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Boreal ecosystems sequestered more carbon in warmer years

Jing M. Chen,[1] Baozhang Chen,[1] Kaz Higuchi,[2] Jane Liu,[3] Douglas Chan,[2]
Douglas Worthy,[2] Pieter Tans,[4] and Andy Black[5]

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[1] A 13-year (1990–1996, 1999–2004), hourly air CO_2 record measured on a 40 m tower in northern Canada is analyzed against interpolated marine boundary layer CO_2 data representing the free troposphere above the tower. In warmer years, the planetary boundary layer was more depleted with CO_2, suggesting that the land area (10^3–10^4 km^2) upwind of the tower sequestered more carbon. After using a novel approach to derive the photosynthetic flux from the air CO_2 diurnal variation pattern, it is confirmed that boreal ecosystem photosynthesis increased more than ecosystem respiration in warmer years.

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1. Introduction

[2] Atmospheric measurements, as interpreted using atmospheric transport models [*Tans et al.*, 1990; *Denning et al.*, 1995; *Gurney et al.*, 2002; *Rodenbeck et al.*, 2003] and global carbon budgets based on land use history [*Houghton et al.*, 1999] suggest the existence of a strong carbon sink on land, but the mechanisms are still uncertain [*Pacala et al.*, 2001; *Caspersen et al.*, 2001; *Field and Fung*, 1999]. At high latitudes, the impacts of temperature change on ecosystems are of great concern [*Braswell et al.*, 1997; *Oechel et al.*, 2000]. Greater biospheric activities at higher temperatures were inferred from remote sensing [*Myneni et al.*, 1997] and atmospheric CO_2 measurements [*Keeling et al.*, 1996]. From micrometeorological measurements at the stand level, some studies [e.g., *Goulden et al.*, 1998] found that warming increased carbon release more than uptake in a boreal forest, while others [e.g., *Black et al.*, 2000] showed the opposite. The effect of temperature on the forest carbon cycle is highly variable depending on species, age and stand history [*Chen et al.*, 2003], and the boreal landscape consists of fragmented forest patches of various ages on variable soils and mixed with grassland and tundra due to frequent fire and insect disturbances as well as human activities. How these ecosystems collectively respond to climate change is, therefore, important in understanding the mechanisms controlling regional and global carbon cycles, as boreal forests globally store 13% of carbon in aboveground biomass and 43% in soil organic matter [*Schlesinger*, 1991; *Jarvis et al.*, 2000]. CO_2 fluxes measured on micrometeorological towers in many flux networks worldwide [*Baldocchi et al.*, 2001] have provided useful information on how various ecosystems behave under different climates. However, such towers can only sample a very small fraction of the land surface as each can only represent a footprint area of about 1 km^2. We seek ways to retrieve carbon cycle information from atmospheric CO_2 concentration measurements, which have much larger footprints (10^3–10^4 km^2) [*Lin et al.*, 2003] than flux towers.

2. Data and Site

[3] A 13-year (1990–1996, 1999–2004), hourly averaged air CO_2 concentration record measured on a 40-m tower at Fraserdale, northern Ontario, Canada (49°52′29.9″N, 81°34′12.3″W), is used for this purpose (no data were collected from January 1997 to June 1998). The measurements were made according to the WMO (Global Atmospheric Watch) guidelines, with an accuracy of 0.1 ppm [*Higuchi et al.*, 2003]. Temperature, humidity and wind speed at 20 m and 40 m and precipitation were also measured, allowing for accurate vertical mixing simulations under various atmospheric stability conditions. The interannual variation in air temperature was very similar to that at the weather station Kapuskasing, 87 km southwest of Fraserdale. The Globalview CO_2 matrix data in 41 latitudinal bands based on weekly flask samples in the marine boundary layer (MBL) for the 13 years [*Conway et al.*, 1994] were linearly interpolated to represent CO_2 concentration in the free troposphere (FT) at the site as the top boundary condition of the planetary boundary layer (PBL). According to a Landsat TM image at a 30 m resolution acquired in 1998, the landscape (3600 km^2 around the tower) consists of 66% of black spruce (*Picea mariana*) and Jack pine (*Pinus banksiana*), 20% open land after forest fires and logging, 11% aspen (*Populus tremuloides*) and paper birch (*Betula papyrifera*), and 3% open water. In the prevailing northwest wind direction, the forests are predominantly undisturbed.

