Biogeosciences Discuss., doi:10.5194/bg-2017-172, 2017
Manuscript under review for journal Biogeosciences
Discussion started: 29 May 2017
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Explaining CO_2 fluctuations observed in snowpacks

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Abstract. Winter soil carbon dioxide (CO_2) respiration is a significant and understudied component of the global carbon (C) cycle. Datasets have shown that winter soil CO_2 fluxes can be surprisingly variable, owing to physical factors such as snowpack properties and wind. This study aimed to: quantify the effects of advective transport of CO_2 in soil-snow systems on the sub-diurnal to diurnal (hours to days) timescale, use an enhanced diffusion model to replicate the effects of CO_2 concentration depletions from persistent winds, and use a model-measure pairing to effectively explore what is happening in the field. We took continuous measurements of CO_2 concentration gradients and meteorological data at a site in the Cape Breton Highlands of Nova Scotia, Canada to determine the relationship between wind speeds and CO_2 levels in snowpacks. We adapted a soil CO_2 diffusion model for the soil-snow system, and simulated stepwise changes in transport rate over a broad range of plausible synthetic cases. The goal was to mimic the changes we observed in CO_2 snowpack concentration to help elucidate the mechanisms (diffusion, advection) responsible for observed variations. On sub-diurnal to diurnal timescales with varying winds and constant snow levels, a strong negative relationship between wind speed and CO_2 concentration within the snowpack was often identified. Modelling clearly demonstrated that diffusion alone was unable to replicate the high frequency CO_2 fluctuations, but simulations using above-atmospheric snowpack diffusivities (simulating advective transport within the snowpack) reproduced snow CO_2 changes of the observed magnitude and speed. This confirmed that wind-induced ventilation contributed to episodic pulsed emissions from the snow surface and to suppressed snowpack concentrations. This study improves our understanding of winter CO_2 dynamics to aid in continued quantification of the annual global C cycle, and demonstrates a preference for continuous wintertime CO_2 flux measurement systems.

1 Introduction

Organic C reserves of high latitude soil are disproportionately affected by anthropogenic climate change. With the global soil C pool storing three times the amount of C of the atmosphere (IPCC, 2013), careful assessment of the soil C pool is critical for understanding the future global C cycle.

Cold and wet conditions pose challenges for measuring wintertime CO_2 fluxes (Liptzin et al., 2009), and overall, studies tend to neglect ecosystem respiration when soils are snow covered or when soil temperatures drop below freezing. Despite this skewed focus, soil CO_2 is still exchanged throughout the winter, even at -5°C to -7°C (Flanagan and Bunnell, 1980; Coxson and Parkinson, 1987; Brooks et al., 1996). In some cases, an insulating snowpack can also protect soils from freezing completely. Even with the observed decrease in Northern Hemisphere snow cover since the 1950s as a result of climate change

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(IPCC, 2013), snow covers 44–53% of Northern Hemisphere land area during winter months (Barry, 1992). Therefore, because winter soil CO_2 measurements are important for accurate estimates of annual CO_2 soil respiration, current rates are likely underestimated.

Measurement frequencies of wintertime CO_2 fluxes in past studies have ranged widely, from only twice per winter, to half-hourly (Liptzin et al., 2009). Measurements of wintertime CO_2 fluxes recorded at a higher frequency (half-hourly) have shown that wintertime CO_2 fluxes can be surprisingly variable. Higher-resolution studies have shown that these variations depend less on microbial variation, and more on transport of CO_2 (Bowling et al., 2009; Seok et al., 2009). For example, Seok et al. (2009) observed patterns of high temporal variability in wintertime subniveal CO_2 flux, ranging from 0 µmol $m^{-2}s^{-1}$ to 1.2 µmol $m^{-2}s^{-1}$ during a period of relatively steady soil conditions below 0°C. Advective transport does not increase production of CO_2 in soils, but changes the rate of transport (Bowling and Massman, 2011). This variability presents a problem, because it obfuscates any biological sensitivity to environmental drivers. Under what conditions does the soil microbial community thrive over-winter? This is difficult to determine if observed variations are caused by abiotic factors.

Transport of this CO_2 out of soils into the overlying media, whether snow or open air, is driven by two main mechanisms: diffusion and advection (also known as bulk flow or mass flow) (Janssens et al., 2001). The mode of gas transport through snowpacks affects the timing and magnitude of CO_2 release to the atmosphere, and will potentially create significant lags between the times of CO_2 production and emission. Under calm conditions, it is generally accepted that trace gases are transported out of soils and through snowpacks into the overlying atmosphere via diffusion (Bowling and Massman, 2011). Explained by Fick's first law, the background theory assumes that trace gas transport out of soils or through a snowpack occurs vertically, with fluxes determined by the concentration gradient (Seok et al., 2009). Wind affects trace gases such as CO_2 through porous media like soil and snow (Kelley et al., 1968). Studies are increasingly showing that non-diffusive (advective) mass transport through snow is significant, and must therefore be taken into consideration (Bowling and Massman, 2011). Advective transport of traces gases through naturally permeable media such as soil and snow occurs due to variations in atmospheric pressure at the surface. These natural advective flows are ubiquitous. Bowling and Massman (2011) make it clear that wind pumping in the snowpack enhances outward rates of transport. They measured slower bulk air velocities in snow, which fell within the range of 10^{-3} to 10^{-2} m s^{-1}, implying that the contribution of advection to trace gas transport through snowpacks was smaller than that of diffusion. The net combined effect of advective and diffusive transport in snow environments on CO_2 and other trace gas transport is considered to be an enhancement to diffusive transport. Modelling results from Massman et al. (1997) indicate that advective transport can either enhance or diminish fluxes by a wide range of 1.5% to 25%, indicating that further studies with field experiment components are required. A more recent study by Bowling and Massman (2011) found enhanced transport of CO_2 beyond diffusive transport by up to 40% in the short term, and 8% to 11% when considering the snow-covered season as a whole.

