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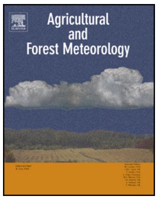

Free and forced gas convection in highly permeable, dry porous media

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ABSTRACT

The spatial and temporal distribution of gas species within the vadose zone is determined by biochemical sources and by transport mechanisms. Here, two mechanisms that can transfer gas at high rates across the earth-atmosphere interface are studied. The first is thermal convection venting (TCV), a free convection process that develops under conditions of sufficient temperature and density gradients. The second mechanism is wind-induced convection (WIC), an outcome of atmospheric surface winds that drive air movement within the porous media by a forced-convection process. Both of these advective mechanisms can dominate gas transport in high permeability porous media, and the objective of this study was to determine the permeability values that are relevant for these mechanisms to become significant for gas transport. Experiments were performed using large columns filled with four different single-sized spherical particles of 1 to 4 cm in diameter. The experiments were conducted in a climate-controlled laboratory, where surface winds and temperature gradients were imposed and monitored. A tracer gas of CO_2-enriched air was used to quantify the impact of TCV and WIC on gas exchange between the porous media and the atmosphere. A permeability range of 10^{-7} to 10^{-6} m^2 was found to be sufficient for the onset of TCV when imposed temperature gradients were similar to standard nighttime atmospheric conditions, leading to full or partial venting of the column. Surface wind with a velocity of 1.5 $m\,s^{-1}$ drove WIC to a depth of 0.3 m in most experimental conditions. The impact of WIC on net gas transport was not observed at the bottom-most sensor (0.9 m), except under conditions of very high permeability (2.4 10^{-6} m^2) and a large temperature difference (6.5 $^\circ C\,m^{-1}$), when both TCV and WIC worked simultaneously. Results confirm that TCV and WIC can significantly contribute to gas transport through porous media with sufficiently high permeability.

1. Introduction

Gas movement within the earth's subsurface and its exchange with the atmosphere is one of the principal processes contributing to soil, ecosystem and atmospheric changes. Gas transport is controlled by diffusive and advective mechanisms (e.g., Kuang et al., 2013 and references therein), and its fate is impacted by biological, chemical, and physical processes. Vadose zone source gases moving across the earth-atmosphere interface are an important source of greenhouse gas emission. Significant emissions are feasible from terrestrial soils (Blagodatsky and Smith, 2012; Maier and Schack-Kirchner, 2014), Landfills (Allaire et al., 2008) and other environmental settings (Kang et al., 2014). Consequently, to improve our understanding of the abovementioned processes and their impacts on the environment, we need to quantify the mechanisms that control gas transport at the earth-atmosphere interface. This study quantifies how gas exchange is controlled by conditions imposed by the physical properties of the upper vadose zone and atmospheric temperature (Blagodatsky and Smith, 2012; Weisbrod et al., 2009).

Diffusion occurs across all permeable interfaces (Allaire et al., 2008) and historically has been considered the dominant or even the only significant process for gas transport in low-permeability media (Moldrup et al., 2004). With increasing permeability, transport by advection may increase gas exchange rates (You and Zhan, 2013) and even dominate the process of net gas flux across the earth-atmosphere interface (Massman et al., 1997; Weisbrod and Dragila, 2006). Several mechanisms can drive advective gas transport at this interface: (1) thermal convection venting (TCV), a type of free convection, which may develop in response to density

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gradients. Density gradients may result from either temperature gradients in the subsurface or a temperature contrast at the interface between atmospheric and porous media air (e.g., Ganot et al., 2014; Kamai et al., 2009; Lahmira et al., 2014a; Nachshon et al., 2008; Nield and Kuznetsov, 2013); (2) forced wind-induced convection (WIC), which develops from surface winds that create pressure differences that drive convective air circulation (e.g., Amos et al., 2009; Nachshon et al., 2012; Reicosky et al., 2008; Turner and Pinshow, 2015); and (3) barometric pumping, which is the inward and outward motion of subsurface air due to cycles in atmospheric pressure (Neeper, 2002; Rossabi and Falta, 2002; Tillman and Smith, 2005; You and Zhan, 2013).

The effectiveness of the various gas transport mechanisms are determined by media properties, gas properties, and atmospheric conditions. The most significant porous media properties that affect gas transport are porosity, permeability, and water content (Abu-El-Sha'r and Abriola, 1997; Choi and Smith, 2005). Gas transport is also affected by the gas properties, namely density, viscosity and solubility (Hillel, 1998). In the upper part of the vadose zone, atmospheric conditions of wind, temperature and barometric pressure control the boundary condition and the energy gradient driving gas transport (Poulsen and Moldrup, 2006). In this work, we focused on the effect of the media's permeability and the temperature gradient on the development and magnitude of TCV. The potential contribution of WIC to gas convection within the media was also studied.

