Author response to comment on "Explaining CO_2 fluctuations observed in snowpacks" by Laura Graham and Dave Risk

By Anonymous (Referee 3)

(referee comments in black, author responses in blue)

General Comments

Graham and Risk explore carbon dioxide flux through snow in two different snowpacks in Nova Scotia. The focus is on the timescales of CO2 "recovery" (if you will) after wind-induced pressure pumping events (this is similar to the Venturi effect where an increase in speed results in a decrease in pressure).

We thank the referee for their thoughtful comments and suggestions. We have responded to each comment below.

It honestly took me a while to figure out the major points of the manuscript, which was in the timescale of the re-establishment of consistent CO2 gradients in the snowpack after disturbances for the use of gradient-based approaches. This is fine, but wasn't entirely apparent from the introduction, where the findings of Bowling, Massman and others could have been written in a way to point to a more clear overarching question. Doing so will lead in my opinion to a much more compelling manuscript.

To alleviate some of this confusion, we have added some linking statements to the end of the second last paragraph of the introduction (where Bowling and Massman studies are already discussed). The new sentences are: "These studies that investigated advective influence on CO_2 transport in snow systems encouraged further study in this area, and so we intended to help fill this gap with our study. To do so, we investigated the mid-range timescale of the re-establishment of consistent CO_2 concentration gradients in the snowpack after a wind-induced disturbance using both field and modelling methods."

The text could be more efficient throughout. As a first example, " Datasets have shown that winter..." on line 2 could simply be, "Winter...".

Thank you for this observation. Small edits have been made throughout to streamline the text.

The paper was not particularly well-referenced with a mere 27 references on a topic that has attracted much more attention than this.

We have added a few key references with the advent of this comment. We believe that our paper is methodically cited with references of high quality and relevance.

line 7 of page 2 isn't entirely accurate. 7% of what? Saturated vapor pressure?

We thank the referee for pointing out this oversight. Detail has been added, with the phrase changed to "an increase of approximately 7% in water holding capacity of air per 1˚C warming".

On what basis is the snowpack diffusion approach the most commonly used technique? One may argue that eddy covariance is used much more frequently but also that careful studies of flux through snow using this technique are perhaps a bit lacking.

That particular statement was in reference to the McDowell 2000 paper, referenced later in the paragraph. Since eddy covariance prevalence may have risen over the past two decades, we have edited the statement to: "The snowpack gradient technique is a commonly used technique […].” A reference to McDowell and Seok has been added, as well.

on page 2 line 34, the major finding of Bowling and Massman is that "enhanced diffusion" is a major mechanism of gas transport through snow, so citing it here isn't the most accurate thing to do.

Thank you for this observation. The citation has been removed.

On page 4, the GMP can be heated as noted, but this impacts the advection when adding heat to a snowpack. It would be forthcoming to estimate the advective flux induced by the GMP sensors for a conservative estimate of their impact on advection. This also creates a risk of melting and freezing snow and encapsulating sensors.

Though the GMP343 sensors do produce some heat, we believe that the amount of heat produced in this context is negligible, given that the sensors were switched on for the minimum amount of time possible, and that our CO_2 concentration values were recorded either half-hourly or hourly. Discussed in earlier revision dialogue, our GMP343 sensors were turned off in between measurements to save power, as well as to minimize the potential impacts on snowpack structure (e.g. freezing snow and encapsulating sensors) and gas dynamics (air movement due to heat—convection). The programmed 30 minute cycle for these sensors was: GMP343 on for 10 minutes to “warm up”, 1 minute of measurement, and GMP343 off for the remaining 19 minutes of the 30 minute cycle. Additionally, it is important to note that the optics heaters of the GMP343 sensors remained off (default setting) for the entirety of this experiment. Optics heaters should be turned on when there is a risk of condensation on the optics surface. However, in relatively constant temperature environments like snowpack and soils, even if humid, we have found that this (on/off) approach does not render the sensors subject to condensation. Condensation is often more of an issue in atmospheric settings that have quick changes in temperature. As for the power consumption of the sensors, “without optics heating” is < 1 W, and “with optics heating” is < 3.5 W. Having a sensor on for 11 minutes out of every 30 minutes with the optics heating off results in ~9.5 times less heat emitted from sensor power than when compared with having a sensor on continuously for 30 minutes with optics heating on (11min/30min = 0.367, 1 W continuously with optics heating off → 3.5W/0.367W = ~9.5). Yes, the measurement sample was taken during the “warmest” minute of the 30-minute interval—the 11th minute—but we believe that the potential heating impacts were avoided overall. Finally, it is important to note that adding heat to a system of fluids typically induces convection (rather than advection, specifically). Convection is often defined as movement of molecules due to some combination of both diffusion and advection, and so we conclude that estimating the impacts of the minimal GMP343 sensor heating on advective flux is unwarranted.

I'm rather confused by section 2.2 in which it seems like only periods that conform to certain assumptions are chosen, which will bias the results in favor of these conditions and not provide a representative estimate of CO2 flux during the snow-covered period. This topic is covered in the discussion, but led to confusion in the results section.