In this study we aimed to quantify the effects of advective transport of CO_2 in soil-snow systems on the sub-diurnal to diurnal (hours to days) timescale, and to mechanistically describe these behaviours using a 1-dimensional advective-diffusive model adapted for the soil-snow-atmosphere system.

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2 Methods

2.1 Continuous automated field monitoring

The primary motivation for establishing these field stations was to determine the relationship between wind speed, snowpack ventilation, and snowpack CO_2 concentration. The site selected is on a plateau in a recovering boreal system at North Mountain, Nova Scotia, Canada in the Cape Breton Highlands National Park. Wintertime snow patterns at North Mountain allow for snowpacks of up to 3 m, with the last of the snow melting in May or June, depending on the timing and amount of snow in a given year. Average annual air temperature at North Mountain is 5.1°C (1999-2013). Average winter air temperature is -6.1°C (January–March, 1999–2013). An insulating snowpack is often established before soils have a chance to freeze completely. Therefore, soils often remain above 0°C throughout each winter, and overwinter CO_2 production from these soils is very likely. Average annual wind speed is 17.3 km h^{-1}, with highest wind speeds in the winter (20.7 km h^{-1}, January–March, 1999–2013). Obviously, gusts greatly exceed these mean values. High winds and variable meteorological conditions create varying snow depths within close proximity (tens to hundreds of m).

Two measurement stations were installed 60 m apart at North Mountain in the winter of 2014. The sites are referred to as NM1 (North Mountain 1: 46°49'7.41" N, 60°40'20.16" W) and NM2 (North Mountain 2: 46°49'9.15" N, 60°40'18.67" W). The key environmental difference between the two sites was the predictably differing snow depth. At each of the two stations, CO_2 concentration through the snow profile was measured at three depths (0, 50, and 125 cm from the soil surface) using Vaisala CARBOCAP® Carbon Dioxide Probe GMP343 sensors. A Campbell Scientific CR3000 datalogger was used at NM1, and a Campbell Scientific CR1000 datalogger was used at NM2 to control the instrumentation, recording values every 30 minutes and storing the values in the logger memory. To save power and to minimize potential heating impacts, the GMP343 sensors were turned on for 10 minutes preceding measurement, a measurement was taken averaged over 1 minute, and then the sensors were turned off for the remainder of the 30 minute interval. Optics heaters of the GMP343 sensors were kept off entirely, as there was a very limited risk of condensation formation in the relatively constant temperature environment of a snowpack. This further reduced potential sensor heat from < 3.5 W (optics heaters on) to < 1 W (optics heaters off). Together, turning the GMP343 sensors off regularly and keeping the optics heaters off at all times minimized any small potential heating impacts of the sensors. Data was collected from the dataloggers at the end of the winter. One BP Solar 50 W solar panel and one Discover D12550 12 V battery was used to power each of the two stations. Snow depth was measured at both stations using SR50A Sonic Ranging Campbell Scientific sensors. A Young Wind Monitor (Model 05103) anemometer measured wind speed at NM1. Figure 1 gives the general structure of these stations.

Measurements recorded at NM2 include CO_2 concentration at 5 cm soil depth, at the soil surface, and at 25 cm, 50 cm, 75 cm, and 100 cm above the soil surface (in the snowpack). We also recorded ambient air CO_2 concentration, wind speed, and snow depth. Measurement recording frequency for all measurements was hourly for this field campaign. In winter 2015, improvements were made to the NM2 station by adding additional CO_2 measurements through the profile. These were done using two Eosense eosGP sensors, with a pumped system extracting snow air samples from 550 mL gas permeable waterproof sampling volumes at hourly frequency.

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2.2 Field data analysis

In order to examine the degree of concentration decrease after wind ventilation started, we attempted to focus on periods in which the likelihood of steady state gas transport was maximized. We extracted data for time periods during which snow depth had not changed more than several cm in the previous 3 days, meaning that there had been no melt or appreciable new snow. We conducted regression analyses of CO_2 concentration at the three depths and the corresponding wind speeds during these steady-state periods. The ideal situation was satisfied when winds increased slowly, then abated several hours later. In order to reduce to data for which we understood that characteristic response patterns of concentration depletion with increasing wind were present, data were further filtered to satisfy the following conditions: 1) the relationship produced a slope < 0, i.e. there was a negative relationship between the two variables, and 2) $R^2 \geq 0.1$. Any relationships that had a strength of $<$ 0.1 were discarded to eliminate weak relationships that may have occurred due to highly turbulent winds, overly short-term winds, overly persistent winds, or other mechanisms that would have resulted in significant complexity. Mean R^2 values were then calculated, divided by site (NM1 and NM2) and height within snowpack (0, 50, and 125 cm). While these criteria seem demanding, in practice they were less restrictive than one might expect, and nearly one-third of all the measured data passed these filters and were included in the final analysis.

We inspected the enhanced concentration profile experiment data as a time series to analyze the effect of changing wind speed on CO_2 concentration at various levels within the snowpack. To quantify the effect of wind on CO_2 snowpack concentration, we identified the time periods when an abrupt increase in wind speed resulted in a rapid decrease in CO_2 concentration. These time periods were then used to determine the rate at which CO_2 decreased with an increase in wind speed. This was done in order to directly compare the field data with the modelled CO_2 data.

