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Field-based determination of air diffusivity using soil air and atmospheric pressure time series

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Abstract. Air diffusivity in two zones over a 4.6-m interval of the unsaturated zone was determined through analysis of atmospheric pressure and soil air pressure time series. Regression analysis was used to calculate the ratio of amplitudes (admittance) and phase lag between these series at diurnal and semidiurnal frequencies. The admittance for each of the monitoring zones was close to unity for both frequencies. Phase lags between the two time series were statistically equivalent to zero at the diurnal frequency but were as large as 20° ± 7° at the semidiurnal frequency. The phase lag at diurnal and semidiurnal frequencies for each zone was compared to a diffusional model of soil air pressure response to atmospheric loading. From this comparison a composite air diffusivity was determined for each zone. The absence of large variability in air diffusivity and the trends in phase shift with depth suggest that macropores or fractures propagate through a clay layer at a depth of 0.5–1.2 m. The length of the time series (110 days) allowed for the examination of the magnitude of temporal changes in phase shift and air diffusivity. Temporal and spatial trends in phase lag are smaller than the error bounds in the phase estimates. Air diffusivity determined from the entire time record deviated only slightly from the average diffusivity determined from the analysis of a sequence of partial records.

Introduction

Determination of the air diffusivity of a soil is important in understanding the dynamics of the unsaturated zone. Soil and plant root interaction, the migration of gaseous contaminants, and soil air–stripping strategies for remediating volatile contamination in the unsaturated zone require knowledge of air diffusivity under field conditions. Laboratory methods for the determination of this soil parameter require careful sampling and, even when performed correctly, are unable to account for field-scale anisotropy or heterogeneity. It is therefore attractive to develop techniques for determining air diffusivity in situ.

Field measurements of air diffusivity or permeability generally involve monitoring soil air pressure in response to air or gas injection or removal [*Kirkham*, 1946; *Kearl et al.*, 1990; *Baehr and Hult*, 1991]. These techniques are advantageous because they can be performed quickly and can offer accurate measurements. However, they are unable to determine seasonal-scale temporal variability or the vertical component of air permeability.

Several studies have used natural fluctuations in soil air pressure induced by atmospheric pressure fluctuations to determine air diffusivity in situ. This approach is attractive because it does not greatly disturb the air pressure in the unsaturated zone, and it has the potential for long-term estimates of air diffusivity or permeability at large length scales. *Fukuda* [1955] used the response of shallow (less than 1 m) soil air pressure to surface pressure variations caused by wind gusts to estimate soil air permeability. *Yusa* [1969] used fluctuations in a water table well as an indicator of atmospherically induced changes in the air pressure of the unsaturated zone. From these measurements he was able to determine the bulk air diffusivity of the unsaturated zone. *Morris and Snoeberger* [1971] and *Snoeberger et al.* [1972] suggested that it might be possible to estimate permeability of nuclear chimneys (vertical fracture zones induced by subsurface nuclear blasts) by monitoring the atmospherically induced pressure changes in the chimneys. *Weeks* [1978] estimated the air diffusivity and permeability of the unsaturated zone at several sites by comparing the atmospheric pressure fluctuation signal and the corresponding air pressure at a given depth in the unsaturated zone.

While both *Yusa* [1969] and *Weeks* [1978] determined air properties from short-term measurements (less than 1 week), long-term measurements (over a period of several months or longer) have also been made. The advantage of long-term measurements is that they yield enough data to quantitatively estimate confidence intervals in soil air pressure response. *Rojstaczer* [1988], *Rojstaczer and Riley* [1990], and *Evans et al.* [1991] used aquifer response to long-term pressure fluctuations, in conjunction with spectral analysis, to infer bulk air diffusivity. A key disadvantage in the analysis of long-term measurements is the assumption that air diffusivity is constant over time. This assumption would, at face value, appear to be a poor one. Over periods of months, water content can be expected to vary greatly, especially near the surface. These variations in water content could cause significant changes in bulk air diffusivity.