We assuage this confusion by reiterating the fact that we are not in fact trying to provide an estimate of CO_2 flux during the snow-covered period. Clarifications found in the discussion section are now emulated in both section 2.2 and in the results section with statements like: “With the use of our filtering process, our analysis does not represent an estimate of CO_2 flux during the snow-covered period,” and, “This value does not represent an estimate of the CO_2 flux during the snow-covered period, since we used a biased filtering process to identify wind events during periods of steady snow cover.”

The 1D model development on page 5 was a bit lacking as the role of temperature, pressure, and tortuosity was ignored or described in a cursory manner. The sensitivity analysis in section 2.4 helps assuage some of these concerns but it should be placed after the model description for continuity.

We thank the referee for the suggestion regarding relocating the “Sensitivity testing” section. It has now been incorporated into section 2.3 (formerly “Model development”), and we hope this clarifies any concerns regarding the more superfluous aspects of the model.

'is considered impossible' is incorrect on page 6, it's just that 3D transport is not modeled in a 1D model.

The referee makes a fair point. The sentence including the mentioned phrase has been adjusted to, “These features are unaccounted for in our modelling, as modelling lateral CO_2 transport through a snowpack in addition to vertical transport would require a 3-D model.”

'under certain conditions' in the results induces curiosity as to what these conditions are. Do they fall under certain classes or conditions?

Confusion arises here due to the flexible definition of the word “conditions”, and if a given reader interprets the word in a mathematical or environmental sense. We’ve removed this confusion, as we are trying to make the point that wind speed sometimes strongly controlled CO_2 concentration within the snowpack (but not always). The reworded sentence states: “Wind speed sometimes had a very strong effect on CO_2 concentration within the snowpack (Figs. 3 and 4).”

"These values were a good representation of the CO2 concentration at the snow-air interface." what does this mean?

This statement arises because we are commenting on the usefulness of having CO_2 values from where the snow surface is approximately equal to the measurement height (124 cm and 125 cm from the soil surface, respectively). These sentences have been clarified, now stating: “Figure 4 shows measurements at NM1 over the same time period from 125 cm above ground. 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, very near the measurement height. The closeness of the measurement height to the snow surface indicates these values were likely a good representation of the CO_2 concentration at the snow-air interface.”

On page 10 line 27 or so, note the findings of Rains et al. (2016, doi: 10.1016/j.coldregions.2015.10.003) that variations in wind speed at low (multiple hour) frequencies may be more effective than variations in atmospheric pressure for explaining changes in snowpack CO2 concentrations. (see also the upper part of page 12 on multi-measurement comparisons).

Thank you for pointing out this comprehensive study by Rains et al. (2016). Detail pertaining to that study has been added to both sections 4.1 (Wind causes short-lived advective anomalies) and 4.3 (Field-model comparisons), as recommended.

in section 4.2, these are essentially the findings of Bowling and Massman (2011) which should be cited.

We thank the referee for this observation. A citation for Bowling and Massman (2011) has been added to section 4.2.

We hope that these minor changes have added to the overall cohesiveness of the test. Thank you for your time, comments, and consideration.

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~~ 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

The global soil carbon (C) pool stores three times the amount of C as the atmosphere. Organic C reserves in high latitude soil are disproportionately affected by anthropogenic climate change (IPCC, 2013). Careful assessment of the soil C pool and corresponding fluxes in these often snow-covered, high-latitude regions is critical for understanding the future global C cycle, as increasing global temperatures are likely to stimulate soil CO_2 emissions (Raich et al., 2002).

Cold and wet conditions, ~~such as~~ like snow cover, pose challenges for measuring wintertime carbon dioxide (CO_2) fluxes (Liptzin et al., 2009), leading many studies to focus on ecosystem respiration during the growing season. For instance, seasonal variation in soil CO_2 fluxes is not always discussed in meta-analyses of global soil C studies, whether or not wintertime measurements were ~~incorporated into~~ included in individual studies (Scharlemann et al., 2014). Despite this skewed focus, soil CO_2 is still produced throughout the winter, even at $-7°C$ (Flanagan and Bunnell, 1980; Coxson and Parkinson, 1987; Brooks et al., 1996). In some cases, the insulating snowpack can prevent soils from freezing completely, further stimulating soil CO_2 emissions (Grogan and Jonasson, 2006; Larsen et al., 2007; Monson et al., 2006). Further, snow is a porous medium where soil CO_2 emissions easily pools, complicating measurement techniques. There has been an observed decrease in Northern Hemisphere snow cover and an earlier onset of spring melt since the 1950s as a result of climate change (Dyer and Mote, 2006; IPCC, 2013). Dyer and Mote (2006) indicate indicated that these changes in snow cover are associated with increasing air temperatures and variations in precipitation. Additionally, increasing air temperature results in increased water vapour in the atmosphere (an increase of approximately 7% in water holding capacity of air per 1°C warming), generating more intense precipitation events, including snow storms (Trenberth, 2011). Despite decreases, snow covers 44–53% of Northern Hemisphere land area during winter months (Barry, 1992). With the complex interplay between changes in precipitation, temperature, snow cover, and CO_2 emissions in recent and future decades, winter soil CO_2 measurements are important for accurate estimates of annual CO_2 soil respiration (Fahnestock et al., 1999).