3. Modeling Methodology

[4] The diurnal variation in CO_2 concentration above vegetation depends on the magnitudes of nighttime ecosystem respiration and daytime net photosynthesis. Atmospheric diffusion also contributes to the diurnal variation because the strength of vertical mixing varies greatly from nighttime to daytime. For the purpose of retrieving ecosystem information from atmospheric CO_2 data, we used a model to simulate both ecosystem and atmospheric processes. The model consists of two components: (1) Boreal Ecosystem

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[1] Department of Geography, University of Toronto, Canada.
[2] Meteorological Service of Canada, Toronto, Canada.
[3] Department of Physics, University of Toronto, Toronto, Canada.
[4] CMDL/NOAA, Boulder, Colorado, USA.
[5] Department of Soil Science, University of British Columbia, Vancouver, Canada.

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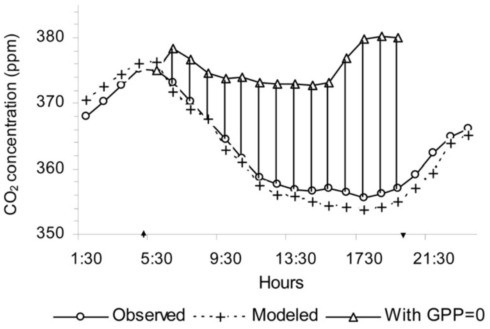

Figure 1. An example of modeled and measured hourly values of atmospheric CO_2 on 11 July 1996 at 40 m at Fraserdale. The agreement indicates that both ecosystem metabolism (photosynthesis and respiration) and atmospheric diffusion are well modeled. A new series is obtained from sunrise to sunset (indicated by triangles) after turning off the gross primary productivity (GPP) in the model. In the absence of GPP, the concentration remained higher than the corresponding measured values. The vertical line is the difference between measured and simulated (with GPP = 0) CO_2, that is, ΔC_i used for estimating the cumulative difference resulting from GPP since sunrise.

Productivity Simulator (BEPS) [*Liu et al.*, 2002], which simulates ecosystem processes including water balance, photosynthesis [*Farquhar et al.*, 1980], and autotrophic and heterotrophic respiration, and radiation and energy balances of the canopy and the soil surface; and (2) the Vertical Diffusion Scheme (VDS) [*Chen et al.*, 2004], which simulates CO_2 diffusion within the planetary boundary layer (PBL) under both stable and unstable atmospheric conditions. The combined BEPS-VDS model simulated well the measured hourly CO_2 concentration at 40 m for the 13 years (r^2 = 0.71, the root mean square error, RMSE, = 5.32 ppm, n = 103858). For 10-day averaged hourly values, the agreement between measurements and the model is significantly improved (r^2 = 0.84, RMSE = 1.06 ppm, n = 11306) as the effects of horizontal advection and infrequent strong vertical diffusion associated with synoptic events become less significant in longer time periods. The 10-day averaged diurnal amplitudes of measured and modeled CO_2 agree very well (r^2 = 0.96) over the 13 years.

