Dynamic carbon dioxide exchange through snowpack by wind-driven mass transfer in a conifer-broadleaf mixed forest in northernmost Japan

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[1] CO_2 efflux in the period of snow cover can be a large carbon source in the yearly carbon budget of snowy ecosystems. However, the behavior of CO_2 in snowpacks and the mechanisms of the snow surface efflux are still unclear. We performed continuous (half-hourly) midwinter measurements of CO_2 concentrations in a conifer-broadleaf mixed forest snowpack, and found that concentrations in the snowpack fluctuated significantly as wind speeds varied. The snow surface efflux was evaluated as the sum of the CO_2 storage change in the snowpack and the CO_2 input from the soil to the snowpack, taking into account the mixing due to airflow. The median value over 52 days (49 mmol m^{-2} d^{-1}) was almost the same as the daily net ecosystem exchange rate in this forest (50 mmol m^{-2} d^{-1}) estimated by the eddy covariance technique and the storage-change flux in the air column. These values are clearly larger than the value we estimated using Fick's law of diffusion. These results show that airflow can be a dominant cause of mixing within snowpacks in midwinter. In addition, in the soil pores under the snowpack, the CO_2 concentration was primarily related to air temperature, implying that soil respiration responds directly to air temperature, not to soil temperature, even beneath a 1-m-thick snowpack. We infer that the air temperature affected the root activity of trees through their trunks and that the variation in root respiration strongly affected the CO_2 concentration fluctuation in soil under the snowpack.

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1. Introduction

[2] CO_2 efflux in the period of snow cover can be a large carbon source in the yearly carbon budget of snowy ecosystems [*Sommerfeld et al.*, 1993; *Oechel et al.*, 1997; *Mariko et al.*, 2000; *McDowell et al.*, 2000; *Roehm and Roulet*, 2003]. Recent studies have shown that the main effect of a snowpack on CO_2 efflux is temperature insulation and the interruption of gas diffusion [*Sommerfeld et al.*, 1996]. The temperature insulation enhances biological activity in the underlying soil and increases the snow surface efflux, while the snowpack acts as a passive cap controlling the concentrations of CO_2 at the snow-soil contact. Several studies on the distribution of CO_2 in snowpacks have found that concentrations increase linearly with snow depth [*Solomon and Cerling*, 1987; *Sommerfeld et al.*, 1993, 1996; *Mast et al.*, 1998]. On the basis of this finding, they used Fick's law to calculate the snow-period CO_2 efflux, assuming that the gas moved through the snowpack by one-dimensional diffusion. On the other hand, several researchers have suggested the potential importance of a wind-pumping effect, which can be caused by pressure drag, atmospheric turbulence, or low-frequency barometric changes, as a driving force in the transfer of gases and heat in the snowpack [*Kelley et al.*, 1968; *Clarke et al.*, 1987; *Albert and Hardy*, 1995; *Winston et al.*, 1997; *Jones et al.*, 1999]. The effect has been theoretically or experimentally examined [*Colbeck*, 1989; *Albert and McGilvary*, 1992; *Albert*, 1993; *Albert and Hardy*, 1995; *Massman et al.*, 1997]; however, its magnitude is still unclear [*Sommerfeld et al.*, 1996; *Mast et al.*, 1998; *Jones et al.*, 1999].

[3] To clarify the movement of CO_2 in the snowpack and the effect on the exchange rate at the snow-atmosphere interface, we conducted continuous measurements at short,

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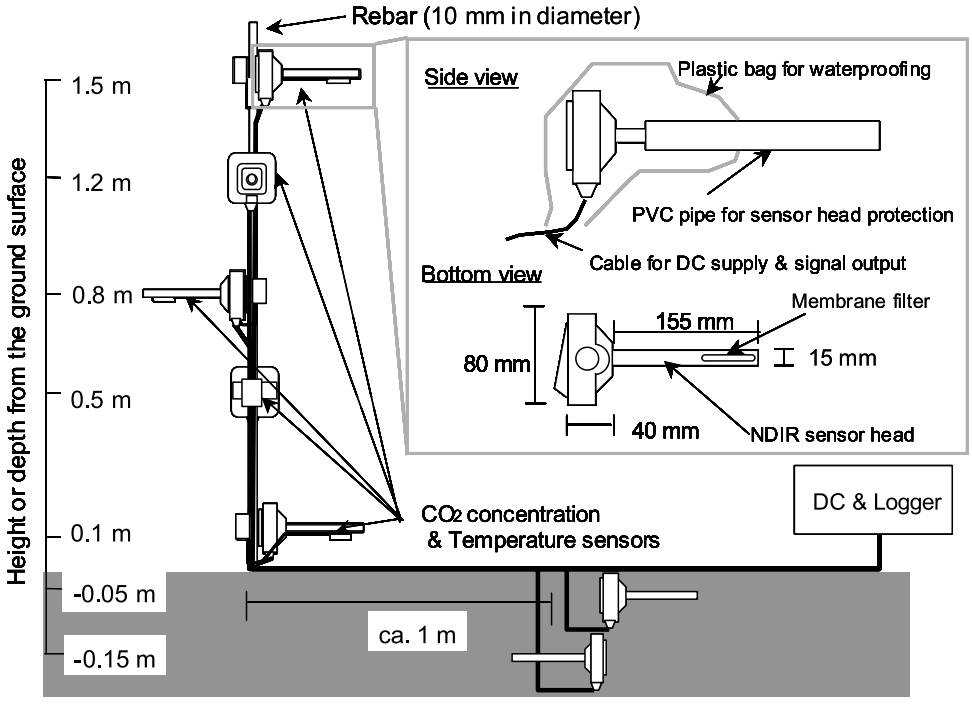

Figure 1. Schematic drawing of the observation system.

