We appreciate Referee #1's invaluable suggestion regarding the estimation of winter CO_2 in the snow-covered high-latitude boreal forest soil of interior Alaska.

We have presented our findings on the effect of wind pumping when estimating CO_2 flux in boreal black spruce forest soil during the seasonally snow-covered period of 2006/7, when the snow depth was at one of its lowest accumulations of the last 80 years. The snow characteristics at our location were much more different than in subalpine and temperate regions—characteristics such as changes in wind speed, accumulative snow depth, soil temperature, soil moisture, and so on.

Here, the yellow highlighting indicates questions from Referee #1; however, highlighting in the manuscript denotes portions corrected and/or changed, based on the underlined responses here and as pointed out by Referee #1.

We have not added Figures S1-S4 in the manuscript without the approval of the Referee #1.

Anonymous Referee #1

Received and published: 19 March 2012

General Comments:

There is lot of uncertainty in the response of CO2 soil fluxes to changes in climate, in particular to winter conditions and snowpack at high Northern Latitudes. Therefore, the wintertime flux measurements reported in this paper are of high value for advancing this research. They also are one of the few reports that are based on continuous wintertime observations.

A noteworthy advantage of the measurements presented here is that CO2 in snow- pack air was determined by a passive measurement method that does not require withdrawal of air from the snowpack and therefore avoids inducing artificial snowpack ventilation. While flux measurements based on vertical gas concentration gradient measurements in the snowpack are a commonly used approach, this measurement is based on a number of simplifications and assumptions. Most researchers are aware of these shortcomings and present their results in the light of the rather large uncertainty of this measurement. It is regrettable that the Kim and Kodama manuscript does not provide any error/uncertainty estimates whatsoever.

>>>*We have now added "uncertainty in estimating CO_2 flux using the diffusion model" to section 2.2:*

The snowpack at high-latitude boreal black spruce forest sites has always been under dry conditions, except for the snow-melting period. At a snow density of 150 kg/m^3 and assuming all other variables unchanged, the diffusion rate was 79% faster than at a snow density of 300 kg/m^3, indicating that errors in the estimate of CO_2 flux through the snowpack caused by incorrect measurements of density varied as snow density changed (Seok et al., 2009). In our case, measured snow density and snow depth were much smaller than Seock et al. (2009)'s values. Nevertheless, we used the sensitivity of calculated CO_2 fluxes to estimate snow density as suggested by Seok et al. (2009) (see Figure S1). They demonstrated that the propagated errors from porosity and tortuosity estimation resulted in snow density uncertainties estimates of ±10, 20, and 30%, shown as a function of absolute snow density value. For example, a 10% error in the measurement of snow density resulted in an error in the estimated CO_2 flux on the orders of 3 and 5% for a snow density of 150 and 300 kg/m^3, respectively. We estimated that the error in calculating CO_2 flux ranged from 1 to 11%, compared to the 2-9% error evaluated by Seok et al. (2009). Crust was formed by the sublimation; however, we did not consider the effect of the ice layer upon estimating CO_2 flux, because freeze-thaw events did not occur under the cold environment before the onset of snow thaw.

Flux data are broken up in segments of four different classes of which three are based on atmospheric pressure levels. These analyses eventually come to the conclusion that “atmospheric temperature, modulated by the pressure, is a significant factor in determining winter CO2 flux in the seasonally snow-covered boreal forest soil of interior Alaska”. This is by no means surprising as numerous other previous studies have shown the sensitivity of the subniveal CO2 flux on soil temperature. The presentation in this paper does not provide a convincing case that indeed the fluxes are modulated by pressure. Most likely it is simply the subniveal temperature that is the determining variable. Pressure fluctuations do, however, exert a strong influence on the formation of gas gradients in the snowpack. It is striking that this manuscript neglects new findings and literature published in this field over the past five years. For instance, the work by (Seok et al. 2009) shows data examples on the effects of pressure fluctuations/wind pumping on the snowpack gas gradients. The Seok et al. paper also presents a quantitative description of this dependency and an approach to correct the CO2 flux determination for the wind pumping effect. It is regrettable that the Kim and Kodama manuscript does not address the need to consider this effect.

