

Short communication

High-frequency pressure variations in the vicinity of a surface CO₂ flux chamber

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Abstract

We report measurements of 2 Hz pressure fluctuations at and below the soil surface in the vicinity of a surface-based CO₂ flux chamber. These measurements were part of a field experiment to examine the possible role of pressure pumping due to atmospheric pressure fluctuations on measurements of surface fluxes of CO₂. Under the moderate wind speeds, warm temperatures, and dry soil conditions present at the time of our observations, the chamber had no effect on the pressure field in its near vicinity that could be detected above the level of natural pressure fluctuations in the vicinity. At frequencies at or <2 Hz, pressure fluctuations easily penetrated the soil to depths of several cm with little attenuation. We conclude that the presence of the chamber does not introduce pressure perturbations that lead to biases in measurements of surface fluxes of CO₂.

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1. Introduction

Accuracy in measurements of CO₂ fluxes from soils requires understanding of the role of ambient physical processes in the vicinity of the measurement instrument. Natural pressure variations had been suggested as a possible mechanism for gas movement in soils nearly a century ago by Buckingham (1904), who con-

cluded that barometric pressure changes were unimportant for the upper 15 m of soil. More recent studies indicate pressure changes are important and that these variations may arise from diurnal and semi-diurnal barometric waves, passage of synoptic weather systems, atmospheric turbulence, and quasi-static pressure fields induced by wind blowing across irregular topography. Baldocchi and Meyers (1991) provide a first report of increased CO₂ efflux rates with increased levels of standard deviation of static pressure.

Dynamical pressure fluctuations induced by wind in the vicinity of obstacles near the earth's surface

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create forces that under some circumstances dominate the momentum budget (Wang and Takle, 1997). A constant (speed and direction) horizontal wind impinging on obstacles (plants, micro-terrain irregularities) establishes dynamically induced horizontal static pressure gradients at the surface-atmosphere interface (Waddington et al., 1995). These pressure gradients typically can be as large as $10\text{--}20\text{ Pa m}^{-1}$ across a windbreak. For example, Schmidt et al. (1995) measured 14 Pa difference for 6 m s^{-1} oblique wind flow through a 10-m wide windbreak, which gives a horizontal acceleration of about $1\text{--}2\text{ m s}^{-2}$. It should be emphasized that these pressure perturbations are stationary (they are time independent if the wind is constant in speed and direction and are present even in the absence of turbulence) and will persist for long periods of time if the wind persists. They are different from atmospheric pressure variations caused by, say the passage of gravity waves or other mesoscale or synoptic scale phenomena, which would not be expected to establish horizontal pressure gradients of significant magnitude to influence micrometeorological flows. Takle and Wang (1997) briefly discuss the importance of the horizontal surface pressure gradient established by atmospheric flow through vegetation and its possible role in soil gas exchange. We distinguish pressure fluctuations attributable to variations of the mean wind interacting with obstacles from pressure fluctuations in turbulent flow. The latter are based on the square of wind speed fluctuations, whereas, obstacle-induced pressure is based on the square of the mean wind speed. For the case of mean wind being much larger than the fluctuating wind, the obstacle-induced pressure will dominate over turbulent pressure.

A question then arises as to the possibility that these horizontal pressure gradients (and associated forces in the horizontal momentum equation for gases in soil) might lead to horizontal flow of air in the soil around the surface-placed measurement device. If such flow existed it could contaminate estimates of fluxes of CO_2 into the surface-based CO_2 chamber, which are assumed to represent only vertical movement of gases in the soil. Hutchinson and Mosier (1981) were probably the first to address this issue in connection with chamber design, but the issue remains a source of uncertainty in chamber measurements (Conen and Smith, 1998; Hutchinson and Livingston, 2002).

We herein report measurement of high-frequency (2 Hz) pressure fluctuations at and below the soil surface in the vicinity of a surface-based CO_2 flux chamber. These measurements were part of a field experiment to examine the role of pressure pumping due to atmospheric pressure fluctuations on measurements of surface fluxes of CO_2 , the results of which will be reported elsewhere.

