Thank you to the referees for their valuable and insightful comments. We have addressed each comment individually below and the recommended major revisions have been made to the manuscript. The marked-up version of the manuscript is included here, showing all changes. In addition to the major revisions, small editorial adjustments and changes were made as needed. We believe that all of these changes together have resulted in an improved manuscript.

Thank you for your time, comments, and consideration.

Sincerely,
Laura Graham

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

**By F.A. Rains (Referee 1)**

**(referee comments in black, author responses in blue)**

General Comments

First of all, I would like to say this was a very well put together study. Having performed wintertime respiration measurements myself, I know that it is not an easy task, kudos. Also, the system design seems robust, and accurate. Please take the below questions/comments with an open mind. Does the rate of flux affect the total quantity of CO2 released to the atmosphere? A bit of a rhetorical question, however this seems pertinent. It's clear that total C released is obviously a significant metric, but perhaps you could expand on how/why the rate of release is significant.

Thank you kindly. The referee's insightful and thoughtful comments will help clarify some key concepts throughout our study.

The question of whether the rate of flux affect the total quantity of CO2 released to the atmosphere is indeed important, and should not be overlooked. Though we mentioned in the Introduction the importance of organic C reserves in high latitude soils, we acknowledge that we neglected to make the connection to fluxes from soils and their contribution to atmospheric CO2 concentrations. This detailed is added to the introduction, as suggested, along with corresponding references (e.g., Raich et al., 2002).

You mention a trend of thinning snowpack in North America over the last number of decades. Also mentioned is the insulating effect that a deeper snowpack plays in allowing microbes to exist/or allowing for microbial respiration. It would follow logically then that assuming no change in air temperature, a thinning snowpack would decrease microbial, wintertime respiration by allowing the soil to reach sub 0 Celsius, or whatever that lower threshold may be. This may be slightly off topic but it seems related and pertinent. This could perhaps be addressed by mentioning other long term meteorological trends in North American winters, such as average air temperature, etc…

Thank you for bringing this up. There are certainly some perceptible flaws in this logic, which can be clarified with the addition of detail regarding long-term meteorological trends in North American winters. One helpful assumption is that this thinning snowpack is a result of increasing air temperatures with the onset of anthropological climate change (rather than assuming no change in air temperature). Dyer and Mote (2006) help to address this, with their study indicating earlier onset of spring melt (associated with higher temperatures and variations in precipitation). The most important details are perhaps that there is still significant global snow coverage despite increasing global temperatures, and that soil respiration occurs beneath this snow. Thinning snowpacks are certainly prevalent on average, but air with the coldest temperatures have the lowest ability to hold water vapour—so more intense individual snow events are likely to occur with increasing air temperatures.

Content Comments

Section 1, lines 28-29. An example of “underestimating” winter contribution to atmospheric C would be supportive of your statement. It seems that assumptions are being made that current models assume that the wintertime contribution is nil. In fact some models may over estimate this variable. Again, an example of a widely used, modern model that excludes or under represents wintertime production of CO2 would be illustrative.

The referee raises a good point here. Rewording is necessary, as it has proven difficult to come up with a specific example of a widely used, modern model that underrepresents wintertime production. Instead, we can draw our attention to the fact that seasonal variation in soil CO2 fluxes is not always mentioned in meta-analyses of global soil carbon studies (Scharlemann et al., 2014). Though wintertime measurements may have been incorporated into individual studies, by neglecting this information in a meta-analysis, the reader is left wondering if overwinter CO2 emissions were taken into account at all. Rather than imply that all current models assume that wintertime contribution is nil, we clarify in the manuscript that there is an existing abundance of growing season studies and a general lack of wintertime CO2 soil knowledge, along with continued efforts to include non-growing season/overwinter soil CO2 emission measurements in various models and inventories (Fahnestock et al. 1999, Raich and Potter, 1995).

Section 2.3 Model Development. Line 30. How did you calculate snow pack porosity, and tortuosity? Was snow pack density measured at different intervals or assumed homogeneous for the different “steps”? Also, Fick’s 1st Law of Diffusion is adequate for explaining flux in a 1-dimensional, relatively homogeneous medium. However we know that a snowpack stratigraphy is highly variable in space and time. Furthermore, assuming the non-static/non-homogeneous nature of wind and how it affects the snowpack in a very localized manor, could lateral flux occur with the snow pack. Also, elaboration on the role of dense wind slabs, sun crusts, and other ice crusts/lenses within the snowpack would be enlightening. In addition, it seems plausible that Fick's 2nd Law of Diffusion could potentially be useful.

Several assumptions were made for the model and have not been previously stated clearly. As suggested, detail is added to the manuscript to further explain parameters such as snow pack porosity and tortuosity. Snow pack diffusivity values in the model were based off a range of acceptable values to encompass all possibilities in iterations of model runs (at step-change). The step-change snow diffusivity possibilities range from "dense" snow (close to soil diffusivity values) to "light" snow (close to values of CO2 diffusivity in air). With this simplification, we were able to avoid the difficulty of estimating snow pack porosity and tortuosity, as snow pack diffusivity encompasses porosity and tortuosity measurements. Similarly, snowpack density values were not individually calculated or estimated, as snowpack diffusivity also encompasses snowpack density. It is important to note that we did not iterate through a range of snowpack diffusivities for pre-step-change conditions. Simply put, our initial conditions before the simulated advective event varied in snow depth and soil diffusivity, but not snow diffusivity. The referee brings up a critical point with our assumptions in terms of variation in snowpack density in space and time. Yes, our model does assume homogeneous density through vertical space, though "tests" a range of densities by working through a range of step-change snow diffusivities. It is certainly possible that lateral flux could occur within the snowpack, especially with wind slabs, sun crusts, and ice lenses. These physical features likely occurred at our field sites, but are unaccounted for in our modelling—as noted, modelling lateral CO2 transport through a snowpack with this 1-D model is considered impossible. Once we breach the possibility of Fick's 2$^{nd}$ Law of Diffusion, we could be over-complicating the situation for what we were looking to do: understand and observe the differences in diffusive and advective transport through snowpacks, despite the challenges of wintertime measurement. A few studies in the past have used Fick's 2$^{nd}$ Law of Diffusion to model similar events (Solomon and Cerling, 1987), but the overwhelming majority of CO2 diffusive studies use Fick's 1$^{st}$ Law. This is likely because Fick's 2$^{nd}$ Law of Diffusion reduces to Fick's 1$^{st}$ Law of Diffusion when it is simplified and applied to a steady state.

