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CO_2 flux through a Wyoming seasonal snowpack: diffusional and pressure pumping effects

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Abstract The movement of trace gases through porous media results from a combination of molecular diffusion and natural convection forced by turbulent atmospheric pressure pumping. This study presents observational and modeling results of an experiment to estimate the CO_2 flux through a seasonal snowpack in the Rocky Mountains of southern Wyoming, USA. Profiles of CO_2 mole fraction in the top 1 m of the snowpack, CO_2 mole fraction just above and at the base of the snowpack, and snowpack density profiles were obtained at a meadow site during February and March 1994, when the snowpack was about 2 m deep. Turbulent atmospheric pressure fluctuations, sampled at 15 Hz at the snow surface, were obtained using a fast response differential pressure sensor. A one-dimensional steady state diffusion model and a one-dimensional time-dependent pressure pumping model are used to estimate CO_2 fluxes through the snowpack. Boundary conditions are provided by the CO_2 mole fraction grab samples just above the snowpack and at the snow/soil interface. The pressure pumping model is driven by the observed pressure fluctuations. Both models include the observed layering of the snowpack. The CO_2 flux predicted by the diffusion model varied between 0.026 mg-CO_2 m^{-2} s^{-1} (on 3 March) and 0.032 mg-CO_2 m^{-2} s^{-1} (on 23 February). The pressure pumping model fluxes were greater than the steady state diffusional CO_2 fluxes by 19 to 31%.

INTRODUCTION

A worldwide increase of atmospheric CO_2 may be a major contributor to global warming. Consequently, much recent scientific effort has been directed toward identifying CO_2 sources and sinks. Because snow can cover 50% of the land surface in the northern hemisphere during winter, one important source of atmospheric CO_2 in the wintertime is the biological production of CO_2 within the soil and its subsequent diffusion through seasonal snowpacks (Sommerfeld *et al.*, 1993; Zimov *et al.*, 1993). The exhalation of CO_2 from the snowpack is a combination of molecular diffusion and atmospheric pressure pumping. Naturally occurring atmospheric pressure fluctuations at the top of the snowpack create pressure gradients within the snowpack. These gradients in turn induce a periodic air flow that can cause mass or heat to move into and out of the snowpack. The air flow velocity is determined by the permeability of the medium and the direction and magnitude of the pressure gradient. In general pressure pumping occurs on time scales ranging from weeks (Massmann & Farrier, 1992) to fractions of a second (Clarke *et al.*, 1987). The purpose of this study is the investigate the effects that high-frequency atmospheric pressure fluctuations (with periods between 0.1 and 1000 s) can have upon the rate of diffusion of CO_2 through a seasonal snowpack.

MATERIALS AND METHODS

Site description

The data for this study were obtained at a subalpine wet meadow site (elevation 3186 m) within the larger Glacier Lakes Ecosystem Experiments Site (GLEES; 41°20′N, 106°20′W), located in the Rocky Mountains of southern Wyoming about 70 km west of Laramie, Wyoming. All measurements were taken at this wet meadow site during February and March of 1994. This meadow is surrounded by subalpine forest dominated by Engelmann spruce (*Picea engelmannii* (Parry) Engelm.) and subalpine fir (*Abies lasiocarpa* [Hook.] Nutt.), ranging in age between 250 and 450 years old. The height of most of the trees is between 15 and 20 m, while the wet meadow itself measures about 120 m (north-south axis) by about 40 m (east-west axis).

The snow cover season at this site usually begins in November and ends in June. Maximum snow depth is usually reached in February or March and can vary yearly between 1 and 4 m. Observed ambient diurnal temperatures during the winter season typically ranged between −2°C and −20°C and measured soil temperatures are fairly constant at about 1°C. The average winter wind speed is about 10 m s^{-1} ranging between 2 and 25 m s^{-1}. The dominant wind direction throughout most of the year is from the west (230 to 310°). This sector is heavily forested for more than 3 km upwind and the terrain slopes gently downward toward the site. A secondary wind direction is from the south and southwest (160 to 230°). This sector is more open and grassy with fewer trees and it slopes steeply downward away from the site.