2.3 Model development

We developed a model to explore the control of three parameters on the CO_2 dynamics of a soil-snow system: soil diffusivity, snow diffusivity at step change (advective wind intensity), and snow depth. A previously existing multilayer 1-D soil diffusion model (Nickerson and Risk, 2009) was adapted for the soil-snow system. The exchange of CO_2 between layers was determined by Fick's first law, which assumes that gas transport through a diffusive medium is controlled by the concentration gradient, and occurs vertically. Fick's first law is given as follows:

$$F_{CO_2} = -D_{CO_2}\left(\frac{\partial C_{CO_2}}{\partial z}\right),$$

where F_{CO_2} is CO_2 flux (µmol m^{-2}s^{-1}), D_{CO_2} is CO_2 diffusivity within the snowpack (m^{-2}s^{-1}), and $\frac{\partial C_{CO_2}}{\partial z}$ is the CO_2 concentration gradient of the snowpack (µmol m^{-3}). The diffusivity of CO_2 within the snowpack can be calculated empirically using snowpack porosity, tortuosity, the diffusion coefficient of the specific gas under standard temperature and pressure, ambient pressure, and snowpack temperature (Seok et al., 2009).

Varying numbers of snow layers were added on top of the 100 cm of modelled soil layers with the following distinctions: 1) we assumed that snow has a higher porosity than the underlying soil, therefore the snow layer diffusivities were always set to a

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value higher than the soil layers, and 2) we assumed that snow does not produce CO_2, therefore CO_2 production was removed from the snow layers.

To simulate how a modelled diffusive system responds to an advective wind event, the model simulated step changes in transport rate within the snowpack over a broad range of plausible synthetic cases (Table 1). Figure 2 shows the apparent storage flux and corresponding change in snowpack CO_2 concentration at every 10 cm, with a step change in CO_2 snowpack diffusivity, which was the mechanism used to mimic an advective wind event. Snow diffusivity before the step change was held constant at 8.06×10^{-6} m^2s^{-1}. Each model run began with the system in equilibrium state (with storage flux set to 1 μmol m^2s^{-1}).

2.4 Sensitivity testing

The goal of the step change with increased snow diffusivity was to mimic observed changes in CO_2 flux and snowpack concentration, by inducing an increase in snowpack CO_2 diffusivity. Specifically, the induced increase in snowpack CO_2 diffusivity was used to simulate an advective wind event within a diffusive model. With Atlantic Computational Excellence Network (ACEnet) high performance computers, we used model runs to explore the control of each of three parameters on the CO_2 dynamics of the soil-snow system. The three parameters investigated were soil diffusivity (m^2s^{-1}), snow diffusivity at step change (m^2s^{-1}), and snow depth (cm). The tested range for each of the parameters is given in Table 1.

For sensitivity analysis, we calculated fractional change. Each post-wind event CO_2 value was compared to a CO_2 value under the same conditions as if a wind event had not occurred:

$$\text{fractional change} = \left|\frac{w-n}{n}\right|,$$

where w is a post-wind event and n is an event under no elevated wind conditions.

2.5 Field-model comparisons

In order to properly compare the field and modelled data, we determined the rate at which modelled CO_2 responded to an induced wind event. Of the modelled data, we considered only scenarios with a soil diffusivity of 1.00×10^{-7} m^2s^{-1}. Additionally, only “low wind" and “high wind" events were considered, which had stepped snow diffusivities of 1.72×10^{-5} m^2s^{-1} and 9.08×10^{-5} m^2s^{-1}, respectively. Output included CO_2 concentration at every 10 cm within the modelled environment (both soil and snow). For field-model comparison purposes, we only considered the CO_2 concentration of the topmost layer of snow.

We processed the enhanced concentration profile experiment data (16 April–29 April) to calculate the rate of change of CO_2 concentration (ppm) per unit time (s) after a noticeable wind event.

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3 Results

3.1 Snowpack CO_2 concentration profile experiment

Initial field campaigns showed a relationship between wind speed and CO_2 concentration within the snowpack at NM1 and NM2. Under certain conditions, wind speed had a very strong effect on CO_2 concentration within the snowpack (Figs. 3 and 4).

There was a negative correlation between average wind speed and CO_2 concentration 50 cm above the ground (Fig. 3a). During this time period of 31.5 h, snowpack CO_2 concentration at this height above soil ranged from 587 ppm to 965 ppm. Wind speeds over this same time period ranged from 3.2 km h^{-1} to 31.1 km h^{-1}. The corresponding linear regression (Fig. 3b) shows the effect that average wind speed exerted on CO_2 concentration ($R^2 = 0.70$, $P < 0.001$). As wind speed increased, CO_2 concentration decreased at a rate of 14.4 ppm $km^{-1}h$.

Figure 4 is also of NM1 over the same time period as in Fig. 3, but the CO_2 concentration was measured at 125 cm above ground instead. These CO_2 values were very close to predicted atmospheric concentrations, as the average snow depth over this time period at NM1 was 124 cm. These values were a good representation of the CO_2 concentration at the snow-air interface. Despite increased atmospheric mixing, average wind speed exerted good control over CO_2 concentration (Fig. 4a). This result is reinforced with the corresponding linear regression (Fig. 4b; $R^2 = 0.53$, $P < 0.001$). As wind speed increased, CO_2 concentration decreased at a rate of 1.57 ppm $km^{-1}h$.

