Carbon dioxide sources from Alaska driven by increasing early winter respiration from Arctic tundra

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High-latitude ecosystems have the capacity to release large amounts of carbon dioxide (CO2) to the atmosphere in response to increasing temperatures, representing a potentially significant positive feedback within the climate system. Here, we combine aircraft and tower observations of atmospheric CO2 with remote sensing data and meteorological products to derive temporally and spatially resolved year-round CO2 fluxes across Alaska during 2012–2014. We find that tundra ecosystems were a net source of CO2 to the atmosphere annually, with especially high rates of respiration during early winter (October through December). Long-term records at Barrow, AK, suggest that CO2 emission rates from North Slope tundra have increased during the October through December period by 73% ± 11% since 1975, and are correlated with rising summer temperatures. Together, these results imply increasing early winter respiration and net annual emission of CO2 in Alaska, in response to climate warming. Our results provide evidence that the decadal-scale increase in the amplitude of the CO2 seasonal cycle may be linked with increasing biogenic emissions in the Arctic, following the growing season. Early winter respiration was not well simulated by the Earth System Models used to forecast future carbon fluxes in recent climate assessments. Therefore, these assessments may underestimate the carbon release from Arctic soils in response to a warming climate.

Significance

Rising arctic temperatures could mobilize reservoirs of soil organic carbon trapped in permafrost. We present the first quantitative evidence for large, regional-scale early winter respiration flux, which more than offsets carbon uptake in summer in the Arctic. Data from the National Oceanic and Atmospheric Administration’s Barrow station indicate that October through December emissions of CO2 from surrounding tundra increased by 73% since 1975, supporting the view that rising temperatures have made Arctic ecosystems a net source of CO2. It has been known for over 50 y that tundra soil remains unfrozen and biologically active in early winter, yet many Earth System Models do not correctly represent this phenomenon or the associated CO2 emissions, and hence they underestimate current, and likely future, CO2 emissions under climate change.


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Data deposition: The data reported in this paper are available at the following links: regional gridded CO2 fluxes, doi: 10.3334/ORNLDAAC/1318; CARVE aircraft CO2 data, doi: 10.3334/ORNLDAAC/1402; VRPM-5P data, doi: 10.3334/ORNLDAAC/1314; CRV tower CO2 data, doi: 10.3334/ORNLDAAC/1316; and BRW tower CO2 data, doi: 10.7289/V5RRWV68.

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whereas a study of eddy flux towers in tundra ecosystems across the Arctic calculated highly variable carbon sources (18).

In this paper, we present a three-part synthesis to assess carbon fluxes and carbon–climate feedbacks in arctic and boreal Alaska. (i) We combine recent in situ ceilometer and tower CO₂ observations, eddy covariance flux data, satellite remote sensing measurements, and meteorological drivers to estimate regional fluxes of CO₂. By taking advantage of the spatially integrative properties of the lower atmosphere, we use CO₂ mole fraction data to constrain spatially explicit, temporally resolved CO₂ flux distributions across Alaska during 2012–2014. We compute the annual carbon budget for Alaska, partitioned by season, ecosystem type, and source type (biogenic, pyrogenic, and anthropogenic, Figs. 1 and 2). (ii) We analyze the 40-y record of hourly atmospheric CO₂ measurements from the land sector at Barrow, AK [BRW tower, operated by the National Oceanic and Atmospheric Administration (NOAA)], to place recent regional carbon fluxes in a historical context. (iii) We evaluate the Alaskan CO₂ flux simulated by a representative set of Earth System Models (ESMs) against our CO₂ fluxes for Alaska in 2012–2014. We compute the annual carbon budget for Alaska, partitioned by season, ecosystem type, and source type (biogenic, pyrogenic, and anthropogenic, Figs. 1 and 2). We obtained modeled column CO₂ enhancements by convolving the land surface influence functions with diurnally resolved surface CO₂ fluxes on each of the 231 vertical profiles collected on the CARVE flights. We used statistical properties of the inputs to the GIM to constrain a model of the flux correction by combining a linear model of predictors and a random component. Our GIM framework ensures an unbiased model of the flux correction under the assumption that all other errors (errors in the background concentration, transport model, etc.) are random and have a mean of zero. Uncertainties in our GIM (shaded uncertainty bounds in Fig. 1) were quantified using restricted maximum likelihood estimation (ReML). ReML uses statistical properties of the inputs to the GIM to constrain a model of the uncertainty. Our model does not account for systematic errors or bias in the background concentration, transport model, or sampling bias, although our model and observations were carefully chosen to minimize the effects of any bias.