2. Measurement site, instruments, and procedure

2.1. Site

The field measurement program was carried out during 16–17 September 1999 under clear skies and temperatures ranging from $20\text{--}25\text{ }^\circ\text{C}$ at the University of Nebraska Agricultural Research and Development Center near Mead, NE, USA. Measurements were made in the vicinity of a 1.2 m snow fence with vertical slats 3.8 cm wide giving the fence a porosity of 62%. The fence was 45.3 m long and was oriented east-west in a field in which wheat was grown in the 1999 crop season. In mid-August, the soil was tilled so that only small amounts of crop residue and no live vegetation remained on the surface at the time of measurements. The soil is a Tomek Silty Clay Loam (Fine, smectitic, mesic Pachic Argiudoll). At the surface, the soil was dry and had been compacted with a water-filled roller prior to installation of the fence.

2.2. Pressure transducers and ports and data logging

Differential pressure was measured by Setra Systems Model 264 pressure transducers (Schmidt et al., 1995). The reference pressure port for all differential transducers was provided by a 0.75 in. garden hose with open end at the surface 77.2 m south of the fence. The hose had a manifold at the fence that offered reference pressure for the “reference” side of each pressure transducer. The “measurement” side of each transducer was connected to 0.25 in. tubing of approximately 1-m length to the open port at the test location. The Setra transducers had their filters removed to increase the high-frequency response. Under these conditions the transducers recovered to 90% value of a

step function in about 0.5 s. Fluctuations in differential pressure reported by the transducers under this arrangement will be dominated by pressure fluctuations induced by obstacles established for the experiment which will be much larger than those arising from atmospheric turbulence at the reference port. Pressure measurements at 2 Hz were recorded by a LiCor 6400 CO₂ flux meter (CO₂ chamber flux data also were recorded but these results are reported elsewhere).

2.3. Procedure

We located the ports of the four transducers in the vicinity of the LiCor 6400 chamber, which was mounted on a 5 cm high cylinder that was pressed 2.5 cm into the soil. Tubing leading to one of the pressure ports was buried under the cylinder so that its open end exited the soil inside the LiCor 6400 chamber. Other ports were distributed at the surface outside but within 0.3 m of the chamber. Four series

of measurements were taken at the upwind and five series downwind of the fence. Each series consisted of samples taken at 0.5 s intervals for approximately 120 s. With port P1 being under the chamber and ports P2, P3, and P4 being outside, we have three combinations of horizontal pressure differentials (P1–P2, P1–P3, P1–P4) to examine pressure perturbations induced by the chamber. For comparison, we have three combinations of pressure differentials (P2–P3, P2–P4, P3–P4) to assess horizontal pressure perturbations between nearby locations outside the chamber. The differential pressures outside the chamber represent natural variations (not influenced by the chamber), so their magnitude provides a basis for evaluating possible pressure fluctuations induced by the chamber.

We examined pressure fluctuations in the soil by constructing a vertical array of pressure ports at 0 (surface), –15, –45, and –60 cm near the position of the LiCor 6400 chamber. Characteristics of natural