30-min sampling intervals of CO_2 concentrations in the snowpack throughout a winter using in situ nondispersive infrared (NDIR) CO_2 sensors, which was the same kind of sensor used for soil CO_2 efflux evaluation by some researchers [*Hirano et al.*, 2003; *Tang et al.*, 2003]. After evaluating the CO_2 behavior in the snowpack in relation to the micrometeorology, we also examined the effect of the concentration variation on the efflux by comparing concentration data to eddy flux data.

2. Methods

2.1. Site Description

[4] The study site was located in a conifer-broadleaf mixed forest at the Teshio Experimental Forest, FSC-Hokkaido University (45°03′N, 142°06′E, 66 m asl), in northernmost Japan. In 2002, daily average air temperatures at a height of 30 m ranged from −13.3°C in winter to 22.8°C in summer, and the annual precipitation and maximum snow depth were 122 and 116 cm, respectively. The soils are Gleyic Cambisols [*Food Agriculture Organization* (*FAO*), 1998] and have a surface organic horizon approximately 10 cm thick. The dominant tree species are *Quercus crispula*, *Betula ermanii*, *Abies sachalinensis*, *Betula platyphylla* var. *japonica*, *Picea jezoensis*, and *Acer mono*, and an evergreen dwarf bamboo (*Sasa senanensis*) forms dense undergrowth on the forest floor [*Koike et al.*, 2001]. In winter, the dwarf bamboo is under the snow cover.

2.2. Field Observations

[5] The sensor system was constructed in the forest understory on DOY (day of the year) 326, 2001, and left throughout the winter to be covered by natural snowfall. In situ nondispersive infrared (NDIR) CO_2 sensors (Vaisala GMD 20; Helsinki, Finland) were set on a length of rebar (1 cm diameter) at five levels (1.5, 1.2, 0.8, 0.5, and 0.1 m above the ground surface) (Figure 1). This sensor is a silicon-based sensor based on the patented CARBOCAP® technique and is the same kind of sensor as has been used for soil CO_2 efflux evaluation [*Hirano et al.*, 2003]. It comprises a plastic box containing electric circuitry and a sensor head projecting from the center of the box. Box dimensions are 80 mm (width) × 80 mm (height) × 40 mm (thickness). The sensor head (155 mm long and 15 mm in diameter) contains an NDIR source, optical filter, and detector, and a 50-mm-long and 4-mm-wide slit on the head allows CO_2 to diffuse through membranes into the small sample cell (~2.6 cm^3). When the sensor was moved from a low CO_2 concentration chamber (300 ppmv) to a high concentration chamber (1990 ppmv) in the laboratory, the sensor responded to the change in the CO_2 concentration within 5 min. Thus the residence time of air within the sample cell is short. The sensor heads were arranged radially about the rebar to minimize the influence of the sensors on each other. Similar sensors were buried in the soil at depths of 0.05 and 0.15 m below the ground surface and at a distance of 1 m from the rebar to minimize the influence of the aboveground system on the sensors. Temperature sensors were placed beside the NDIR sensor heads.

[6] The NDIR sensors were calibrated for 2 days (DOY 319, 2001, and DOY 109, 2002) before and after the continuous measurement period by introducing two standard gases of 0 and 1990 ppmv in the field, and a regression equation for each sensor was determined for each calibration day. The average value from the two calibration equations was adopted as the 30-min interval value for each sensor. In order to validate the stability of the sensor output, data sets during the study period were converted by each

calibration equation determined on the 2 days and the values were compared. The difference was 32 ± 8 ppmv (average ± standard deviation; n = 7121) for the sensor showing the maximum difference and 2 ± 1 ppmv (n = 7031) for that showing the minimum one, and the difference was small for all the sensors.

[7] The NDIR sensors required a 24-V electric power source. To prevent excess heating of the snow, power was supplied only during the last 7 min of each 30-min interval, and the average values for 5-s intervals in the last 1.5 min were recorded.

[8] Snow depth and melting were measured by a sonic ranging sensor (SR-50, Campbell Scientific Inc., Logan, Utah) and a square-pan snow lysimeter with an area of 7.3 m^2, respectively. Wind speed and atmospheric pressure were recorded every 30 min at a height of 2 m by a cup anemometer and barometer, respectively, and volumetric water content at a depth of 0.05 m below the ground surface was monitored by a time domain reflectometry sensor. Vertical profiles of snow type and the bulk snow porosity were surveyed every 2 weeks throughout the period of snow cover. A snow pit was dug for the snow type observation as close as practical to the points measuring the CO_2 concentration profile, but not so close as to affect the gas flux at the sampling plot. Two to six snow samples were obtained for each survey event near the pit dug by a snow sampler (the cross section is 20 cm^2) for the evaluation of the bulk snow porosity.

[9] CO_2 flux (F_c) was monitored above the canopy layer at a height of 32 m using a closed-path eddy correlation system, originally developed by *Wang et al.* [2004, 2005]. An ultrasonic anemometer (DA600-3TV, Kaijo, Tokyo, Japan) and a CO_2 fluctuation meter (Li-7000, LiCor, Lincoln, Nebraska) were used for the evaluation. The sampling tube length was 6 m, and the air was drawn by a diaphragm pump at a flow rate of 10 L min^{-1}. The fluctuation meter was calibrated every day by introducing two standard gases of 320 and 420 ppmv. Fluctuation data were sampled at 10 Hz with a digitizing data recorder. The data sampling started every 30 min with a duration time of 27 min 20 s. The rotation-correction to force $\overline{v} = 0$ and $\overline{w} = 0$ was applied, where $\overline{v}$ and $\overline{w}$ are the 30-min averages of lateral and vertical wind velocities, respectively, and the linear trend was subtracted by the least squares method. Then the covariance between the CO_2 concentration and vertical wind velocity was calculated, and the WPL correction [*Webb et al.*, 1980] was applied. Net ecosystem exchange (NEE) was determined as $F_c + F_a$, where F_a is the CO_2 storage change in the air column from the snow surface to the flux measurement height. The storage per unit ground area was calculated by multiplying the average of the concentrations at 32 m (by Li-7000) and 1.5 m (by GMD 20) height by the column height.

