

## From atmospheric winds to fracture ventilation: Cause and effect

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[1] Vadose zone fractures and soil cracks exposed to the atmosphere have an impact on gas exchange processes at the Earth–atmosphere interface. In this study we explored and quantified the role of ground-surface winds on fracture ventilation. While the governing physical mechanisms that cause ventilation are relatively well understood, this is the first work to quantify these processes in natural fractures and to determine the net effect on gas exchange. In this study field measurements pointed to a correlation between surface wind velocity and the ventilate rate of surface-exposed fractures. To better explore and quantify this phenomenon, laboratory experiments were carried out using a Hele-Shaw chamber to simulate a natural fracture and the ventilation of smoke, used as a gas tracer, was explored as a function of controlled surface-wind and fracture aperture. It was found that ventilation depth is linearly correlated to wind velocity and nonlinearly with fracture aperture. Results were used to formulate an empirical model for Earth-atmosphere air exchange. This model can be used to estimate by how much the presence of fractures enhances that exchange under windy conditions. Incorporating this venting process into Earth-atmosphere gas exchange simulations is another step toward improving our ability to better predict and quantify soil aeration, soil temperature variation, water vapor loss and processes related to climate change, such as the fate and transport of greenhouse gases.

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### 1. Introduction

[2] Gas exchange between the Earth's upper crust and the atmosphere has far-reaching impacts on Earth processes, including the global water cycle, soil aeration and greenhouse gas emissions. From a hydrological perspective, water vapor is the most important component of Earth-atmosphere gas exchange, controlling above-land water vapor concentration, soil water content and soil salinity. These three hydrological parameters affect the global water cycle [Hillel, 1998], water management and agricultural practices. For example, the accumulation of salts at and near land surface that leads to soil salinization [e.g., Amit and Gerson, 1986; Gee and Hiller, 1988; Scanlon *et al.*, 1997; Nachshon *et al.*, 2011] poses serious agricultural challenges. Gas transport in the upper soil profile, i.e., the root zone, is important for soil aeration or movement of oxygen within the soil. This is

critical for plant root growth, as plants generally cannot get enough oxygen from their leaves [Lambers *et al.*, 2008]. Oxygen is not always readily available in soil pores since respiration of plants and other organisms, as well as microbial degradation of organic compounds, emit high amounts of CO<sub>2</sub> into soil pores, while consuming O<sub>2</sub> [Brady, 1990]. The exchange rate of air between soils and the atmosphere, which is affected by soil moisture, is therefore crucial to maintain needed soil aeration and oxygen concentration for plant growth [Drew, 1992] and for soil biogeochemical processes in general.

[3] Efflux of gases from the Earth has an important role in environmental processes. Water vapor and CO<sub>2</sub> are important components of the global warming process: as these are important greenhouse gases together with N<sub>2</sub>O and CH<sub>4</sub> [Weihermüller *et al.*, 2011; Wickramarachchi *et al.*, 2011]. Movement of volatile radionuclides, such as <sup>3</sup>H, <sup>14</sup>C and Rn from radioactive waste disposal facilities, as well as natural emission of Rn from natural sources and industrial volatile organic components such as chlorinated volatile organic compounds [e.g., Lenhard *et al.*, 1995; Conant *et al.*, 1996; Smith *et al.*, 1996; Choi *et al.*, 2002; Kristensen *et al.*, 2010; Ronen *et al.*, 2010] can greatly affect public health when emissions occur in buildings or populated areas [Nazaroff, 1992; Scanlon *et al.*, 2001]. Thus, it is important to understand the transport of these gases across the Earth-atmosphere interface.

[4] Migration of gases is not limited to soils alone, therefore the general term 'vadose zone', is here used to include

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both unsaturated soil and rock environments above the water table. For example, the world's largest carbon reservoir are carbonate rocks, containing about  $6.1 \times 10^7$  billion tons of carbon, which is 1694 and  $1.1 \times 10^5$  more than the carbon content in oceans and world vegetation, respectively [Houghton and Woodwell, 1989]. Chemical interactions between these carbonate rocks and atmosphere may be a source or a sink for large volumes of  $\text{CO}_2$  [Liu and Zhao, 2000]. Kowalski et al. [2008] and Sánchez-Cañete et al. [2011] reported on anomalies in  $\text{CO}_2$  fluxes from a karstic region, that reflects both geochemical processes of  $\text{CO}_2$  production from carbonate rocks and ventilation processes of the karstic region. While anomalies in  $\text{CO}_2$  fluxes were observed, the mechanisms responsible for these observations were not explored in the frame of these studies.

[5] Traditionally, diffusion is considered the main mechanism of gas exchange between the atmosphere and the vadose zone, driven by gas concentration gradients [Hirst and Harrison, 1939; Penman, 1940a, 1940b; Marshall 1958, 1959; Millington and Quirk, 1961; Cunningham and Williams, 1980; Amali and Rolston, 1993]. In the last few decades several advective gas transport mechanisms were suggested to also participate in increasing gas exchange rates between the terrestrial environment and atmosphere. While diffusion impacts the transport of each gas independently, according to its concentration gradient, advective mechanisms impact the migration of the bulk assembly of gases. Advective mechanisms suggested to drive gas flux across the Earth-atmosphere interface include: (1) wind pumping [Fukuda, 1955; Weeks, 1991, 1994; Waddington et al., 1996]; (2) atmospheric barometric changes [e.g., Pirkle et al., 1992; Rossabi, 2006]; and (3) density differences between the fracture [air] and the atmospheric air, mostly due to thermal gradients [Weisbrod et al., 2005; Weisbrod and Dragila, 2006; Weisbrod et al., 2009], but also possibly due to different air composition [Kowalski and Sánchez-Cañete, 2010]. Although it is generally accepted that these advective fluxes could exist and if so likely to impact the overall gas circulation across the Earth-atmosphere interface, the literature still lacks of experimental data, especially field data. Moreover, quantification of these processes and their actual impact under various environmental conditions is still in its infancy.