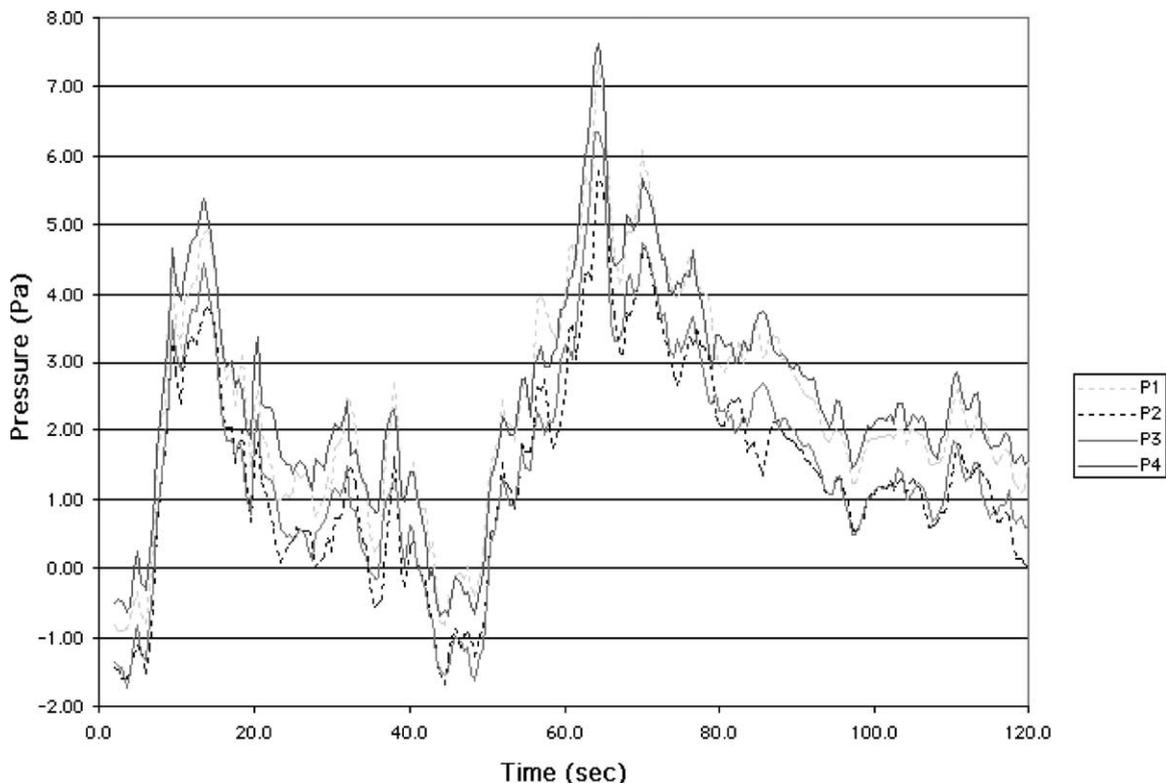


Fig. 1. Time series of differential pressure with ports positioned at the soil surface. P1 under LiCor 6400 chamber; P2, P3, and P4 at the surface outside but within 30 cm of chamber.

pressure variations were further clarified by comparison with artificially inducing surface pressure fluctuations over this vertical array of ports. These artificial fluctuations were created by use of an inverted cylindrical galvanized stock water tank of diameter 91.5 cm and height 60 cm placed over the chamber and vertical array of pressure ports. The tank was seated firmly in the dry soil to prevent large volumes of air from escaping around the perimeter. Despite some care in positioning the tank, manual pumping on the tank bottom produced noticeable dust movement at the interface due to the dry soil conditions at the time of the measurements. Artificial pressure fluctuations were induced into the soil by firm periodic downward thrust and release on the bottom of the tank, which caused abrupt downward/upward displacement of about 3 cm of the drum-like surface.

3. Results

3.1. Surface pressure fluctuations

During the measurements of the surface pressure fluctuations (17 September) the wind speed at 3 m averaged 3.4 m s^{-1} , and measurements of soil pressure profiles were made under ambient winds of 3.7 m s^{-1} . The time series of differential pressure from the four transducer ports located on the soil surface (Fig. 1) reveals very high correlation among the four transducers. Fig. 1 is typical of the other eight series. Close inspection reveals that small differences occasionally exist at high frequency, perhaps partly due to the high-frequency response limitations of the differential pressure transducers as previously noted. With rare exceptions, all transducers responded in phase at