We conducted a regression analysis of CO_2 concentration versus average wind speed for filtered data for Winter 2014 (1 February 2014 to 27 March 2014, total of 1302 h), as per the three conditions specified in the Methods section. From this summary table (Table 2), there were some identifiable trends with the increasing height of CO_2 concentration measurement. With this increase from 0 cm to 125 cm, there was a decrease in the y-intercept, which was the mean predicted value of CO_2 concentration if average wind speed was 0 km h^{-1}. Additionally, the average slope of individual regressions became flatter with an increase in measurement height. Finally, the strength of the relationship (R^2) decreased with an increase in measurement height (towards the open air).

The measurements that satisfied all conditions accounted for 33.6% of the time analyzed.

3.2 Enhanced concentration profile experiment

We collected CO_2 concentration profile data at the enhanced NM2 station from 16:00 on 4 April 2015 to 11:00 on 29 April 2015, which is a total of 356 uninterrupted hours (Fig. 5). Average snow depth over this time period was 157 cm, ranging from 149 cm to 167 cm. Average air temperature was -1.4°C, ranging from -8.6°C to 7.6°C.

Figure 5 shows a time series of CO_2 concentration throughout the snowpack (0, 25, 50, 75, and 100 cm from the ground), atmospheric CO_2 concentration (250 cm from the ground), and mean wind speed. There was considerable variability in snowpack CO_2 concentration and wind speed over the two week period, with snowpack CO_2 values ranging from 151 ppm to 4161 ppm and wind speeds ranging from 0.0 km h^{-1} to 34.0 km h^{-1}. Average wind speed over the two week period was 13.5 km h^{-1}.

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Average CO_2 concentration decreased with increasing proximity to the atmosphere: 1244, 1076, 1007, 886, and 867 ppm at 0, 25, 50, 75, and 100 cm, respectively. Average atmospheric CO_2 concentration was relatively constant at 512 ppm. For some time periods between 4 April and 29 April 2015, there may have been a negative correlation between wind speed and snowpack CO_2 concentration (Fig. 5).

3.3 Modelling

Figure 6 shows results from sensitivity testing of an enhanced diffusion model used to simulate advection, and the effect of several parameters as deviations from a base case (Table 1). Model activity was investigated at the following layers: the topmost snow layer (CO_2 concentration in Fig. 6a and storage flux out of the top of the layer in Fig. 6c), the bottommost snow layer (CO_2 concentration in Fig. 6b), and the topmost soil layer (CO_2 concentration in Fig. 6d).

Results are shown as fractional depletion of CO_2 concentration in the snowpack (Figs. 6a, 6b, 6d), and factor increase in short-term CO_2 storage flux (Fig. 6c). Of the three parameters (soil diffusivity, snow diffusivity at step change mimicking advection, and snow depth), soil diffusivity had negligible control on layers involving snow (Figs. 6a, 6b, and 6c), though showed some control on the modelled soil layer (Fig. 6d).

In the modelled topmost layer of snow (Fig. 6a), CO_2 concentration was depleted to a maximum fraction of 0.39 once equilibrium was reached after a severe wind event. Snow depth had no effect on CO_2 depletion for both equilibrium scenarios at the top of the snowpack. For scenarios immediately following a wind event, severe winds had a greater effect on the fraction of CO_2 depleted, but this effect decreased with increasing snow depth (approaching no CO_2 depletion).

CO_2 concentration at the bottommost layer of snow (Fig. 6b) behaved similarly to the CO_2 concentration in the topmost layer. Depletions at the bottom of the snowpack were up to two times that of the depletions at the top of the snowpack (maximum fraction of 0.81 once equilibrium was reached after a severe wind event, with 100 cm of snow). Scenarios that immediately followed a wind event showed that severe winds had a greater effect on CO_2 depletion, although this decreased with increasing snow depth, reaching a minimum fraction of 0.06 at 100 cm.

Storage flux from the top of the snowpack into the modelled atmosphere is shown as factor increase in short-term CO_2 flux (Fig. 6c). Scenarios at equilibrium are not shown, as there was no change in CO_2 concentration once equilibrium was reached. Of the scenarios that immediately follow a wind event, light and severe winds had similar effects on factor increase with 20 cm of snow: a factor of 0.53 (light wind) and a factor of 0.25 (severe wind). With increasing snow depth, severe winds showed a much greater fractional increase (9.92) in storage flux than light winds (1.15).

At the topmost soil layer (Fig. 6d), CO_2 concentration was affected by soil diffusivity and unaffected by snow depth. With increasing soil diffusivity at equilibrium, a greater fraction of CO_2 was depleted from the soil layer. Severe winds depleted a greater fraction than light winds. There was essentially no effect on the fraction of CO_2 depletion immediately following wind events of any severity.

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4 Discussion

4.1 Wind causes short-lived advective anomalies

Findings of the initial snowpack CO_2 concentration profile experiment showed that there was a negative correlation between wind (advective) events and the CO_2 concentration in a snowpack, on a timescale of hours to days. This was clear from specific examples (Figs. 3 and 4), as well as from the overall summary of linear regressions performed between CO_2 snowpack concentration and wind speed (Table 2). However, this was not continuous over the entire winter and was only true under particular conditions where filtering criteria were satisfied. The balance of the datasets that did not meet criteria were simply noisy with visible but weak trends. Analysis of data from the first experiment showed that there was a CO_2 concentration gradient throughout the snowpack, with highest concentrations closest to the soil and lowest concentrations closest to the atmosphere. This was consistent with previous literature (Seok et al., 2009).