Conclusion. Why is total "accounting" via eddy covariance lacking in this regard? At the outset it would appear that eddy covariance can tell you not only the rate of flux, but the net production of CO2 for a given footprint (accounting?), while eliminating margin for error i.e. snowpack variability. What other sources of CO2 would be accounted for in addition to soil respiration that would not allow you assume all measured net wintertime CO2 was in fact from the soil? A few more sentences explaining your statements/reasoning that in-situ CO2 probes are superior would be enlightening.

Detail added, as suggested. We are not intending to give the impression that total "accounting" via eddy covariance is lacking in this regard. What we are trying to indicate here is that in-situ CO2 probes are not superior to eddy covariance, but are typically cheaper, can be deployed more easily and more frequently, and can give us an indication of what is going on within the snowpack in terms of CO2 transport.

Technical comments

Line numbering appears off, continues from abstract through first portion of introduction, and then switches back mid way. No other technical or grammatical errors were noted.

Thank you.

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**Author response to comment on “Explaining $CO_2$ fluctuations observed in snowpacks” by Laura Graham and Dave Risk**

**By Anonymous (Referee 2)**

**(referee comments in black, author responses in blue)**

This work presents both field data and a simple model to address a methodological problem with winter CO2 flux measurements. While both field and model data are presented it isn’t really a model-data comparison as the field data isn’t directly compared to the model data. As currently structured, there isn’t a convincing narrative nor is it clear what is novel. While continuous CO2 datasets are not that abundant, the authors don’t present that data and focus on a confusing method of comparing CO2 concentrations to wind speeds. They have adapted a soil diffusion model to the soil-snow system. I’m not sure if the model is too simplistic or if the text just needs greater clarity, but I couldn't follow how this model could help explain the field data. Figure 2 shows that it can create a step change in CO2 concentration gradient, but that isn't enough to be able to match the field data. The paragraph starting on P10 L8 describes how combining modeling and field data could be really powerful, but the temporal changes in the CO2 concentration gradient related to advection that we know happen based on the field data presented here and elsewhere weren't clearly shown. The writing is generally good; my main criticism is that the flow of the narrative, in particular the connections between paragraphs, could be improved. In addition, both the introduction and conclusion sections contain overly broad statements that aren't supported by the rest of the paper. There is certainly need for this type of work and perhaps with some modifications to the model and/or greater clarity of what was done in both the text and the figures could show how the model and field data can be compared, this paper would be acceptable for publication. Finally, I appreciate the authors presenting all the CO2 data. However, it is somewhat surprising to me that snowpack CO2 concentrations could be as low as 151 ppm on Page 6 or well under 400 in Figure 4 or that the atmospheric concentrations was 512 ppm on Page 7, about 100 ppm higher than what it should be. Could the authors justify these seemingly strange measurements?

Thank you kindly. Our goal is that the Biogeosciences community can easily understand this CO2 model-data work, and therefore we appreciate these thoughtful comments by the referee. Through this review process, we hope to clarify the text, improve flow, and solidify how this simple model can be used to help us understand the physical processes of CO2 transport through snowpacks—and not simply generate the CO2 concentrations observed in the field.

Variable concentrations are addressed below with the P6 L34 comment.

P1 L19-21 These lines are way too general for the rest of the paper. The paper is about making the winter flux techniques better not about the soil C and the global C cycle. Or at least it needs to be demonstrated how the results might directly affect the global C cycle.

Introduction altered, as suggested.

P2 L1-3 The authors haven't presented any evidence for yet about why rates might be underestimated

Referee 1 had a similar comment—refer to our reply to Referee 1 for details.

P2 L4-5 This paragraph is just about using the diffusion gradient in the snowpack method to measure soil flux. This method should be explained and its advantages and disadvantages to the other methods should be described.

Detail added, as suggested.

P2 L10-12 This is the key piece of knowledge that this paper is attempting to explain. There is a methodology for measuring $CO_2$ flux that has known limitations. The net result is that it is difficult to separate variability from advection (an artifact) from microbial processes (the actual goal). It would be very helpful if there was a standard correction that could be used with the diffusion based method to account for advection.

We agree, a standard correction that could be used with the diffusion-based method to account for advection would be very helpful. However, at this point, we must first understand the physical processes of $CO_2$ transport through snowpacks before we can move toward pinpointing a standard correction.

P2 L13-31 Somewhere in this paragraph it needs to be made clear that the assumption is that $CO_2$ production is happening in snow-covered soils, but there are methodological limitations to how the production is quantified. This paper is not about the controls per se, but about how to overcome the methodological limitations so that the mechanisms of $CO_2$ production can be studied.

Thank you for pointing this out. Detail added, as suggested.

P2 L32-34 It would be helpful to talk about of the role of timescale in advective processes in the introduction to justify why you are looking at the hours to days timescale. There is a mention of it in the discussion, but is important here too.

Detail added, as suggested.

P3 L14 Delete the sentence starting with obviously. How do “variable meteorological conditions” affect snow depth?

Sentence deleted, as suggested. Detail added to explain how “variable meteorological conditions” affect snow depth, as suggested.

P3 L16 How long were the measurements made during winter 2014? (as well as winter 2015 in line 34).

Thank you for picking up on this oversight. Detail added, as suggested.

P3 L32-37 I’m confused by this paragraph. In the preceding paragraph, it says that at each of the two stations there were $CO_2$ measurements at 0, 50, and 125 cm, but now it says 25, 50, 75, and 100 cm for NM2. Similarly, in this paragraph, it says the data were collected hourly whereas above it was half hourly. Were the Eosense sensor in addition to Vaisala sensors at the depths above? These sensors need more description. You already said that snow depth and wind speed were measured at both stations in lines 29-31. Somewhere in the methods or results can you indicate what the timing of snow-cover and the maximum depth were.