There are several methods of measuring CO_2 fluxes through snowpacks including the snowpack gradient technique, chamber methods, and eddy covariance. The snowpack gradient technique is the most a commonly used technique, and, based on Fick's first law of diffusion, uses CO_2 concentration measurements through a vertical profile from the soil to the snowpack surface to calculate flux (McDowell et al., 2000; Seok et al., 2009). This technique minimizes disturbance to the snowpack when compared with the chamber method and does not require homogenous terrain, as for eddy covariance. However, the snowpack gradient technique requires many assumptions and cannot easily account for advective transport of CO_2 through snowpacks (McDowell et al., 2000; Seok et al., 2009). Measurement frequencies of wintertime CO_2 fluxes in past gradient 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, depending more on transport of CO_2 than on microbial variation (Bowling et al., 2009; Seok et al., 2009). 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. 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 (temperature, moisture) below 0°C. Steady soil conditions therefore rule out a microbial driving force when variable fluxes were observed. Advective transportAs for advective transport, it does not increase production of CO_2 in soils, but changes the rate of exchange (Bowling and Massman, 2011).

Although we accept the assumption that CO_2 production occurs in snow-covered soils, there are methodological limitations for quantifying this CO_2 production. 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)(Janssens et al., 2001 The mode of this 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 of diffusion assumes that trace gas transport out of soils or through a snowpack occurs vertically, with the magnitude of fluxes determined by the concentration gradient (Seok et al., 2009). Advective transport from wind, however, can also affect the transport of trace gases such as CO_2 through porous media like soil and snow (Kelley et al., 1968)(Kelley et al., 1968; Janssens et al., 2001).

Studies are increasingly showing that this non-diffusive (advective) mass transport (i.e. wind) through snow is significant, and must be taken into consideration (Bowling and Massman, 2011)(Bowling and Massman, 2011; Rains et al., 2016), while considering the appropriate timescale. Advective transport of trace gases through naturally permeable media occurs due to variations in atmospheric pressure at the surface, and have been studied on both high frequency timescales (seconds to minutes (Massman et al., 1995)) and low frequency timescales (barometric (Bowling and Massman, 2011)). These natural advective flows are ubiquitous, and should also be considered on the mid-range timescale of hours to days (Rains et al., 2016). 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. 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 and so 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. 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. These studies that investigated advective influence on CO_2 transport in snow systems encouraged further study in this area, and so we intended to help fill this gap with our study. To do so, we investigated the mid-range timescale of the re-establishment of consistent CO_2 concentration gradients in the snowpack after a wind-induced disturbance using both field and modelling methods.

Our overarching objective through this study was to help overcome the methodological limitations of quantifying wintertime CO_2 production. Specifically, 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.

2 Methods

2.1 Continuous automated field monitoring

The primary motivation for establishing our field stations for this study 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 the winter, and over-winter CO_2 production from these soils is very likely (Grogan and Jonasson, 2006; Larsen et al., 2007; Monson et al., 2006), as soils produce CO_2 down to -7°C (Flanagan and Bunnell, 1980; Coxson and Parkinson, 1987; Brooks et al., 1996). 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). High winds and variable meteorological conditions (intense snowsqualls, freeze-thaw cycles) create varying snow depths within close proximity (tens to hundreds of m).

Two measurement stations were installed 60 m apart at North Mountain in late 2013, with data collection from 12 November 2013 to 26 March 2014 and 15 April to 29 April 2015. 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.

To enhance the field campaign, adjustments were made to the NM2 station for winter 2015 by adding additional CO_2 measurements throughout the vertical profile. Specific measurements recorded at NM2 include CO_2 concentration at 5 cm depth in the soil, soil surface, and at 25 cm, 50 cm, 75 cm, and 100 cm above the soil surface (in the snowpack). We continued to record ambient air CO_2 concentration, wind speed, and snow depth. Measurement recording frequency for all measurements was adjusted to hourly for 2015. The profiler system for the enhanced concentration profile experiment contained two Eosense eosGP (dual channel nondispersive infrared) sensors to measure CO_2 concentrations for select time periods over the 2015 winter. A pump within the station enclosure extracted air samples from the various sampling locations via flexible nylon tubing, carrying the air to the sensor. In-snow and in-soil terminal ends of nylon tubing sampled from 550 mL PVC tubes that had openings covered with high-density polyethylene membranes to exclude liquid water. Data extracted from winter 2015 for analysis ranged from 15 April to 29 April 2015.

2.2 Field data analysis

In order to To examine the degree of concentration decrease after wind ventilation started, we focused on periods in which the likelihood of steady state gas transport was maximized (initial winter 2014 experiment). This is an assumption of the snowpack gradient technique, and we assumed that disturbance to the snowpack, including snowfall, results in deviations from steady state (McDowell et al., 2000). 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. To do this, we took the rolling four-hour mean of the snow depth values and found the difference between each set of consecutive snow depth values. We retained the values for which the difference of the rolling mean was < 0.001 m. 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 , or (the best set of environmental conditions for which a strong negative correlation could be found,) was satisfied when winds increased slowly, then abated several hours later (and vice versa). In order to select data where 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 cm, 50 cm, and 125 cm). Our data filtering technique was biased towards selecting periods of steady state and negative correlations between wind speed and CO_2 concentration. While the criteria seem demanding, in practice they were less restrictive than one might expect, and nearly one-fifth of all the measured data passed these filters and were included in the final analysis. With the use of our filtering process, our analysis does not represent an estimate of CO_2 flux during the snow-covered period.