Adjustments to the PVPRM-SIF flux estimates were generally small, less than ±1.5 μmol·m⁻²·s⁻¹ for most regions and measurement periods. Large positive adjustments were needed, however, in early winter (September through November) of 2013, indicating considerably higher respiration rates than prior estimates from PVPRM-SIF. We linearly interpolated the additive flux corrections between aircraft measurement periods and used the PVPRM-SIF fluxes for late winter (January through April) to obtain regional-scale CO₂ fluxes for Alaska during 2012–2014 (Si Appendix, Fig. S9). We independently confirmed the accuracy of these late winter fluxes by comparing year-round predicted CO₂ enhancements with observations at tower
sites in Alaska (24) (SI Appendix, Validation of Regional CO2 Fluxes Using Tower Data and Fig. S10).

**Long-Term CO2 Data.** The BRW tower, located just outside Barrow, AK [71.323°N, 156.611°W, ground elevation 11 m above sea level (masl)], is a 16.46-m tower operated by NOAA since 1973 (25), with consistent continuous CO2 data available from 1975 onward (SI Appendix, Long-Term BRW CO2 Observations and Fig. S11). The tower is located within the footprint of the CARVE flights and provides a long-term context for the aircraft observations. We calculated the CO2 land influence as the difference between the ocean and land sector CO2 data (dCO2) (ref. 26 and SI Appendix, Fig. S12). We calculated the monthly mean dCO2 for early winter months (September through December) in each 11-y time interval (SI Appendix, Fig. S13) and, using the years with data in each month, calculated the 95% confidence interval for the change in dCO2 over October through December between 1975 and 1989 and between 2004 and 2015 (Fig. 3). Results were indistinguishable using alternative statistical approaches, including linear regressions or locally weighted least squares (“loess”) assessment of the time series of fall observations. We used the CARVE flux calculations to infer the magnitude of the change in early winter CO2 flux corresponding to the change in dCO2 from land emission on the North Slope surrounding BRW. The largest unaccounted uncertainties in the BRW tower analysis include the potential for systematic shifts in the circulation patterns in the region between 1979 and 2014, or changes in the surrounding environment of the tower. We performed comprehensive tests for these possible effects, and found no evidence for systematic changes in either, as discussed in SI Appendix, Long-Term BRW CO2 Observations.

**Earth System Models.** We examined the Alaskan CO2 fluxes from ESM simulations contributed to the Coupled Model Intercomparison Project Phase 5 (CMIP5) (27), a community modeling effort designed to support the Intergovernmental Panel on Climate Change (IPCC) Fifth Assessment Report scientific assessment (SI Appendix, Coupled Model Intercomparison Project 5 and Fig. S14). We analyzed future ESM projections forced with Representative Concentration Pathway 8.5 atmospheric CO2 mole fractions, and extracted time series from 2006 through 2014, when fossil fuel emissions, CO2 concentrations, and ambient climate closely matched observations (28). The models reported simulated monthly mean CO2 fluxes (net ecosystem exchange) at each grid cell. We extracted fluxes from each model for the same Alaskan domain used in our inversion of the aircraft observations (58°N to 72°N, 140°W to 170°W).