Detail and clarification added, as suggested. There were some differences and design improvements between the stations for winters 2014 and 2015, which should certainly be made clearer in this paragraph.

P4 L5-7 You need to say why it is important for steady state conditions that snow depth had not changed. Is there a quantitative way that this was determined?

Detail added concerning why it is important that snow depth had not changed. Yes, there was a quantitative way to determine "no change in snow depth". This detail will be added to the updated manuscript.

P4 L9-11 What does "ideal" mean?

"Ideal" in this sense refers to the best set of environmental conditions for which a strong negative correlation between CO2 concentrations and wind speeds could be found.

P4 L18-22 I'm confused about the time period selection. Let's say the snowpack didn't change depth from January 1 to January 5th. Did you look at that whole time period with one regression? In the caption for figure 2 it says that the average number of 30 minute measurements in the filtered dataset was 29-50 at different heights/sensors. Does that mean the snow depth was changing every day? Or was there some other criteria besides snow depth changing that set the length of time. It seems like the time period selection was based on finding a change in CO2 after an increase in wind speed. Is this assuming that advection is equally affecting the snowpack from the soil surface to the snow surface? Is that a valid assumption? I'm not convinced that this is the right approach to determine the effects of wind on snowpack CO2, but there needs to be a better justification and description of the approach.

The referee's understanding is correct—if the snowpack did not change depth from January 1 to January 5, that entire time period was looked at with one regression. We believe the referee is referring to the caption for Table 2, not Figure 2. The average number of 30-minute measurements is 29-50 at different heights/sensors to effectively indicate "average sample size", and does not necessarily indicate that the snow depth was changing every day. This n indicates the mean number of values (each value is one half-hourly measurements) that was used for each group of regressions (for a given sensor height at each station). Since measurements were recorded half-hourly, we can see how the average duration of each time period ranges from 15 h to 25 h. A potential conclusion from this could be that the snow depth is changing every day—however, there are three distinct criteria that were used for data filtering, as indicated in section 2.2 and in the caption for Table 2. We recognize that this filtering biases our dataset towards having negative relationships between CO2 concentration and wind speed, but this was necessary in order to pick out the advective events we were interested in investigating further.

Is there a different way to do this calculation with fewer assumptions? For example, could you calculate the R2 for the snowpack concentration gradient every 30 minutes and plot that vs. wind speed as a test of whether the wind speed affects the predicted gradient with zero wind? Or compare the concentration gradient to the wind like Seok et al. (2009)? If you examine every time point there is the problem that the previous time points likely affect the relationships. Perhaps you could also try averaging different lengths of time (e.g. 30 minutes to 12 hours or longer)?

The referee presents an interesting suggestion here. However, given the setup of our experiment, it would not be possible to calculate the R2 for the snowpack concentration gradient every 30 minutes. Though it is possible to have higher frequency measurements with the instrumentation we were using, we recorded one value for every 30-minute time interval in order to save battery power—a concern especially when attempting to collect continuous overwinter measurements (with limited solar power, while at a remote location). Evidently, a 1-point regression would not be possible. Though it may be possible to compare concentration gradient to the wind like Seok et al. (2009) with our 2014 data, we reserved this for our 2015 data (Figure 5) when we had more sample heights throughout the snow profile. Though we could try averaging different lengths of time, we are unsure of what purpose that would serve, as we were specifically looking for time periods within our dataset when we would find a negative correlation between wind speed and CO2 concentration within the snowpack.

More detail can be added to this section, especially to indicate that we acknowledge a bias in our data filtering technique.

P5 L6-11 This paragraph needs to be clarified to describe what the model is doing. How are the initial conditions set? What are "step changes in transport rate?" I thought there were step changes in the parameters. Based on figure 2 there is some constant CO2 gradient before time zero and then there is a step change in the diffusivity and the CO2 gradient adjusts quickly. Is there a fixed emission of CO2 from the soil and then the combinations of the diffusion/depth parameters determine the CO2 concentration gradient? Is there a temporary step change and then it returns to the initial value? Or does Storage flux needs to be defined, perhaps even in the introduction. Why is the soil diffusivity included in the model? How is snow depth included? Is the model run with all possible permutations of the 3 parameters?

Detail can be added and this paragraph can be clarified, as suggested. For instance, initial conditions are mentioned in the last two sentences of that paragraph already, but perhaps not clearly stated as initial conditions: "Snow diffusivity before the step change was held constant at $8.06 \times 10^{-6}$ m2s−1. Each model run began with the system in equilibrium state (with storage flux set to 1 μmol m2s−1)." "Step changes in transport rate" refers to the step changes in the parameter "snow diffusivity at step change"—this can be easily clarified. The referee is correct: there is a fixed emission of CO2 from the soil in the model, and the changes in parameters determine the CO2 concentration gradient (and therefore calculated storage flux). A definition of storage flux can be added for further clarification. Soil diffusivity was included in the model to determine if CO2 transportation in a diffusive model behaved as expected with an abrupt vertical switch in diffusivity. A description of how snow depth is included is in the paragraph immediately preceding the paragraph in question. Yes, the model was run with all possible permutations of the 3 parameters—this will be clarified both in the text and in the Table 2 caption.

P5 L24-25 What does “the rate at which modelled $CO_2$ responded to an induced wind event” mean? What is the rate? Is an induced wind event the same as an advective wind event in line 15?

The “rate at which modelled $CO_2$ responded to an induced wind event” refers to change in $CO_2$ over time (ppm/s) with the step change in snowpack $CO_2$ diffusivity. Graphically, it is the slope of the line of recovering modelled flux. Yes, an induced wind event is the same as an advective wind event in line 15. Clarification added, as suggested.

P5 L30-31 What is the “enhanced concentration profile experiment?” How were the data processed?