[10] Besides these field observations, an experiment was conducted in the backyard of the experimental forest office on DOY 105, 2003, in order to assess the effect of the concentration measurement by GMD 20 on the surrounding snow. In the experiment, the sensor was set at 0.3 m below the snow surface and the power was supplied and cut off 5 times with the same on-off periods as the field observation. During this procedure, temperatures of the sensor (GMD 20) body, sensor head, and the surrounding snow, and the sensor output were monitored every 30 s. Snow depth, porosity, and temperature were 0.7 m, 0.5, and 0°C, respectively.

2.3. Calculating CO_2 Efflux

[11] To reveal the quantitative effect of the CO_2 storage change on the NEE, CO_2 storage-change efflux from the snow surface (F_s) was determined as $F_s = \Delta S + F_p$, where ΔS is the storage decrease in the snowpack and F_p is the upward soil surface flux. To evaluate the storage, a column per unit ground area in the snowpack was divided into three layers aligned with the heights of the CO_2 sensors (0 to 0.3, 0.3 to 0.65, and greater than 0.65 m above the ground surface), and the CO_2 mole per unit ground area (mol m^{-2}) was determined for each layer by multiplying the concentration by the thickness of the layer and air-filled porosity. In this determination, the volume fraction (ppmv) data were converted to the mole-based concentration (mol m^{-3}) using the snow temperature and the atmospheric pressure. The bulk snow porosity was surveyed in the field every 2 weeks; however, in order to interpolate the day-to-day changes between observations, and to estimate the vertical profiles, we used a model based on viscous compression [*Motoyama*, 1990]. The equation requires a daily depth of snowfall (mm) and the density, and daily snowmelt at the base of the snowpack. Parameters and variables obtained in the backyard of the experimental forest office [*Nomura et al.*, 1999], approximately 17 km south of the study site, were used for the calculation. The average porosity was then calculated for each of the three layers.

[12] F_p values were evaluated by Fick's diffusion law as $F_p = -D_c\theta\lambda\Delta C/\Delta z$ [*McDowell et al.*, 2000], using a concentration gradient between the two depths in the soil ($\Delta C/\Delta z$; mol m^{-3} m^{-1}). A fixed value of the volumetric solid content (0.099) and variable values of the volumetric water content were used to calculate the air-filled porosity (θ) in the soil, and the tortuosity factor (λ; the range was 0.758–0.759) was estimated using the equation $\lambda = (1 - (1 - \theta)^{2/3})/\theta$ [*Prieur du Plessis and Masliyah*, 1991]. The binary diffusion constant for CO_2 in air (D; 0.138 × 10^{-4} m^2 s^{-1} at standard temperature (T_0) and pressure (P_0)) was corrected for observed temperature (T) and pressure (P) to determine the diffusion coefficient (D_c) as, $D_c = D\ (P_0/P)\ (T/T_0)^{1.81}$ [*Massman*, 1998]. F_s could be obtained every 30 min; however, when the 30-min increase in snow depth was more than 1 cm, the flux value was excluded from the calculation of the daily average, because the increase in snow depth directly decreases the F_s by increasing the volume of the snowpack and the CO_2 storage even if there is no change in the CO_2 efflux from the snow surface. In addition, during the snowmelting period (from DOY 59), the snow beside the sensors melted faster than in the surrounding area, similarly to the well that forms in melting snow around the trunk of a tree; therefore F_s was evaluated only during the midwinter before the snowmelting period began.

[13] Diffusion efflux from the snow surface (F_d) was evaluated by the same procedure as F_p (the range of λ

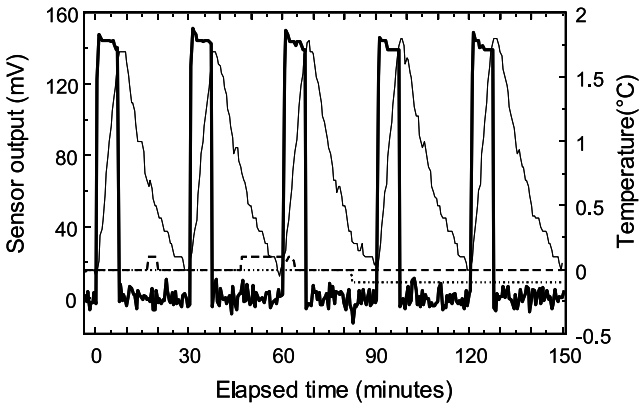

Figure 2. Effect of the power supply to the CO_2 sensor on the surrounding temperatures. Sensor output (thick solid line), sensor body temperature (thin solid line), sensor head temperature (dashed line), and snow temperature near the sensor head (dotted line).

was 0.768–0.790), using the concentration data at heights of 0.1 and 0.8 m above the ground surface and an average snow porosity between the two heights as a comparison to the efflux computed by the change in column CO_2 storage, F_s. Upward fluxes from each 30 min were summed to obtain daily estimates of the diffusive flux, F_d.

3. Results

3.1. System Check of the CO_2 Concentration Measurement

[14] During the system check experiment, temperature of the sensor body increased by 1.8°C (Figure 2). After power was cut off, the temperature of the sensor body returned to its initial value before the power was turned on again. There was little temperature change at the sensor head (NDIR-Cell) or the surrounding snow throughout the experiment. We therefore concluded that the effect of the measurement on the surrounding environment was small.