[5] In order to gain information on ecosystem behavior, a methodology is developed to separate the effects of atmospheric diffusion and ecosystem metabolism on the CO_2 concentration measurements. Figure 1 shows an example of measured and simulated hourly CO_2 concentrations on a typical day (11 July 1996). The simulated values generally follow closely the measured values in the diurnal cycle. To investigate the effect of daytime photosynthesis on the measured CO_2, we turned off the gross primary productivity (GPP) in BEPS from sunrise to sunset. As shown in Figure 1, the simulated CO_2 with GPP = 0 increases considerably from the measured CO_2. This increase is expected as the carbon uptake by photosynthesis is artificially terminated while the total ecosystem respiration (both heterotrophic and autotrophic) remains unchanged. As atmospheric diffusion is unchanged in both simulations and has the same effect on the measured and modeled CO_2, the difference between the simulated and measured values is therefore solely due to photosynthesis. In this way, the signal of photosynthesis is extracted from the CO_2 time series. Physically, the hourly average difference in CO_2 (ΔC_i, in ppm) between the measured and simulated (with GPP = 0) cases reflects the accumulating reduction of CO_2 by GPP. Assuming that this reduction is uniform in the mixed layer, the simulated mixed layer height (z_i) and the average dry air density (ρ_{air}) can then be used to estimate the time-integrated (since sunrise) GPP per unit surface area as $\Delta C_i \rho_{air} z_i$ (mol m^{-2}). As the air moves across the landscape, this effect of GPP on air CO_2 gradually accumulates. For hour *i* after sunrise, the total accumulated effect is $\Delta C_i \rho_{air} z_i$, and GPP in this hour is ($\Delta C_i\ \rho_{air}\ z_i - \Delta C_{i-1}\ \rho_{air} z_{i-1}$, in mol m^{-2}). The daily total GPP then equals $\sum_{i=SR+1}^{SS} (\Delta C_i z_i - \Delta C_{i-1} z_{i-1})\ \rho_{air}$, where SR is the hour of sunrise and SS is sunset. The accumulation of this photosynthesis effect starts at sunrise and moves with the air from sunrise to sunset, and the tower CO_2 measurements therefore integrate the influence of the land surface of daily air travel length upwind of the tower. This simple methodology makes no assumptions related to horizontal homogeneity. Since no flux measurements were made at the Fraserdale site, this methodology was validated at a tower flux site in a black spruce forest in Saskatchewan, where the upwind area is covered by forests of similar density. Half hourly carbon fluxes in 1999 were converted into GPP using an existing method developed at the Saskatchewan site [*Griffis et al.*, 2003], and the concentration-derived daily GPP was highly correlated with that derived from eddy covariance flux measurements (r^2 = 0.82, RMSE = 0.11 g C m^{-2} d^{-1}, n = 186).

4. Results and Discussion

[6] A simple analysis of the CO_2 record against FT data reveals important temperature- dependent ecosystem signals (Figure 2a): the annual mean difference in CO_2 ($\Delta C_{FT\text{-}PBL}$) between FT and the daily minimum measured at 40 m increased with the annual mean air temperature. The daily minimum CO_2 value represented closely the mean value in the well mixed PBL [*Chen et al.*, 2004, 2005], and the daily $\Delta C_{FT\text{-}PBL}$ resulted from the net difference between gross primary productivity (GPP) in daytime and ecosystem respiration (ER) in both nighttime and daytime, as well as the mixing between FT and PBL [*Bakwin et al.*, 1998]. The increase in the annual mean $\Delta C_{FT\text{-}PBL}$ with temperature suggests that GPP increased considerably faster with temperature than did ER. Daily balloon temperature soundings at Moosonee (200 km N from Faserdale) and Maniwaki (540 km SE) weather stations in the same years were used to determine the very weak correlations between the annual PBL height and the annual mean temperature (r^2 = 0.12 and 0.19, respectively). The PBL height increased 2% and 5% from the coldest to warmest year at these two locations, respectively, and bias estimates in Figure 2a are based on the 5% increase. The difference in the frequency of southerly or northerly airflows was about 4% between two coldest (1992 and 1993) and two warmest (1999 and 2001) years. Since southerly flows had a lower CO_2 concentration than the northerly flows by ~1 ppm in the growing season (largest in the year), the flow direction had