We inspected the enhanced concentration profile experiment data (winter 2015) 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 (see section 2.52.4, Field-model comparisons).

2.3 Model development and sensitivity testing

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 after initialization (advective wind intensity), and snow depth. The goal of this model was to use a diffusive model to mimic advective wind events through a snowpack. 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 (based on density), tortuosity, the diffusion coefficient of the specific gas under standard temperature and pressure, ambient pressure, and snowpack temperature (Seok et al., 2009). We tested a range of diffusivities (soil and snow), along with snow depth, but for simplicity, we did not test ranges for individual parameters that are used to calculate diffusivity (e.g. snowpack porosity, tortuosity).

The ~~model was initialized~~ purpose of the induced change of an increased snowpack CO_2 diffusivity was to mimic observed changes in CO_2 flux and snowpack concentration. 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 the three parameters on the CO_2 dynamics of the soil-snow system. The three parameters investigated were soil diffusivity (m^{2}s^{-1}), snow diffusivity at step change (m^{2}s^{-1}), and snow depth (cm). The tested range for each of the parameters is given in Table 1.

We initialized the model using a linear CO_2 concentration profile through the layers, determined by soil CO_2 diffusivity, layer height, and atmospheric CO_2 concentration (set at 380 ppm). Each model simulation began with the system in equilibrium state, which means storage flux was set to 1 μmol m^{2}s^{-1}. We define storage flux here as the change in CO_2 storage in the snowpack, analogous to the exchange of CO_2 between the snowpack and the atmosphere. 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 value higher than the soil layers, and 2) we assumed that snow does not produce CO_2, therefore we removed CO_2 production ~~was removed~~ from the snow layers.

Initial condition snow diffusivity was held constant at 8×10^{-6} m^{2}s^{-1} for all simulations. Since snow diffusivity encompasses porosity, density, and tortuosity, these parameters also remained constant for initial conditions for all simulations: we assumed a homogeneous snowpack, and did not test a range of snow diffusivities for initial conditions. To mimic a range of wind events, after initialization, we tested a range of snow diffusivities. Our ten test values for this snow diffusivity, mimicking advective "wind events", ranged linearly from 8×10^{-6} (equal to the snow diffusivity at initial conditions) to 9.08×10^{-5} m^{2}s^{-1} (approximately the diffusivity of CO_2 in air) (Table 1). ~~A~~ We tested a plausible range of soil diffusivity and snow depth values (parameters used for initializing)~~were tested~~, though these remained unchanged through the "wind event" in each simulation. ~~A~~ We tested a range of soil diffusivities ~~was tested~~ to mimic a range of CO_2 emission rates out of the soil into the overlying snowpack. A range of snow depths was tested to mimic the natural environment that we tested in the field.

Figure 2 shows an example of the apparent storage flux and corresponding change in snowpack CO_2 concentration at every 10 cm, with an induced change in CO_2 snowpack diffusivity, which was the mechanism used to mimic an advective "wind event". In summary, to simulate how the modelled diffusive system responds to an advective wind event, the model simulated induced changes in transport rate (snow diffusivity) within the snowpack over a range of plausible synthetic base cases (soil diffusivity and snow depth). We ran the model with all possible permutations of the three parameters given in Table 1.

It is very likely that lateral CO_2 flux occurs within the snowpacks at our field sites, especially with the presence of wind slabs, sun crusts, and ice lenses at the sites. These features are unaccounted for in our modelling, as modelling lateral CO_2

transport through a snowpack with this 1-D modelis considered impossiblein addition to vertical transport would require a 3-D model. Our overall objective with this model was to observe and understand the differences in diffusive and advective transport through snowpacks. As such, we refrained from overcomplicating the 1-D model (e.g. Fick's second law of diffusion).

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 the three parameters on the CO_2 dynamics of the soil-snow system. The three parameters investigated were soil diffusivity ($m^2 s^{-1}$), snow diffusivity at step change ($m^2 s^{-1}$), 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.

2.4 Field-model comparisons

In order to properly compare the field and modelled data, we determined the rate at which modelled CO_2 responded to the induced "wind events". This refers to the change in CO_2 concentration over time (ppm s^{-1}) as a result of the change in snowpack CO_2 diffusivity after initialization. Of the modelled data, we considered only scenarios with a soil diffusivity of 1.00×10^{-7} $m^2 s^{-1}$. Additionally, only "low wind" and "high wind" events were considered, which had induced snow diffusivities of 1.72×10^{-5} $m^2 s^{-1}$ and 9.08×10^{-5} $m^2 s^{-1}$, 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 (winter 2015: 15 April–29 April) by calculating the rate of change of CO_2 concentration (ppm) per unit time (s) after a noticeable wind event.