3.2. Snow and Microclimate Condition

[15] Snow accumulation started on DOY 334, 2001, and maximum snow depth was 116 cm during the observation period (Figure 3). During the winter, soil temperature was always higher than 0°C, and small amounts of snowmelt were observed on several days in the midwinter. Beginning in late February (DOY 59, 2002), the daily average air temperature rose above 0°C and the snowmelting period began. The maximum snowmelt (15.9 mm d^{-1}) was observed on DOY 86, 2002, and most of the snow had melted by mid-April (DOY 105, 2002). The change in bulk snow

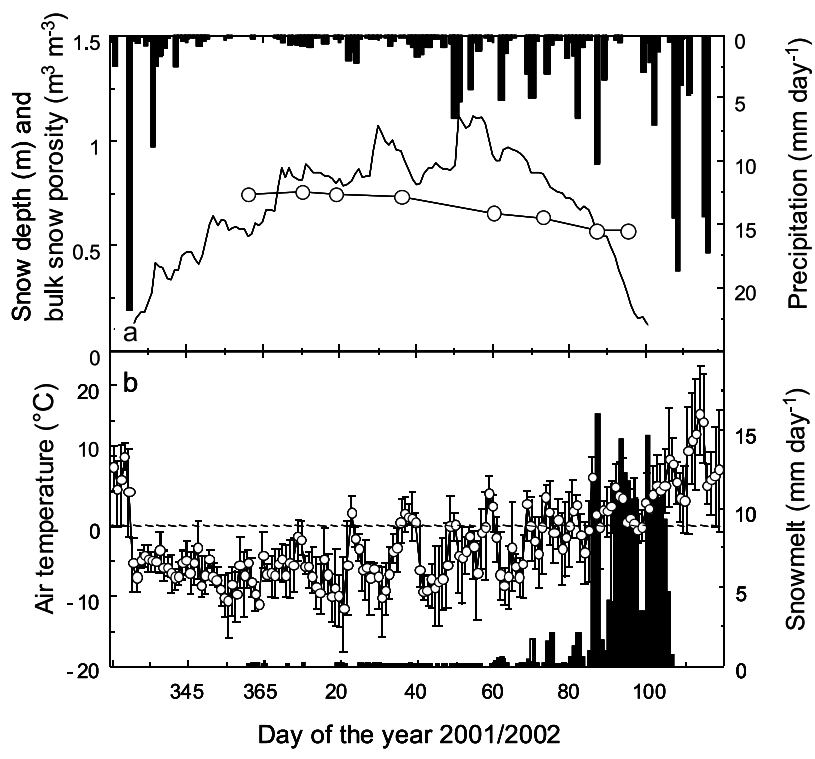

Figure 3. Seasonal changes of snowpack and microclimates. (a) Snow depth (solid line), bulk snow porosity (circles), and precipitation (bars). (b) Daily average air temperature at 30 m height (circles) and snowmelt (bars). Vertical bars across the circles represent maximum and minimum air temperatures for each day.

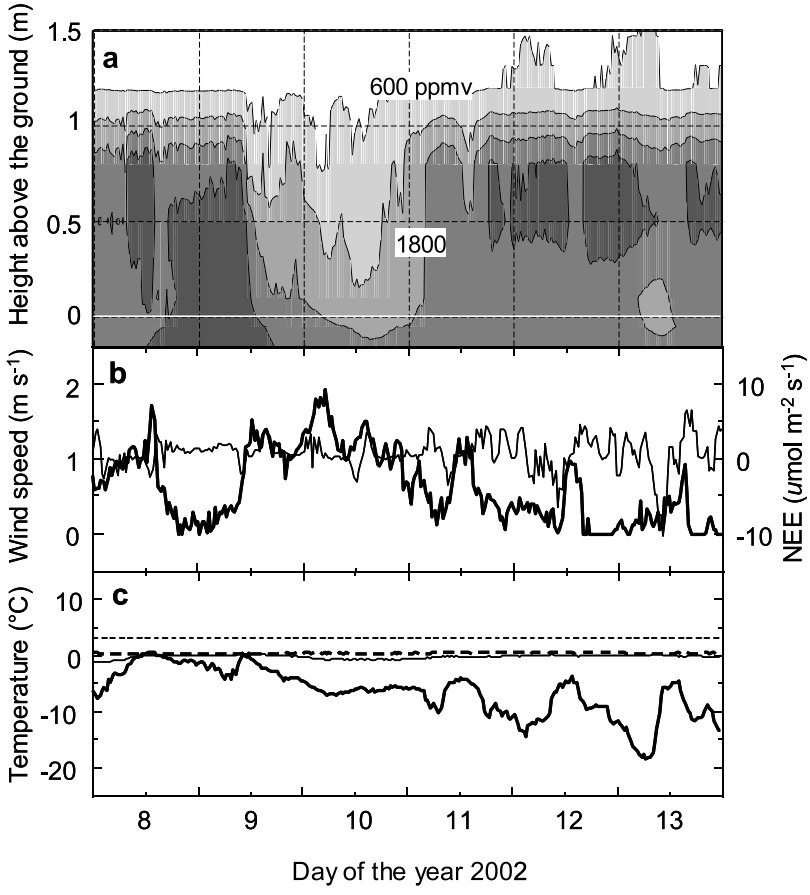

Figure 4. Time series of CO_2 concentrations under snow surface in relation to meteorological data. (a) CO_2 concentration profile. Concentrations were measured at five heights and two depths from the ground surface, and interpolated linearly. Sensors at heights of 0.8, 0.5, and 0.1 m were in snowpack. (b) Wind speed at 2 m height (thick line) and 1.5-hour running averages of net ecosystem exchange (NEE; thin line). (c) Temperatures at heights of 1.5 m (thick solid line), 0.8 m (thin solid line), and 0.1 m (thick dashed line), and at depth of 0.05 m in soil (thin dashed line). Sensors at heights of 0.8 and 0.1 m were in snowpack.