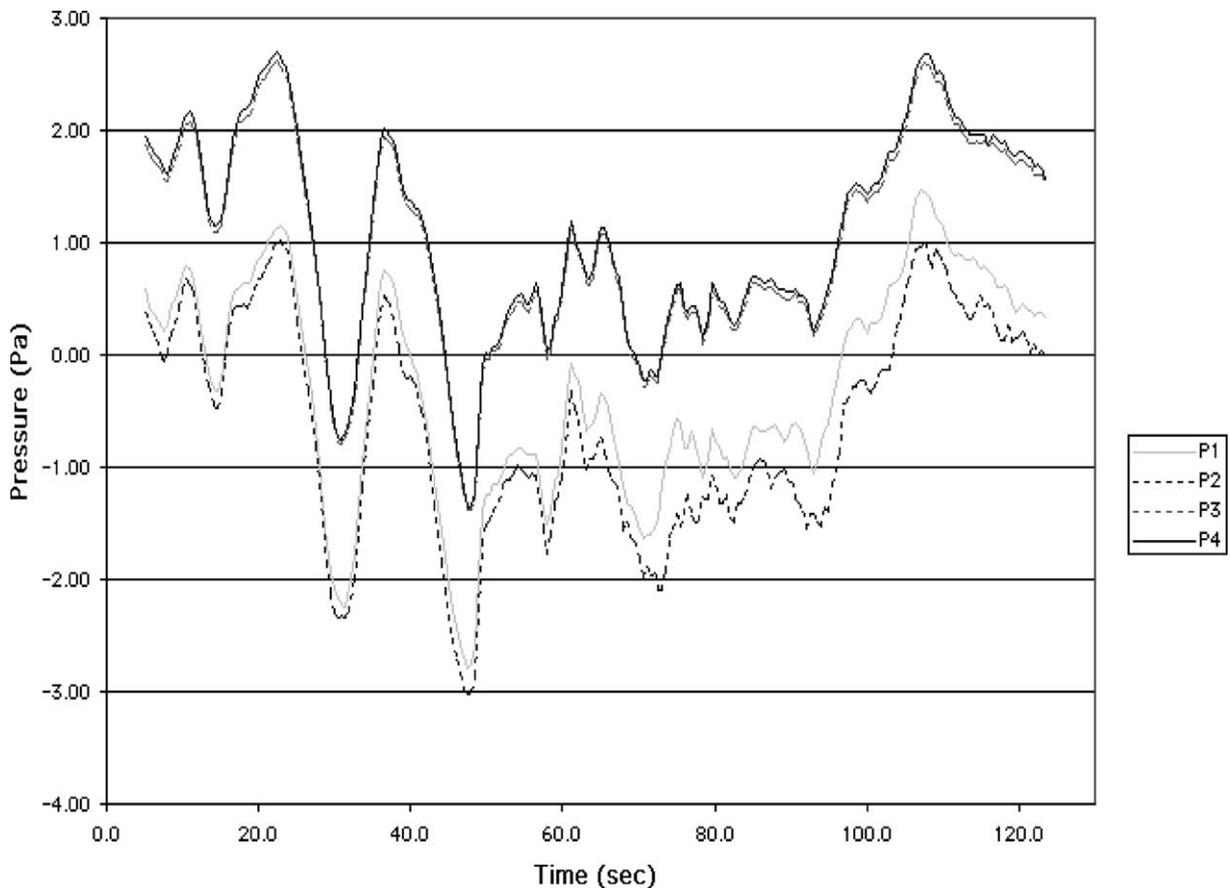


Fig. 2. Time series of differential pressure measured with P2 at the surface and P1, P3, and P4 at soil depths of 15, 45, and 60 cm, respectively. The LiCor 6400 chamber was mounted over port P2. All four ports were positioned in a vertical line.

frequencies below 0.1 Hz. Evidently, the chamber does not disturb the phase of ambient pressure fluctuations.

Surface pressure differences for ports outside and inside the chamber for the three different configurations showed no statistical difference and had overall mean (standard deviation) of 0.559 (± 0.442) Pa. For comparison, the pressure ports located at the surface outside the chamber but in the near vicinity at comparable spacings gave mean differences (standard deviation) of 0.230 (± 0.107), 1.180 (± 0.199), and 0.953 (± 0.126) Pa. Evidently ambient horizontal pressure gradients outside the chamber had magnitudes significantly larger and smaller than those introduced between ports inside and outside the chamber. Therefore, we conclude that ambient conditions include pressure influences comparable with those introduced by the chamber.