>>>Seock et al. (2009) demonstrated the effect of wind speed, sampling frequency, and physical conditions of snow upon estimating CO_2 flux in subalpine LTER sites, as many scientists have. To the contrary of the subalpine area, the black spruce forest of interior Alaska has much weaker relative wind speed during the winter season, due to geographical characteristics (e.g., basin). Wind speeds at 2, 4, and 8 m on the eddy covariance tower have been measured at intervals of 30 minutes, within the same forest. We have considered that changes in wind speed at 2 m are related to the variability of CO_2 flux during the winter. During the winter, wind speeds at 2 and 8 m ranged from 0 to 2.01 m/s and 0 to 3.89m/s, respectively. If wind speed was measured at 1m above the soil surface, this speed would be much less than 2 m/s. We present the temporal variations of air pressure and wind speed at 2m during the winter of 2006/7, as shown in Figure S1. In that figure, wind speeds are less than 2 m/s over the whole winter period, including for the snow-melting period. This indicates a much lower relative change in wind speed in the black spruce forest of interior Alaska than in alpine forest sites (Seok et al., 2009), Filippa et al. (2009), and Liptzin et al. (2009), and in the Japanese temperate region (Takagi et al., 2005), suggesting that changes in wind speed when estimating CO_2 flux here may be smaller than at subalpine LTER site and temperate-climate sites. Hence, we must conduct additional systematic study when estimating CO_2 flux in response to the pumping effect of weak wind speed in other, sparse black spruce forest of interior Alaska during the winter period.

As suggested by Referee #1, we will add the following to Section 3 (Results and Discussion) in the text:

<u>The wind speed measured at 2 m from the eddy covariance tower was less than 2 m/s in the black spruce forest of interior Alaska during the observed winter period, compared to the 0-6 m/s measured in subalpine regions (Massman et al., 1997; Filippa et al., 2009; Liptzin et al., 2009; Seok et al., 2009), and 0-3 m/s in a temperate-climate region (Takagi et al., 2005), which were affected by wind-pumping when estimating CO_2 flux through the snowpack. Relationships here between air pressure and wind speed at 2 m, and between CO_2 concentration gradient and wind speed at 2 m, had low correlation, showing correlation coefficients of 0.017 and 0.069, respectively. This suggests wind speed in the</u>

black spruce forest of interior Alaska during the winter may not have played a significant role when estimating CO_2 flux in response to changes in wind speed, contrary to strong wind speed in subalpine and temperate regions

Nevertheless, we plan additional study on the wind-pumping effect, using installation of pressure sensors and build-up of NDIRs in the snowpack in the relatively sparse black spruce forest of interior Alaska.

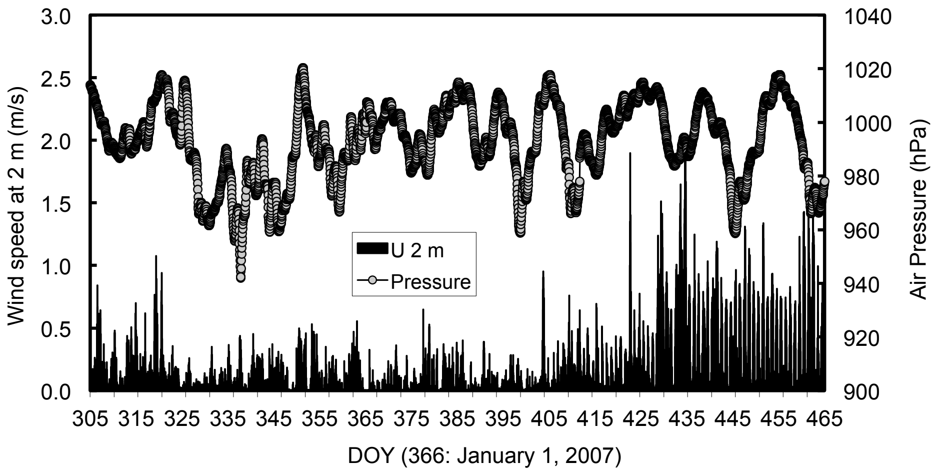

Figure S1. Temporal variations of wind speed at 2 m and air pressure measured by the eddy covariance tower in black spruce forest of interior Alaska during the winter period of 2006-2007.