Clarification added, as suggested. The “enhanced concentration profile experiment” is the winter 2015 data. The data “processing” refers simply to how the rate of change of $CO_2$ per unit time after a noticeable wind event was calculated (indicated at the end of the sentence).

P6 L14-19. I’m confused by this example. I thought the ideal situation was when wind speed increased gradually and then abated. These figures show the opposite with wind speeds gradually decreasing and then increasing. Figure 3 seems like a good example, but I’m confused by Figure 4. The snow-atmosphere interface seems hard to measure. Is there a time period with a deeper snowpack that could be shown instead? Why are the $CO_2$ concentrations so much lower (360-390 ppm) than atmospheric (512 ppm)? There was a brief period when the concentration was around 420 ppm that seems to be driving the relationship in this case. If those few hours of data were removed, it doesn’t look like there would be much of a relationship.

Clarified, as suggested. For instance, though wind speed increasing gradually and then abating is stated as an ideal situation, the opposite process could be considered similarly ideal—this edit has been made. Figure 3 shows the same time frame, but deeper in the snowpack. Showing these figures side-by-side allows for direct comparison of how the $CO_2$-wind relationship changes with depth into the snowpack. The $CO_2$ concentrations here are considerably lower than the average reported atmospheric concentration, yes. However, there is considerable variability in atmospheric $CO_2$ concentrations throughout the sampling period.

P6 L20-22 Wasn’t data collected the whole winter? The data shown in figure 3 and 4 are not included in this time period. This should be clarified in the methods section.

Clarified, as suggested.

P6 L22 How come there is no data for the 0 depth on NM1?

Clarified, as suggested.

P6 L34 How can you get a concentration of 151 ppm $CO_2$ in the snowpack? Is $CO_2$ being consumed or is it some kind of measurement error? Similarly, why is the atmospheric $CO_2$ 512 ppm (P7 L5)? Is this a calibration error.

Detail added, as suggested. Upon further inspection, it is possible that the 151 ppm value is a result of a measurement error (ice in tubing, for example). Other than the 151 ppm value, most values are > 290 ppm. Average atmospheric CO2 over the sampling period in 2015 is calculated as 512 ppm. There is no indication that this is a calibration error, though it is important to recall that the sensors used have an error of 1-2%. Atmospheric wintertime CO2 concentrations in the northern hemisphere are typically higher than summertime CO2 concentrations due to changes in biospheric processes (less take-down of CO2 by vegetation, for example).

P7 L5-7 Either test for a relationship between wind speed and CO2 or delete this sentence. It is surprising to me that so much of the first week or so there is no concentration gradient in the snowpack. That is on the 16th-17th and 19th-23rd the whole snowpack is essentially the same as the atmosphere. This seems somewhat surprising. It doesn't seem that much windier than the second week of the experiment. What is happening?

Clarification added, as suggested. For instance, "may have" is changed to "was". Based on the data we collected, it is unclear why the snowpack concentrations from the $16^{th}$-$17^{th}$ and $19^{th}$-$23^{rd}$ are essentially the same as the atmosphere. Possibilities include ice lenses, temperature changes, or changes in density. Referee 1 had a similar comment—refer to our reply to Referee 1 for details.

P7 L18, L23 What does equilibrium mean? Based on Figure 2 it seems like the model has some step change in parameter and then the CO2 gradient adjusts instantaneously. Similarly, I don't know what a scenario is.

Detail added, as suggested. Equilibrium refers to no change in the modelled storage flux (storage flux at a constant 1 μmol m2s−1). A scenario is a model run under a given set of parameters.

P7 L31-34 I'm not sure why soil diffusivity was included the model as a parameter.

Detail added, as suggested. Explanation also found with P5 L6-11 comment.

P8 L6-13 There are two different phenomena described in this paragraph. One is that there is a monotonic decrease in CO2 from the soil surface to the snow surface if the only source of CO2 production is the soil. I'm sure with ice lenses or if the density of the snowpack isn't constant that there are ways this couldn't be true, but it seems like this should generally be true. The more important question is whether there is a relationship between CO2 concentration and wind speed. The authors have chosen to look over time to see if

Referee 1 also brought up the consideration of ice lenses and variations in density—refer to our response to Referee 1 for further detail. P8 L6-13 comment was left incomplete by Referee 2.

P8 L14-17 You should either calculate storage fluxes or remove this paragraph.

Storage fluxes could perhaps be calculated with this data. However, it is still important to look at concentration gradients before over-complicating our understanding of the physical processes.

P8 L18-26 I'm not sure why you can conclude that advective transport needs to be taken into account by the fact that during 33.6% of the time analyzed there is a relationship between CO2 and wind speed. These two paragraphs don't have much quantitative analysis in them.

The 33.6% value refers to a simple calculation of percentage of wintertime measurements that satisfied all three conditions. This statistic is important especially since the filtering process biased the data we presented. This is clarified, as suggested.

P8 L27-35 Can you give a clearer description of how these processes that occur at different time scales would affect the CO2 concentration gradients and the fluxes measured with Fick's Law? What are "a continuously enhanced friction velocity" and "an enhanced diffusive regime?" It seems like 54 days of measurements should be enough to capture some synoptic variability if you looked for it.

Detail and clarification added, as suggested.

P9 L9-12 I'm not sure I understand exactly what the model did or what equilibrium means. If I look at figure 2 it seems like an instantaneous change in diffusion led to an instantaneous chance in concentration gradient. I don't see any change over time in CO2 concentration which is what I would have thought disequilibrium would be.

Clarification made, as suggested. Figure 2(b) does in fact indicate an instantaneous change in CO2 concentration, along with the instantaneous change in concentration shown in Figure 2(a).

P9 L13-14 I don't understand these sentences.

Sentences clarified in the text. Generally speaking, these sentences are meant to indicate that the diffusive model used can be used to mimic advective events, and that this method is simpler than other models that use a diffusive-advective coupled approach.

P9 L16-27 Why not try to match the model conditions exactly to the field conditions to start at least in terms of CO2 concentration

Other studies have applied an iterative procedure to do something similar, as the referee suggests (Latimer and Risk, 2016). Though we could have attempted this, our primary goal was to properly understand and illustrate the underlying physics of CO2 transport through snowpacks. As such, matching the model conditions exactly to the field conditions is unnecessary.