porosity was within a small range (0.73–0.75) in midwinter, and the value decreased during the snowmelting period. At the end of the period, the porosity became 0.56 (DOY 94, 2002). The estimated snow porosity by the model based on viscous compression (thin line in Figure 5b in section 3.3) agreed well with the observed values (circles) throughout the efflux calculation period. Discontinuous ice layers were first observed on DOY 35, 2002, at three heights in the snowpack (0.13, 0.32, and 0.68 m), and a continuous ice layer was observed at the beginning of the snowmelting period (DOY 59, 2002). In the snowmelting period, coarse grained granular snow dominated in the snowpack and a continuous midpack ice layer was frequently observed.

3.3. CO_2 Concentration Fluctuation Under the Snow Surface

[16] Under low wind speed conditions, CO_2 concentrations were highest in the air-filled pores in the soil, and then decreased in the snowpack with distance from the ground surface during the snow-covered period (e.g., during the night on DOY 8, 2002, in Figure 4a). The difference between CO_2 concentrations measured at two sensors below and above the snow surface (0.8 and 1.2 m, respectively, above the ground surface) in the observation period was as high as 3000 ppmv (DOY 54, 2002).

[17] However, when the wind speed increased, CO_2 concentrations decreased sharply in the snowpack with little change in the temperatures under the snow surface (Figure 4). Within 29 hours (from DOY 9 to 10, 2002), the CO_2 concentration decreased from 2690 to 950 ppmv at a height of 0.5 m above the ground surface, and the increase of the wind speed affected the CO_2 concentration even under the ground surface. Corresponding to decreasing CO_2 concentrations in the snow, NEE at the forest-atmosphere interface increased (Figure 4b).

[18] CO_2 storage values in the snowpack ranged between 16 and 126 mmol m^{-2} in midwinter (Figure 5a), when the NDIR sensor at 0.8 m above the ground surface was covered by snow and the snowmelting period had not yet begun. The minimum and maximum storage values indicate

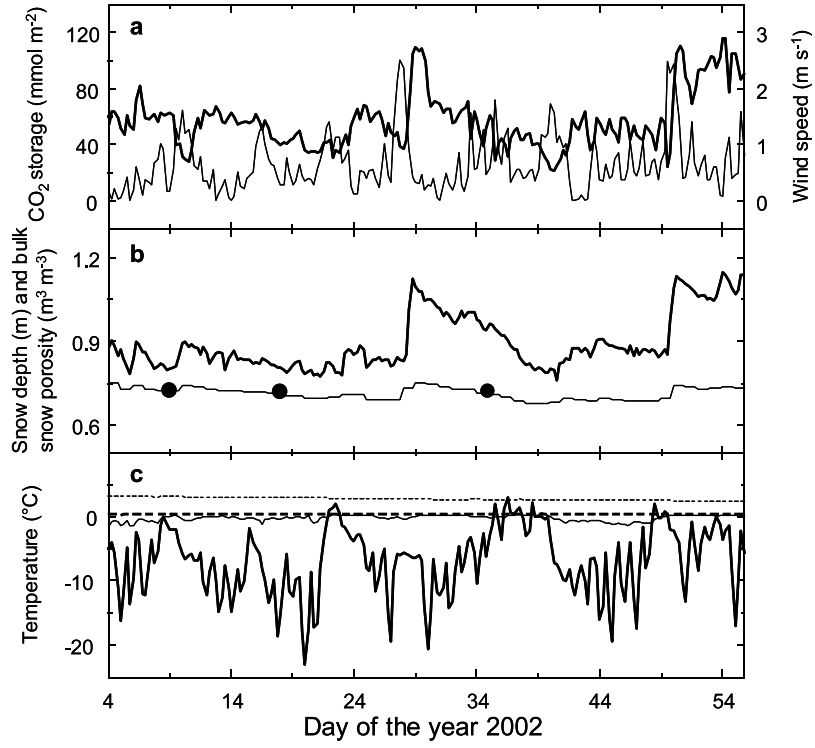

Figure 5. Relationship between CO_2 storage in snowpack and meteorology in midwinter. (a) Six-hour averages of CO_2 storage in snowpack (thick line) and wind speed at height of 2 m (thin line). (b) Observed snow depth (thick line) and observed (circles) and estimated (thin line) bulk snow porosity. (c) Six-hour averages of temperatures at heights of 1.5 m (thick solid line), 0.8 m (thin solid line), and 0.1 m (thick dashed line), and depth of 0.05 m in soil (thin dashed line). Sensors at heights of 0.8 and 0.1 m were in snowpack.

that the average CO_2 concentrations in the air-filled pores in the snowpack were 710 and 3610 ppmv, respectively, when the storage values were converted to the volume fraction for each snow and microclimate condition (i.e., air-filled porosity and temperature of each snow layer, snow depth, and atmospheric pressure). CO_2 storage decreased with increased wind speed throughout the midwinter under isothermal conditions and with little change in bulk snow porosity in the snowpack (Figure 5). Because the storage value (S; mmol m^{-2}) was primarily correlated with snow depth (SD; m), the trend in the storage data that related to snow depth was removed using the regression equation as $S - [34 + 0.14 \exp(5.5\, SD)]$, and a negative correlation was obtained between the wind speed and the detrended storage data (Figure 6).

