steady state seasonal cycle of NPP, simulated CO_2 change rates lagged behind the observations by two months. Late season NPP increases (and subsequent late season increases in ecosystem uptake) generated monthly CO_2 change rates with even greater lags.

In the inversion analyses, surface fluxes that fit the atmospheric CO_2 time series from 1980 to 1997 were estimated using a 2-D model (latitude, height) of atmospheric transport [*Tans et al.*, 1989]. In one case, only NOAA/CMDL flask stations that were online for most of the 1980 to 1997 period (veteran stations) were used to calculate the time series of surface flux (Figure 2a). In a second case, all of the NOAA/CMDL flask stations that became active at any time during the 1980-1997 period (all stations) were included (Figure 2b). For both cases note that 1) fossil fuel sources were subtracted from the derived fluxes and 2) the fluxes include ocean exchange. Following a similar procedure to the CO_2 concentration analysis, for each seasonal interval of modeled surface flux we estimated the linear rate of change

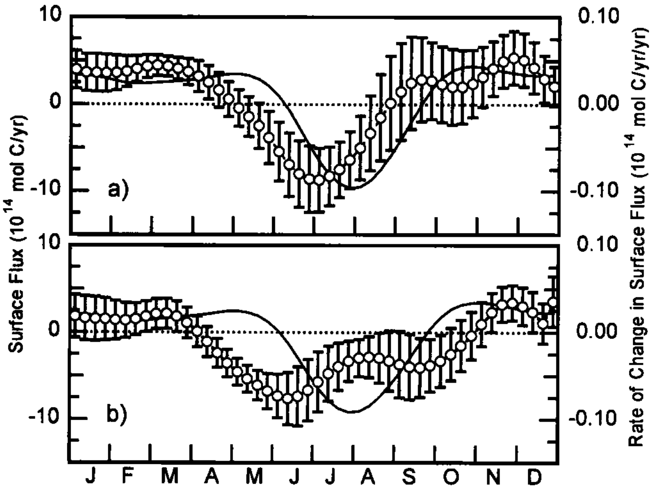

Figure 2. The mean seasonal cycle of surface fluxes (solid line, left axis) and change rates (circles with standard error bars, right axis) from 53°N to 90°N estimated from an atmospheric inversion analysis. a) Only NOAA/CMDL surface stations that were active for most of the 1980-1997 period were included in this analysis. These stations were MBA, BRW, STM, CBA, KEY, KUM, GMI, ASC, SMO, and SPO. b) All NOAA/CMDL surface stations that became active in the 1980-1997 period were included in this analysis. The standard error describes only the interannual variability in fluxes during each of the 48 seasonal intervals.

from 1980 to 1997. For both cases, the most dominant feature of change was an increase in uptake (or a decrease in release) during the first half of the growing season (before August). Surface fluxes changed most rapidly (and had a significant downward trend at the $p < 0.05$ level) during June and July for the veteran stations case and during May and June for the all stations case.

Carbon flux and temperature anomalies

We investigated the effect of interannual temperature anomalies on CO_2 exchange using surface fluxes from the all stations inversion analysis and Global Historical Climatology Network monthly temperature anomalies [*Vose et al.*, 1992]. Fluxes at the start of the growing season show a significant negative correlation with spring temperatures (Figures 3a and 3b). The negative correlation suggests that the increased early season uptake from 1980 to 1997 resulted from increased photosynthesis outpacing ecosystem respiration during spring and early summer. Warmer spring air temperatures would allow higher photosynthetic rates in conifers, permit leaf out to occur at earlier times in deciduous tree species [*Goulden et al.*, 1996], and cause an acceleration of snow melt – allowing photosynthesis to occur in mosses and low stature herbaceous species [*Running et al*, 1999]. Further, much of the soil profile is frozen or at very low temperatures in regions north of 50°N during the spring, limiting the response of the soil microbial community.

In contrast, at the end of the growing season, soil temperatures are high and in permafrost regions, the depth of the thaw is at a maximum. During this period, surface fluxes show a significant positive correlation with temperatures, although there are no long-term trends (Figure 3c). This is consistent with findings by *Goulden et al.* [1998] that document the presence of a large pool of active soil organic matter and peak rates of soil respiration during August and September in a northern black spruce forest. In addition, diminished light levels and photoperiod induction of leaf senescence in deciduous species during the fall may limit the response of photosynthesis to temperature anomalies.