Further, we did not measure the pressure in the snowpack in this study; however, we show in Figure S2 the relationships between a) air pressure and wind speed at 2m, and between b) CO_2 concentration gradients in the snowpack and wind speed at 2m. This indicates much weaker relationships between a) air pressure and b) the gradient against the wind speed at 2m than the strong relationships among them reported by Seok et al. (2009: see Figures 7 and 8a). Hence, we shall conduct additional measurement of wind-pump effect upon estimating CO_2 flux with changes in wind speed in the relatively sparse, other black spruce forest of interior Alaska during the winter period.

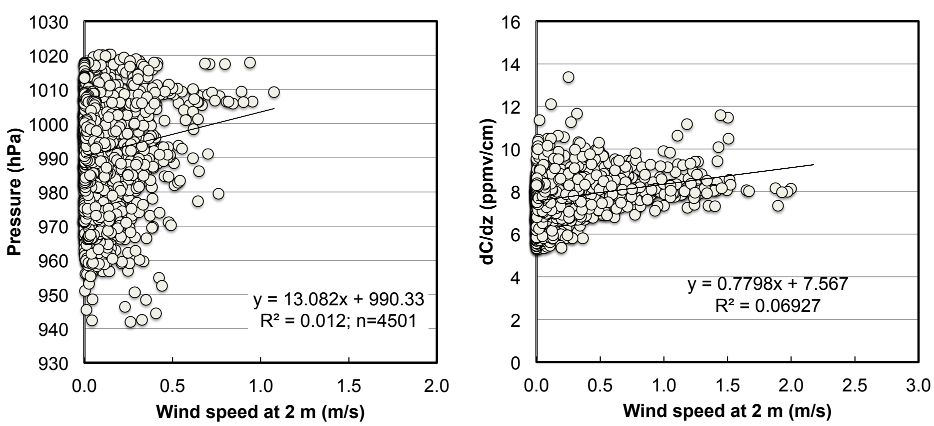

Figure S2. Relationships between a) air pressure and wind speed at 2m, and b) concentration gradients and wind speed.

In summary, my recommendation is to first correct the data for wind pumping effects and then analyze the dependency of the CO2 flux on the nice soil temperature data that were collected. Another relationship that would be of interest to investigate more closely is dependency on soil humidity. It would also be of interest to more thoroughly examine the evolution of the CO2 flux over the portion of the snow-covered season that was captured with these measurements.

>>> If our site was influenced by wind during the winter season like subalpine sites (Seok et al., 2009; see Figure 10) as pointed out by Referee #1, we would happily correct CO_2 flux. However, as described, wind speed may not be a significant factor in estimating CO_2 flux in black spruce forests of interior Alaska. We illustrate in Figure S3 the frequency of the wind speed occurrence at 2 m, suggesting that wind speed from 0 to 0.2 m/s indicates 70.5% of the total and that our study site in the black spruce forest of interior Alaska has relatively weak wind speed during the winter.

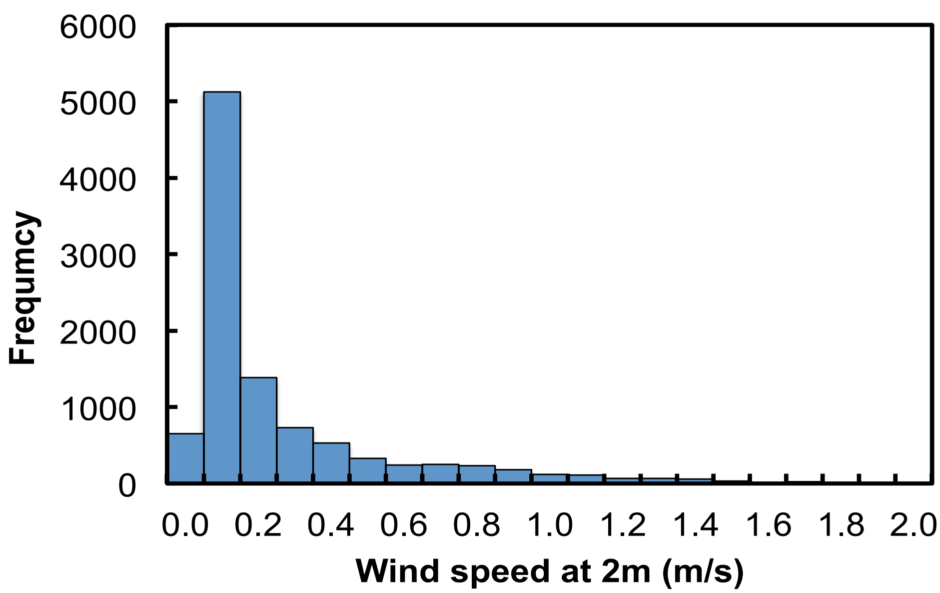

Figure S3. Frequency of wind speed at 2m (m/s) during the winter period of 2006/7.

