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The Importance of Advective Fluxes to Gas Transport Across the Earth-Atmosphere Interface: The Role of Thermal Convection

Uri Nachshon[1], Noam Weisbrod[1], Maria I. Dragila[2] and Yonatan Ganot[1]
[1]*Ben Gurion University of the Negev*
[2]*Oregon State University, Oregon*
[1]*Israel*
[2]*USA*

1. Introduction

Understanding of gas exchange between the Earth's upper crust and the atmosphere is vital, as it affects many important processes which concern the water cycle, agricultural activities, greenhouse gas emissions, and more. From a hydrological aspect, water vapor transport is the most important process related to Earth-atmosphere gas exchange, since it affects above-land water vapor concentration; soil water content; and soil salinity. These three important hydrological parameters respectively affect the global water cycle (Hillel, 1998); water management and agricultural practices; and the formation of salt crusts at and near land surface – which can lead to soil salinization (Weisbrod et al., 2000; Nachshon et al., 2011), an important process from an agricultural point of view. In addition to soil salinization, with respect to agriculture, gas transport in the upper soil profile, i.e., the root zone, is important for soil aeration or movement of oxygen within the soil. Soil aeration 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 the soil pores, since respiration of plants and other organisms and microbial degradation of organic compounds in the ground emit high volumes of CO_2 into soil pores, while consuming O_2 (Brady, 1999). The exchange rate of air between soils and the atmosphere is crucial to maintain the needed soil aeration and oxygen concentration for plant growth.

Since most underground biological activity takes place in the upper parts of the soil profile, the majority of CO_2 is formed from the ground surface down to shallow depths of a few meters (Amundson, 2005). As soil temperature and water content increase, the CO_2 production increases (Fang & Moncrieff, 1999; Rastogi et al., 2002; Buyanovsky et al., 1986). The increase of organic matter availability will also lead to an increase in CO_2 production (Amundson, 2005). For example: Buyanovsky et al. (1986) calculated CO_2 production in soil surface cultivated with wheat. Values varied from 4 to 8 g/m d in spring, but in winter as soil temperature dropped below 5°C, CO_2 production was reduced to less than 1 g/m d. As for organic matter availability; soil CO_2 concentrations at 1 m depth in Tundra, temperate grassland and tropical rain forest are 1000, 7000 and 20,000 ppm, respectively (Amundson, 2005), corresponding to the richness of these soils in organic matter. CO_2 concentration in the pores of unsaturated soils, in the range of 3000 ppm is very common for agricultural and grasslands areas (Brady, 1990; Reicosky et al., 1997). Even though this concentration seems minor, it is eight times greater than atmospheric CO_2 concentration (391.48 ppm in 2011, (NOAA, 2011)). This difference emphasizes the importance of understanding gas exchange mechanisms between terrestrial environments and atmosphere as it affects CO_2 atmospheric concentration.

Migration of gases in unsaturated rocks is also very important in the context of Earth-atmosphere gas exchange. Therefore, the general term 'vadose zone', which includes both unsaturated soils and rocks above the water table, is often used. For example, the world's largest carbon reservoir are carbonate rocks, containing about $6.1*10^7$ billion tons of carbon, which is 1694 and $1.1*10^5$ fold more than the carbon content in oceans and world vegetation, respectively (Houghton & Woodwell, 1989). Chemical interactions between these carbonate rocks and atmosphere may be a source or a sink for large volumes of CO_2 (Liu & Zaho, 2000).

Emission of gases from the Earth's subsurface has an important role from an environmental aspect. For example, water vapor and CO_2, beside being important for agricultural and hydrological concerns, are important components of the global warming process, as they are major green house gases, together with N_2O and CH_4 (Weihermüller et al., 2011). Thus, it is important to understand the transport of these gases across the Earth-atmosphere interface. Additionally, understanding of gas transport is important for environmental and public health concerns. Movement of volatile radionuclides, such as ^3H, ^{14}C and Rd 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; Ronen et al., 2010) can greatly affect public health when emissions occur in buildings or populated areas (Nazaroff, 1992; Scanlon et al., 2001).