This paper examines the degree of temporal and spatial variation in air diffusivity inferred from monitoring barometric and soil pneumatic pressure over a 110-day time period. The approach used is similar to that given by *Fukuda* [1955], *Hsieh et al.* [1987], *Rojstaczer and Riley* [1990], and *Evans et al.* [1991]. Through discrete frequency regression analysis the ratio of amplitudes (admittance) and phase lag between the soil air and atmospheric pressure are determined. The calculated admit-

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tances and phase lags are then matched to curves generated from theoretical solutions of airflow in the unsaturated zone.

The approach of this study extends the long-term, measurement research noted above in two primary ways. Rather than use the water table as a surrogate for the air pressure of the soil, the air pressure of the unsaturated zone was monitored directly. Also, the frequency response over discrete time intervals was examined to evaluate temporal changes in the relationship between soil air and atmospheric pressure. Our results indicate that seasonal and vertical bulk air diffusivity can vary by less than 1 order of magnitude.

Theory

The governing equation for isothermal flow of air in the unsaturated zone may be written as [*Katz et al.*, 1959]

$$\frac{\partial^2 P^2}{\partial z^2} = \frac{\mu \theta_d}{K_{ra} k P_{\text{ave}}} \frac{\partial P^2}{\partial t} \tag{1}$$

where

P soil air pressure at time t and point z;
K_{ra} relative air permeability of the soil;
k intrinsic permeability of the soil;
P_{ave} mean pressure during pressure change;
μ absolute air viscosity;
θ_d interconnected air-filled porosity.

In this equation the following assumptions have been applied: (1) gas flow due to a change in atmospheric pressure occurs only in the vertical direction, (2) absolute pressure is small enough that the ideal gas law applies, and (3) the air permeability of the medium is high enough that the *Klinkenberg* [1941] effect may be ignored. Equation (1) is linear with respect to P^2 rather than P. However, in problems where the soil air pressure varies only slightly from the mean value, (1) may be written

$$\frac{\partial^2 P}{\partial z^2} = \frac{\mu \theta_d}{K_{ra} k P_{\text{ave}}} \frac{\partial P}{\partial t} \tag{2}$$

where the term $K_{ra} k P_{\text{ave}}/\mu \theta_d$ is the air diffusivity, D_a. The simplification of the diffusion equation so that it is linear with respect to P allows for the possibility of relatively simple analytical solutions. Assuming $z = 0$ at the land surface and L at the top of the capillary fringe, the following boundary conditions apply:

$$P = f(t) \qquad \text{at } z = 0 \tag{3a}$$

$$\frac{\partial P}{\partial z} = 0 \qquad \text{at } z = L \tag{3b}$$

When $f(t)$ in (3a) is a cosine wave, $A \cos(\omega t)$, the solution of (2) subject to the boundary conditions (3a) and (3b) is [*Carslaw and Jaeger*, 1959]

$$P = (M - iN)A \exp(i\omega t) \tag{4}$$

where A is the amplitude, ω is the frequency (for our application ω is either 1 cycle/d or 2 cycles/d), t is time, and M and N are

$$M = \{[(\cosh(R)\cos(R))(\cosh(S)\cos(S))] - [(\sinh(R)\sin(R))(\sinh(S)\sin(S))]\} \cdot \{[\cosh(R)\cos(R)]^2 + [\sinh(R)\sin(R)]^2\}^{-1} \tag{5a}$$

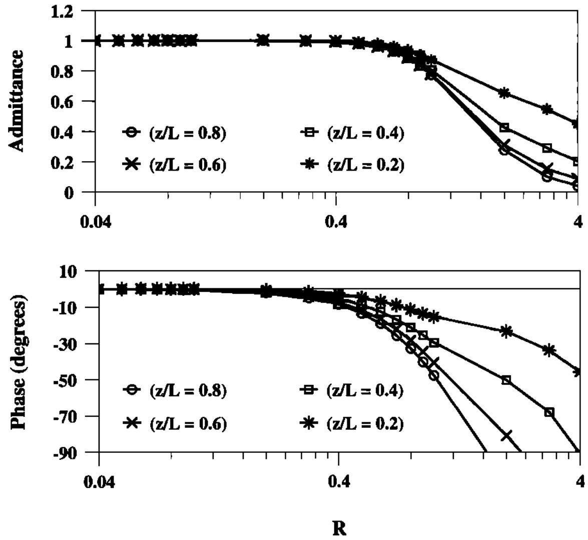

Figure 1. Theoretical admittance and phase lag (equation (4)) versus dimensionless frequency, R, for a range of values of z/L.