1.1. Thermal convection venting: free convection

Unstable gas density gradients of sufficient magnitude may drive free (natural) convection within the porous media or across the porous media-atmosphere interface. A special case of convective instability is driven by temperature gradients (TCV) (Lebeau and Konrad, 2009). The criteria for the onset of TCV is typically defined by the Rayleigh-Darcy number (*Ra*), a dimensionless number that relates convection to the ratio between gravitational (buoyancy) and dissipative potentials (viscosity and thermal diffusion) for a given fluid and a given media permeability. The *Ra* number for a nonlinear temperature gradient is given as (Nield and Bejan, 2006; Tan et al., 2003):

$$Ra = \frac{g\beta k H^2}{\nu\alpha_s}\frac{dT}{dZ} \tag{1}$$

where g [m s^{-2}] is the gravitational acceleration, β [K^{-1}] is the volumetric thermal expansion coefficient of the fluid, k [m^2] is the permeability of the porous media, H [m] is the characteristic length of the porous media defined here as the distance from the impermeable boundary, ν [m^2 s^{-1}] is the kinematic viscosity of the fluid, α_s [m^2 s^{-1}] is the thermal diffusivity of the bulk porous media, *T* [K] is the temperature, and *Z* [m] is the vertical spatial coordinate.

Numerical studies have explored the value of the critical *Ra* (Ra_{critical}), which is defined as the threshold value for the onset of TCV. A value of $Ra_{\mathrm{critical}} = 27.1$ is typically used as a threshold for the onset of convection in porous media, under a nonlinear temperature gradient, as is the case in natural soils, and assuming homogeneous and isotropic permeability (Tan and Sam, 1999; Tan et al., 2003).

A large number of analytical methods have been suggested for estimating the permeability of the media. For the case of coarse media composed of uniform spherical particles, the Kozeny-Carman equation is commonly used (Bear, 1972):

$$k = \frac{{d_p}^2}{180}\frac{f^3}{(1-f)^2} \tag{2}$$

where d$_p$ [m] is the particle diameter, and *f* is the media's air-filled porosity. Substituting Eq. (2) for Eq. (1) yields:

$$Ra = \frac{g\beta H^2}{\nu\alpha_s}\frac{{d_p}^2 f^3}{180(1-f)^2}\frac{dT}{dZ} \tag{3}$$

which implies that $Ra \propto {d_p}^2$ and $Ra \propto dT/dZ$.

Only a few studies have explored TCV in porous media under natural atmospheric conditions. These studies include several applications, including: waste rock dump (Lahmira et al., 2014b) and natural aggregates from an agricultural field (Ganot et al., 2014). To the best of our knowledge, a general relationship between TCV and either permeability or particle size (PS) has not been studied. We also note that in some studies, *Ra* was calculated using an average linearized *dT/dZ* value to represent the entire system (e.g., Ganot et al., 2014). In this study, we use a continuous function to represent the temperature gradient (*dT/dZ*) for the nonlinear temperature profile of the media, which is more representative of natural soil settings (Hillel, 1998; Holmes et al., 2008).

1.2. Wind-induced convection: forced convection

Surface wind (SW) can drive gas transport within the porous media and across its interface with the atmosphere via two mechanisms: (1) Wind blowing over an irregular interface will drive turbulent eddies that penetrate the subsurface zone (Brickner-Braun et al., 2014; Hillel, 1998). This mechanism is effective for high-permeability media corresponding to particle diameters greater than 1–2 cm (Ishihara et al., 1992). (2) High-frequency pressure changes at the interface cause a pressure gradient between the interface and the porous media (Nachshon et al., 2012; Poulsen and Moldrup, 2006). Even a small pressure deficit of 1 Pa m^{-1} at the earth-atmosphere interface can drive a significant advective gas flux (Amos et al., 2009; Kimball and Lemon, 1972).

In general, relatively few studies have explored WIC gas transport within porous media and across the earth-atmosphere interface. Ishihara et al. (1992) investigated water transfer beneath bare soil driven by WIC on a laboratory scale. Riley et al. (1999) studied subsurface radon transport due to time-varying winds. Takle et al. (2004) examined the possible role of WIC on the efflux of CO$_2$ from the earth's subsurface. Poulsen and Moldrup (2006) and Poulsen and Sharma (2011) investigated WIC effects on earth-atmosphere gas exchange for porous media, focusing on landfills. Because gas fluxes in the shallow subsurface resulting from WIC can be of up to one order of magnitude higher than the fluxes originating from diffusion (Takle et al., 2004), further research to understand this mechanism is warranted, particularly regarding the manner in which permeability mediates the effectiveness of WIC.

1.3. Conditions leading to the onset of free and forced convection in natural systems

To illustrate the potential likelihood that natural atmospheric conditions may lead to TCV and WIC, temperature and wind data are presented from the Negev Desert, Israel, for a typical summer (Fig. 1a) and winter day (Fig. 1b). Significant temperature differences (TDs) between the atmosphere and the earth's subsurface at a depth of 1 m occur during the second part of the night. Maximum TDs > 10 °C and 7 °C are evident in the summer and winter data, respectively. Depending on the media permeability, these differences can potentially activate TCV. Higher maximum TD values are typically expected in winter since the vadose zone is warmer than the mean ambient temperature, and arid climates, like the Negev Desert, usually experience a higher diurnal temperature range in the winter than in the summer (Dai et al., 1999; Ganot et al., 2014).