This work reinforced earlier observations of depleted CO_2 concentrations in field datasets (Seok et al., 2009), although we did not measure CO_2 storage flux directly in the field at the snow surface. However, we inferred that sporadic changes in snow-atmospheric flux would have been present from the large decreases in concentration. Positive storage fluxes were balanced by negative storage fluxes following wind events.

As the measurements taken satisfied all specific conditions for 33.6% of the time analyzed, we can conclude that advection showed significant control over snow CO_2 transport for this location during the 54 day period in 2014. This value did not represent the percentage of annual flux during the snow-covered season (Liptzin et al., 2009), although it did indicate that advective transport needed to be taken into account when studying snowpack CO_2 transport.

The enhanced concentration profile experimental data reinforced the results of the initial findings and added CO_2 concentration measurements throughout the snowpack, increasing the total in-snow measurements from three to five. This gave us a clearer indication of how the CO_2 concentration gradient behaved, even without taking snow properties into account. This data covered the late winter period, so ice layers within the snowpack were likely present. Despite this, the wind seemed to have an effect on CO_2 snowpack concentrations, even at 0 cm with a snowpack of 157 cm.

Some authors have used turbulent atmospheric pressure pumping to explain anomalous CO_2 storage fluxes, but have often focused this work on shorter, high frequency timescales of seconds to minutes (Massman et al., 1995). On the longer, low frequency range of the timescale, Bowling and Massman (2011) and Massman et al. (1995) mentioned the importance of synoptic scale changes in atmospheric pressure. Our work showed how a continuously enhanced friction velocity (persistent wind) and an enhanced diffusive regime controlled CO_2 concentration and fluxes across timescales of hours to days, in the midrange between very high frequency pressure pumping and low frequency barometric pressure effects. The low frequency, synoptic processes occur on a longer time scale than the wind depletion events discussed in this study, though would be present here as well, and would likely contribute to some of the variability (Robinson and Sextro, 1997; Tsang and Narasimhan, 1992). With longer continuous wintertime CO_2 records, it may be possible to extricate these synoptic process periodicities.

4.2 A diffusive model can help explain advective questions

The 1-D diffusional transport model and enhanced diffusion approach was able to replicate the CO_2 depletions seen in the field in this experiment, as well as those in previous observations (Seok et al., 2009) and in other plausible situations. Advective events were induced with abrupt changes in snowpack diffusivity, which worked well to mimic wind events.

In general, when rapid step changes in snowpack diffusivity were inputted into a diffusive transport model, we observed rapid disequilibria in the snowpack CO_2 concentration, CO_2 storage flux, and soil CO_2 concentration. This effectively simulated advective events observed in the field. According to this model, severe wind events always produced more dramatic results than light wind events.

This modelling work showed that we can reduce the effects of sustained advection on CO_2 in a soil-snow system to an effective diffusion problem. This approach was simpler than the diffusive-advective coupled solution.

4.3 Field-model comparisons

To determine the applicability of the model to real-world scenarios, we compared our field and model results. To do so, we calculated the rate of change of CO_2 concentration (ppm) per unit time (s) after a wind event for both the modelled wind events and the field wind events (for the enhanced experiment). Table 3 summarizes the rates of change of modelled CO_2 concentration at varying snow depths, at low and high simulated wind speeds (step change in snow diffusivity), and at various times since the modelled wind event. All of these modelled measurements were taken from the topmost snow layer. Table 4 shows a similar summary, though for four wind events in the field in April 2015. All of these CO_2 field measurements were taken at 100 cm from the ground within the snowpack, which was the in-snow measurement farthest from the ground and closest to the atmosphere at the time.

Change in modelled CO_2 concentration per second (Table 3) did not align perfectly with the change in field CO_2 concentration per second (Table 4) after a wind event. However, the rates of change in the field events $(-0.07, -0.04, -0.20. -0.04)$ were of approximately the same order of magnitude as the rates of change in the modelled events (ranging from 0.00 to -2.08). This indicated that the model was able to mimic advective events with some accuracy.

This study showed the importance of continuous monitoring of CO_2 concentrations and fluxes from soils through snowpacks. Similarly, Webb et al. (2016) highlighted the non-growing season contributions to annual CO_2 flux. They also showed that different wintertime measurement methods at one Alaskan site resulted in a fourfold range in CO_2 loss. The eddy covariance (EC) method showed the highest fluxes, as more CO_2 was released under windy conditions and the EC method was able to measure fluxes in turbulent conditions (Webb et al., 2016). Accompanying these findings, we noted that infrequent measurement can lead to significant error in the annual C budget of various ecosystems once inaccurate values are upscaled (Fig. 7). The effects of advection on these soil-snow systems can lead to variability in storage flux, as effective diffusion is closely related to wind. Snowpack depth, density, and layering will also affect the timing and amounts of CO_2 storage flux from these systems. We recommend that future studies utilize continuous CO_2 monitoring methods and consider the effects of wind, in order to capture the uncertainties of soil CO_2 emissions in snow-covered ecosystems.

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Manuscript under review for journal Biogeosciences
Discussion started: 29 May 2017
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5 Conclusions

Although this study was conducted at one site over two winters, the findings have global implications for measuring wintertime CO_2 fluxes in snow-covered environments.

As seen from the fieldwork in winters 2014 and 2015, advective transport by wind is important for CO_2 concentration (and therefore flux) through a soil-snow profile. Additionally, this process can be simulated with some accuracy by a model of enhanced diffusion. In both field and model cases we observed how sustained winds could deplete CO_2 concentration in the snowpack, and create storage flux outward to the atmosphere. During the re-equilibration phase, fluxes across the snow-air interface would have been depressed, as most of the production contributed initially to pore space storage. This process of buildup and release occurs with regularity in snow profiles, and is likely more severe in snowpacks than in soil, which has lower permeability and is therefore less vulnerable to wind invasion.