$$N = \{[(\cosh(R)\cos(R))(\sinh(S)\sin(S))] - [(\cosh(S)\cos(S))(\sinh(R)\sin(R))]\} \cdot \{[\cosh(R)\cos(R)]^2 + [\sinh(R)\sin(R)]^2\}^{-1} \tag{5b}$$

The parameters R and S are dimensionless frequencies referenced to the air diffusivity, D_a, and the depth of observation, z, or the distance between the land surface and the capillary fringe, L:

$$R = L^2\omega/2D_a \tag{6a}$$

$$S = (L - z)^2\omega/2D_a \tag{6b}$$

Figure 1 shows the solution to (4) in terms of admittance (ratio of amplitudes between the soil air pressure and atmospheric pressure) and phase. Attenuation and phase lag increase with increasing frequency (phase lag is represented as a negative phase shift). Significant phase shift occurs before significant attenuation. The parameters that control the response of unsaturated zone soil air pressure to atmospheric pressure are the dimensionless frequency, R or S, and the ratio of the observation depth to the distance between the land surface and the capillary fringe, z/L. If z and L are known, then determining the air diffusivity of the soil, D_a, can be performed by matching the observed phase shift and admittance to the theoretical solution of (4). Once the air diffusivity is estimated, it should be possible to estimate the air permeability, $K_{ra}k$, since the mean atmospheric pressure, P_{ave}, and interconnected air content, θ_d, can be measured independently.

Field and Laboratory Methods

Field measurements were made in a deciduous forest in the southwest portion of Durham County, North Carolina, on a topographical high, approximately 136 m above mean sea level. The soil from the site is a member of the Helena series [*U.S. Department of Agriculture*, 1971]. The parent material of this soil consists of felsic crystalline rocks that are mostly granite to

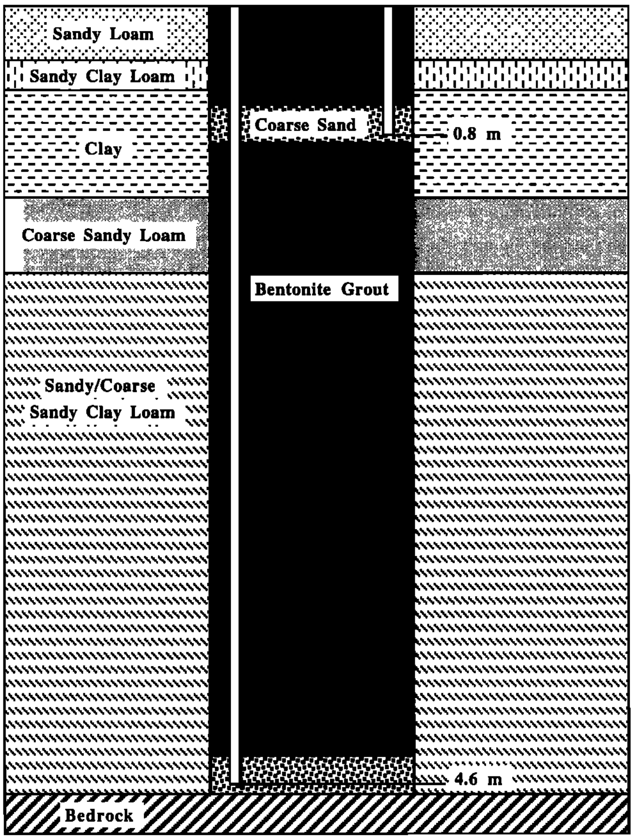

Figure 2. Diagram of the installed monitoring zones and the surrounding soil.

granodiorite, schist, and gneiss. The soil has low to medium shrink-swell potential and hydraulic conductivity ranging from less than 0.004 to 0.14 m/s [*U.S. Department of Agriculture*, 1971].