**Results and Discussion**

**Biogenic Carbon Fluxes Across Alaska.** We inferred a net source of biogenic CO2 from Alaska for the years 2013 and 2014, whereas 2012 was nearly CO2 neutral (Figs. 1 and 2 and SI Appendix, Total Alaskan CO2 Flux and Table S1). The PVPRM-SIF fluxes (when convolved with the transport model) captured much of the observed diurnal, seasonal, and interannual variability in column CO2 observations across the 3 y (SI Appendix, Fig. S5). Sunlight and air temperature, which generated the diurnal variability of the PVPRM-SIF CO2 fluxes, were key drivers of the highly variable summer CO2 uptake in Alaska.

Uncertainties were larger for individual subregions, but basic patterns clearly emerge. Tundra regions on the North Slope (NS tundra) and in the Yukon–Kuskokwim Delta of south-west Alaska and the Seward Peninsula to the west (SW tundra) were consistently, and statistically significant, net sources of CO2 (Fig. 2 and SI Appendix, Table S1). Losses of CO2 from the NS tundra were nearly 3 times greater in 2013 and 2014 than in 2012. The mean net CO2 source from SW tundra in 2012–2014 was similar to the NS tundra, but the SW tundra yearly variations were different, with a large source in 2013, smaller in 2014, and smallest in 2012 (Fig. 1). The source of CO2 from NS tundra is consistent with the CO2 budget calculated from the sparse eddy flux measurements for the region (29–32). There were no year-round CO2 flux measurements in the SW tundra region to help confirm our airborne estimates.

The boreal forest ecoregion was a net CO2 sink in all years, neglecting biomass burning (Figs. 1 and 2 and SI Appendix, Table S1). Carbon uptake by boreal forests was smaller in 2013 than in other years, when the climate was warmer and drier. There was less CO2 respiration during the early winter periods of 2014, possibly due to high June through August precipitation and cooler temperatures; long-term measurements of CO2 fluxes have shown that water-saturated soils exhibit lower rates of soil respiration in boreal forests (33–35). The remaining 18% of Alaskan land surface (here called the “Mixed” area), which includes coastal plains, mountainous areas, and areas that cannot be classified as mostly forest or tundra, was a net source of carbon each year.

Net carbon uptake started 6 d to 16 d earlier in Alaskan boreal forests than in the NS tundra regions, depending on the year (Fig. 1). In tundra, uptake is delayed for some time after snow melts and ecosystem greenness increases, whereas evergreen trees may begin to take up CO2 when air temperatures rise above freezing.
Biomass burning emissions of CO2 were highly variable across source of carbon to the atmosphere: 67.8 (40.3, 94.6) TgC in 2012. In 2013, and to a lesser extent in 2014, the biogenic land sector dCO2 increased by 73.4% averaged over early winter (October through December) in 2012, resulting in a large net increase by 73.4% during the 41-y of the record (1975–2015; Fig. 3 and SI Appendix, Fig. S13). The land sector respiration signal was strongly correlated with the nighttime air temperature of the previous summer (r² = 0.95), a measure of the temperature at the air–soil interface and an indicator of the amount of heat that will be trapped under the snow during early winter. Long-term records of soil temperature within permafrost increased by nearly 2 °C at a depth of 10 m near Barrow since 1950 (37).

Using the CARVE flux estimation framework (SI Appendix, Framework to Predict Integrated CO2 Column), we calculated that the observed dCO2 increase corresponded to a comparable increase in the early winter CO2 flux over the 41-y record (Fig. 3). Emissions of CO2 in early winter lag the uptake in the growing season by 3 mo to 4 mo, and hence this increase in emissions very likely contributed to the increase of the seasonal amplitude of regional CO2 concentrations observed since 1960 (38).

The occurrence of early winter respiration in arctic ecosystems has been known for nearly 50 y (39–42). Early flux studies at tundra sites on the North Slope hinted that cold season CO2 respiration might offset increases in summer uptake with warming (30), and recent studies show large early winter respiration at some tundra sites (31). However, cold season CO2 respiration has not previously been quantified at regional scales. The extended respiration during early winter is likely linked to continuing microbial oxidation of soil organic matter during the “zero curtain” period, the extended interval when soil temperatures in the active layer are poised near 0 °C and some water is still liquid (9). Complete freezing of soils in the fall is delayed by release of latent heat, dissolved solutes, and insulation of the soil by overlying snow (27). The length of the zero curtain period appears to be increasing with warming temperatures, with the duration at some sites now reaching up to 100 d (9). From our results, we expect a warming climate and extended zero curtain periods to drive larger biogenic emissions and further increase early winter respiration in the future.