Soils within the wet meadow are rocky, often broken by rock outcroppings and vary in depth between about 0.1 and 0.7 m. Soils typically possess a loam texture, but a few deeper soils show a silt-loam or sandy-loam texture. All soils were typic or pachic cryoborols. Measured soil bulk densities varied between 0.68 and 1.07 g cm^{-3}.

Model development

The equations that describe the one-dimensional pressure pumping model, given below, correspond to the equations for forced air flow through a porous medium. Equation (1), therefore, is a variant of the advective-diffusive equation for mass transport through a porous medium.

$$\frac{\partial \chi}{\partial t} = \frac{1}{\eta}\frac{\partial}{\partial z}(\chi v) + \frac{P_{00}}{P_0}\frac{T}{T_0}\frac{D_0}{\eta}\frac{\partial}{\partial z}\left[\left(\frac{T}{T_0}\right)^{0.81} \eta\, \tau \frac{\partial \chi}{\partial z}\right] \tag{1}$$

$$v = -\frac{k}{\mu}\frac{\partial p}{\partial z} \tag{2}$$

$$\frac{\partial p}{\partial z} = \frac{T}{\eta} P_0 \frac{\partial}{\partial z}\left[\frac{k}{T\mu}\frac{\partial p}{\partial z}\right] \tag{3}$$

where t = time, z = distance downward into the snowpack and soil from the snow surface, χ = mole fraction of CO_2 (ppmV), v = Darcian convective velocity, η = porosity of the layered snowpack and soil, P_{00}=101.3 kPa, T_0= 273.15 K, D_0 = diffusivity of CO_2 in air at 0°C(= 0.139 m^2 s^{-1}), T = temperature of snowpack or soil, P_0= ambient pressure, τ = tortuosity of snowpack or soil, k = permeability of snowpack or soil, μ = dynamic viscosity of air within the snowpack or soil (a function of T), p = dynamic pressure responsible for pressure pumping.

The pressure pumping model, as formulated by these three equations, is based on several important assumptions. First, we ignore two and three dimensional effects. Higher dimensional pressure pumping effects can be important for both snowpacks (Albert & McGilvary, 1991) and soils (Ishihara *et al.*, 1992). However, both studies suggested that these effects are largely confined to the top few centimeters of the medium. Furthermore, the ultimate source of CO_2 is soil biological activity which is largely controlled by temperature and moisture. Since neither of these variables changed very much during the experiment (as discussed below), then neither should CO_2 production rate. Consequently, the soil CO_2 flux should be fairly spatially uniform. For these two reasons we do not think that two- or three-dimensional effects are likely to be too important. Second, we ignore Knudsen transport, gravitational effects, time dependent temperature effects, possible generation of CO_2 within the snowpack and effects associated with viscous flow. None of these latter effects was found to be important for this study (e.g. Albert & McGilvary, 1991; Farr, 1993; Sommerfeld *et al.*, 1993). Third, and possibly most importantly, these three equations are approximations to the full nonlinear equations, as discussed by Farr (1993). They result from assuming a binary gas system (air and CO_2) with the concentration of CO_2 being much less than air. For the present purposes these equations should be a good approximation.

The model that describes the pressure within the snowpack, equations (2) and (3), also includes a layered soil component. Because the soil is also porous, it is included in the formulation of the lower boundary condition for the pressure fluctuations within the snowpack. On the other hand, the domain of the CO_2 component of the model, equation (1), includes only the snowpack. Consequently we do not explicitly model the CO_2 evolution and transport within the soil. We can avoid the additional complexity because the CO_2 evolution within the soil and its transport to the soil/snowpack interface is thought to be sufficiently slow that the lower boundary condition for the CO_2 model, located at the soil/snowpack interface, can be assumed to be steady state during the few hours of flux data simulated by the model.