A 0.10-m-diameter hole was drilled to bedrock (4.6 m). Soil samples were collected during the drilling placed in airtight storage bags at 6-cm intervals. A Honeywell Microswitch PK 8869 (series 24PC) 350-mbar transducer was inserted into the bottom of the hole and vented to the land surface with a 2-mm-internal-diameter hose. The bottom of the hole was covered with 8 cm of coarse sand and backfilled with a slurry of bentonite clay to the shallow monitoring depth (0.8 m). Another transducer was installed and covered with sand, and then the remainder of the open hole was backfilled with bentonite slurry. A diagram of the installation is found in Figure 2.

A Qualimetrics 1200-mbar absolute pressure transducer and a Texas Electronics tipping bucket rain gage were used to monitor atmospheric pressure and precipitation on site. A Campbell Scientific CR10 data logger was used to initiate data collection and to store data. The data logger was programed to excite, monitor, and record instrumentation hourly for a period of 110 days.

After the time series measurements, a 3.1-m vertical hole was dug at the site for porosity and water content determination. The samples recovered were immediately placed in airtight bags to retain the field water content and subsequently weighed. Water content and porosity were then determined by drying the samples at 90°C for 24 hours.

Analysis of Time Series

A low-pass filter was used on each of the soil air pressure and atmospheric pressure time series to aid in the removal of changes in pressure associated with weather patterns (see the appendix). The time series generated by the low-pass filter was subtracted from the original data, leaving only diurnal and higher frequencies. This process of filtering greatly simplifies the data analysis because the residual time series consists almost entirely of signals with constant frequency (diurnal and semidiurnal). Regression was used to determine the amplitude and phase of the diurnal and semidiurnal frequencies present in each residual time series (original time series minus the low-pass-filtered time series) [*Godin*, 1972]:

$$P(t) = A \cos (2\pi\omega_1 t) + B \sin (2\pi\omega_1 t) + C \cos (2\pi\omega_2 t) + D \sin (2\pi\omega_2 t)$$

where P is pressure (atmospheric or soil air), and ω_1 and ω_2 are diurnal and semidiurnal frequencies, respectively. The amplitude and phase of diurnal and semidiurnal frequencies are given by

$$\text{Amplitude}_{\text{diurnal}} = \sqrt{(A)^2 + (B)^2}$$

$$\text{Amplitude}_{\text{semidiurnal}} = \sqrt{(C)^2 + (D)^2}$$

$$\text{Phase}_{\text{diurnal}} = \arctan (B/A)$$

$$\text{Phase}_{\text{semidiurnal}} = \arctan (D/C)$$

Regression of components in the atmospheric time series of higher frequency than semidiurnal was not performed because their signal was too small to be identifiable. For each soil air pressure time series, the resulting phase and amplitude were compared to the phase and amplitude of the atmospheric pressure time series to determine admittance and phase lag. Finally, to determine air diffusivity, the calculated values of admittance and phase lag were fit to the model of airflow in the unsaturated zone given by (4). In making our estimates of diffusivity, we used a value of L of 6.0 m, the average depth of the water table in a nearby well over the monitoring period.

To examine temporal changes in soil air pressure response, the analysis described above was first performed on the entire soil air pressure time series for each zone. The pressure time series were then split into halves, and the data from each half were analyzed independently. Finally, the data were also divided into quarters and analyzed. Figure 3 shows time series of rainfall, atmospheric pressure, and soil air pressure at a depth of 0.8 m.

In our analysis, admittance of each of our soil air pressure series was generally statistically identical to unity for both diurnal and semidirunal frequencies. Mean admittance determined from all of the analyses was 1.05 for the shallow interval at both the semidiurnal and diurnal frequencies. For the deeper interval, mean admittance was 1.05 and 1.07 for the diurnal and semidiurnal frequencies, respectively. Standard error estimates for admittance were generally greater than 0.05 for the diurnal frequencies and generally greater than 0.15 for the semidiurnal frequencies. The lack of attenuation in the signal is consistent with the relatively small observed phase shift in each time series. As a result of the lack of any trends in admittance, analysis of the admittance data is omitted below.