[6] A few previous studies explored wind effect on porous media ventilation [Kimball and Lemon, 1972; Ishihara et al., 1992; Bowling and Massman, 2011]. Others explored the effect of wind on ventilation of various surface exposed cavities such as deep boreholes with a diameter of tens centimeters and tens of meters in depth [Weeks, 1991], and smaller cavities like animal burrows [Vogel et al., 1973; Kay and Whitford, 1978; Kleinedam et al., 2001]. Kimball and Lemon [1972] and Ishihara et al. [1992] reported gas flux increases of a few orders of magnitude, driven by surface winds over homogeneous porous media, but their investigation was limited to a depth of a few centimeters. Wind was found to have a much deeper impact on surface exposed cavities. For example, its impact reached depths of a few tens of meters in boreholes, due to their high permeability [Weeks, 1991]. Rogie et al. [2001] showed a positive correlation between  $\text{CO}_2$  emission and wind from a fractured volcanic region. By contrast, for the same site Lewicki et al. [2007] reported a negative correlation, indicating either

ambiguity in understanding of these processes or the complexity of the mechanisms.

[7] In the engineering literature, ventilation of cavities is known as "cavity flow." In this arena the physical processes are well formulated and quantified but the scales of interest are usually for very small cavities in the range of a few millimeters or centimeters [e.g., Lattimer and Fitt, 1998; Betyaev, 2008]. While the works cited above and others reported on the potentially important role of winds on vadose zone ventilation via various surface exposed cavities, no quantitative correlation has been presented between winds and the ventilation process, particularly, for surface exposed fractures that are abundant in both clay soils and hard rocks [e.g., Press and Siever, 1986; Walmann et al., 1996; Bahat, 1999].

[8] This study aims to shed new light on the impact of surface wind on fracture ventilation. We report on field measurements that implied a correlation between atmospheric wind speed and fracture ventilation, followed by laboratory experiments to further explore and quantify the effect of wind on fracture ventilation. The laboratory study explored ventilation depth as a function of wind speed and fracture apertures under controlled conditions. Last, an empirical model was developed, based on the laboratory results. We also discuss the value of this model to estimate the effect of near surface wind ventilation of fractured terrain at large (field) scales.

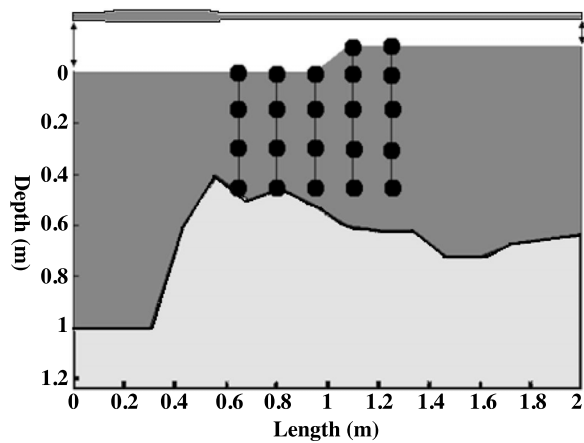
## 2. Theory

[9] Surface wind can drive ventilation of the vadose zone in general and of fractures in particular through pressure fluctuations induced at the ground-atmosphere interface due to wind turbulence [Kimball and Lemon, 1971, 1972; Colbeck, 1989; Ishihara et al., 1992; Waddington et al., 1996; Takle et al., 2004]. In addition, surface roughness can also play a role in vadose zone ventilation, since wind blowing over irregular surfaces forms eddies that increase pressure on the windward side of an obstruction and reduce pressure on the leeward side [Scott, 2000]. These pressure fluctuations result in advective fluxes of vadose zone gases by Darcy's law [Colbeck, 1989], the Bernoulli effect [Vogel et al., 1973; Reimer and Bowles, 1979] and by driving turbulent diffusion [Kimball and Lemon, 1971, 1972; Ishihara et al., 1992]. These same mechanisms are expected to be more effective in mass transfer from fractures and other cavities exposed to the atmosphere than from porous media because of the much higher permeability of these structures [Weeks, 1991]. Colbeck [1989] reported on variations in air pressure at the soil-atmosphere interface due to wind turbulences. The author analyzed data from Elliott [1972] to formulate a relationship between pressure fluctuations and wind turbulences above the ground surface, based on mean wind velocity,

$$P' = 0.0327e^{0.383V}, \quad (1)$$

where  $P'$  is the magnitude of the pressure fluctuations [Pa] induced by an average wind velocity,  $V$  [m/s] at a height of 5 m [Takle et al., 2004].

[10] In spite of the relatively good understanding of the basic principles potentially responsible for wind-induced



**Figure 1.** Schematic cross section of the fracture used in the field experiment. Light gray designates the fracture bottom at bedrock; dark gray indicates the fracture volume; black circles are the thermocouples locations. The irregular shape in the upper part of the image is a horizontal cross-section of the fracture aperture at ground level showing the widening on the left-hand side.

fracture ventilation, mechanistic models to quantify natural fracture ventilation due to surface winds have not been developed. It should be noted that, under natural conditions, wind-induced ventilation processes will act in concert with other advective and diffusive mechanisms already mentioned (i.e., barometric pumping and density-driven convection). This manuscript presents an empirical relationship between surface wind and fracture ventilation. This relationship depends primarily on two parameters, namely: (1) the active fracture depth, and (2) the increase in the mass exchange rate relative to diffusive processes.

### 3. Materials and Methods

[11] This work is based on in situ field measurements that qualitatively indicated a correlation between surface wind speeds and fracture ventilation depth. Laboratory experiments were done to better quantify wind effect on fracture ventilation, under control conditions. Field measurements consisted of thermal measurements of fracture air to detect air exchange between the fracture volume and the atmosphere above. In parallel, wind speed was continuously measured at a nearby weather station to explore the link between air exchanges rate and wind speed. Laboratory experiments used a Hele-Shaw chamber to simulate a fracture and to quantify gas exchange between a fracture and the ambient atmosphere under controlled conditions.