We also show in Figure S4 the relationship between CO_2 concentration measured at each height in the snowpack and wind speed at 2m over the whole winter period of 2006/7, with a 2nd order polynomial fit ($y = cx^2 + bx + a$) as estimated by Seok et al. (2009). This finding is quite different than Seok et al.'s (2009) result. The c in this study, characterizing the curvature of the best fit equation, tends to decrease with increased depth, indicating little sensitivity toward wind speed under shallow snowpack and a much weaker wind speed environment, contrary to the findings of Seok et al. (2009) under deeper snowpack and strong wind speed during the winter. The trend in b is similar to term c. The regression term a, denoting the zero-wind speed snowpack CO_2 concentration at each height, increases linearly, moving from the bottom of the snowpack, indicating that the CO_2 source is from the soil. When the wind speed is zero in this study, the average CO_2 concentration at each height during the whole winter is 627, 532, and

474 ppm at 10, 20, and 30 cm in the snowpack, respectively, which suggests that most wind speed is weak. This demonstrates that there was no wind-pumping effect on the black spruce forest soil of interior Alaska during the seasonal snow-covered period of 2006/7, and that CO_2 flux through the snowpack could be sufficiently estimated with the application of Fick's law (e.g., a molecular diffusion approach).

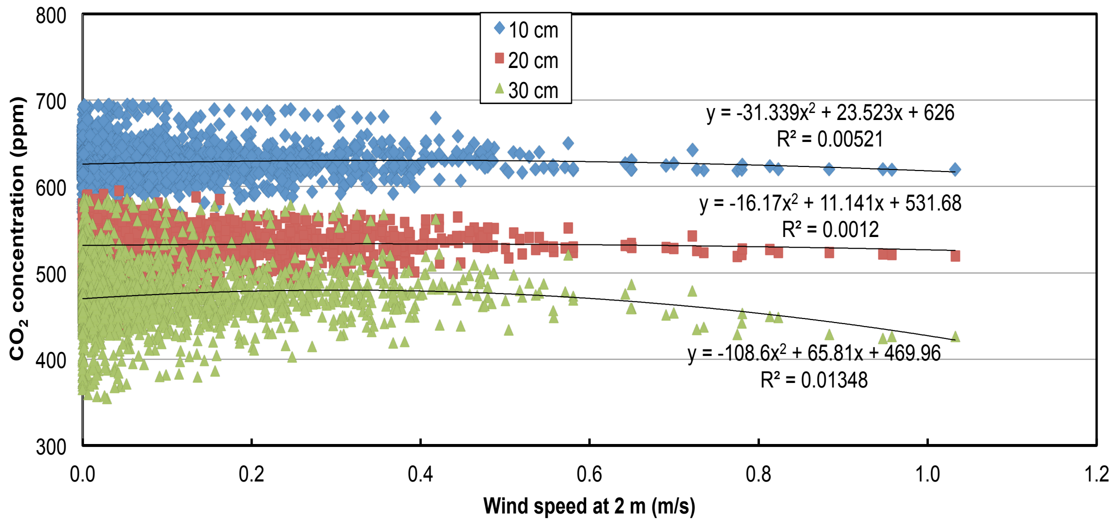

Figure S4. Relationship between CO_2 concentration measured at each height in the snowpack and wind speed 2m during the whole winter of 2006/7 with 2nd ploynomial fit equation ($y = cx^2 + bx + a$) as shown by Seok et al. (2009).