These equations are solved numerically by finite difference methods to produce half-hourly flux estimates for several contiguous half hours of observations on 23 February and 3 March. Equation (3) is solved first and v, determined from equation (2), is then used to solve equation (1). We use the backwards implicit method for the time differencing and a second order mass conserving scheme for the spatial differencing. The spatial grid has a uniform increment of 0.001 m and the time step, determined by the eddy covariance sampling rate, is 0.068 s. Equation (1) is initialized assuming a linear profile for χ and equation (3) is initialized with a weakly decreasing pressure amplitude. The boundary conditions for equation (1) are supplied by several grab samples taken within 1 cm of the snowpack surface and from the soil/snowpack interface. For any given half-hourly flux estimate these boundary conditions are assumed constant. The upper boundary condition on equation (3) is supplied by direct observations and is time-varying. The lower boundary condition on equation (3) is $v = 0$ at the level of the bedrock estimated from soil samples to be 0.69 m below the soil surface. The bedrock is assumed to be impermeable. After the model has been run for the first half hour, it is reinitialized with the resulting profiles of χ and p and then rerun. The intention of this second initialization is to provide better estimates of the initial profiles of χ and p. The half-hourly flux is the average of the instantaneous fluxes computed at each time step.

The diffusion model is the same as equation (1) except that we assume it is steady state ($\partial\chi/\partial t = 0$) and nonadvective ($v = 0$). The spatial resolution and the boundary conditions are the same as with the pressure pumping model. The diffusional model is integrated numerically using the shooting method and a fourth order Runge-Kutta approach and is repeated until the lower boundary condition is satisfied to within a small tolerance.

High frequency pressure data

Turbulent pressure fluctuation data at the snow surface were also sampled at 15 Hz and archived on 3 March between 1330 and 1600 MST and on 23 February between 1530 and 2100 MST. These data were obtained with a differential pressure transducer (Cook & Bedard, 1971) attached to a laser-perforated hose (a common garden hose known as a "soaker" hose). This hose was laid over 10 to 15 m^2 of snow surface. The effects of a 100-s high pass filter, designed as part of the instrument, were removed using numerical techniques before the pressure data were used to drive the pressure pumping model.

Snowpack and soil data

Profiles of snow density and texture were obtained on 25 February and 5 March from snow pits. The snow depth on 25 February was 1.78 m and on 5 March it was 2.02 m with the snowpacks consisting of several distinct layers. Snowpack air permeability profiles were computed from the density profiles using the model of Sommerfeld & Rocchio (1993). The density profiles were also used to obtain the snowpack porosity profiles. Snowpack tortuosity profiles vary weakly with snow density and were assumed to be close to a constant value of 0.7 (Davis, 1994). At each of the interfaces between different snow densities a cubic spline was used to smooth the discontinuity so that the snowpack profiles were described by continuous functions.

Half-hourly averaged snowpack temperatures were estimated from a vertical array of 24-gauge copper-constantan thermocouples deployed at every 20 cm within the snowpack starting at 40 cm above the soil surface. This array, suspended from a piece of string, had been installed during the previous fall and the snow was allowed to build up around it. These temperatures are used in the model directly as well as to model the temperature effects on diffusivity of CO_2 in air within the snowpack and on the dynamic viscosity.

Snowpack CO_2 concentration profiles were obtained by grab samples using Teflon tubing at two sites within the meadow. Samples were taken several times a day on 23 February and on 2, 4, and 5 March at 5, 10, 30, 50, and 100 cm below the surface and at the base of the snowpack. Snowpack CO_2 profile data taken during 23 February were averaged to produce a single daily-averaged profile. The three days of data taken during March were also averaged and used for the 3 March CO_2 profile through the snowpack. Ambient atmospheric CO_2 samples were also obtained within 1 cm of the snow surface. All samples were drawn using 20-ml nylon syringes fitted with two-way nylon stopcocks and analyzed for CO_2 with a gas chromatograph (Sommerfeld *et al.*, 1993).