Carbon Fluxes from ESMs. To create realistic projections of future climate, we must have a robust understanding of the current...
carbon budget simulated by ESMs that are widely used to assess carbon–climate feedbacks. We compared our regional flux observations (43) to the carbon fluxes for Alaska reported by 11 ESMs used in CMIP5 (used by the IPCC) (SI Appendix, Coupled Model Intercomparison Project 5). These models generally predict the start of growing season earlier than observed, and most underestimate the high respiration rates in early winter (SI Appendix, Table S2). Consequently, 8 of 11 model simulations inaccurately predict both the seasonal amplitude of CO2 fluxes and the net annual CO2 flux (Fig. 4A). Only 3 of the 11 CMIP5 models captured the growing season fluxes relatively well, and even those models predicted the annual net CO2 flux as more negative (too much uptake) than observations (Fig. 4B). The most realistic model (MIROC-ESM-CHEM) correctly predicts an annual net source of CO2, but with the growing season shifted a month too early (Fig. 4C).

The amplitude of the CO2 seasonal cycle at high latitudes has increased over the past 50 y (44), a striking indication of significant changes in the carbon cycle. In recent literature, there is considerable debate whether this change arises from increased vegetative uptake (e.g., refs. 44–46), which would enhance carbon sequestration in the region, or increased rates of respiration (1, 2), driving the release of soil organic matter and net emission of carbon. Unequal changes in the timing or magnitude of peak photosynthesis or respiration will also affect the amplitude of the CO2 seasonal cycle. Also, increased photosynthetic uptake in spring could lead to increased respiration in early winter using recent labile organic matter (e.g., refs. 2 and 47), with no effect on net annual carbon sequestration.

Many of the assessments of the changing CO2 seasonal amplitude are based on model simulations that appear not to capture the magnitude or trends in late season respiration, and, indeed, may predict an annual net sink for CO2 in Alaska where we observed net emissions. Our results suggest the need to reevaluate this work. The regional fluxes we infer show the importance of early winter fluxes, and the long-term CO2 data from the BRW tower indicate that early winter respiration rates have increased considerably over the past 41 y. These results imply that carbon release from organic matter may make a more important contribution to trends in the CO2 seasonal amplitude than expected from model simulations that may not capture the late season respiration correctly.

Conclusions

We find that Alaska, overall, was a net source of carbon to the atmosphere during 2012–2014, when net emissions from tundra ecosystems overwhelmed a small net uptake from boreal forest ecosystems. Both ecosystems emitted large amounts of carbon in early winter. Our results suggest that October through December respiration has increased by about 73% over the past 41 y from organic carbon-rich soils on the North Slope of Alaska, correlated with increasing air temperatures. The ESMs used to forecast future carbon fluxes in the CMIP5 and IPCC studies did not represent early winter respiration, especially when soil temperatures hover near 0 °C. Hence these assessments may underestimate the carbon release from arctic soils in response to warming climate.

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Fig. 4. CMIP5 ESM behavior compared with the monthly mean optimized CO2 flux from our analysis. (A) Growing season net CO2 flux (in teragrams of carbon per year) against the CO2 flux seasonal amplitude (in teragrams of carbon per year) indicate three model groupings. (B) Annual net CO2 flux (in teragrams of carbon per year) against early winter (September through December) CO2 flux. The arrow indicates the early winter flux of the GFDD-ESM2G model (annual net flux is ~328 Tg C yr−1). (C) Time series of CO2 flux for the model with the closest matching carbon fluxes in A and B (MIROC-ESM-CHEM) and the aircraft optimized CO2 flux. The modeled peak carbon uptake in summer is too large and a month too early compared with the aircraft optimized CO2 flux. Negative fluxes represent uptake by the biosphere.

Commare et al.