As shown in Figure 3 in the text, soil moisture had no response during the winter period. However, soil moisture did respond on April 4, and its peak at 5 cm was April 9. While snow depth in low-latitudinal regions was distinctly affected by soil insulation effect in temperate (Kim and Tanaka, 2002; Takagi et al., 2005) and subalpine (Seok et al., 2009) regions, snow depth at high latitude, like at this study site, did not produce the effect of soil insulation. Further, soil moisture lacked response because soil temperature at 5 cm below the surface was still below zero and under an extremely cold atmosphere during the winter period. Hence, soil moisture did not affect estimates of CO_2 flux before soil-column thaws.

Other specific comments:

1130: I suggest mentioning in the abstract that this research was conducted at a permafrost site.

>>> I added the suggestion as pointed out by Referee #1.

1130/11: The error margins given for the data are misleading. These values are ways smaller than a realistic estimate of the measurement uncertainty that is adherent to this type experiment.

>>> These values included the estimated uncertainty of snow physical errors. The

Coefficient of Variations (CV, %) ranged from 9 to 12%, and the median under the pressure phase was very similar to the average, as described in the abstract.

1130/14: Explain/be more clear about what is meant by 'correlate at levels of xx%".

>>> I changed the sentence to the following as suggested by Referee #1:

Atmospheric temperature and soil temperature explained 56 and 31% of winter CO_2 flux during the snow-covered period of 2006/7, when snow depth experienced one of its lowest totals of the past 80 years.

1132/5: I suggest to also mentioning the conceptual model of (Liptzin et al. 2009) and to discuss the findings of this study in the light of the cited literature

>>> I added the conceptual model (Liptzin et al., 2009) to the Introduction, as suggested by Referee #1:

Liptzin et al., (2009) demonstrated the conceptual model of the seasonal pattern of CO_2 flux under four distinct zones, divided by changes in the environmental factors (e.g., freeze-thaw cycles, soil temperature, soil moisture, and carbon availability) and based on variability in snow coverage in the subalpine forest.

As previously described (see soil moisture at 5 cm below the soil surface in Figure 3 of the text), our study site in the boreal black spruce forest soil of interior Alaska is not affected by soil insulation and changes in snowpack height during the winter season. Hence, soil moisture is not significant in estimating CO_2 flux in this sub-Arctic region under its extremely cold environment during the seasonally shallower snow-covered period. Contrary to Liptzin et al.'s (2009) findings, the variability of CO_2 flux estimated in this study is modulated by changes in principally ambient temperature and soil temperature, which are controlled by air pressure.

1133/Fig 1: Please provide some explanation of where the gas is actually measured? What is the cuvette volume? How does interstitial air get there?

>>> I added the following explanation as requested by Referee #1:

The in-situ sensor head (155 mm long and 15 mm in diameter) has an NDIR source, optical filter, and detector, and a 50-mm long and 4-mm wide slit on the head that allows CO_2 from the soil to diffuse through membranes into the small sample cell (ca. 2.6 cm^3), as used by Hirano et al. (2003) and Takagi et al. (2005). The sensor detects CO_2 concentration through molecular diffusion from the soil to the snowpack, assuming that soil-originated CO_2 emission within the diameter of the sensor (e.g., 20 cm) is constant.

1134/16: Fig. 2 has no scale for the snow accumulation rate (black data).

>>> The scale is the same for snow accumulation rate and daily snowfall.

1134/2: Give data averaging interval for the precision determination.

>>> I added the following information for precision determination, as suggested by Referee #1.

The precision of each sensor was determined using zero gas and 1000.0 ppm standard cylinders, ranging from 978 ± 6 ppm (0.61%) to 1020 ± 47 ppm (4.30%) before the observation, and from 967 ± 7 ppm (0.72%) to 1031 ± 47 ppm (4.57%) after the observation, for the calibration of 1000.0 ppm standard CO_2 cylinder over an hour.

1134/19: The statement 'was . . . higher than . . . at the lowest' is confusing.

>>> I deleted "at the lowest" in the text, as suggested by Referee #1, because I calculated CO_2 flux when the snow depth was more than 25 cm.

1135/4: Probably what is meant is that gradients between 10 to 20 and 20 to 30 cm were similar?

>>> Yes, I corrected the depth, as suggested by Referee #1:

The CO_2 concentration gradients from 10 to 20 cm and from 20 to 30 cm were similar, indicating that the gradient is almost linear; the gradient ratios for the 10-20 cm and 20-30 cm ranges varied from 0.87 to 1.22 and showed no difference under the 95% confidence level.