P10 L6-7 Just like the beginning of the introduction, this sentence seems like an overreach with no connection to the rest of the text.

Adjustment made, as suggested.

P10 L11-14 This seems like where model data synthesis could really move this field forward.

We agree. However, we believe that we must first have a thorough understanding of the most basic physical processes of $CO_2$ transport within and through the snowpack. There are many other more complicated ways of modelling $CO_2$ transport in various diffusive media—this is a simpler technique to get to the basics of the differences between diffusion and advection of $CO_2$ in snowpacks.

P10 L15-21 Alternative measures of $CO_2$ flux need to be discussed earlier in the manuscript.

Detailed added, as suggested. This is also mentioned in the comment referring to P2 L4-5.

P10 L22-27 This study show snow profile depletions, but I wouldn't say that it explains them. While I agree with the sentiments in the rest of the paragraph, they aren't direct conclusions of the work here.

Text altered, as suggested.

Figure 1. This figure can be deleted. Or it needs to be improved so that the labels match up to the icons and the depths are shown.

Figure improved. Depths are not shown, as the schematic represents two winters with slightly differing sensors depths.

Figure 2. Indicate that an instantaneous change in the diffusivity mimics advection. Storage flux needs to be defined in the text somewhere. Either call it storage flux or apparent storage flux. Indicate the depths on panel b.

Clarifications made, as suggested.

Figure 3. Use the data not the record number on the x axis. Would you expect there to be a hysteresis because of advection? That is, if you drew a line connecting all these points in time would the concentration be higher than average when the winds are decreasing and then lower than average as winds are increasing again? Or maybe vice versa? I realize it is not a crucial question for the model-data comparison, but it seems important for converting concentration gradients into fluxes.

Date used instead of record number on the x-axis, as suggested (applied also to Figure 4). If there is some sort of hysteresis due to advection, it would likely be very hard to distinguish in a time span of hours to days.

Figure 4. Why not pick a time to show when this sensor is really in the snowpack?

A corresponding time when the sensor is "really" in the snowpack is shown in Figure 3. By showing a sensor higher up in the snowpack (closer to the atmosphere) in this figure, we are able to demonstrate a difference in CO2-wind speed relationship with height within the snowpack.

Figure 5. The different colors/dashes are hard to see. It would be better if the wind speeds were in a separate panel. Atmospheric CO2 probably isn't necessary to snow either.

Clarification to the different colours/dashes has been done, as suggested. Atmospheric CO2 is removed, as suggested. We believe wind speeds on the same panel allow for easier direct comparison, even if the figure appears to be confusing at first glance. The wind speeds can be placed in a separate panel, if necessary.

Figure 6. The dashes are hard to distinguish. Why are there 4 cases for a and b but only 2 or 3 for c and d? Are the lines on top of each other? If so, make this clear in the caption.

Dashes altered, as suggested. There are 4 cases for a, b, and d, and only 2 cases for c. Lines are on top of each other in d. The 2 cases for c both refer to short-term storage flux—factor increase in CO2 flux for long-term storage flux is incalculable (0 divided by 0). These clarifications are added to the caption, as suggested.

Figure 7. I like the idea of a conceptual figure, but I'm not sure why lots of little arrows represent diffusion and one big arrow represents advection. Can you make something that shows how the concentration gradient and fluxes change over time in response to wind? Maybe some combination of the information in Figure 2 and Table 3 along with a calculation of the flux using Fick's law and a calculation of the storage flux over time?

A change to this conceptual figure with an "x-axis" demonstrating time will help clarify this confusion with different sized arrows representing diffusion and advection: small, constant movement of CO2 (diffusion) is represented with small arrows, whereas larger packages of CO2 (advection) moves less frequently and is represented with a larger arrow.

Table 2 is a good summary, but it seems like you can get rid of n as duration is essentially n/2

Though duration is essentially n/2, it is important to show both n and duration. This is because they have different purposes: n gives an indication of the robustness of the R2 measurements, whereas duration gives a more practical visualization of the length of the time periods.

Table 4 Can these events also be shown on figure 5? The measurement depth is in the caption and can be removed from the table.

Thanks for these two suggestions. If space allows, these events will be added to figure 5 (there is a lot already going on in Figure 5, but we understand the importance of pointing out the data that was analyzed further). Measurement depth removed from table, as suggested.

# 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

The global soil carbon (C) pool stores three times the amount of C as the atmosphere. Organic C reserves of in 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 (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 snow cover, pose challenges for measuring wintertime carbon dioxide ($CO_2$) fluxes (Liptzin et al., 2009), and overall, studies tend to neglect ecosystem respiration when soils are snow covered or when soil temperatures drop below freezingleading 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 individual studies (Scharlemann et al., 2014). Despite this skewed focus, soil $CO_2$ is still ~~exchanged~~ produced throughout the winter, even at ~~−5~~ −7°C ~~to −7C~~ (Flanagan and Bunnell, 1980; Coxson and Parkinson, 1987; Brooks et al., 1996). In some cases, ~~an~~ the insulating snowpack can ~~also protect~~ prevent soils from freezing completely~~. Even with the~~ , further stimulating soil $CO_2$ emissions. 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 ~~(IPCC, 2013), snow~~ (Dyer and Mote, 2006; IPCC, 2013). Dyer and Mote (2006) indicate 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 (approximately 7% per 1°C), 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). ~~Therefore, because~~ 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 ~~, current rates are likely underestimated~~(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 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. 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~~. Higher-resolution studies have shown that these variations depend less on microbial variation, and~~ , depending more on transport of $CO_2$ ~~(Bowling et al., 2009; Seok et al., 2009).~~ 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 $\mu$mol m$^{-2}$s$^{-1}$ to 1.2 $\mu$mol 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 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.~~ 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). 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). ~~Wind affects~~ 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).