Two soil cores were taken during the fall of 1994 at the meadow site and analyzed for profiles of bulk density, texture and saturated hydraulic conductivity. Soil air permeability was then estimated from the hydraulic conductivity profiles. These data suggested that the soil be modeled with five distinct layers, each varying between 10 cm and 20 cm in thickness with a total depth of 69 cm and each with separate permeabilities varying between $1.2(10^{-14})$ m^2 and $37(10^{-14})$ m^2. Observed soil temperatures within the upper 8 cm of soil were nearly constant with depth and time and averaged about 0.8 °C. For modeling purposes the soil is assumed to have a uniform soil temperature of 1 °C. In general the model results were not significantly influenced by soil temperature. Furthermore, the soil is also assumed to be dry during the time of the experiments. This is quite reasonable because soil moisture is typically extremely low at the beginning of the snow cover season and remains low until spring melt.

RESULTS AND SYNTHESIS

Figures 1(a) (23 February) and (b) (3 March) show the observed and modeled average snowpack CO_2 profiles. The shaded areas in each figure show the maximum variation in the measured CO_2 concentrations in the snowpack. Because of sampling problems on 23 February there was only one valid data point at the snowpack boundaries. Consequently, this day does not show any variation in the CO_2 profiles at the snowpack boundaries. In general, the 3 March simulations agree with observations better than on 23 February. The model profiles are also quite similar, differing from one another only slightly.

Figure 2 shows the 23 February root mean square (RMS) pressure pumping amplitude as a function of depth in the snowpack and soil layers. Also shown are the RMS amplitude of the pressure induced Darcian convective velocity (throughout the whole model domain) and the diffusional drift velocity (for the snowpack only). For this day the induced convective velocity varies between about 0.02 and 0.08 mm s^{-1} and exceeds the diffusional drift velocity throughout the snowpack. On 3 March (results not shown) the RMS pressure amplitude is less than on 23 February and the induced convective velocity is comparable to or less than the diffusional drift velocity.

The model-estimated pressure pumping CO_2 flux through the snowpack on 23 February averaged 0.038 mg-CO_2 m^{-2} s^{-1} and varied between 0.041 and 0.036 mg-CO_2 m^{-2} s^{-1} and on 3 March the average flux was 0.034 mg-CO_2 m^{-2} s^{-1}, varying