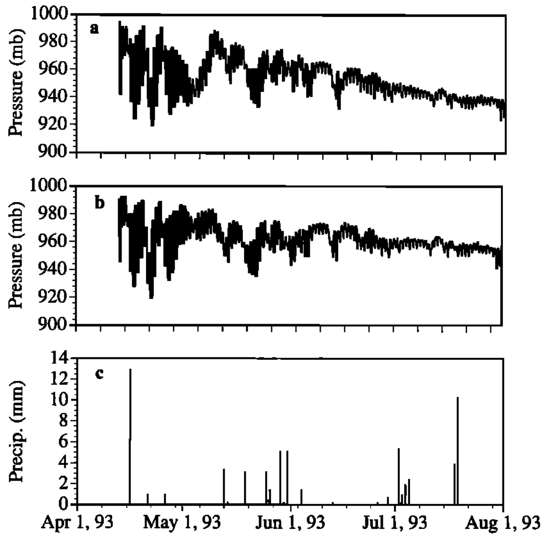

Figure 3. Time series of (a) soil air pressure at 0.8 m, (b) atmospheric pressure, and (c) precipitation.

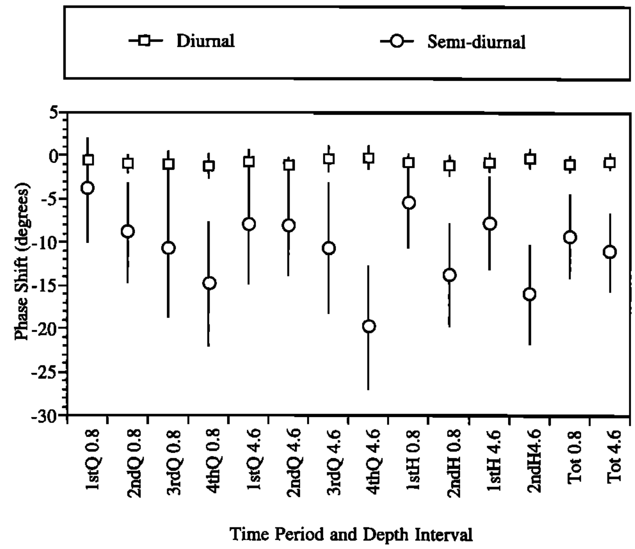

Figure 5. Phase shift results from regression analysis of diurnal and semidiurnal frequencies. Error bounds represent 95% confidence intervals. Q refers to the data sectioned into quarters, H refers to the data sectioned into halves, and Tot refers to the total time series. Numbers 0.8 and 4.6 denote the depth of the monitoring zone in meters.

Results and Discussion

Porosity and water content determined for the soil at the end of monitoring are shown in Figure 4. An increase in water content occurs as depth increases. The porosity does not change significantly with depth. Saturation at 3.0 m is only 50%, suggesting that the capillary fringe is significantly deeper than the bedrock/soil interface. While the exact depth of the capillary fringe is not known at this location, water level in a shallow well 300 m from the site was at a depth of 6.9 m at the end of the monitoring period. The moisture content of the soil is consistent with a water table of approximately this depth.

The results of the regression analysis are shown in Figure 5 in terms of phase shift for each zone and each time period of analysis. (Admittance values are not shown because there were no statistically significant deviations from unity in the admittance.) Analysis of the diurnal signal indicates that for almost every zone and time period, phase shift associated with the response is very close to zero and is generally insignificant. Diurnal phase shifts are generally between 0° and −2°, with a standard error close to or greater than the estimated phase shift.

Results from the analysis of the semidiurnal frequency, however, show statistically significant phase shifts. Standard error estimates for phase lag at the semidiurnal frequency are significantly larger than those of the diurnal response and make fine comparisons between each series difficult. The increase in standard error is the result of the small magnitude of the semidirunal atmospheric signal at the site relative to the magnitude of the diurnal signal and the relatively coarse resolution of semidiurnal signal obtained from hourly sampling. The amplitude of the atmospheric semidiurnal signal was 15–27% of the diurnal amplitude, depending upon the time interval examined. The phase lags, while statistically significant, are small, and in retrospect, a significantly higher sampling rate would likely have significantly improved our estimates of phase shift.