3 Results

3.1 Snowpack CO_2 concentration profile experiment

Initial field campaigns (2014) showed a relationship between wind speed and CO_2 concentration within the snowpack at NM1 and NM2. Under certain conditions, wind speed Wind speed sometimes had a very strong effect on CO_2 concentration within the snowpack (Figs. 3 and 4).

Trace amounts of snow at NM1 and NM2 began accumulating at the beginning of data collection (11 November 2013), with appreciable (> 25 cm) snowfall at both stations occurring on 15 December 2013, and remaining through the winter. Maximum snow depth at NM1 was 188 cm (26 March 2014), whereas maximum snow depth at NM2 was 137 cm (4 January 2014).

There was a negative correlation between average wind speed and CO_2 concentration 50 cm above the ground, an example of which can be seen in Figure 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 shows measurements at NM1 over the same time period from 125 cm above ground. 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~~, very near the measurement height. The closeness of the measurement height to the snow surface indicates these values were likely 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 (11 November 2013 to 26 March 2014), 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 the increase from 50 cm to 125 cm at NM1 and 0 cm to 125 cm at NM2, 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). Instrumentation error for the NM1 0 cm CO_2 probe prevented data collection at that height.

The measurements that satisfied all conditions accounted for an average of 15.1% of the data collected at a given station (NM1, NM2) and height in the snowpack (0, 50, 125 cm). This value does not represent an estimate of the CO_2 flux during the snow-covered period, since we used a biased filtering process to identify wind events during periods of steady snow cover.

3.2 Enhanced concentration profile experiment

We collected CO_2 concentration profile data at the enhanced NM2 station from 16:00 on 15 April 2015 to 11:00 on 29 April 2015, a total of 331 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 357 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}.

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 over this sampling period was relatively constant at 512 ppm. For some time periods between 15 April and 29 April 2015, there was a slight negative correlation between wind speed and snowpack CO_2 concentration (Fig. 5), however, this was not tested using the methodology of testing the winter 2014 data.

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 mimicking advection, and snow depth), soil diffusivity had negligible control on layers involving snow (Figs. 6a, 6b, and 6c), and is therefore not represented in those panels. Soil diffusivity showed some control on the modelled soil layer (Fig. 6d).

We also considered time when analyzing the modelled data to investigate how CO_2 concentration is affected during the "wind event" recovery period as the system works its way towards equilibrium (immediate change) and once the modelled system had recovered to an equilibrium state. Equilibrium ~~specifically~~ refers to no change in the modelled storage flux, or when storage flux had returned to the initialized condition of 1 μmol $m^{-2}s^{-1}$. ~~)~~ The two time "scenarios" considered were: 1) at 10 minutes, and 2) at 8 days following the simulated "wind event". The 10 minute scenario represented "immediately following a wind event" and the 8 day scenario represented "once equilibrium had been reached".

In the modelled topmost layer of snow (Fig. 6a), the maximum fraction to which CO_2 concentration was depleted was 0.39, once equilibrium was reached after a severe wind event. Snow depth had no effect on CO_2 depletion for either 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 a factor increase in short-term CO_2 flux (Fig. 6c). Scenarios at equilibrium (at 8 days post-event) 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 (at 10 minutes post-event) of any severity, and therefore there is significant overlap of the two 10 minute lines in Fig. 6d.

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. These time periods that did not meet the criteria may have resulted from the presence of vertical density variations (wind slabs, ice lenses) within the snowpacks at our field sites, plausibly causing lateral CO_2 flux. In addition to finding a negative correlation between wind events and CO_2 concentration within the snowpacks, 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, which indicates that the closer in the porous medium to the source of production of the trace gas (e.g. CO_2), the higher the concentration (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 or calculate 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. It is important to consider concentration gradients to help with our understanding of the underlying physical processes of CO_2 transport through snowpacks.

As the measurements taken at each of the snowpack heights at each of the stations satisfied all specific conditions for an average of 15.1% of the time analyzed, we can conclude that advection showed some control over snow CO_2 transport for this location for the equivalent of 20.4 days during the 135 day period in 2014 (12 November 2013 to 26 March 2014). This value did not represent the percentage of annual flux during the snow-covered season (Liptzin et al., 2009), though did confirm that advective transport needed to be taken into account when studying snowpack CO_2 transport. It also gives an indication of how much data was eliminated for analysis, biasing our results.

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. Additionally, Rains et al. (2016) showed that changes in wind speed at multiple hour frequencies (greater than 10 hours) could be more effective than atmospheric pressure pumping when explaining changes in snowpack CO_2 concentration. These processes of different timescales and different mechanisms (atmospheric pressure changes, wind) affect CO_2 concentration gradients and fluxes measured with Fick's law by ventilating diffusive media, like snowpacks~~, on these timescales~~. The ventilation, no matter the timescale, affects the CO_2 concentration gradient by mixing atmospheric air into diffusive media where CO_2 typically pools, thereby affecting the CO_2 flux from the top of the snowpack. Our work showed how persistent wind and an enhanced diffusive profile 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 more longer continuous wintertime CO_2 records, similar to this one, it may be possible to extricate these synoptic process periodicities in addition to the mid-range frequencies we investigated.

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 created with induced increases in snowpack diffusivity after model initialization, which worked well to mimic wind events.