Studies are increasingly showing that this non-diffusive (advective) mass transport (i.e. wind) through snow is significant, and must ~~therefore~~ be taken into consideration (Bowling and Massman, 2011), while considering the appropriate timescale. Advective transport of ~~traces~~ trace gases through naturally permeable media ~~such as soil and snow~~ 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. 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. 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.

~~In this study~~ 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 ~~these field stations~~ 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~~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~~ the winter, and ~~overwinter~~ over-winter $CO_2$ production from these soils is very likely, 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). ~~Obviously, gusts greatly exceed these mean values.~~ 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 ~~the winter of 2014.~~ 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.

~~Measurements~~ 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 ~~soil depth , at the soil~~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 ~~also recorded~~ continued to record 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~~ adjusted to hourly for 2015. The profiler system for the enhanced concentration profile experiment contained two Eosense eosGP ~~sensors, with a pumped system extracting snow~~ (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 ~~gas permeable waterproof sampling volumes at hourly frequency.~~ 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 examine the degree of concentration decrease after wind ventilation started, we ~~attempted to focus~~ 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. ~~We~~ 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 ~~reduce to data for which we understood that~~ 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). ~~While these~~ 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-third~~ one-fifth of all the measured data passed these filters and were included in the final analysis.

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 2.5, Field-model comparisons).

### 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~~ 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 ($\mu$mol 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 ($\mu$mol 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 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 set to 1 $\mu$mol 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 $CO_2$ 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 Initial condition snow diffusivity was held constant at $8\times10^{-6}$ 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 $8\times10^{-6}$ (equal to the snow diffusivity at initial conditions) to $9.08\times10^{-5}$ m$^2$s$^{-1}$ (approximately the diffusivity of $CO_2$ in air) (Table 1). 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 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 a step an induced change in $CO_2$ snowpack diffusivity, which was the mechanism used to mimic an advective wind event. Snow diffusivitybefore the step change was held constant at $8.06\times10^{-6}$ m$^2$s$^{-1}$. Each model run began with the system in equilibrium state (with storage flux set to 1 $\mu$mol m$^2$s $^{-1}$"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 model is considered impossible. 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 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 ($m^2s^{-1}$), 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.~~ 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 $1.00 \times 10^{-7}$ $m^2s^{-1}$. Additionally, only "low wind" and "high wind" events were considered, which had ~~stepped~~ induced snow diffusivities of $1.72 \times 10^{-5}$ $m^2s^{-1}$ and $9.08 \times 10^{-5}$ $m^2s^{-1}$, 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~~ winter 2015: 15 April–29 April) ~~to calculate~~ 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 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~~(Fig. ~~, 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 ~~is also of~~ shows measurements at NM1 over the same time period ~~as in Fig. 3, but the $CO_2$ concentration was measured at~~ from 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~~ winter 2014 (~~1 February 2014 to 27~~ 11 November 2013 to 26 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~~ 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 ~~33.6~~an average of 15.1% of the ~~time analyzed~~data collected at a given station (NM1, NM2) and height in the snowpack (0, 50, 125 cm).

### 3.2 Enhanced concentration profile experiment

We collected $CO_2$ concentration profile data at the enhanced NM2 station from 16:00 on ~~4~~ 15 April 2015 to 11:00 on 29 April 2015, ~~which is~~ a total of ~~356~~ 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 ~~151~~ 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 ~~4~~ 15 April and 29 April 2015, there ~~may have been a~~ 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 ~~at step change~~ mimicking advection, and snow depth), soil diffusivity had negligible control on layers involving snow (Figs. 6a, 6b, and 6c), ~~though~~ 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 $\mu$mol $m^{-2}s^{-1}$.) 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 ~~to a maximum fraction of~~ was 0.39, once equilibrium was reached after a severe wind event. Snow depth had no effect on $CO_2$ depletion for ~~both~~ 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. Analysis of 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 33.6an average of 15.1% of the time analyzed, we can conclude that advection showed significant some control over snow $CO_2$

transport for this location ~~during the 54~~ for the equivalent of 20.4 days during the 135 day period in ~~2014.~~ 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), ~~although it did indicate~~ 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. These processes of different timescales 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 ~~a continuously enhanced friction velocity (persistent wind )~~ persistent wind and an enhanced diffusive ~~regime~~ 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 ~~induced with abrupt changes~~ created with induced increases in snowpack diffusivity after model initialization, which worked well to mimic wind events.

In general, when ~~rapid step changes in snowpack diffusivity were inputted into a~~ snowpack diffusivity was instantaneously increased in this diffusive transport model, we observed rapid ~~disequilibria~~ changes 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 in terms of both rate of change (flux) and overall concentration change.

This modelling work showed that we can ~~reduce the effects~~ simplify the impacts of sustained advection on $CO_2$ in a soil-snow system to an effective diffusion problem. This approach was ~~simpler than~~ 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 (~~for the~~ 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 (~~step~~ 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 ~~, 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. 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) 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~~ 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 effects of wind, in order to capture the uncertainties of soil $CO_2$ emissions in snow-covered ecosystems.

## 5 ~~Conclusions~~

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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. 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 ~~actual~~ 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 ~~explains~~ 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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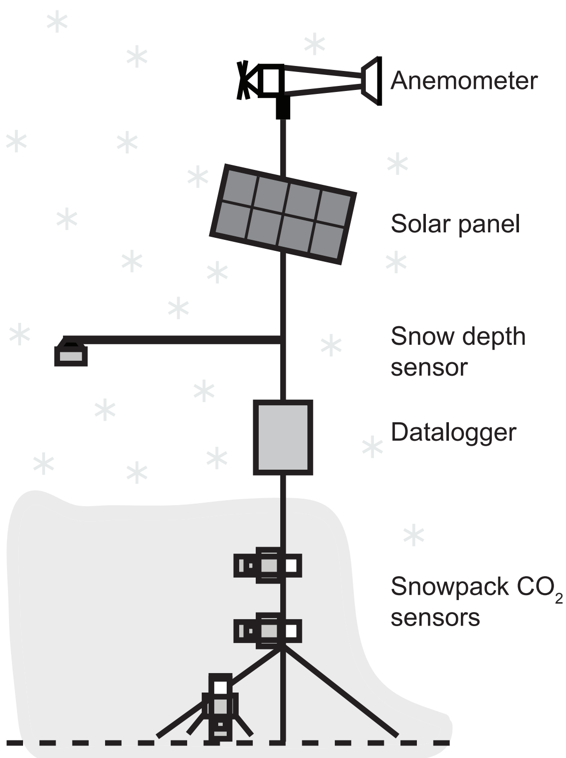


**Figure 1.** Schematic of initial (2014) $CO_2$ monitoring stations (NM1, NM2) at North Mountain, Cape Breton. Snowpack $CO_2$ sensors were at 0 cm, 50 cm, and 125 cm within the snowpack (diagram not to scale).