No significant relationship was found between year-to-year carbon balance and the mean annual temperature (Figure 3d). In addition, we found no significant relation between spring

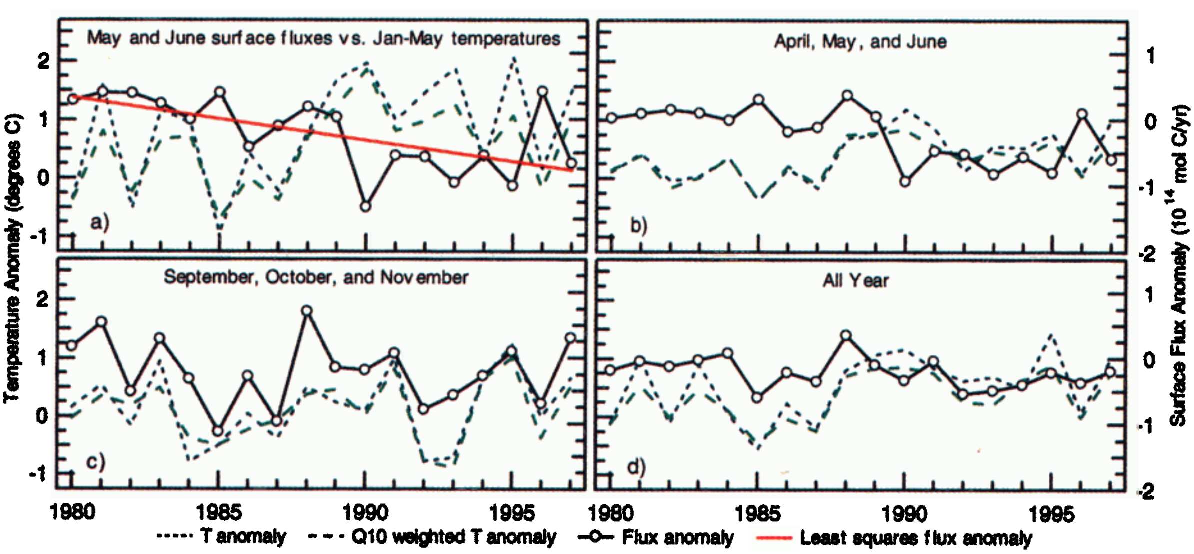

Figure 3. a) Fluxes from the all station inversion analysis during May and June show a significant downward trend from 1980-1997 (red line; F=9.87, p=0.006, df = 16) b) At the beginning of the growing season, fluxes and temperatures are negatively correlated (r = -0.61, p < 0.01; Q10: r = -0.51, p < 0.05). Monthly temperature anomalies were calculated as the average of land temperature anomalies north of 50°N weighted by the spatial distribution of annual NPP from CASA. A second temperature anomaly index was calculated with the additional constraint that temperature anomalies were weighted by a Q10 factor of 2 based on mean monthly temperatures. c) At the end of the growing season, temperature and flux anomalies show a strong positive correlation (r = 0.73, p < 0.01; Q10: r = 0.66, p < 0.01). d) Mean annual temperature anomalies are not significantly correlated with mean annual flux anomalies (r = 0.30, p = 0.23; Q10: r = 0.39, p = 0.11).

temperatures and the mean annual carbon balance or growing season net flux (data not shown). One possibility is that temperature anomalies that cause increased photosynthetic uptake early in the growing season lead to a greater cumulative thaw depth and respiration releases at the end of the season. Another possibility is that the higher temperatures cause greater evaporative demand, water stress, and fires later in the growing season. In either of these cases, the shape of the seasonal cycle of CO_2 would show a large response even though the annual carbon balance would remain largely unchanged.

Discussion and conclusions

On longer (decadal) time scales, other factors besides temperature become critical in regulating in seasonal and annual terrestrial carbon exchange. With increasing levels of disturbance (from fires, insects, and harvesting), the area covered by deciduous shrub and tree species that are abundant in the early stages of secondary succession may be increasing. As deciduous species have a shorter and more intense growing season as compared to evergreen species, the shift in species composition and surface energy balance could also contribute to the observed changes in the seasonal cycle of CO_2 [*Chapin et al.*, 1996; *Zimov et al.*, 1999].

Increases in the peak-to-trough amplitude of the seasonal cycle of CO_2 at high northern latitudes can be generated from increases in ecosystem uptake during the beginning, middle, or end of the growing season (Table 1). Here we demonstrate that it is increased ecosystem uptake during spring and early summer that most closely reproduces the observed changes in the seasonal cycle of CO_2 from 1980 to 1997. Our analyses further suggest that there was no significant extension of the high-latitude growing season during the fall (CO_2 uptake did not increase at the end of the growing season). The strong year-to-year negative correlation between inversion-estimated flux and spring temperature supports previous analyses that implicate spring warming in stimulating photosynthesis in high latitude terrestrial ecosystems [*Keeling et al.*, 1996; *Myneni et al.*, 1997].

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