[19] The daily averages of CO_2 concentration in the soil ranged between 1596 and 3521 ppmv at 0.05 m deep and between 1789 and 3640 ppmv at 0.15 m deep during the midwinter (DOY 4 to 55, 2002). Although the fluctuation in the CO_2 concentration in the snowpack was affected by the wind speed, the wind effect on the concentration in the soil was recognized only under extremely high wind speed conditions, as shown in Figure 4. However, throughout the snowy period, the concentrations in the soil also fluctuated regardless of wind speed or soil temperature, and the variations corresponded to changes in air temperature (Figure 7). It seems strange that the CO_2 concentration fluctuated greatly despite isothermal conditions in the soil and with little effect due to wind speed. An explanation for this correlation will be offered later in section 4.

[20] The median, mean, maximum, and minimum values for the daily efflux determined by Fick's law (6.7, 10, 51, and 0 mmol m^{-2}, respectively, for DOY 4–55, 2002) were significantly lower than those of the storage-change efflux (49, 50, 92, and −2.7 mmol m^{-2}) or NEE (50, 53, 140, and −38 mmol m^{-2}) (Steel-Dwass test, $p < 0.001$). However, the storage-change efflux and NEE did not differ significantly, and the mean and median values were close to each other.

4. Discussion

[21] During the period of snow cover, soil temperatures were always higher than 0°C and were well above the minimum temperature reported for soil respiration [*Kelley et al.*, 1968; *Flanagan and Bunnell*, 1980; *Coxson and Parkinson*, 1987; *Sommerfeld et al.*, 1993]. In fact, throughout the winter, we observed increased CO_2 concentrations in the soil, which we attributed to soil respiration. Accordingly, under low wind speed conditions, CO_2 concentrations were highest in the air-filled pores in the soil, and decreased in the snowpack with distance from the

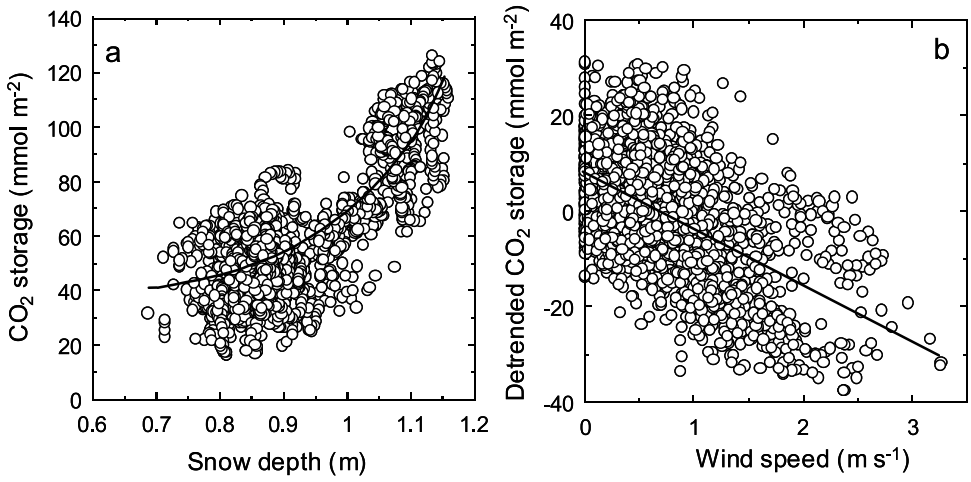

Figure 6. Relations of CO_2 storage (or the detrended value) to (a) snow depth and (b) wind speed. The regression lines in Figures 6a and 6b are $Y = 34 + 0.14 \exp(5.5\,X)$, $r^2 = 0.63$, $n = 2496$ and $Y = -11.9\,X + 7.8$, $r^2 = 0.28$, $n = 2496$, respectively. See text for the trend removing.

ground surface (Figure 4). These results can be attributed to the gas movement through the snowpack by one-dimensional diffusion. In addition, the large difference between CO_2 concentrations measured at two sensors below and above the snow surface (as high as 3000 ppmv on DOY 54, 2002) indicated that the snowpack acted as a passive cap for CO_2 transfer. These results agreed with those of previous CO_2 concentration profile studies [*Solomon and Cerling*, 1987; *Sommerfeld et al.*, 1993, 1996; *Mast et al.*, 1998].

[22] However, when the wind speed increased, CO_2 concentrations decreased sharply in the snowpack (Figure 4), and a negative correlation was observed between the CO_2 storage and the wind speed throughout the midwinter (Figures 5 and 6). These findings revealed that the air in the snowpack is tightly coupled with the atmosphere by wind-driven mass transfer. This conclusion is supported by observations of increased NEE corresponding to decreased CO_2 concentrations. Several researchers have suggested the potential importance of a wind-pumping effect as a driving force in the transfer of gases and heat in the snowpack [*Kelley et al.*, 1968; *Clarke et al.*, 1987; *Colbeck*, 1989; *Albert and McGilvary*, 1992; *Albert*, 1993; *Albert and Hardy*, 1995; *Sommerfeld et al.*, 1996; *Massman et al.*, 1997; *Winston et al.*, 1997; *Mast et al.*, 1998; *Jones et al.*, 1999]. However, our study is the first to present direct evidence of a strong effect of wind pumping on CO_2 movement in the snowpack by continuously measuring CO_2 concentrations at short sampling intervals.