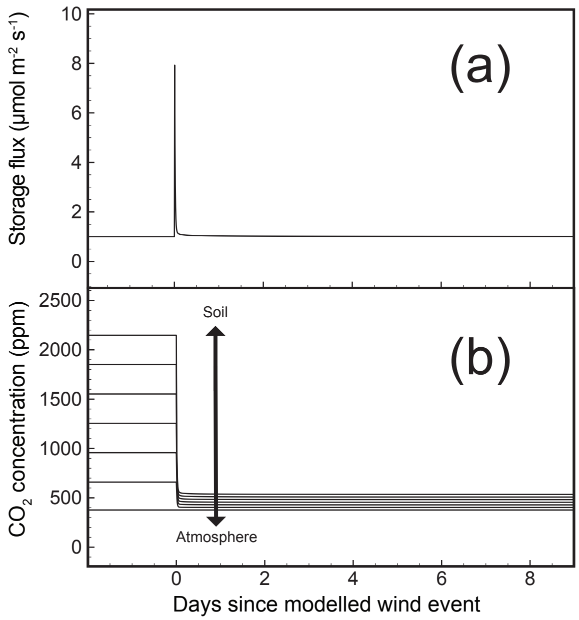


**Figure 2.** An instantaneous change in snowpack diffusivity after model initialization mimics advection. **(a)** Shows the ~~apparent~~ modelled storage flux with ~~a step~~ an induced change in snowpack $CO_2$ diffusivity. **(b)** Shows the corresponding change in snowpack $CO_2$ concentration at every 10 cm. Soil diffusivity = $1.00 \times 10^{-7}$ $m^2s^{-1}$, stepped snow diffusivity $= 9.08 \times 10^{-5}$ $m^2s^{-1}$, 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".

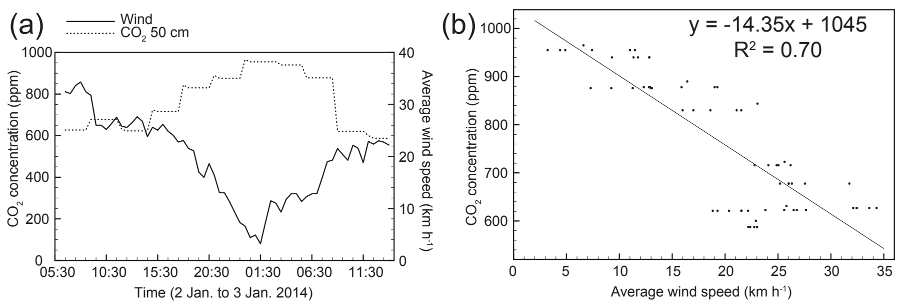


**Figure 3.** **(a)** Time series of wind speed and $CO_2$ concentration at 50 cm above the ground within the snowpack from 06:30 on ~~1~~ 2 January 2014 to 14:00 on 3 January 2014 at NM1. Average snow depth at NM1 over this time period was 124 cm. **(b)** The corresponding linear regression of $CO_2$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

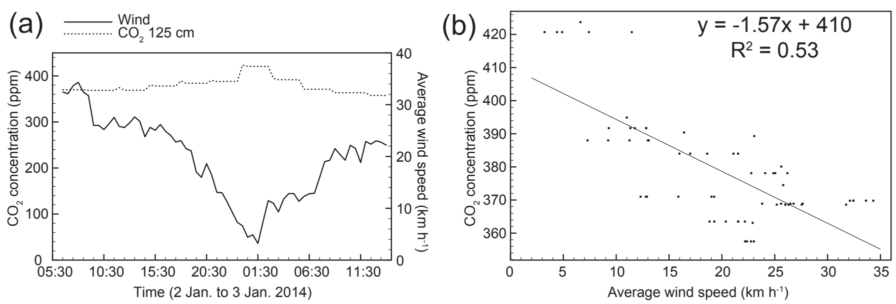


**Figure 4.** **(a)** Time series of wind speed and $CO_2$ concentration at 125 cm above the ground from 06:30 on ~~1~~ 2 January 2014 to 14:00 on 3 January 2014 at NM1. Average snow depth at NM1 over this time period was 124 cm. Therefore, these $CO_2$ values were a good representation of the snow-air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

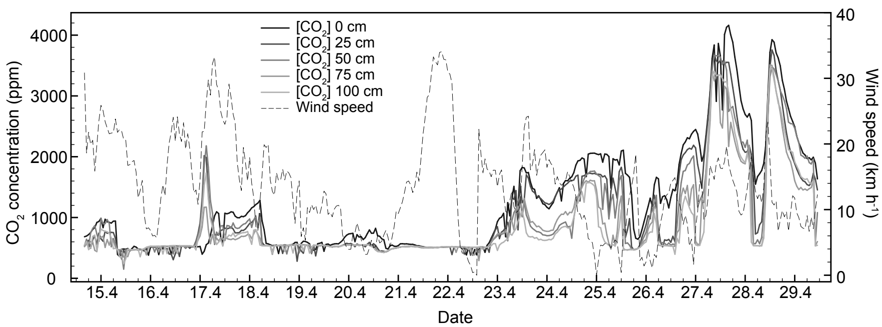


**Figure 5.** Time series of enhanced profiler experiment (winter 2015) $CO_2$ concentrations throughout the snowpack ~~, atmospheric $CO_2$ concentration,~~ and wind speed at NM2 over 2 weeks during late winter 2015 (15 April–29 April). Measurements were recorded hourly.