#### 3.1. Field Measurements

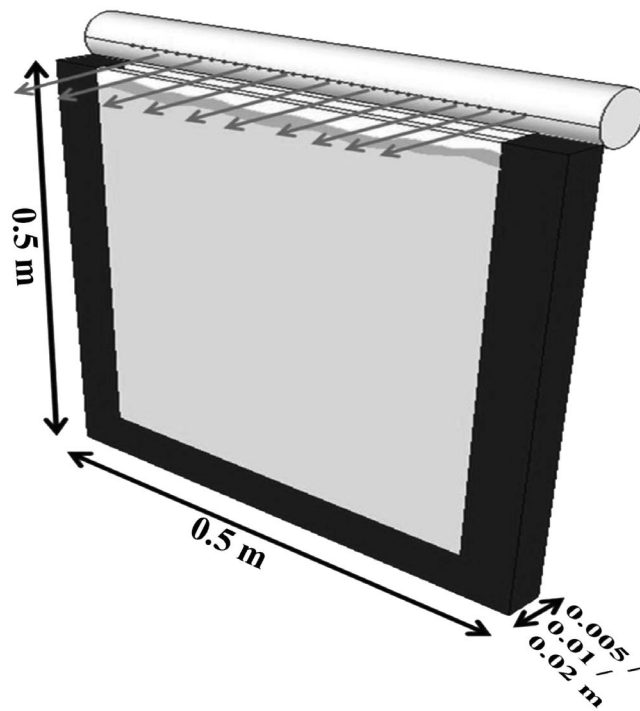
[12] The field measurements were conducted at the same site and within the same fracture that was used for a previous study exploring thermal convection in fractures (see *Weisbrod et al.* [2009] for a full description of the site). Briefly, the fracture is located in the southern part of Israel, the Negev Desert (lat. 31.090°, long. 34.830°) and elevation of 335 m above sea level. The naturally exposed fracture, crossing a massive chalk formation, is open to the atmosphere. The aperture is in the range of 0.01–0.05 m, fracture trace is 2 m

long, dip near vertical and depth of at least 1–1.2 m. A two dimensional grid of 22 thermocouples (copper-constant, Campbell Scientific, Inc. North Logan, Utah) was inserted down the center plane of the fracture to monitor fracture air temperature with a time resolution of 10 min. Figure 1 presents schematically the fracture and thermocouple locations. As seen in Figure 1, the ground surface is not flat and subsequently the fracture aperture is not level, with the right hand side ~0.15 m higher than the left side. The left-most thermocouple (Figure 1) is attached to an opening in the fracture aperture. The effect of these topographic variations will be evident in the results. Another thermocouple measured atmospheric temperature in the shade, just above the fracture and a vertical line of 12 thermocouples were inserted to a depth of 1.2 m into the rock matrix to measure matrix temperatures. All thermocouples were connected through a Multiplexer (AM 16/32, Campbell Scientific, North Logan, Utah, USA) to a data logger (CR10X, Campbell Scientific, North Logan, Utah, USA), located in an underground cabinet at the site. Wind measurements were taken at 10 m above the surface, every hour, from a meteorological station (Wind monitor model 05103–45, Young, Mich., USA) located 2 km south of the fracture site. Due to the distance between the fracture site and the meteorological station, it is hard to conclude the exact wind velocities over the fracture. However, it is assumed that the overall wind directions and velocities in the region are homogeneous, and when an increase in wind velocity is measured at the meteorological station, a similar increase over the fracture is likely to occur. Most prevalent wind directions in the area are from northwest to southeast during day time and from southeast to northwest during nighttime, which is perpendicular to the fracture strike (045°–225°). Average wind velocity 10 m above the surface is 3.03 m/s with standard deviation of 2.06 and maximal wind gusts of 14 m/s for the period reported in this manuscript (03/2009–07/2010). It is important to emphasize that while wind speed was measured at a height of 10 m, the wind near ground surface is expected to be much slower, due to drag forces [*Kaltschmitt and Wiese*, 2007; *Markowski and Richardson*, 2010]. Sporadic wind speed measurements, conducted 0.1 m above ground surface, taken by a portable anemometer (C400, Lufft, Fellbach, Germany) indicated wind speeds slower than 1 m/s, while measured wind speeds at the same times at the meteorological station (10 m height) were ~3.5 m/s. This agrees with theory that predicts an exponential decrease in wind speed toward ground surface, as expressed by [*Markowski and Richardson*, 2010]:

$$V_z = V_r \log(h_z/Z) / \log(h_r/Z), \quad (2)$$

where  $V_z$  is the average wind speed (m/s) at an altitude of  $h_z$  (m), based on the measured wind velocity  $V_r$  (m/s) at a reference height,  $h_r$  (m).  $Z$  is the surface roughness length (m), i.e., it is the height where  $V_z$  equal 0, which for bare soil is in the order of 0.03 m [*van den Berg*, 2004].

[13] Thermal readings from the thermocouple grid within the fracture were spline interpolated to produce a 2 dimensional map of the air temperatures within the fracture. Contrast between fracture and atmospheric air temperatures enabled the observation of advective penetration of atmospheric air into the fracture. To compare wind conditions to



**Figure 2.** Schematic of the Hele-Shaw chamber and the controlled wind-producing manifold. Arrows indicate wind flow direction. Gray area is the smoke-filled chamber. Fracture aperture could be set to 0.005, 0.01 or 0.02 m by increasing the distances between the chamber walls. Wind speeds in the range of 0.25–1.5 m/s were explored.

no-wind conditions, the fracture aperture was covered by a thin (<1 mm) aluminum foil for short periods of two weeks, twice (15–30/11/2006 and 14–28/5/2010). It was assumed that the aluminum foil isolates the fracture from the wind effect, eliminating any convective heat transfer, but does not affect heat transfer by diffusion between fracture and atmosphere, due to the aluminum foil's diminutive thickness and its high heat transfer coefficient (238 W/m K [Lienhard and Lienhard, 2008]). Aluminum foil heating by sun radiation was ignored; however, the results indicated it was a reasonable assumption as no significant heating was measured in the vicinity of the aluminum foil.