In general, when snowpack diffusivity was instantaneously increased in this diffusive transport model, we observed rapid changes in the snowpack CO_2 concentration, CO_2 storage flux, and soil CO_2 concentration, similar findings to Bowling and Massman (2011 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 in terms of both rate of change (flux) and overall concentration change.

This modelling work showed that we can simplify the impacts of sustained advection on CO_2 in a soil-snow system to an effective diffusion problem. This approach was less complicated than other models that use the diffusive-advective coupled solution approach.

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 (using the 2015, enhanced experiment). Figure 5, which displays a time series of CO_2 concentrations and wind speed over two weeks in late April 2015, shows that despite similarly variable wind conditions, snowpack CO_2 concentrations throughout the first week vary less than the CO_2 concentrations observed in the second week. The lack of variation in the first week could be due to a variety of reasons, including the composition of the snowpack, or other meteorological conditions like temperature or humidity. Despite the variation through the two week period, it was still possible to discern change in CO_2 concentration after a wind event (Table 4).

Table 3 summarizes the calculated rates of change of modelled CO_2 concentration at varying snow depths, at low and high simulated wind speeds (induced 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 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 ($-0.07, -0.04, -0.20. -0.04$ ppm s^{-1}) were of approximately the same order of magnitude as the rates of change in the modelled events (ranging from 0.00 to -2.08 ppm s^{-1}). This indicated that the model was able to mimic advective events with some accuracy. Though it may be possible like in other studies (Latimer and Risk, 2016) to apply an iterative procedure to our model with the conditions we observed in the field (e.g. initial CO_2 concentration), we deemed that to be unnecessary. This is because our primary goal was to properly illustrate the underlying physics of CO_2 transport through snowpacks. As such, matching the model conditions exactly to the field conditions was not required.

This study showed the importance of continuous monitoring of CO_2 concentrations and fluxes from soils through snowpacks. Similarly, Webb et al. (2016) and Rains et al. (2016) highlighted the non-growing season contributions to annual CO_2 flux. ~~They also~~ Webb et al. (2016) 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). Rains et al. (2016) noted that there are benefits and disadvantages to the EC, flux gradient, and chamber methodologies for non-growing season soil CO_2 flux measurements, and that accurate parameterization of advective transport through snowpacks is important, regardless of the methodology. This is particularly true because of the likelihood that CO_2 flux through snowpacks is often underestimated (Rains et al., 2016). Accompanying these findings, we ~~noted~~ agreed that infrequent measurement can lead to significant error in the annual C budget of various ecosystems once inaccurate values are scaled up (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 advective effects of wind, in order to capture the uncertainties of soil CO_2 emissions in snow-covered ecosystems.

5 Conclusions

Although this study was conducted at one site over two winters, the findings have implications for measuring wintertime CO_2 fluxes in snow-covered environments. This is important for continued careful assessment of the soil C pool and fluxes of these snow-covered regions, which are experiencing increasing temperatures and variations in precipitation patterns.

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 total accounting purposes, eddy covariance records may not be effective in determining specific 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. Additionally, in situ sensors are typically cheaper and can be more easily and frequently deployed than eddy covariance methods. 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 shows 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, as done in this study. 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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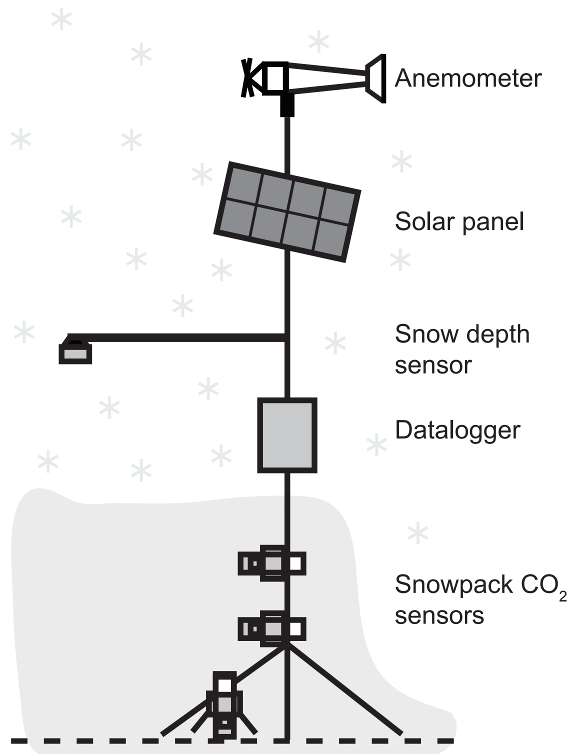

Figure 1. Schematic of initial (2014) CO_2 monitoring stations (NM1, NM2) at North Mountain, Cape Breton. Snowpack CO_2 sensors were at 0 cm, 50 cm, and 125 cm within the snowpack (diagram not to scale).