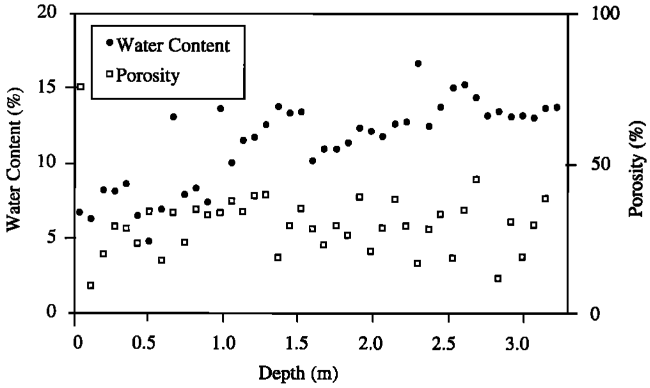

Figure 4. Water content and porosity as functions of depth at the end of the period of air pressure measurement.

The semidiurnal and diurnal responses are not entirely consistent with each other. In theory, the diurnal phase shift should be about 2°–3° when the semidiurnal phase lag is 10° and increase several degrees beyond this value as the semidiurnal phase lag approaches 20°. Upper bounds on phase lag for the diurnal frequency, however, are not greater than 3°, and there are no trends in the diurnal phase lag associated with the trends in semidiurnal response. The lack of a corresponding diurnal phase lag suggests that any trends observed in the semidiurnal phase shift are artifacts of noisy data. This point is further discussed below.

In interpreting the phase response, we have two alternatives. We can ignore the semidiurnal response completely and simply use the diurnal signal to estimate a lower bound for air diffusivity. Alternatively, we can assume that while trends in phase in the semidiurnal response are statistically insignificant, the presence of phase shift is statistically significant and allows us to estimate diffusivity for each zone, albeit with significant error. In this paper we emphasize the latter approach. It is instructive, however, to briefly examine the diurnal response to estimate lower bounds for air diffusivity. Noting that the upper bound on phase shift in the diurnal signal is always less than 3°, we estimate that the air diffusivity exceeds 20 cm^2/s and 60 cm^2/s for the shallow (0–0.8 m) and deep (0–4.6 m) zones, respectively. These lower bounds are slightly higher than the lower bounds on the diffusivities estimated from the semidiurnal response discussed below. It should be noted that the diurnal response lacks any seasonal trends, suggesting that air diffusivity remained above the estimated lower bounds for the entire time period.

Interpretation of Semidiurnal Response

Despite the relatively high level of standard error in the semidiurnal phase shifts, two observations are worth noting. First, phase lag differences between the upper and lower zones are generally smaller than that observed between the surface atmospheric signal and the soil air pressure at 0.8 m. It is likely that much of the observed phase lag in both zones is the result of relatively poor transmission of the atmospheric pressure signal across the clay layer present at 0.5–1.2 m. Below this clay layer, air diffusivity is high enough to allow transmission of the atmospheric signal at semidiurnal frequencies with small to negligible phase shift.

Second, the amount of phase lag appears to increase as a function of time in both intervals. If this trend is real, it is difficult to interpret. The increase in phase lag would be expected to occur if the soil underwent an increase in water content during this time period. While soil water content was not monitored as a function of time, it is likely that the soil underwent some drying over this time period. The water table in a well 300 m distant declined by 1.9 m over the time period of observation. Also, precipitation was relatively absent during the second half of the monitoring period. It should be noted that the trends in phase lag over time are small and are within the bounds of estimated error in phase determination. Hence this trend is likely an artifact of the small magnitude of the semidiurnal signal and a coarse sampling rate relative to the magnitude of the phase shift.

The phase shift for each zone determined from each total time series and each time series sectioned into halves and quarters was fit to the theoretical model of (4) to determine air diffusivity. To estimate error bounds for diffusivity, both the estimated phase shift from the regression analysis and the 95% confidence intervals in the phase shift were fit to the theoretical model. The resultant error bounds for diffusivity are asymmetric because phase shift is a highly nonlinear function of frequency.