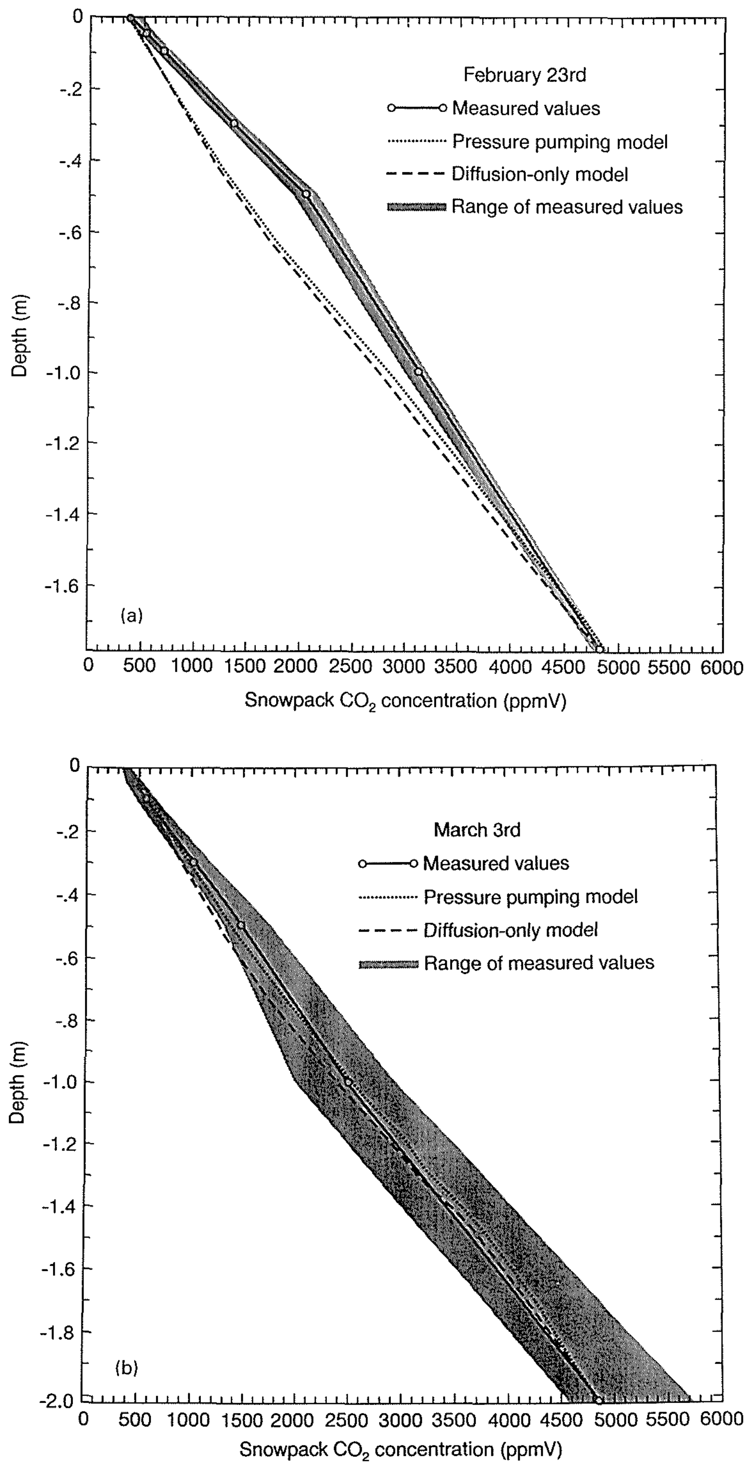

Fig. 1 (a) Modeled and observed snowpack CO_2 profiles for 23 February 1994. (b) Modeled and observed snowpack CO_2 profiles for 3 March 1994.

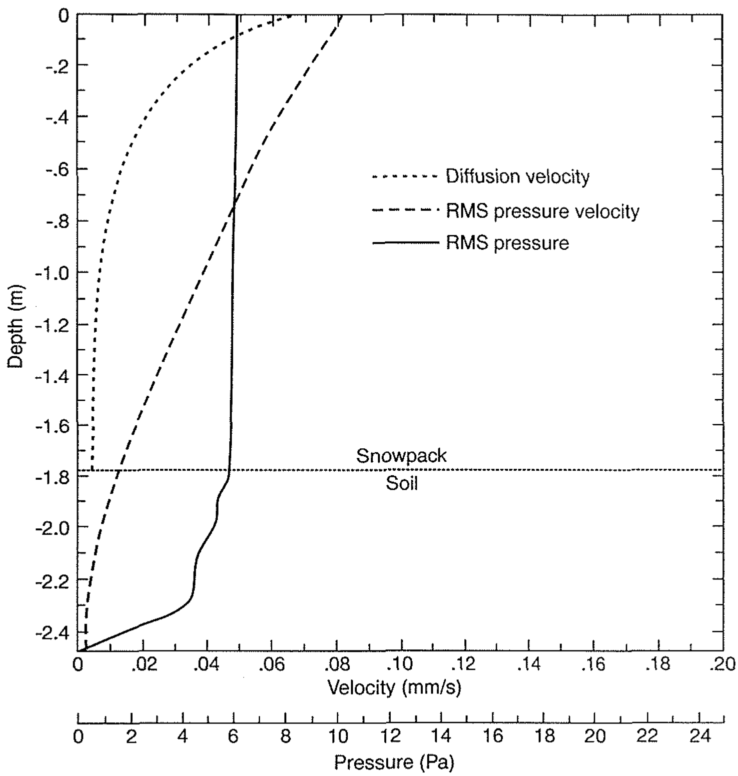

Fig. 2 Model produced RMS pressure amplitude profile, RMS Darcian convective pressure velocity amplitude profile and diffusion drift velocity profile.