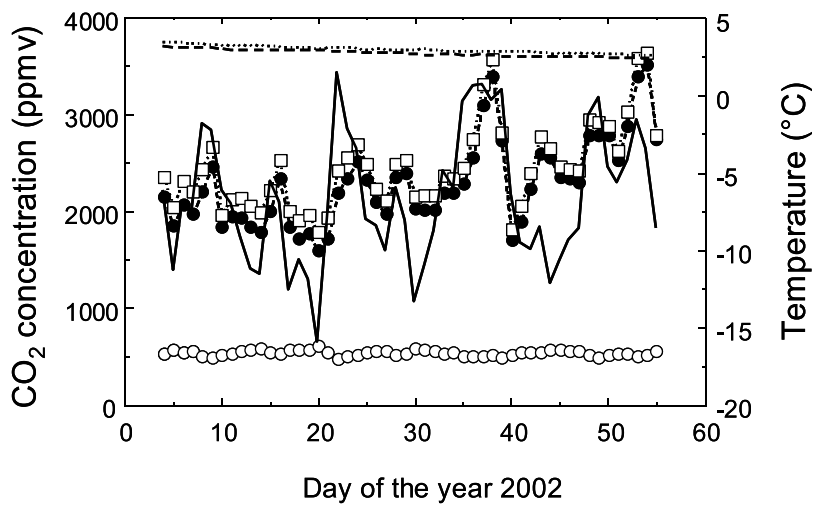

Figure 7. Time series of the daily averages of CO_2 concentration and temperature in the soil and the atmosphere. Open circles indicate the atmospheric CO_2 concentration at 1.5 m height from the ground, and solid circles and open squares indicate the concentration in the soil at 0.05 and 0.15 m deep, respectively. Solid line indicates air temperature at 2 m height, and dashed and dotted lines indicate soil temperatures at the depth of 0.05 and 0.15 m, respectively.

[23] In our study, CO_2 concentrations were measured directly as the sensors were covered by natural snowfall. Although the system check experiment revealed that the effect of the power supply to the sensors on the surrounding temperature was small, the presence of the sensors had some effect on the surrounding environment. In fact, in the period of snowmelt, the snow beside the sensors melted faster than that in the surrounding area, similar to the well that forms in melting snow around the trunk of a tree. However, during midwinter, such melting was not observed and snow remained in close contact with the sensors, as observed from a short distance. The slight temperature fluctuations observed beside the CO_2 sensors with fluctuating air temperatures (Figures 4 and 5) support this observation. In addition, because NEE increased with decreased CO_2 concentrations in the snowpack, we concluded that the dynamic variation of CO_2 concentrations in the snowpack occurred everywhere in the study site, not just in the vicinity of the sensors.

[24] The daily efflux values determined by Fick's law were significantly lower than those of the storage-change efflux or NEE, whereas the bulk snow porosity remained high and there was no obstacle to diffusion, such as a midpack continuous ice layer, at any time during the observation period. The concentration gradient in the snowpack appears to have remained small as a result of airflow within the snowpack, which was the dominant source of CO_2 efflux, and this lowered the estimated efflux by Fick's law. On the other hand, the comparative values of the storage-change efflux and NEE indicated that the wind-driven CO_2 efflux constituted a large portion of the NEE in midwinter.

[25] We attributed the large contribution of airflow to NEE partly to the relatively thin snow layer (approximately 1 m) and high snow porosity (approximately 0.68 to 0.75 in bulk), compared with other intensive research sites in the Rocky Mountains, at which the snow depth exceeds 3 m at its maximum and the porosity decreases to 0.4 in the snowmelting period [*Sommerfeld et al.*, 1993; *Mast et al.*, 1998; *McDowell et al.*, 2000]. In addition, wind speeds at the forest floor increased because of the lack of dense vegetation in winter when the undergrowth was covered with snow (the basal area of the canopy trees was 22 m^2 ha^{-1}). Thus, under such conditions, CO_2 exchange by airflow would occur in the snowpack and would be the major transfer process at the snow-atmosphere interface. In support of this consideration, *Jones et al.* [1999] have reported nonsteady state CO_2 profiles in a thin snowpack in the arctic tundra (the snow depth and porosity were <1.2 m and 0.65–0.84, respectively) and suggested the importance of a nondiffusive process for the in-pack transport of gases.

[26] The daily values of the storage-change efflux that we obtained (median 49; range −2.7 to 92 mmol m^{-2}) were comparable to values of the CO_2 efflux from a forested snow surface obtained by other studies using the closed-chamber measurement technique. *Mariko et al.* [2000] obtained values of 7.6 to 70 mmol m^{-2} in midwinter in a cool-temperate deciduous forest in the central region of the main island of Japan, at which the snow depth and porosity were comparable to those at our study site (~1.2 m and 0.67 at the center of the snowpack, respectively). *McDowell et al.* [2000] performed studies at three sites in the Rocky Mountains (United States), and obtained values of 58 to 67 mmol m^{-2} with a standard deviation of approximately 34 mmol m^{-2} in late March (early phase of spring melt) in a mixed conifer forest and values of 34 to 54 mmol m^{-2} with a standard deviation of approximately 26 mmol m^{-2} during December to March in a *Pseudotsuga menziesii* var. *glauca* forest. *Winston et al.* [1997] reported a maximum value of ~50 mmol m^{-2} during January to February in three types of boreal coniferous forest. However, *Winston et al.* [1997] suggested that the closed-chamber method works best when vertical diffusion is the dominant means of transport and that it cannot measure gas transport driven by a mass transfer process, because the chamber itself disrupts advection across and through the snow surface. Therefore they reported only values obtained during days when there was little or no wind, minimizing the effect of any possible mass transfer process. We suggest that *Mariko et al.* [2000] and *McDowell et al.* [2000] may also have reported only values obtained when there was little or no wind. In support of this assumption, there was no substantial difference between the efflux values obtained by using Fick's diffusion law and those obtained by closed-chamber measurement in these two studies. Accordingly, we can compare their reported values with our storage-change efflux value and with our maximum value estimated by Fick's diffusion law (51 mmol m^{-2}).