Figure 6 shows the variation in air diffusivity over time and space. Air diffusivity ranges from 17 to 70 cm^2/s based upon the mean estimated phase shift for each time series. Even if one includes error bounds, the variation in air diffusivity is only 1 order of magnitude (14–140 cm^2/s). The small degree of variability in air diffusivity is somewhat surprising. While it appears that the bulk air diffusivity for the zone 0–0.8 m is lower than the zone 0–4.6 m, the difference between them is much smaller than what might be expected given the presence of the clay layer at depth 0.5–1.2 m. If one assumes that the soil moisture content and porosity measured in the zone 0–0.8 m at the end of the experiment were representative of soil conditions in the last quarter of the measurement period, then the estimated air diffusivity for this time period indicates that the approximate bulk air permeability is 3×10^{-14} m^2. This value of air permeability is higher than that expected for clays. The value of air diffusivity and permeability for this zone, as well as the relatively small variability in air diffusivity, suggests that the clay layer contains significant macropores or fractures that enhance pressure transmission or that the clay layer is discontinuous. The relatively ubiquitous nature of the clay layer in the area makes the former scenario (macropores or fractures) more likely.

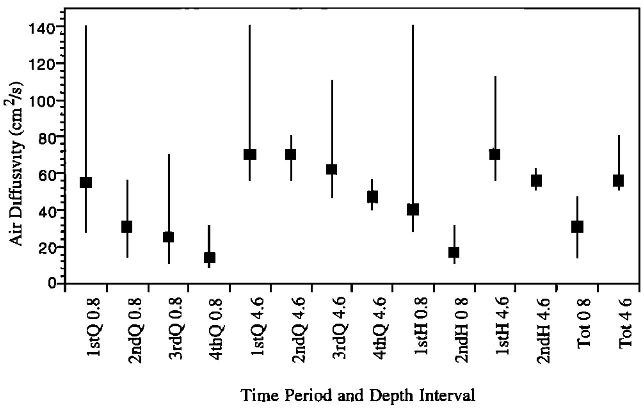

Figure 6. Air diffusivities determined from the fit of the phase shift results to (4). Notation indicating time period and depth interval is the same as in Figure 5.

The inferred air diffusivities shown in Figure 6 represent composite averaged air diffusivities between the land surface and each monitored zone. As such, each inferred value is significantly influenced by the airflow properties of the upper soil. The effect of such a composite average is to smooth any heterogeneity in air diffusivity present. If we assume that the inferred flow properties for each zone represent a harmonic average of the overlying materials, we can eliminate the surface influence and infer airflow properties between the two monitored zones. If the estimated diffusivities shown in Figure 6 are used, the inferred air diffusivity for the interval 0.8–4.6 m ranges from 68 to 110 cm^2/s depending on the time interval chosen. These values are a factor of 2 to 6 higher than that inferred for the zone 0–0.8 m and suggests that the clay layer, while having a high air diffusivity for clay, has a lower air diffusivity than the underlying materials.

This inferred variation in air diffusivity with depth, while small, also suggests that our estimated air diffusivities, which are based on the assumption of homogeneity, have some degree of error. Specifically, the determination of air diffusivity requires an estimate not only of phase shift but also of z/L, the fractional distance between the point of observation and the capillary fringe. Under conditions of heterogeneity the actual value of z and L may be significantly different than homogeneous equivalent values for z and L for the purposes of air diffusivity determination. For example, if the air diffusivity of the clay layer at our site was one fourth of that of the surrounding material (and the surrounding material was homogeneous), the resultant determination of air diffusivity for the clay layer assuming such heterogeneity would be 70% smaller than that determined from a homogeneous model. This degree of error, while significant, is essentially unavoidable, since we cannot determine the degree of heterogeneity in flow properties at any site a priori. The presence of heterogeneity, as well as the standard error involved in estimating the amount of phase shift, indicates that our estimates of air diffusivity based on the semidiurnal signal are probably only accurate to within 1 order of magnitude.