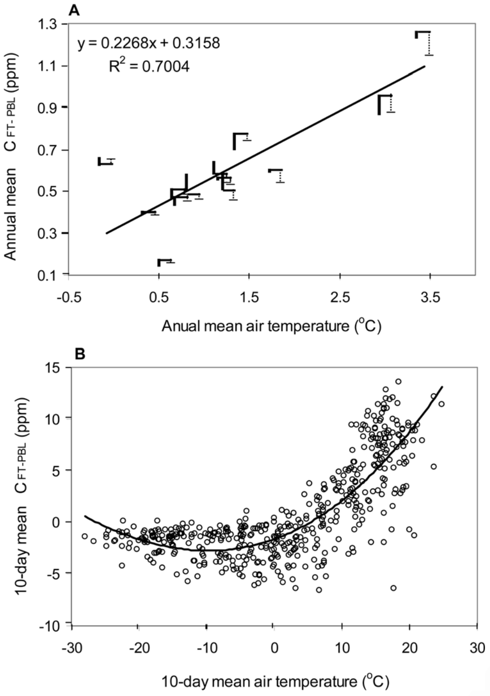

Figure 2. Interannual and seasonal temperature dependencies of atmospheric CO_2 over a boreal region. (a) The annually-averaged difference in CO_2 ($\Delta C_{\text{FT-PBL}}$) between the daily minimum in the planetary boundary layer (PBL) and the free troposphere (FT) increased with air temperature. The vertical bars indicate bias errors due to temperature dependencies of the mixed layer height (left of each data point) and the wind direction (right of each data point). This increase in $\Delta C_{\text{FT-PBL}}$ suggests that the PBL is more depleted with CO_2 in warmer years. The slope of $\Delta C_{\text{FT-PBL}}$ against temperature is highly significant ($p < 0.0008$ in the *t* test). (b) 10-day mean $\Delta C_{\text{FT-PBL}}$ values vs. temperature (T), indicating that in the growing season ($T > 0°C$) an increase in air temperature generally induced an increase in the PBL CO_2 depletion.

small impacts on $\Delta C_{\text{FT-PBL}}$ on a yearly basis depending on the frequency. The total bias error from these two largest sources would only decrease, to the largest extent possible, the slope of $\Delta C_{\text{FT-PBL}}$ against temperature (Figure 2a) by ~15%. The annual mean air pressure and temperature were uncorrelated at Fraserdale for the 13 years and Kapuskasing for 20 years (r^2 = 0.14 and 0.0003, respectively), suggesting that the frequency of low and high pressure systems affecting the vertical mixing regime had only very small interannual variations. The coldest year of 1992 after the Pinatubo volcano eruption is an outlier possibly because of the positive effect of the increased diffuse radiation on photosynthesis. Without the 1992 data point, the r^2 value increases to 0.87.

[7] Seasonal variations in $\Delta C_{\text{FT-PBL}}$ (Figure 2b) reveal the reason for its large temperature sensitivity. In winters, marked by daily mean temperature (T) below −5°C, $\Delta C_{\text{FT-PBL}}$ was negative and decreased slowly with increasing T, indicating a small increase of ER with temperature. At T > °0, $\Delta C_{\text{FT-PBL}}$ increased rapidly, suggesting that the net uptake of CO_2 by the surface, that is GPP-ER, increased rapidly with T. As the T increase in the growing season (May-August) was only slightly less than the annual T increase (65–85%), an increase in the annual T resulted in an increase in the net carbon uptake. The actual amount of the net carbon uptake (in mol C m^{-2} t^{-1}, where t is a time period of interest) equals the change in $\Delta C_{\text{FT-PBL}}$ (in ppm t^{-1} or 44.64×10^{-6} mol C m^{-3} t^{-1} at the sea level and T = 273°K) times the mixed layer height (m). Since the mixed layer height in summers was about 50% higher than that in winters, we expect that the difference in the temperature sensitivity of (GPP − ER) between summers and winters was also about 50% larger than what is indicated as the slope in Figure 2b. This also confirms the importance of the timing of spring warming in ecosystem carbon cycling.

[8] Using the methodology described in Section 2, daily GPP values are derived and summed to annual values. A strong linear relationship is found between the annual concentration-derived GPP and annual mean air temperature (r^2 = 0.71, or 0.69 for active growing season mean temperature) (Figure 3). Other meteorological factors were weakly correlated with GPP (r^2 = 0.04 and 0.13 for precipitation and radiation, respectively). The ratio of annual evapotranspiration modeled by BEPS to precipitation ranged from 0.40 to 0.73 in these 13 years, suggesting that water was not a limiting factor for growth in this area. Also shown in Figure 3 is the annual ER modeled with consideration of both temperature and moisture effects [*Lloyd and Taylor*, 1994; *Potter*, 1997] using a multiple layer soil model. The actual modeled ER has an equivalent Q_{10} value of 2.4 because of the increase in the active layer in summers. The ER modeling is constrained (to <4%) by the CO_2 concentration measurements, as the nighttime CO_2 increase to the maximum was highly sensitive to ER, especially in calm nights with a large T inversion, when a 4% increase in ER caused a 1.0 ppm increase in modeled CO_2 concentration at 40 m. An optimization method was used to find ER model parameters that produce the minimum RMSE between modeled and measured CO_2 at 40 m. Consistent with the finding that the net uptake of CO_2 by ecosystems increased with T (Figure 2), the concentration-derived GPP had a larger T sensitivity than that of ER (Figure 3).