### 3.2. Laboratory Study

[14] While the field measurements enabled us to show qualitatively the effect of wind on fracture ventilation, laboratory experiments enabled us to quantify the wind effect under controlled conditions. A Hele-Shaw chamber (Figure 2) with dimensions of  $0.5 \times 0.5$  m and aperture settings of 0.005, 0.01 and 0.02 m was used to simulate a surface-exposed fracture, with the Hele-Shaw chamber walls and the interior volume acting as the fracture walls and fracture volume, respectively. A similar chamber was used by *Nachshon et al.* [2008] to explore gas flow due to thermal convection in fractures. Fracture walls were made of glass. To produce a constant, stable and controlled wind a plastic tube, 0.55 m long and 0.0254 m in diameter, was used as a wind simulator. The tube was perforated along its long axis with small holes with a diameter of 2 mm, at 4 mm intervals. The plastic tube

was connected to a high pressure air supply by a thin (2 mm) tube. A valve on the supply tube was used to control wind intensity. Wind imposed was in the range of 0.25–1.5 m/s concurring with theoretically expected and measured wind speeds at ground level at the field site. It is important to emphasize that the imposed wind in the laboratory was probably less turbulent than the natural wind in the field, due to the field ground surface roughness. Consequently, the wind effect in the field is potentially greater than that observed in the laboratory, as turbulence has a great effect on the wind pumping mechanism [Waddington *et al.*, 1996]. Therefore, the laboratory results represent a minimum exchange value. A high resolution anemometer (C400, Lufft, Fellbach, Germany) was used to measure wind velocity continually throughout the experiment. Smoke was used as tracer to observe airflow within the Hele-Shaw. The smoke source, with density similar to air, was from a portable smoke machine (Flow Check, Dräger Safety, Luebeck, Germany), which was previously shown to be suitable as tracer to visualize airflow [Nachshon *et al.*, 2008].

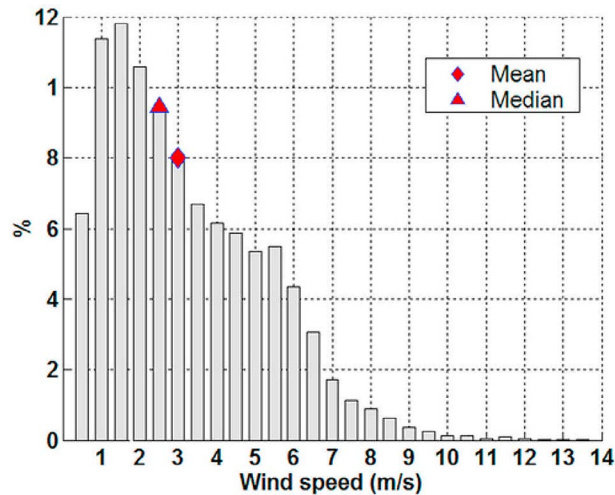
[15] The smoke was inserted into the Hele-Shaw chamber by pouring it in through the open top of the chamber at a constant flux rate from the smoke machine nozzle. During filling of the chamber with smoke, the aperture opening was sealed except for the immediate location used for smoke filling to avoid diffusion of the smoke out of the fracture. Pouring of the smoke was done for 1 min, until the chamber was homogeneously filled by the smoke (visual observation). Once the chamber was filled with smoke, the seal over the chamber opening was gently removed to enable free exchange of chamber and ambient atmospheric air, and then wind was immediately applied. The movement of the smoke was documented by a video camera (Flip video-UltraHD, CISCO, Calif.). As areas of the chamber were cleared from the smoke by wind induced advection, these boundaries were marked directly on the transparent chamber walls to enable quantitative comparison of chamber ventilation depth, with time, for different apertures and wind velocities. Moreover, the time needed to clean out a certain volume of the Hele-Shaw chamber of the smoke, was used to calculate an effective upward airflow “replacement velocity” within the Hele-Shaw chamber ( $v$  (m/s)).  $v$  was determined from calculations of the specific discharge ( $q$  (m/s)) of the smoke from the smoke-replacement measurements by

$$q = v = \frac{\psi}{\chi}, \quad (3)$$

where  $\chi$  is the cross-sectional area of the chamber opening ( $\text{m}^2$ ) and  $\psi$  is the smoke-replacement rate ( $\text{m}^3/\text{s}$ ).  $\psi$  was calculated by dividing the volume of the Hele-Shaw chamber ventilated from the smoke by the time needed for ventilation of this volume (both measured from the video sequences), and  $\chi$  was calculated by multiplying the chamber aperture (0.005, 0.01, or 0.02 m) by 0.5 m which is the Hele-Shaw chamber width.

## 4. Results and Discussion

[16] Field measurements indicate that wind plays an important role on fracture ventilation. The temperature readings of the thermocouple network show penetration of atmospheric air to a depth of approximately 0.5 m into the



**Figure 3.** Histogram of measured wind velocity: percent occurrence for each measured wind velocity.

fracture under high wind speed conditions. Hele-Shaw chamber experiments were used to develop an empirical relationship for the venting process (venting depth and flux rate) as a function of environmental parameters (wind velocity and fracture aperture).

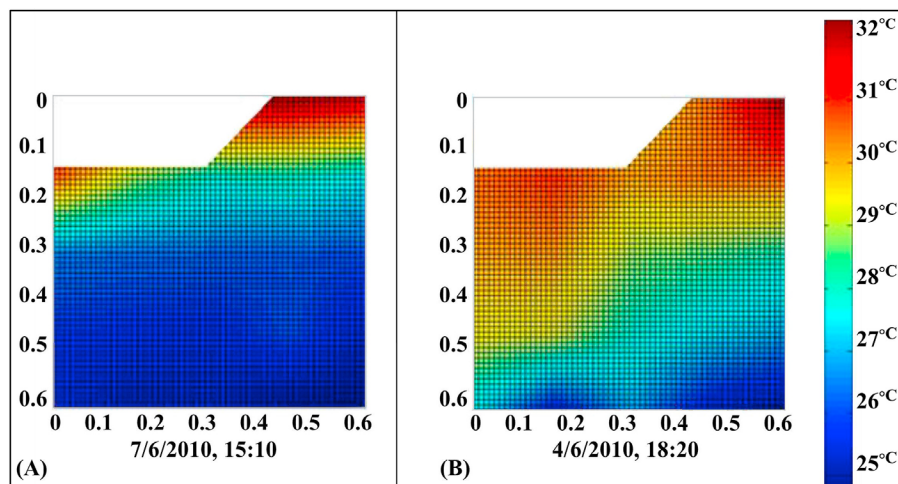
#### 4.1. Wind Effect on Natural Fracture Ventilation