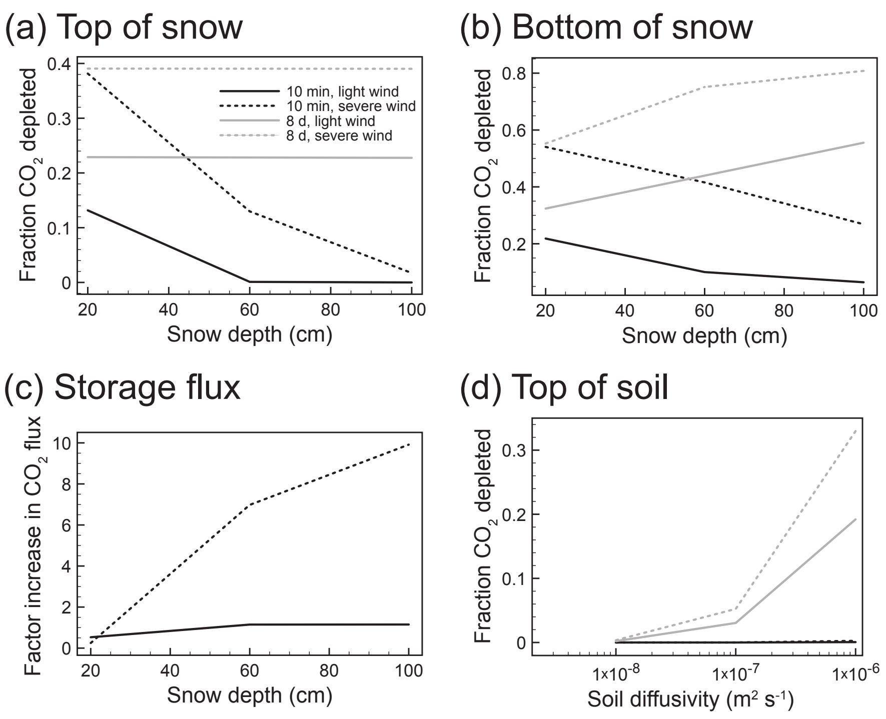


**Figure 6.** **(a)** Modelled results at top of snowpack shown as the fraction of $CO_2$ concentration depleted from the snowpack. **(b)** Modelled results at bottom of snowpack shown as the fraction of $CO_2$ concentration depleted from the snowpack. **(c)** Modelled storage flux, shown as factor increase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

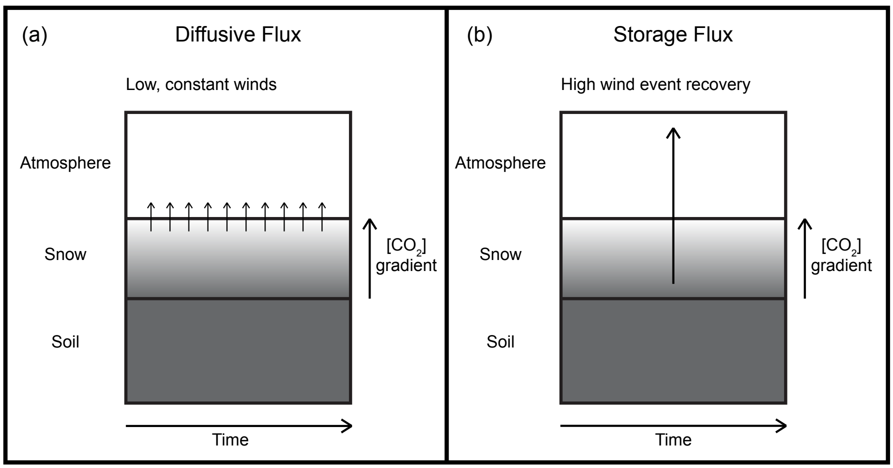


**Figure 7.** Conceptual diagram of ~~(a)~~ diffusive versus storage flux. **(a)** Diffusive flux through a snowpack, with $CO_2$ originating from soils and ~~**(b)** storage flux~~ consistently passing through a ~~snowpack~~diffusive medium into the atmosphere as a result of a concentration gradient. ~~Low~~ Small arrows indicate low levels of diffusive flux that are ~~more~~ prevalent and constant ~~than storage~~ through time. **(b)** Storage flux through a snowpack, ~~which occurs~~ 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** | ~~**Increments**~~**Number of values tested** |
|---|---|---|
| Soil diffusivity | $1 \times 10^{-8}$ to $1 \times 10^{-6}$ $m^2s^{-1}$ | 3 |
| Snow diffusivity at step change | $8 \times 10^{-6}$ to $9.08 \times 10^{-5}$ $m^2s^{-1}$ | 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 | $708 \pm 600$ | 0 | n/a | n/a | n/a | n/a | n/a | n/a |
| | | 50 | 29 | $1399.2 \pm 1000$ | $-23.2 \pm 30$ | $0.41 \pm 0.2$ | $30 \pm 20$ | $15 \pm 10$ |
| | | 125 | 27 | $642.3 \pm 700$ | $-12.0 \pm 30$ | $0.36 \pm 0.2$ | $29 \pm 20$ | $15 \pm 10$ |
| NM2 | $625 \pm 300$ | 0 | 29 | $1196.8 \pm 500$ | $-13.1 \pm 8$ | $0.49 \pm 0.2$ | $38 \pm 30$ | $19 \pm 20$ |
| | | 50 | 22 | $547.4 \pm 200$ | $-6.8 \pm 10$ | $0.35 \pm 0.2$ | $50 \pm 80$ | $25 \pm 40$ |
| | | 125 | 25 | $379.2 \pm 7$ | $-0.5 \pm 0.5$ | $0.29 \pm 0.2$ | $41 \pm 30$ | $21 \pm 20$ |

**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** cm | **Relative wind speed** | **Rate of change of $CO_2$** 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 ~~$CO_2$ 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 |