3.2. Soil air pressure fluctuations

Clarke and Waddington (1991) provide a detailed mathematical description of three-dimensional penetration of a surface-pressure fluctuation into a uniform permeable half space (e.g. snow or soil). Vertical penetration of a disturbance of a single frequency, ω , is described by the penetration depth $z_0 = 1/2\alpha$, where

$$\alpha^2 = \frac{\mu n |\omega|}{2\kappa p_0}$$

and μ is the air viscosity, n the porosity, κ the permeability, and p_0 is the ambient surface pressure. By use of typical mks-unit values ($\mu = 1.5 \times 10^{-5}$, $n = 0.50$, $\kappa = 10^{-10}$ to 10^{-12} , $p_0 = 10^5$, Moldrup et al., 1998), for a pumping frequency of 0.25 Hz, we get $\alpha = 0.77$ to 7.7 m^{-1} and a penetration depth of

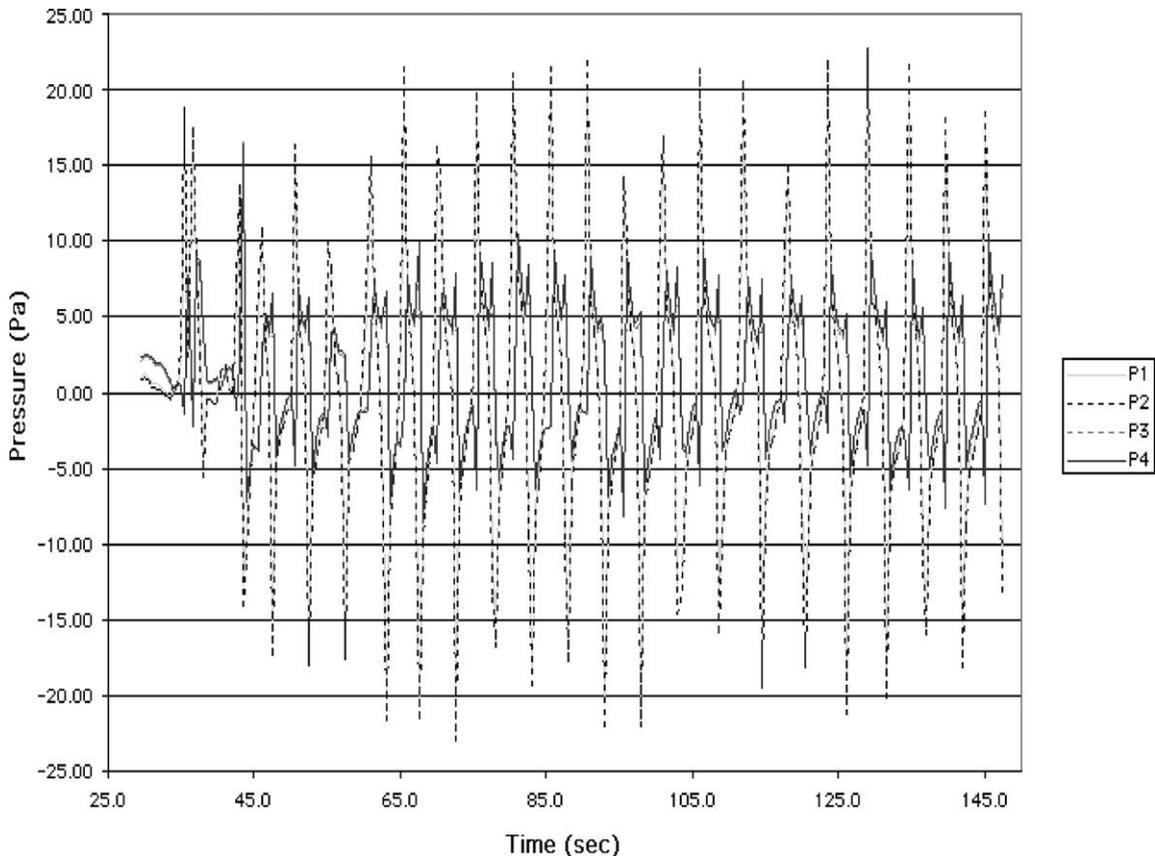


Fig. 3. Time series of differential pressure measured with P2 at the surface and P1, P3, and P4 at soil depths of 15, 45, and 60 cm, respectively. The LiCor 6400 chamber was mounted over port P2. All four ports were positioned in a vertical line. Pressure oscillations at approximate frequency of 0.25 Hz were induced on the bottom of an inverted stock tank positioned over the chamber.