Transport lags are the main effect of diffusion and advection. Measurements such as eddy covariance, which can be made above the snow profile with speed, are at an advantage for detecting storage flux events. While useful for accounting purposes, eddy covariance records may not be effective in determining actual overwinter biological soil CO_2 production. For this, sensors within or at the base of the snowpack would also be needed, allowing the results to quantify soil-snow fluxes or concentration gradients within the first few centimetres of snow. Alternatively, the model used here, which accurately simulated gas transport physics, could be applied through an inversion scheme to determine microbial changes in CO_2 production by removing the effects of snow gas transport.

This study explains snow profile CO_2 depletions that exist on timescales of hours to days. Putting this knowledge into practice would help to improve our understanding of global winter soil CO_2 release because it improves our efforts to quantify winter fluxes. As a start, we recommend that researchers approach winter data like they do summer data, which means that they should consider using continuous automated approaches for wintertime CO_2 flux observations. We also recommend close collaboration between the modelling community and soil field scientists. This will ensure that available physical models are being effectively used for stripping flux data of transport-related artefacts, thereby isolating soil biological behaviour.

Competing interests. Authors have no competing interests to declare.

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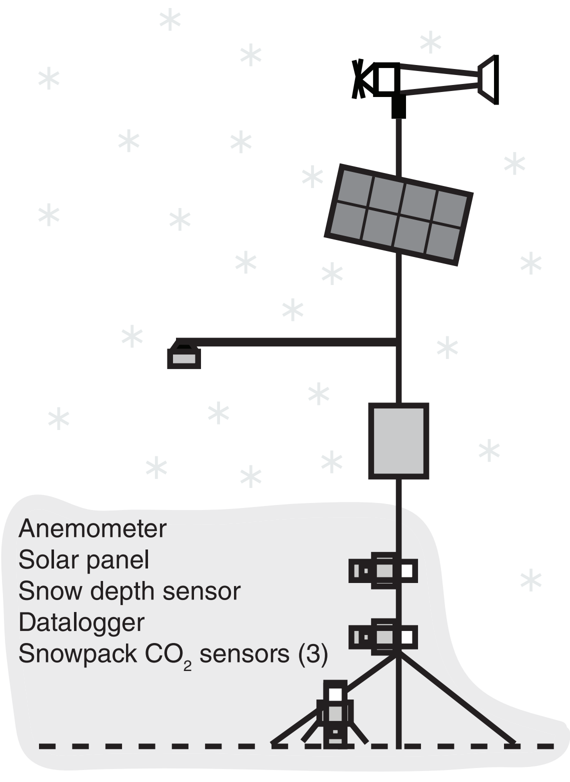

Figure 1. Schematic of initial CO_2 monitoring stations at North Mountain, Cape Breton.

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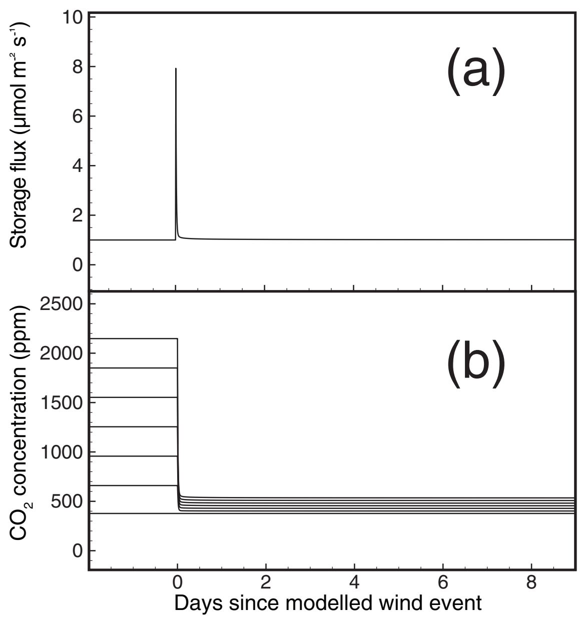

Figure 2. (a) Shows the apparent storage flux with a step change in snowpack CO_2 diffusivity. **(b)** Shows the corresponding change in snowpack CO_2 concentration at every 10 cm. Soil diffusivity = 1.00×10^{-7} m^2s^{-1}, stepped snow diffusivity $= 9.08 \times 10^{-5}$ m^2s^{-1}, and snow depth = 60 cm.

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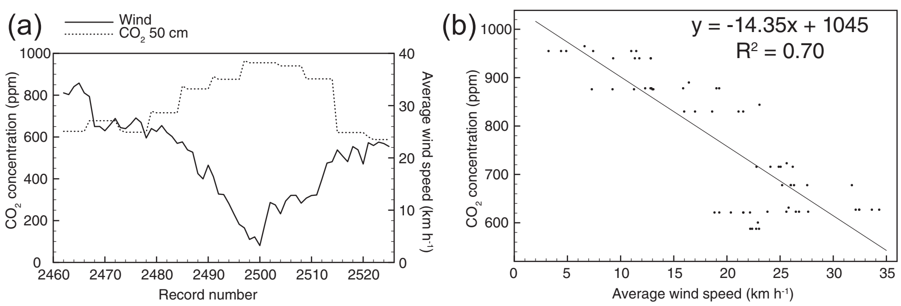

Figure 3. (a) Time series of wind speed and CO_2 concentration at 50 cm above the ground within the snowpack from 06:30 on 1 January 2014 to 14:00 on 3 January 2014 at NM1. Average snow depth at NM1 over this time period was 124 cm. **(b)** The corresponding linear regression of CO_2 concentration versus average wind speed ($R^2 = 0.70$, $P < 0.001$).