[17] Average and median wind speed at the meteorological station during our experiment were 3.03 and 2.6 m/s respectively (Figure 3). Maximal wind velocities were around 14 m/s, occurring mainly in the afternoons, and early evenings. 91% of measured wind velocities were below 6 m/s (Figure 3). According to equation (2), near-ground wind

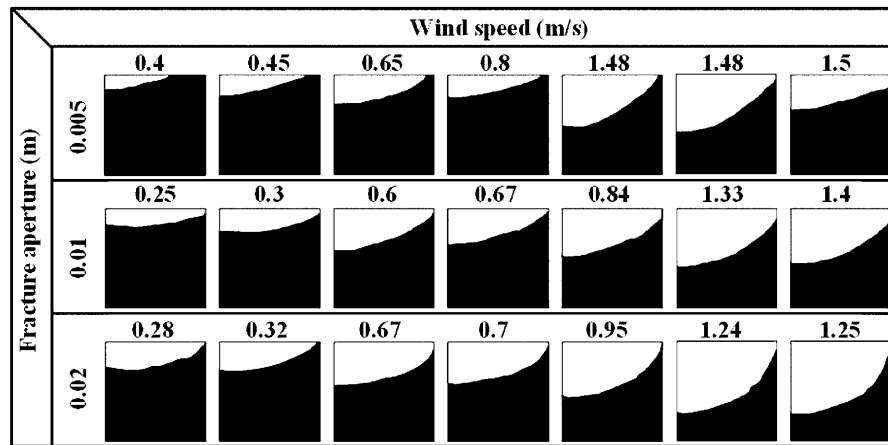
speed is expected to be much lower, on the order of 1 m/s. This was verified by measurements done periodically 0.1 m above ground level at the site.

[18] During the day time, the fracture is not expected to exhibit thermally driven convection since the fracture air is cooler than the atmospheric air (Figure 4). Therefore, the fast penetration of hot atmospheric air into the fracture during the day, as sensed by the 2D thermocouples grid within the fracture, indicates the existence of forced (wind-driven) convection as the mechanism imposing ventilation of the fracture (Figure 4). Sealing the fracture opening disabled convective flow of air into the fracture, while permitting thermal continuity. It can be seen (Figure 4) that under similar ambient atmosphere temperature, heat penetrates to a greater depth (down to 0.5 m) for open relative to sealed fracture conditions (down to  $\sim 0.2$  m). It should be emphasized that the thermal conditions during these measurements were unfavorable for thermal convection. The left-right asymmetry seen in the thermal maps (deeper hot air penetration on the left) is caused by asymmetry of the fracture aperture, which is wider than 0.05 m on the left side, but on the right side it is thinner than 0.02 m. Moreover, ground surface on the left side is about 0.15 m lower than on the right (Figure 1).

[19] During nighttime, thermal convection and wind-driven convection are superposed, and separating the contribution of each mechanism is problematic. The relative contribution of each mechanism can be assessed by comparing measurements of wind-driven venting during daytime conditions, to thermal convection venting at night during a period of no wind. The thermal convection mechanism can enhance exchange of atmospheric and fracture air by two orders of magnitude, compared to pure diffusive venting [e.g., *Nachshon et al.*, 2008; *Kamai et al.*, 2009; *Weisbrod et al.*, 2009]. To quantify the effect of only the wind



**Figure 4.** Typical air temperature distribution inside a natural surface-exposed fracture for (a) sealed (no wind) conditions and (b) open (wind) conditions for a similar ambient atmospheric temperature and rock thermal profile. Vertical and horizontal axes indicate depth and length (m), respectively, of the monitored fracture wall. Date and time of data acquisition are shown below each image. The deep penetration of the hot air into the fracture when surface wind is blowing can be clearly seen in Figure 4b for a measured wind speed of 7 m/s at 10 m height ( $\sim 2$  m/s at ground surface; equation (2)).



**Figure 5.** Digitized images of the Hele-Shaw cell during ventilation experiments. Each square presents the Hele-Shaw chamber at different wind velocity (increasing velocity from left to right, corresponding velocity noted above each cell) and aperture (0.005, 0.1 and 0.2 m, increasing top to bottom). The white regions designate the area of the fracture ventilated, and the black regions are the areas that were visually unaffected by advective ventilation (i.e., smoke was not removed). For 0.005 m aperture and at wind speed of 1.5 m/s, the ventilation depth is smaller compared to the wind speed conditions of 1.48 m/s. This disparity is due to random and uncontrolled changes in the experimental conditions.

mechanism, we turn to the laboratory experiments using the Hele-Shaw chamber.

#### 4.2. Quantifying Effect of Wind on Hele-Shaw Chamber Ventilation

[20] The Hele-Shaw experiments were used to quantify the depth of fracture ventilation as affected by fracture aperture and horizontal surface-wind speed. For no wind and isothermal conditions (i.e., diffusive conditions), smoke removal from the top 0.1 m of the fracture took more than 15 min. Under an imposed wind, removal time decreased to a few seconds (5–10 s). Average upward velocities within the Hele-Shaw chamber ( $v$ ), calculated using equation (3), were on the order of 0.01–0.04 m/s under imposed horizontal surface wind velocities in the range of 0.25–1.5 m/s, respectively. Ventilation depth (VD) was calculated as the vertical fraction of the chamber from which the smoke was visually removed. As wind velocity and/or aperture increased, larger parts of the chamber were ventilated (Figure 5). While penetration of atmospheric air into the ‘ventilated zone’ was very rapid (a few seconds), removal of smoke below this region was much slower, reflecting a diffusive mass transfer process between the deeper fracture and the ventilated zone. The convective pattern that formed was characterized by the inflow of atmospheric air from the upper left corner of the fracture opening and the outflow of fracture air via the opposite corner. In natural settings, air circulation morphology and the locations of entering and exiting air would be subject to the micro-topography of the fracture, wind disturbances and other random changes in environmental conditions. In the Hele-Shaw experiments, the preferential entrance of the air from the left corner could be related to the method used to open the chamber after smoke filling. In the field, a preferential entrance of the air was observed through the left hand side of the fracture (Figure 4), due to the variation in fracture surface topography (Figure 1). A movie of

the Hele-Shaw experiments and the ventilation of the fracture can be seen in the auxiliary materials.<sup>1</sup>