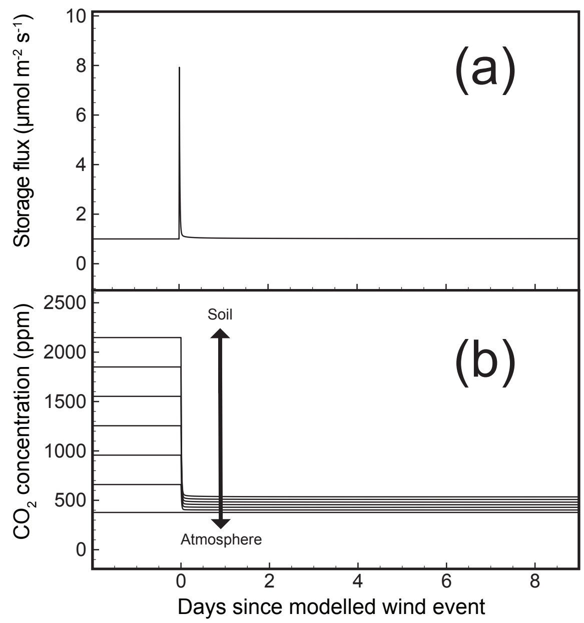

Figure 2. An instantaneous change in snowpack diffusivity after model initialization mimics advection. **(a)** Shows the modelled storage flux with an induced change in snowpack CO_2 diffusivity. **(b)** Shows the corresponding change in snowpack CO_2 concentration at every 10 cm. Soil diffusivity = 1.00×10^{-7} $m^2 s^{-1}$, stepped snow diffusivity $= 9.08 \times 10^{-5}$ $m^2 s^{-1}$, and snow depth = 60 cm. The Soil-Atmosphere arrow indicates depths within the 60 cm snowpack: highest modelled CO_2 concentrations occur at the soil-snow interface, whereas lowest modelled CO_2 concentrations occur at the snow-atmosphere interface, before and after the advective "wind event".

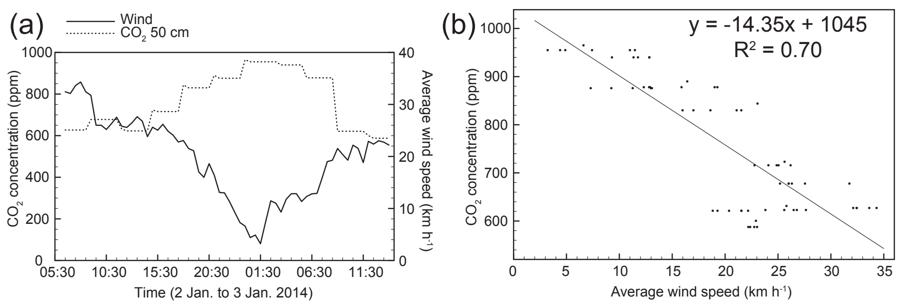

Figure 3. **(a)** Time series of wind speed and CO_2 concentration at 50 cm above the ground within the snowpack from 06:30 on 2 January 2014 to 14:00 on 3 January 2014 at NM1. Average snow depth at NM1 over this time period was 124 cm. **(b)** The corresponding linear regression of CO_2 concentration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

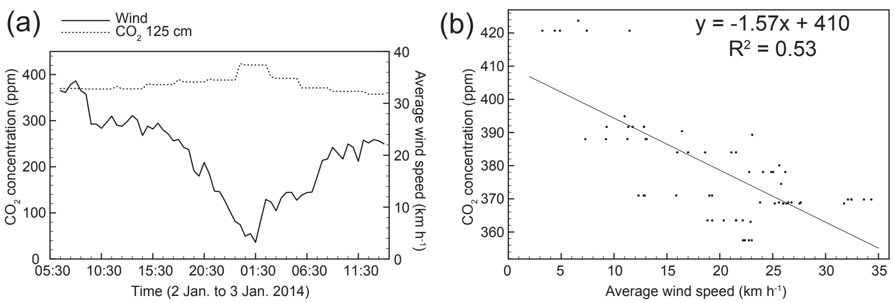

Figure 4. **(a)** Time series of wind speed and CO_2 concentration at 125 cm above the ground from 06:30 on 2 January 2014 to 14:00 on 3 January 2014 at NM1. Average snow depth at NM1 over this time period was 124 cm. Therefore, these CO_2 values were a good representation of the snow-air interface.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

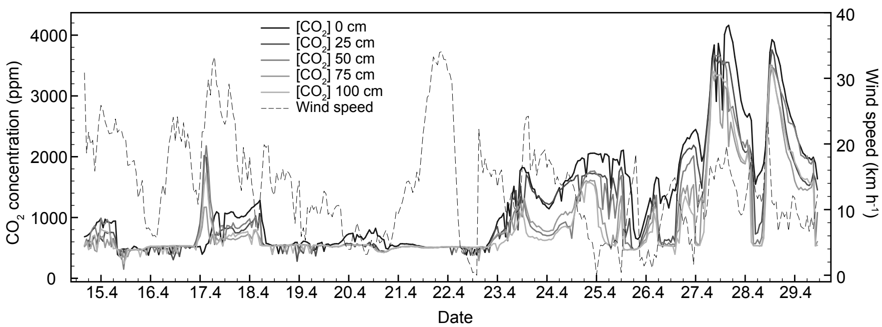

Figure 5. Time series of enhanced profiler experiment (winter 2015) CO_2 concentrations throughout the snowpack and wind speed at NM2 over 2 weeks during late winter 2015 (15 April–29 April). Measurements were recorded hourly.