[27] Despite the negative correlation between CO_2 storage and wind speed (Figure 6), the relation of NEE to wind speed was weak. In addition, the correlation between the storage-change efflux and NEE was weak. These weak relationships may have been partly caused by the different response time of the fluxes to the wind and/or by the different initial condition of the storage value for each wind event. Figure 8 shows the correlation coefficients between the fluxes and the wind speed with changing lag times. The correlation coefficient between the storage-change efflux and the wind speed marked its maximum positive value immediately. On the other hand, there was a time lag of 100 to 250 min before the correlation coefficient between NEE and the wind speed reached its highest value, and the time coincided with the negative maximum of the correlation between the storage-change efflux and the wind speed. Although the results in Figure 8 were obtained by a simple spectral analysis using the continuous 2048 (42.7 days) data sets of 30-min-interval values, the lag time agreed with the results, shown in Figure 4, that peaks of NEE occurred about 2 hours after wind events. This result appears anomalous. One possible explanation is that a very stable surface layer causes the air just above the snowpack to be decoupled from the air at the level of the NEE evaluation. However, we cannot determine whether this lag is a natural phenomenon or was caused by the measurement system. In our study, we used CO_2 concentration data obtained at two heights (1.5 and 32 m above the ground surface) to evaluate the CO_2 storage change in the air column from the snow surface to the flux measurement height. Therefore uncertainty still remains as to whether the concentration data

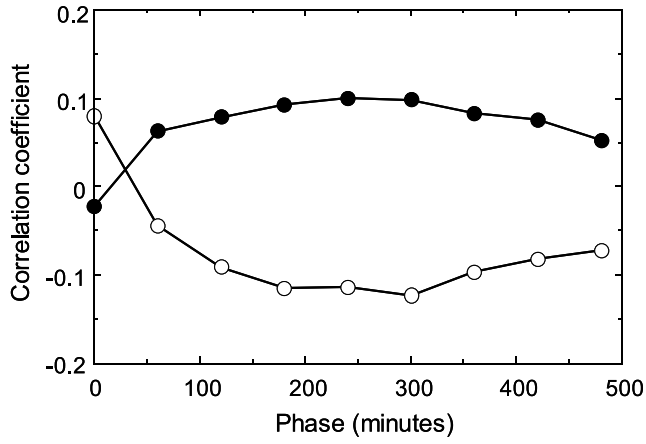

Figure 8. Change in the correlation coefficients between the CO_2 storage-change efflux and the wind speed (open circles) and between net ecosystem exchange and the wind speed (solid circles) with the change in the time lag. Thirty-minute-interval values (n = 2048) were used for the analysis.

obtained at the two heights are sufficient to detect an immediate response of the CO_2 storage change in the air column to the wind. On the other hand, if the lag is a natural phenomenon, it implies that high winds increase the CO_2 efflux from the snow surface, and that the increase in the efflux leads to a delayed increase in NEE. However, because the amount of CO_2 storage in the snowpack is limited, the storage-change efflux decreases soon after the efflux increases, leading to the weak relationship observed between the storage-change efflux and NEE. In any case, the long lag time is difficult to explain and requires further study.

[28] The CO_2 concentration in the soil under the snowpack was primarily related to the air temperature (Figure 7). Because the atmospheric CO_2 concentration at 1.5 m height above the ground surface was not sensitive to change in the air temperature, this correlation was not caused by a temperature dependence of the observation system. This finding is interesting because it implies that the soil respiration responds directly to the air temperature, not to the soil temperature, even beneath a 1-m-thick snowpack. *Coxson and Parkinson* [1987] reported that soil water content affected soil respiratory activity over a wide range of soil temperatures (0°–18°C). However, the air temperature rarely exceeded 0°C during the study period (Figure 7). In addition, only minor snowmelt occurred (Figure 3; 0.21 mm d^{-1} at maximum), and the water content of the soil was constant throughout this period. Accordingly, the data do not support that an increase in the air temperature enhanced the snowmelt or increased the soil water content and soil respiratory activity. Literature on root respiratory activity at low temperatures is limited; however, some studies [*Limbach et al.*, 1982; *Lawrence and Oechel*, 1983; *Boone et al.*, 1998] show that root respiratory activity may occur at temperatures below 5°C. Thus we infer that the air temperature affected the root respiratory activity of trees through their trunks and that the variation in root respiration strongly affected the CO_2 concentration fluctuation in soil under the snowpack.

5. Conclusion

[29] We reported the dynamic behavior of CO_2 in a snowpack based on continuous measurement of CO_2 concentrations with a short measurement interval. Our results showed that CO_2 concentrations fluctuated significantly in the snowpack in response to wind speed, and that the snow surface efflux caused by wind-driven mass transfer accounted for a large portion of the CO_2 exchange rate at the snow-atmosphere interface in midwinter. Although the potential importance of mass transfer has been suggested by several model studies and experiments, our study is the first to present direct evidence of a strong wind-pumping effect on CO_2 movement in a snowpack. We believe that our findings improve our understanding of efflux mechanisms and will contribute to the quantitative evaluation of all scalar fluxes at the snow- (or soil-) atmosphere interface.

[30] In addition, in the soil pores under the snowpack, the CO_2 concentration was primarily related to the air temperature. This implies that soil respiration responds directly to air temperature, not to soil temperature, even beneath a 1-m-thick snowpack. We infer that the air temperature affected the root respiratory activity of trees through their trunks and that the variation in root respiration strongly affected the CO_2 concentration fluctuation in soil under the snowpack. Root respiration must be studied further in order to prove this hypothesis.

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