[21] Ventilation depth was determined to be the maximum depth of atmospheric air penetration into the fracture (see Figure 5). It can be seen that, as the surface wind speed or the fracture aperture increased, the ventilation depth increased correspondingly. A linear correlation was observed between the wind speed and the fracture ventilation depth, as presented in Figure 6 for the three apertures studied. Moreover, it can be seen in Figure 6 that the impact of the fracture aperture on the ventilation depth is nonlinear, with the aperture having a stronger impact at higher wind speeds.

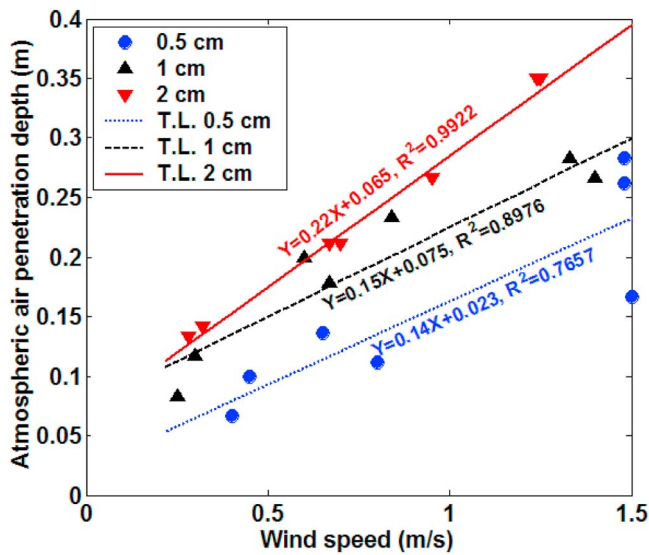
[22] Advective mass transport efficiency is commonly estimated with the use of the Sherwood (Sh) number [Weast, 1980; Nilson and Griffiths, 2003; Nachshon et al., 2008], which is a dimensionless number comparing advective to diffusive mass transport [Weast, 1980]:

$$\text{Sh} = \frac{vL}{D}, \quad (4)$$

where  $v$  is advective flow velocity (m/s),  $L$  is the length scale of interest (m) and  $D$  is the diffusion coefficient of a certain substance ( $\text{m}^2/\text{s}$ ). For  $\text{Sh} > 1$  advection is the dominant transport mechanism, while for  $\text{Sh} < 1$ , diffusion is the main transport mechanism. For example, for  $v$  equal to 0.025 m/s, being the average velocity measured in the experiments, and  $L = 0.2$  m, being a reasonable characteristic length scale as it is the median of measured ventilation depths, and for  $D = 2.82 \times 10^{-5} \text{ m}^2/\text{s}$ , which is the water vapor diffusion coefficient in free air [Cussler, 1997],  $\text{Sh} \approx 177$ . This means that for fracture air containing water vapor, wind-driven ventilation result in advective mass

<sup>1</sup>Auxiliary materials are available in the HTML. doi:10.1029/2011JG001898.





**Figure 6.** Measured (symbols) and calculated (linear regression) trend lines (T.L.) for atmospheric penetration depth into the Hele-Shaw cell for various wind velocities and fracture apertures. Equations for each trend are shown near each respective line.

transport of the vapor that is more than 2 orders of magnitude higher than diffusion alone; indicating the important role of wind in fracture ventilation.

[23] Examination of the data obtained by *Nachshon et al.* [2008] for mass transfer rates for venting at night due to thermal convection indicates that wind-driven convection is a mechanism of similar magnitude. The main difference is that wind driven convection only lasts as long as the wind is active, whereas thermal convection is a diurnal process. Thus, on a large timescale, the relative contribution of these two mechanisms would be directly associated with the relative amount of time each mechanism is active per day or per the period of time that is of interest.

### 4.3. Empirical Model to Predict Wind Effect on Gas Extraction in Large Scales

[24] The experimental data collected in this study were used to formulate an empirical model to estimate ventilation of gases in fractured rock or cracked soil. The linear equations in Figure 6 can be used to predict venting penetration depth for any (ground level) wind speed in the range of 0–1.5 m/s but for only three specific fracture apertures of 0.005, 0.01, and 0.02 m. To extend the model to other apertures within that range we interpolated those functions. For simplicity, it is assumed that the functions change linearly between these three curves. The separation between curves in Figure 6 indicates a nonlinear relationship of aperture and venting depth, thus the proposed linear interpolation is considered a first order approximation. The data were used also to assess the potential error of the linear interpolation approach: a linear interpolation was done between  $VD_{(0.005)}$  and  $VD_{(0.02)}$  (subscripts indicate fracture aperture) to generate a predicted curve for an aperture of 0.01 m, and the calculated curve was compared to the measured data from the 0.01 m aperture. The maximum error

was less than 0.025 m, which is a reasonable error, especially for the high wind velocities, where ventilation depth is on the order of a few tens of centimeters.