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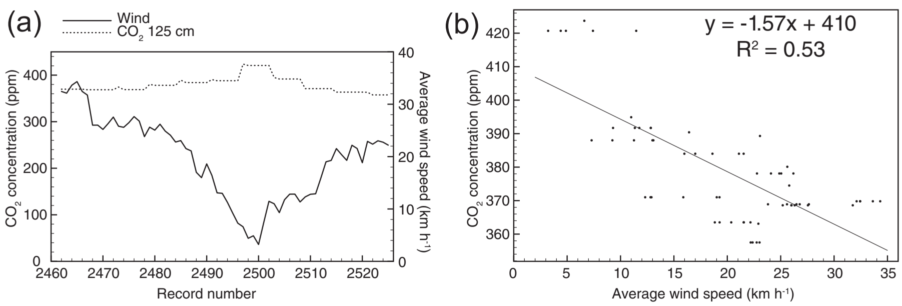

Figure 4. **(a)** Time series of wind speed and CO_2 concentration at 125 cm above the ground from 06:30 on 1 January 2014 to 14:00 on 3 January 2014 at NM1. Average snow depth at NM1 over this time period was 124 cm. Therefore, these CO_2 values were a good representation of the snow-air interface. **(b)** The corresponding linear regression of CO_2 concentration versus average wind speed ($R^2 = 0.53$, $P < 0.001$).

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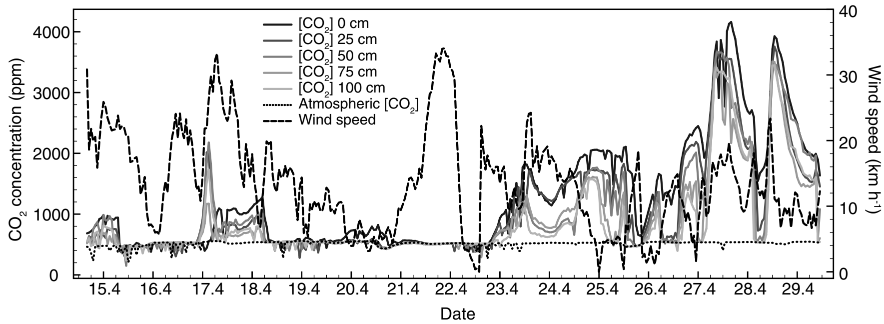

Figure 5. Time series of CO_2 concentrations throughout the snowpack, atmospheric CO_2 concentration, and wind speed at NM2 over 2 weeks during late winter 2015 (15 April–29 April). Measurements were recorded hourly.

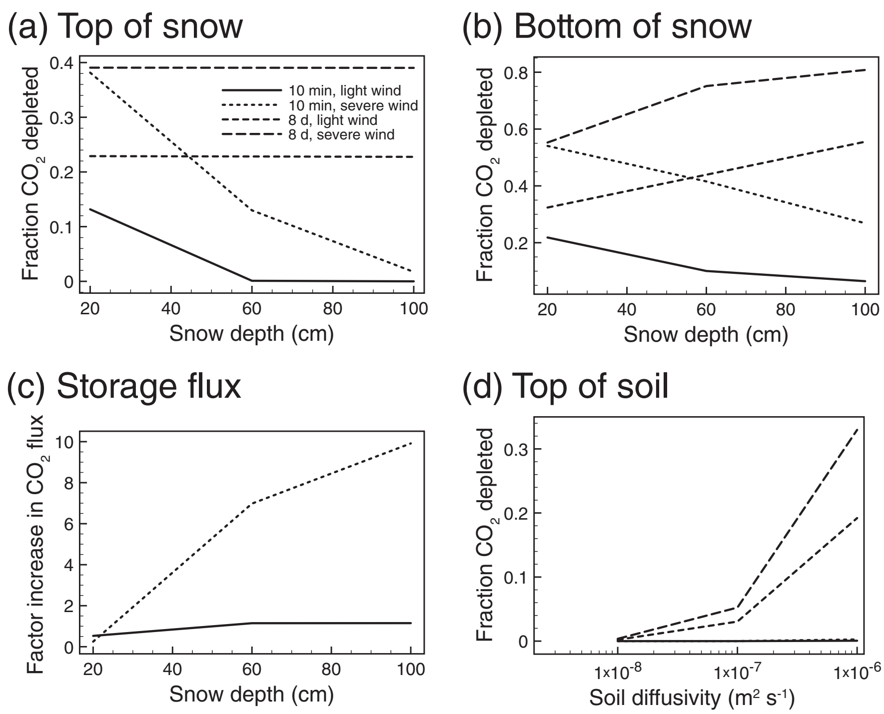

Figure 6. **(a)** Modelled results at top of snowpack shown as the fraction of CO_2 concentration depleted from the snowpack. **(b)** Modelled results at bottom of snowpack shown as the fraction of CO_2 concentration depleted from the snowpack. **(c)** Modelled storage flux, shown as factor increase in short-term CO_2 flux. **(d)** Modelled CO_2 at the topmost soil layer, shown as the fraction of CO_2 concentration depleted from the snowpack.