1136/14: Is indeed wind speed affecting the flux, or do the authors refer to the gas concentration gradient (again, see (Seok et al. 2009))?

>>> As previously described regarding the wind-pumping effect when estimating CO_2 flux in the snowpack, the study site was mostly calm (less than 0.4 m/sec for 83% of the whole winter period of 2006/7, as well as other winter periods). Nevertheless, we plan to examine wind-pumping effect when estimating CO_2 flux in much sparser black spruce forests of interior Alaska.

1136/17: What is probably meant with this sentence is that wind speed has an effect on the CO2 flux, not vice versa?

>>> As previously shown in Figure S3, most (> 96%) of the wind speed at 2 m during winter at our study site was less than 1.0 m/sec. We have described why we did not consider the effect of wind pumping during winter.

1137/29 – Fig 5: The data and discussion would be easier to follow if below surface measurements (in the soil) would be labeled with negative depths (i.e. -5 cm).

>>> The levels of measured CO_2 concentrations were at 10, 20, and 30 cm above the soil surface, indicating the height of NDIR sensors as shown in Figure 1.

1142/8: This statement is misleading. This result is not representative for the 'snow-covered period', but instead for the 'experimental period', which according to the information provided in the paper, only covered a fraction of the snow season.

>>> Strictly speaking, Referee #1's suggestion is correct, because we could not calculate CO_2 flux under certain snow-covered periods (< 25 cm). However, due to shallow snow depth in the early winter of 2006/7, CO_2 flux through the snowpack may be much smaller than in a usual winter. Hence, we have rewritten: winter CO_2 emission during the experimental period of 109 days, as suggested by Referee #1.

1142/14-15: This estimation is highly speculative. It, for instance, neglects changes in the soil gas fluxes that have been seen in other studies during the snow melting phase (Liptzin et al. 2009), (Filippa et al. 2009).

>>> Liptzin et al. (2009) demonstrated the enhanced CO_2 flux with the increase of soil moisture during the snow-melting period, as shown in Figures 1, 4, and 7. According to additional CO_2 flux-measurements during the snow-melting period (DOY 100) of 2007/8, mean CO_2 flux was 0.07±0.03 gCO_2-C/m^2/day (n=24) on the melting snow surface at the same study site, corresponding to almost a half of 0.17±0.02 gCO_2-C/m^2/day after DOY 466 (21 March 2007), as described in the text. We have added the additional results to the text as suggested by Referee #1.

Because N_2O flux is modulated by environmental factors such as soil moisture and soil O_2 availability (Kim and Tanaka, 2003), the flux was stimulated during the snow-melting period. Then, soil-originated N_2O concentration and flux increased around DOY 120 (see Figures 2 and 3 for winter 2007; Filippa et al., 2009) during the snow-melting period. However, N_2O concentration and flux dramatically decreased after DOY 140.

References

Bowling, D.R., W.J.Massman, S.M. Schaeffer, S.P. Burns, R.K. Monson, and M.W. Williams, 2009. Biological and physical influences on the carbon isotope content of CO2 in a subalpine forest snowpack, Niwot Ridge, Colorado. Biogeochemistry. 95:37-59.

Filippa, G., M. Freppaz, M.W. Williams, D. Helmig, D. Liptzin, B. Seok, B. Hall and K. Chowanski 2009. Winter and summer nitrous oxide and nitrogen oxides fluxes from a seasonally snow-covered subalpine meadow at Niwot Ridge, Colorado. Biogeochemistry. 95:131-149.

Liptzin, D., M.W. Williams, D. Helmig, B. Seok, G. Filippa, K. Chowanski and J. Hueber 2009. Process-level controls on CO2 fluxes from a seasonally snow-covered subalpine meadow soil, Niwot Ridge, Colorado. Biogeochemistry. 95:151-166.

Seok, B., D. Helmig, M.W. Williams, D. Liptzin, K. Chowanski and J. Hueber 2009. An automated system for continuous measurements of trace gas fluxes through snow: an evaluation of the gas diffusion method at a subalpine forest site, Niwot Ridge, Colorado. Biogeochemistry. 95:95-113.

>>> We have cited these references and added them to the text.