[25] Figure 7 and Table 1 introduce the calculated array of numbers produced by the linear interpolation of the data, for fracture apertures between 0.005 and 0.02 m and wind velocity in the range of 0–1.6 m/s. Moreover, Table 1 enables calculation of a linear equation for ventilation depth of every aperture as a function of wind velocity:

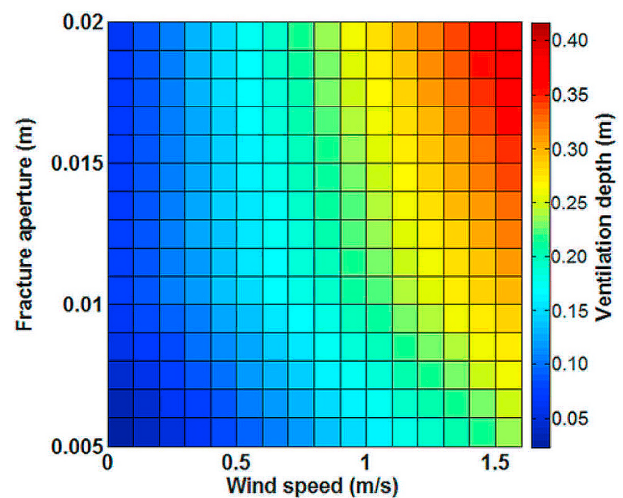
$$VD_{(ap)} = a_{(ap)} \cdot V + b_{(ap)}, \quad (5)$$

where parameters  $a$  and  $b$  are shown in Table 1, wind speed is  $V$ , and the subscript  $ap$  refers to the aperture.

[26] Ventilation depth (VD) values from Table 1 can be used to predict by how much gas exchange with the atmosphere could be potentially enhanced by this wind-driven convection mechanism. However, in most cases, it is likely that the limiting process for gas exchange between vadose zone and atmosphere will be gas diffusion from the porous matrix toward the fracture where convection is occurring because diffusion is a much slower process compared to advective ventilation [*Nachshon et al.*, 2008]. In natural environments gas diffusion is due to differences in gas concentration, temperature, and pressure. The gas diffusion flux of a dilute gas (species 1) in another gas (species 2) is defined as [*Landau and Lifšic*, 1987]:

$$J = -\rho_0 \left[ D_{12} \frac{\partial \rho_1}{\partial x \rho_0} + \frac{D_T}{T} \frac{\partial T}{\partial x} + \frac{D_P}{P_0} \frac{\partial P_0}{\partial x} \right], \quad (6)$$

where  $J$  ( $\text{kg/m}^2 \text{ s}$ ) is the diffusive flux of species 1;  $\rho_0$  and  $\rho_1$  ( $\text{kg/m}^3$ ) are mass density for species 1 and 2 together and for species 1 alone, respectively.  $T$  (K) is temperature and  $P_0$  (Pa) is pressure.  $D_{12}$  ( $\text{m}^2/\text{s}$ ) is the mutual diffusion coefficient of the species 1 and 2 through the soil,  $D_T$  ( $\text{m}^2/\text{s}$ ) is the thermo-diffusion coefficient [*Landau and Lifšic*, 1987; *Elperin et al.*, 1997],  $D_P$  ( $\text{m}^2/\text{s}$ ) is the baro-diffusion



**Figure 7.** Ventilation depth as a function of fracture aperture and wind speed. Color graph of data presented in Table 1, showing an increase in ventilation depth with aperture or wind velocity increase.

**Table 1.** Calculated Ventilation Depths (in Meters) for a Range of Apertures and Wind Speeds<sup>a</sup>

		Fracture Aperture (m)						
		0.005	0.0075	0.01	0.0125	0.015	0.0175	0.02
Wind Speed (m/s)	0.0	0.02	0.05	0.08	0.07	0.07	0.07	0.07
	0.1	0.04	0.06	0.09	0.09	0.09	0.09	0.09
	0.2	0.05	0.08	0.11	0.11	0.11	0.11	0.11
	0.3	0.07	0.09	0.12	0.12	0.13	0.13	0.13
	0.4	0.08	0.11	0.14	0.14	0.14	0.15	0.15
	0.5	0.09	0.12	0.15	0.16	0.16	0.17	0.18
	0.6	0.11	0.14	0.17	0.17	0.18	0.19	0.20
	0.7	0.12	0.15	0.18	0.19	0.20	0.21	0.22
	0.8	0.14	0.17	0.20	0.21	0.22	0.23	0.24
	0.9	0.15	0.18	0.21	0.22	0.24	0.25	0.26
	1.0	0.16	0.19	0.23	0.24	0.26	0.27	0.29
	1.1	0.18	0.21	0.24	0.26	0.27	0.29	0.31
	1.2	0.19	0.22	0.26	0.27	0.29	0.31	0.33
	1.3	0.21	0.24	0.27	0.29	0.31	0.33	0.35
	1.4	0.22	0.25	0.29	0.31	0.33	0.35	0.37
	1.5	0.23	0.27	0.30	0.32	0.35	0.37	0.40
1.6	0.25	0.28	0.32	0.34	0.37	0.39	0.42	
Linear Equation	<i>a</i>	0.140	0.145	0.150	0.168	0.185	0.203	0.220
	<i>b</i>	0.023	0.049	0.075	0.073	0.070	0.068	0.065

<sup>a</sup>Wind speeds are just above the Hele-Shaw cell's upper boundary. Parameters *a* and *b* are used in equation (5).

coefficient [Landau and Lifšic, 1987; Elperin et al., 1997], and  $x$  (m) is distance through which diffusion occur. The overall mass transfer rate,  $Q$  (kg/s) is a function of  $J$  and the surface area ( $A$  (m<sup>2</sup>)) between the soil and atmosphere, through which diffusion occurs,