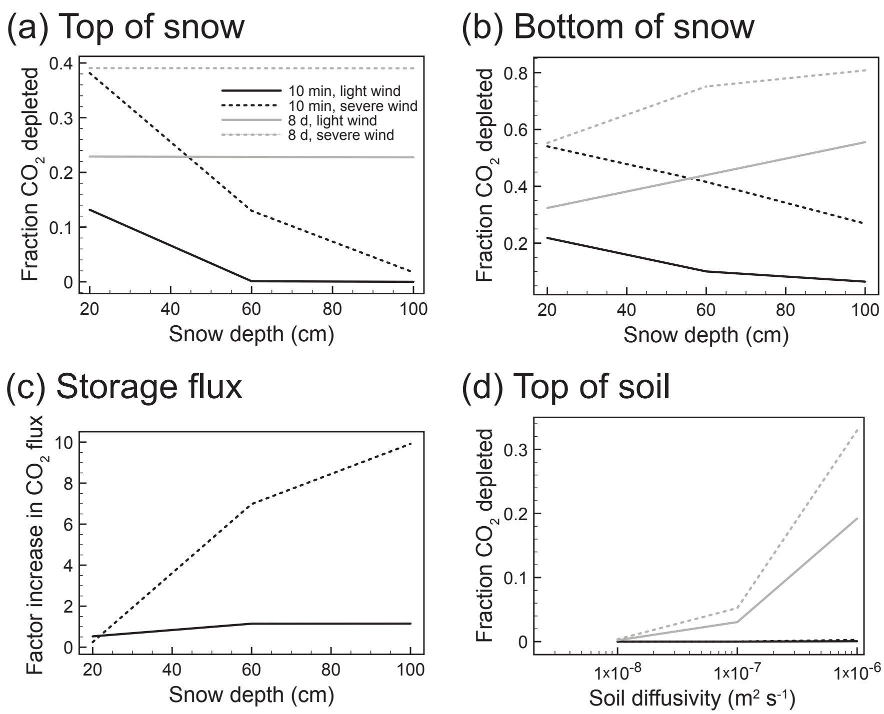

Figure 6. (a) Modelled results at top of snowpack shown as the fraction of CO_2 concentration depleted from the snowpack. **(b)** Modelled results at bottom of snowpack shown as the fraction of CO_2 concentration depleted from the snowpack. **(c)** Modelled storage flux, shown as factor increase in short-term CO_2 flux. Scenarios at equilibrium (8 days) were incalculable (not shown), as there was no change in CO_2 concentration once equilibrium was reached. **(d)** Modelled CO_2 at the topmost soil layer, shown as the fraction of CO_2 concentration depleted from the snowpack. There was very minimal effect on the fraction of CO_2 depletion for immediate scenarios (10 minutes), and so there is significant overlap of the two 10 minute scenarios (light wind and severe wind).

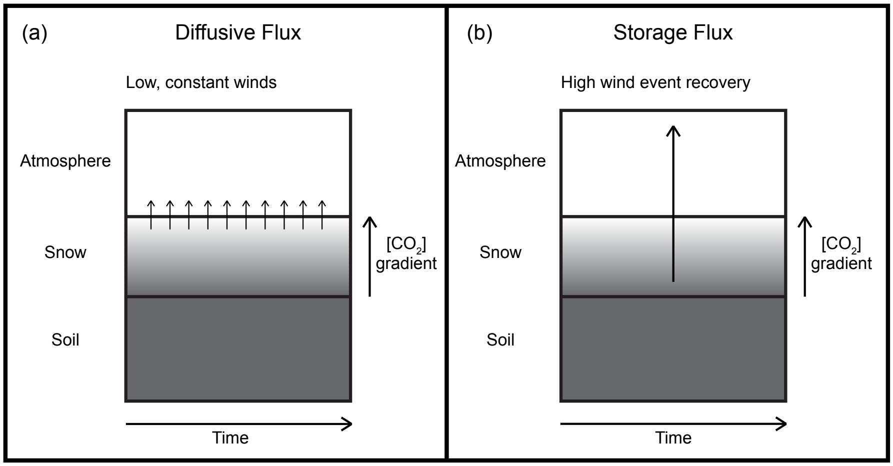

Figure 7. Conceptual diagram of diffusive versus storage flux. **(a)** Diffusive flux through a snowpack, with CO_2 originating from soils and consistently passing through a diffusive medium into the atmosphere as a result of a concentration gradient. Small arrows indicate low levels of diffusive flux that are prevalent and constant through time. **(b)** Storage flux through a snowpack, with CO_2 originating from soils, pooling in a diffusive medium, and then released to the atmosphere at a higher rate (than diffusive flux) following a high wind event, which has ventilated the top of the diffusive medium and steepened the concentration gradient. One, larger arrow indicates the higher rate and lower frequency of storage flux out of snowpacks when compared with diffusive flux.

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. Soil diffusivity ranged logarithmically, whereas snow diffusivity and snow depth ranged linearly. We ran the model with all possible permutations of these parameters.

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

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. Instrumentation error for the NM1 0 cm CO_2 probe prevented data collection at that height.

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

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

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
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