0.65–0.065 m, the former being more characteristic of dry soils and the latter relating to moist soils. The horizontal dimension of the tank being 0.915 m suggests a horizontal wave number, k , of about 6.9 m^{-1} . Natural atmospheric boundary-layer fluctuations of significant amplitude would be expected to have much longer horizontal dimensions and correspondingly lower k values. By using the analysis of Clarke and Waddington (1991), we find that if $k \ll \alpha$, one-dimensional effects will dominate, whereas if $k \gg \alpha$, three-dimensional effects will be important and additional attenuation would be expected in the vertical direction.

A vertical profile of measured pressure fluctuations confirmed that pressure fluctuations do, indeed, penetrate the soil at frequencies of 2 Hz, with no obvious phase change nor significant attenuation. The time sequence of measurements with no pumping on the tank (Fig. 2) reveals a lack of amplitude attenuation with depth under natural pressure fluctuations. By contrast, the pressure fluctuations induced by periodically (about 0.25 Hz) pumping on the tank (Fig. 3) are strongly attenuated as would be expected for a three-dimensionally propagating disturbance. These results suggest that the horizontal spatial scales of the natural pressure disturbances are large compared to the vertical distances between ports of the array.

4. Summary

We report measurements of 2 Hz pressure fluctuations inside, outside, at the surface, and in the soil below a LiCor 6400 CO₂ measurement chamber under summertime conditions in a bare field having relatively dry soil conditions. Results show that, under the meteorological and soil conditions present at the time of observation, the effect of the chamber on the pressure field in its near vicinity was within the range of natural pressure fluctuations. At frequencies at or below 2 Hz, natural pressure fluctuations easily penetrated the soil to depths of several centimeters with little attenuation but that pressure fluctuations introduced over a limited region are strongly attenuated. We conclude that the presence of the chamber does not introduce pressure perturbations that could lead to biases in measurements of surface fluxes of CO₂.

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References

- Baldocchi, D.D., Meyers, T.P., 1991. Trace gas exchange above the floor of a deciduous forest. 1. Evaporation and CO₂ efflux. *J. Geophys. Res.* 96 (D4), 7271–7285.
- Buckingham, E., 1904. Contributions to our knowledge of the aeration of soils. USDA, Bureau of Soil Bulletin No. 25. US Government Printing Office, Washington, DC.
- Clarke, G.K.C., Waddington, E.D., 1991. A three-dimensional theory of wind pumping. *J. Glaciol.* 37, 89–96.
- Conen, F., Smith, K.A., 1998. A re-examination of closed flux chamber methods for the measurement of trace gas emissions from soils to the atmosphere. *Eur. J. Soil Sci.* 49, 701–707.
- Hutchinson, G.L., Livingston, G.P., 2002. Vents and seals in non-steady-state chambers used for measuring gas exchange between soil and the atmosphere. *Eur. J. Soil Sci.* 52, 675–682.
- Hutchinson, G.L., Mosier, A.R., 1981. Improved soil cover method for field measurement of nitrous oxide fluxes. *Soil Sci. Soc. Am. J.* 45, 311–316.
- Moldrup, P., Poulsen, T.G., Schjønning, P., Olesen, T., Yamaguchi, T., 1998. Gas permeability in undisturbed soils: measurements and predictive models. *Soil Sci.* 163, 180–189.
- Schmidt, R.A., Takle, E.S., Brandle, J.R., Litvina, I.V., 1995. Static pressure at the ground under atmospheric flow across a windbreak. In: Proceedings of the 11th Symposium on Boundary-Layers and Turbulence, Charlotte, NC, USA. *Am. Meteorol. Soc.*, 517–520.
- Takle, E.S., Wang, H., 1997. Reply to comments by J.D. Wilson, C.J. Mooney on 'A numerical simulation of boundary-layer flows near shelterbelts'. *Boundary-Layer Meteorol.* 85, 151–159.
- Waddington, E.D., Cunningham, J.C., Harder, S.L., 1995. The effects of snow ventilation on chemical concentrations. In: Wolf, E.W., Bales, R.C. (Eds.), Proceedings of the NATO Advance in Research Workshop II Ciocco on the Chemical Exchange between the Atmosphere and Polar Snow, Italy. pp. 403–451.
- Wang, H., Takle, E.S., 1997. Momentum budget and shelter mechanism of boundary-layer flow near a shelterbelt. *Boundary-Layer Meteorol.* 82, 417–435.