between 0.037 and 0.032 mg-CO_2 m^{-2} s^{-1}. On these two days the ambient CO_2 concentration was 367 ppmV (23 February) and 396 ppmV (3 March) and the CO_2 concentration at the soil/snowpack interface was 4841 ppmV (23 February) and 4875 ppmV (3 March). The average RMS pressure amplitudes at the snow surface were about 6 Pa (23 February) and 4 Pa (3 March) and the maximum instantaneous (peak-to-trough) differences were about an order of magnitude greater than these average RMS values.

The molecular-diffusion-only model estimated the CO_2 fluxes through the snowpack to be 0.032 mg-CO_2 m^{-2} s^{-1} (23 February) and 0.026 mg-CO_2 m^{-2} s^{-1} (3 March). Comparing the pressure pumping model results with these suggests that pressure pumping increased diffusion-only fluxes by about 19% on 23 February and by 31% on 3 March. The relatively higher 23 February fluxes are probably the result of a relatively larger CO_2 gradient through the snowpack and the greater strength of the pressure pumping on 23 February than on 3 March.

Although all the present flux estimates are in good agreement with values of CO_2 efflux through snowpacks and/or wintertime soil respiration rates at montane and coniferous sites (Solomon & Cerling, 1987; Raich & Schlesinger, 1992; Sommerfeld *et al.*, 1993), they are nevertheless not without some degree of uncertainty because they are model derived. To estimate this uncertainty a sensitivity analysis was done to evaluate the largest sources of possible error. For the pressure pumping model, the two most important input parameters were found to be the CO_2 concentration at the soil/snowpack interface and the soil permeability. Observed variations in χ at the base of the snowpack could introduce between -10 and $+20\%$ change in the flux estimates. An order of magnitude change in soil permeability could cause a change between -10 and $+60\%$ in the CO_2 fluxes. Uncertainties in tortuosity, snow density, and soil temperature gradients introduced much less uncertainty into the fluxes than did these two. For the diffusion-only model the largest source of uncertainty was also the observed variations in χ at the base of the snowpack and it was associated with similar percentage uncertainty values.

In addition to providing estimates of uncertainty in the fluxes, this sensitivity analysis also highlights an important difference between the pressure-pumping and diffusion-only models. In the diffusion-only model the flux is proportional to the effective diffusion coefficient ($\eta\tau D_0$) and a 10% change in this quantity will yield a 10% change in the flux. However, a 10% change in $\eta\tau D_0$ in the pressure-pumping model yielded (at most) a 1% change in the flux during 23 February and (at most) a 2% change for the 3 March case. This suggests that the dynamics of CO_2 release are quite different for pressure pumping and simple diffusion even on days when pressure pumping is relatively weak as may have been the case on 3 March. Dynamically, then, pressure pumping may be much more significant for the movement of trace gases through snowpacks than is diffusion. Consequently since pressure pumping varies with location and time, trace gas movement through snowpacks (and by analogy through any permeable medium) may also show significant variation with location and meteorological conditions. Furthermore, since atmospheric pressure variations are the norm at the earth's surface the present results also suggest that pressure-pumping is likely to be significant for trace gas movement through any highly permeable medium.

SUMMARY AND CONCLUSIONS

Pressure pumping appears to significantly enhance molecular diffusional transport of CO_2 through snowpacks. It is also strongly influenced by the permeability of the underlying soil, the depth of the snowpack and the CO_2 concentration beneath the snowpack. Furthermore, the dynamics of trace gas movement due to pressure pumping appears to differ significantly from pure diffusion.

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