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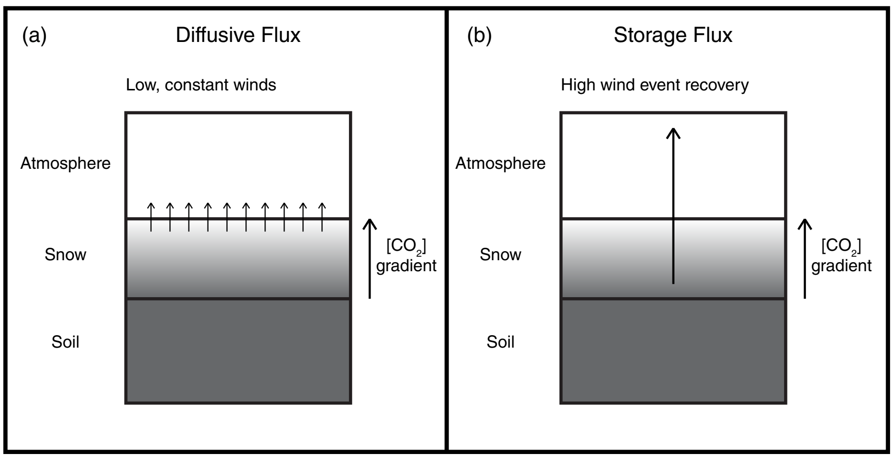

Figure 7. Conceptual diagram of **(a)** diffusive flux through a snowpack and **(b)** storage flux through a snowpack. Low levels of diffusive flux are more prevalent and constant than storage flux, which occurs following a high wind event.

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Table 1. A 1-D soil CO_2 diffusion model was adapted for the soil-snow system. The model simulated step changes in transport rate over a broad range of plausible synthetic cases.

Parameter	**Range of values**	**Increments**
Soil diffusivity	1×10^{-8} to 1×10^{-6} m^2s^{-1}	3
Snow diffusivity at step change	8×10^{-6} to 9.08×10^{-5} m^2s^{-1}	10
Snow depth	20 cm to 100 cm	3

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Table 2. Summary of regression analysis between CO_2 concentration within the snowpack and wind speed. Data were filtered to satisfy the following conditions: 1) snow cover was considered to be at equilibrium, 2) the relationship produced a slope < 0, and 3) $R^2 \geq 0.1$. N is the number of time periods that satisfy all 3 conditions. Each time period covered a minimum of six hours. Y-intercept is the mean CO_2 concentration when wind speed = 0 km h^{-1}. Slope is the mean change in CO_2 concentration with a 1 km h^{-1} increase in wind speed. R^2 is the mean strength of the relationship between CO_2 concentration in the snowpack and mean wind speed. n is the mean number of half-hourly observations within each N. Duration is the mean duration of N.

Site	**Snow depth**	**Height in snowpack**	**N**	**y-intercept**	**Slope**	**R^2**	**n**	**Duration**
	cm	cm		ppm	ppm km^{-1}h			h
NM1	708 ± 600	0	n/a	n/a	n/a	n/a	n/a	n/a
		50	29	1399.2 ± 1000	-23.2 ± 30	0.41 ± 0.2	30 ± 20	15 ± 10
		125	27	642.3 ± 700	-12.0 ± 30	0.36 ± 0.2	29 ± 20	15 ± 10
NM2	625 ± 300	0	29	1196.8 ± 500	-13.1 ± 8	0.49 ± 0.2	38 ± 30	19 ± 20
		50	22	547.4 ± 200	-6.8 ± 10	0.35 ± 0.2	50 ± 80	25 ± 40
		125	25	379.2 ± 7	-0.5 ± 0.5	0.29 ± 0.2	41 ± 30	21 ± 20

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Table 3. Summary table of change in modelled CO_2 concentration per second at 1, 2, 4, 6, and 24 h since the wind event (step change in modelled snowpack diffusivity) at the topmost layer in the model. Snow depths of 20, 60, and 100 cm are shown, along with lowest and highest simulated wind speeds.

		Time since wind event (h)				
		1	2	4	6	24
Snow depth	**Relative wind speed**	**Rate of change of CO_2**				
cm		ppm s^{-1}				
20	low	−0.55	−0.20	−0.06	−0.03	0.00
20	high	−0.03	−0.01	−0.01	0.00	0.00
60	low	−0.80	−0.64	−0.38	−0.24	−0.03
60	high	−1.71	−0.67	−0.22	−0.11	−0.01
100	low	−0.16	−0.26	−0.27	−0.23	−0.06
100	high	−2.08	−1.24	−0.54	−0.29	−0.02

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Table 4. Summary table of change in actual CO_2 concentration per second for four events in April 2015 when a decrease in CO_2 concentration corresponded to an increase in wind speed. CO_2 concentration was measured in the snowpack at 100 cm from the ground. Rate of change of CO_2 concentration, snow depth, start time, end time, range of CO_2, and range of wind speed are given in the table.

Event number	**1**	**2**	**3**	**4**
Rate of change of CO_2 (ppm s^{-1})	−0.07	−0.04	−0.20	−0.04
Snow depth (cm)	162	152	155	156
CO_2 measurement depth (cm)	100	100	100	100
Duration of ppm decrease (h)	4	3	2	14
Initial CO_2 (ppm)	1733	1105	2061	3445
Final CO_2 (ppm)	648	690	596	1771
CO_2 decrease (ppm)	1085	415	1465	1674
Duration of wind increase (h)	8	4	5	4
Initial wind value (km h^{-1})	10.8	10.5	9.2	11.0
Final wind value (km h^{-1})	33.2	24.2	18.1	23.4
Wind increase (km h^{-1})	22.4	13.8	8.9	12.3