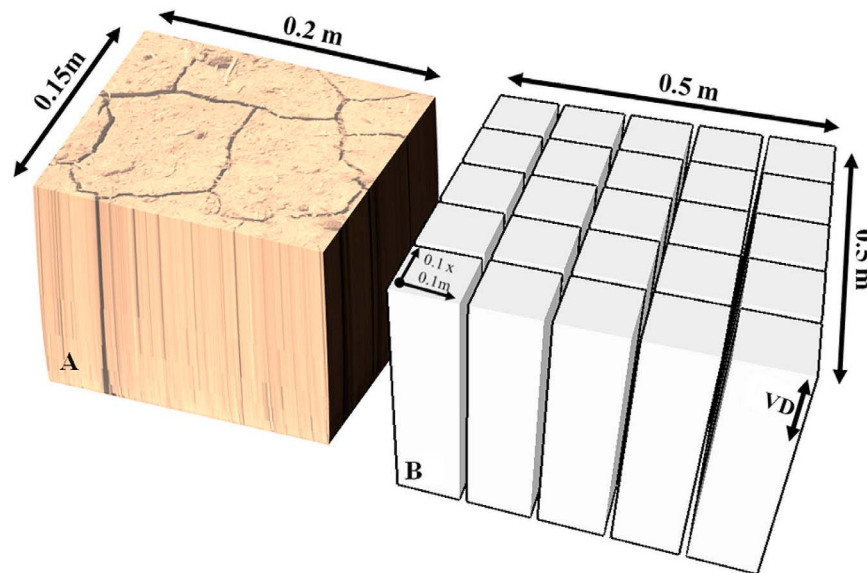
$$Q = J \cdot A \quad (7)$$

For a nonfractured vadose zone, diffusion of gases occurs solely through the ground surface. On the other hand, for fractured media, diffusion of gases may occur also through the fracture walls. Because wind driven convective venting rates are two orders of magnitude faster than gas diffusion rates (equation (4)), it can be assumed that the ventilated portion of the fracture walls are directly exposed to the

open atmosphere. Therefore, ventilated fractures essentially increase the effective surface area ( $A$ ) through which diffusion occurs, increasing the flux rate ( $Q$ ).  $A$  is determined by ground surface area  $S$  (m<sup>2</sup>), block density  $n$  (m<sup>-2</sup>), which is the number of soil/rock blocks per square meter, the perimeter of a single representative block,  $a$  (m), and VD.

$$A = S + (S \cdot n \cdot VD \cdot a) \quad (8)$$

For example: shrinkage cracks in clay soils with lateral distances of 0.1–0.2 m between cracks and crack depths of few tens of centimeter is a common phenomenon [e.g., Chertkov and Ravina, 2000; Weinberger, 2001; Yesiller et al., 2000; Trabelsi et al., 2011] (Figure 8a). Consider 0.25 m<sup>2</sup> of such



**Figure 8.** (a) Picture of shrinkage cracks in clay soil from an irrigated agricultural field in a semi-arid environment at the north of the Negev desert in Israel (lat. 31.451, lon. 34.729). (b) The model representation of this structure as a bundle of rectangles. VD indicates the depth affected by fracture ventilation.



soil ( $S = 0.25 \text{ m}^2$ ) with the shrinkage fractures generating clay blocks with average lateral dimensions of 0.1 by 0.1 m (Figure 8b), thus  $a = 0.1 \times 4 = 0.4 \text{ m}$  and  $n = 100 \text{ m}^{-2}$ . Assuming average fractures aperture of 0.01 m and wind velocity of 1 m/s, Ventilation depth is equal to 0.23 m (from Table 1). The effective  $A$  for this configuration is equal to  $2.55 \text{ m}^2$  (equation (8)), which is 10.2 times higher than the unfractured surface area. Since  $Q$  is linearly correlated to  $A$ , gas flux of the fractured media will be also  $\sim 10$  times higher compared to the nonfractured media.

[27] This very rough method for estimating enhancement of gas exchange at the Earth-atmosphere interface due to fracture ventilation demonstrates the potential importance of this to air circulation and subsequently to the aforementioned biogeochemical cycles and processes.

## 5. Summary and Conclusions

[28] Wind can drive convective venting of fractures open to the Earth's surface. This work quantified the effect of ground surface wind on convective ventilation of fractures and its subsequent impact on Earth-atmosphere air circulation. Field measurements obtained from a natural, surface-exposed fracture crossing a massive chalk formation showed that natural horizontal winds above the fracture resulted in ventilation of the fracture down to a maximum depth of  $\sim 0.5 \text{ m}$ , with greater ventilation depth at locations where the aperture was larger or as wind speed increased. Laboratory experiments carried out under controlled conditions in a fracture simulator confirmed and quantified field observed behavior, establishing that ventilation depth is linearly correlated to wind velocity and nonlinearly to fracture aperture. These relationships were used to develop an empirical model to predict the magnitude of the increase in gas mixing and net gas flux from the vadose zone.

[29] The model was used to estimate the increase in landscape level gas exchange caused by the presence of fractures. Model results indicate that for cracks in soil under windy conditions could produce an order of magnitude greater gas mixing relative nonfractured landscapes. Velocity measurements of air circulating between fracture and atmosphere indicated mass transfer rates two orders of magnitude higher than pure diffusive mass transfer rates. Mass transfer by wind driven venting is similar in magnitude to thermally induced convection within surface exposed fractures that also drives atmosphere-vadose zone air exchange [Nachshon et al., 2008; Weisbrod et al., 2009].

[30] Air exchange between the soil and atmosphere affects gas composition within the soil as well as soil moisture and soil heat, all of which impact soil microbial activity and the net loss of moisture and heat to the atmosphere. Thus, such a model is very valuable for better prediction of hydrological and biogeochemical cycles. Convective venting may also influence fundamental ecological processes that are involved in soil respiration by increasing the depth of soil vented, changing the soil moisture conditions at those depths and thus increasing the depth that contributes to soil respiration. Gas species generated by aerobic processes (e.g., volatilization of  $\text{NH}_3$ ) differ from those generated anaerobically (e.g., denitrification to  $\text{N}_2$ ,  $\text{N}_2\text{O}$ , and  $\text{NO}$ ). And, because soil commonly exhibits a moisture gradient (i.e., more moisture with increasing depth), venting and drying by venting will

change the relative proportion of gas components comprising atmospheric flux. Potential changes to soil respiration in cracked soil are important to consider since soil respiration is the main terrestrial source for the flux of trace gases such as  $\text{CO}_2$ .

[31] Soil cracks and fractures on the Earth's surface are ubiquitous features that can be commonly found in arid, moist and frigid climatic settings, such as the frost cracks associated with ice wedges in permafrost environments. Therefore, a mechanism that can enhance gas exchange by one or two orders of magnitude is of great importance to both vadose zone and atmospheric processes. This work shows that wind-induced venting is an important contributor to gas exchange and should be incorporated into models predicting gas exchange at the Earth-atmosphere interface.

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