Conclusions

Airflow properties of the unsaturated zone have been inferred from the response of soil air pressure or the water table to atmospheric pressure changes for over 40 years. However, there has been little analysis of the quality of the estimates of airflow properties and to what degree these properties can vary over time. The methods and results outlined above indicate that temporal and vertical spatial variability in air diffusivity can be quite small, even in the presence of heterogeneity in soil texture and with the relative absence of precipitation. Since air diffusivity is strongly dependent upon the air permeability of a soil, this site may exhibit relatively small variations in air permeability over time and space. Air diffusivity is also dependent on interconnected air porosity, and it may be possible that air permeability does vary significantly, but its influence is partially masked by corresponding variations in air-filled porosity.

At this site the variability in air diffusivity is of the same order as the accuracy of our measurement. Of course, the time period of this experiment (110 days) and the depth interval monitored were both relatively short. Extensive monitoring in regions with variations in recharge with period of years or more would likely show greater temporal variability. Also, in regions with a deep water table, the greater vertical extent of the unsaturated zone would likely allow for greater vertical heterogeneity.

The results shown here are somewhat difficult to generalize to other sites. A significant limitation in the experiment detailed above is the lack of temporal data on soil moisture. While estimated variations in air diffusivity are slight over the time period monitored, it is unknown to what degree soil moisture varied temporally and spatially during the experiment. Hence it is not possible to explicitly determine a quantitative relationship between soil moisture and air diffusivity variations. We can only say that the influence of soil moisture variations was small during our experiment.

Despite the limitations in the depth interval, time period, and soil moisture information during our experiment, the lack of variation is somewhat surprising and suggests that estimates of air diffusivity based upon long-term average response of soil air and atmospheric pressure can be of value. For example, our estimates of diffusivity based upon the semidiurnal response of the entire time record are 14–47 cm^2/s and 51–80 cm^2/s for the intervals 0–0.8 m and 0–4.6 m, respectively. These estimates very nearly bound the variability in air diffusivity estimated from the data partitioned into quarters. The lack of variation also suggests that the soils at this location are well drained.

It should be emphasized that the actual errors in our estimates of air diffusivity are probably larger than even our error estimates suggest. Our estimates are based on the assumption of homogeneity in fluid flow properties in time and space. Although temporal and spatial variability at our site appears to be limited, it is present and indirectly observable.

While there are inherent limitations in the accuracy of our estimates, they are useful. Analysis of soil air pressure time series in response to atmospheric pressure changes allows for determination of airflow properties in situ. Owing to the presence of heterogeneities introduced by fractures and macropores, it is likely that a laboratory measurement of airflow parameters would not be representative of field conditions. The methods outlined above allow for measurement at length scales large enough to sample the influence of inhomogeneities. As a result, our approximate estimates of field air diffusivity can usually be expected to be more valuable than a "precise" estimate determined in the laboratory.

Appendix: Description of Low-Pass Filter

A low-pass filter was used in the process of removing pressure variations in the soil air and atmospheric pressure time series due to weather patterns. The basic operation of the low-pass filter is the consecutive summation of n data points and can be denoted as S_n such that S_n/n is the average of n consecutive data points. The average value, S_n/n, is assigned to the center of the interval of n points. For example, considering the data sequence $z_1, z_2, z_3, \cdots, z_m$. The operation S_n/n consists of calculating

$$X_k = \sum_{j=0}^{n-1} Z_{j+k} \qquad k = 1, 2, 3, \cdots, M - n + 1$$

and results in the sequence $X_1, X_2, \cdots, X_{M-n+1}$. If n is odd, X_k is assigned to the time of data point $z_{k+(n-1)/2}$. If n is even, X_k is assigned to the time halfway between data points $z_{k+n/2-1}$ and $z_{k+n/2}$.

The low-pass filter is of the form $S_n^2 S_{n+1}/[n^2(n + 1)]$, which requires three averaging operations [*Godin*, 1972, p. 66]. The $S_{24}^2 S_{25}/(24^2)(25)$ operator was used as the low-pass filter to isolate the low-frequency components of the time series. The remaining data set consisted of the low-frequency signals. This was subtracted from the original data set to leave diurnal and higher-frequency signals.

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