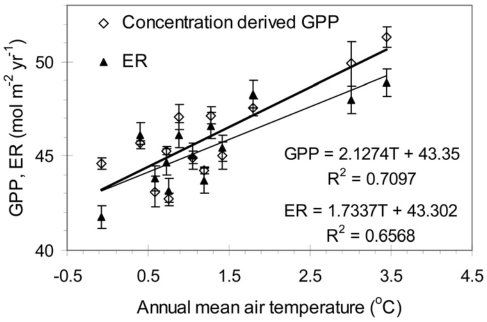

Figure 3. Sensitivities of gross primary productivity (GPP) and ecosystem respiration (ER) to temperature in boreal ecosystems. The vertical bars indicate their errors. The concentration-derived GPP increased more with temperature than did ER, providing a reason for the larger PBL CO_2 depletion in warmer years (Figure 2). The standard error in the slope against temperature is 0.1184 and 0.1091 mol $m^{-2}y^{-1}°C^{-1}$ for GPP and ER, respectively, and these two slopes are significantly different in the *t* test ($p < 0.017$).

[9] We used the same model to explore the possible reasons for the difference in the T sensitivity between GPP and ER. The large T sensitivity of GPP shown in Figure 3 could not be captured by the model (r^2 = 0.54, RMSE = 20.5 g C $m^{-2}y^{-1}$) when the nutrient availability was kept constant, but was well simulated (r^2 = 0.79, RMSE = 8.3 g C $m^{-2}y^{-1}$) when coupled carbon (C) and nitrogen (N) dynamics in soil and vegetation were included [*Chen et al.*, 2003] based on C:N ratios of vegetation and soil [*Dickinson et al.*, 2002].. At higher T, the decomposition of soil organic matter is faster, producing more mineralized N available for immediate uptake by plant roots [*Braswell et al.*, 1997; *Jarvis et al.*, 2000]. As boreal ecosystems are nutrient limited and plant growth is sensitive to the amount of available nitrogen, more mineralized N at higher T leads to higher productivity. These model experiments, though explorative, suggest that nutrient conditions in the soil played an important role in the response of boreal ecosystems to T changes [*Jarvis et al.*, 2000], in agreement with N mineralization data from a 10-year soil heating experiment in a temperate forest [*Melillo et al.*, 2002]. Our result is in general agreement with the finding from a 5-year, 5°C soil warming experiment inducing an accumulated increase of about 80% in growth in a boreal forest [*Jarvis et al.*, 2000]. This suggests that in global carbon cycle modeling, it is important to consider coupled carbon and nutrient dynamics.

[10] The retrieved GPP and ER values constrained by the concentration measurements suggest that boreal ecosystems in the vicinity of the Fraserdale tower were collectively a carbon sink of 10.8 ± 14.2 g C m^{-2} y^{-1} in these 13 years, which is in agreement with previous work based on remote sensing [*Chen et al.*, 2003]. However, the uncertainties in the absolute values of GPP and ER are still of the same order of magnitude as the difference between them. As the record gets longer, these uncertainties would become smaller. Tower flux measurements allow immediate assessments of carbon balance within a small footprint, while concentration measurements can provide reliable information on the ecosystem response to climate change for much larger areas. The fact that the temperature sensitivity of GPP is larger than that of ER suggests that global warming could lead to increased carbon sequestration in boreal ecosystems.

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A. Black, Department of Soil Science, University of British Columbia, MCML 129 - 2357 Main Mall, Vancouver, BC, Canada V6T 1Z4.

D. Chan, K. Higuchi, and D. Worthy, Meteorological Service of Canada, 4905 Dufferin Street Downsview, Toronto, ON, Canada M3H 5T4.

B. Chen and J. M. Chen, Department of Geography, University of Toronto, 100 St. George St., Room 5047, Toronto, ON, Canada M5S 3G3. (chenj@geog.utoronto.ca)

J. Liu, Department of Physics, University of Toronto, 60 St. George St., Toronto, ON, Canada M5S 1A7.

P. Tans, CMDL/NOAA, 325 Broadway R/GMD1, Boulder, CO 80305–3328, USA.