For the reasons mentioned above and more, it is vital to understand gas exchange processes and gas flow rates between the Earth crust and atmosphere. Traditionally, diffusion was considered as the main mechanism of gas exchange between the atmosphere and the vadose zone, driven by gas concentration gradients (Hirst & Harrison, 1939; Penmann, 1940a, 1940b; Marshall 1958, 1959; Millington & Quirk, 1961; Cunningham & Williams, 1980; Amali & Rolston, 1993). In the last few decades several advective gas transport mechanisms, corresponding to pressure gradients, were introduced, resulting in faster gas exchange rates between terrestrial environments and atmosphere. Moreover, 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 within pores. Advective mechanisms that could result in gas flux across the Earth-atmosphere interface include: (1) wind pumping (Fukuda, 1955; Weeks, 1993, 1994); (2) atmospheric barometric changes (Pirkle et al., 1992; Wyatt et al., 1995; Rossabi, 2006); and (3) thermal convection flows in fractures and other cavities (Weisbrod et al., 2005; Weisbrod & Dragila, 2006; Weisbrod et al., 2009).

This chapter first presents a general overview of relatively known gas transfer mechanisms between the vadose zone and atmosphere, which include diffusion, wind driven advection and advection driven by atmospheric barometric changes. Subsequently, we describe recent exploration and findings regarding thermal convection flow within surface exposed fractures and its important effect on fracture ventilation. This is followed by a description of field and laboratory investigations conducted to study thermal convection in rock fractures. Lastly, results are presented with an aim to answer the following scientific questions:

- Is there a temporal dependence on development of thermal convections in surface-exposed fractures?
- Do fracture aperture and thermal conditions affect convection flow velocities and to what extent?

- Do fracture aperture and thermal conditions affect convection flow cell dimensions and geometry?
- Do fracture aperture and thermal conditions affect total mass transfer rates between fractures and atmosphere and to what extent?

Deciphering these issues enables quantitative estimation of gas exchange rates between the vadose zone and atmosphere for fractured media. Moreover, while the studies presented here focus on thermal convection developing within fractured media, these same processes are likely pertinent for other surface exposed cavities in the vadose zone such as animal burrows, boreholes and karstic structures.

2. Gas transfer mechanisms

As aforementioned, two gas transport mechanisms, diffusion and advection, control gas movement between the Earth and the atmosphere. While the former occurs spontaneously, whenever there is a concentration gradient of a certain substance (gas or liquid, even under isothermal and isobaric conditions), the latter occurs only if there is a thermal or a pressure gradient. Diffusion mass transfer rates are usually several orders of magnitude lower than advection mass transfer rates. If a total pressure gradient exists in a soil in response to natural phenomena such as barometric changes or surface wind, gases will flow from points of higher to those of lower pressure. It has been shown that relatively small gradients of total pressure can result in advective gas fluxes that are much higher than diffusive gas fluxes (Thorstenson & Pollock, 1989; Massmann & Farrier, 1992, Scanlon et al., 2001).

2.1 Diffusion

Diffusion has long been considered the dominant process by which gases move from the vadose zone to the atmosphere. Penman (1940a, 1940b) explored soil properties and their effect on water vapor and CO_2 diffusion across the vadose zone-atmosphere boundary. This work showed that diffusion alone can support CO_2 transfer rates needed for plant respiration. Fick (1855) formulated gas and liquid diffusive fluxes as a function of their concentration field, with flow resulting from regions of high concentration to regions of low concentration. Fick's law is:

$$J_D = -D\nabla C \quad (1)$$

where J_D (kg/m^2 s) is the mass flux, D (m^2/s) is the gas diffusion coefficient in free air, and C is gas (e.g., water vapor) concentration (kg/m^3). Table 1 introduces D (in free air) for common vadose zone gases.

Gas	Temperature (°C)	Diffusion coefficient x10^{-5} (m^2/s)
H_2O	16	2.82
CH_4	9	1.96
O_2	0	1.76
CO_2	9	1.02

Table 1. Diffusion coefficients in free air for common vadose zone gases (from: Cussler, 1997)

A few relationships have been proposed to describe gas diffusion in porous media (e.g., Marshall, 1958, 1959; Millington & Quirk, 1961; Moldrup et al., 2000); in all of them, the diffusion coefficient in porous media (D_{eff}) is low compared with that in free air and is proportional to the air-filled porosity ϕ_a. As per Millington & Quirk (1961):

$$D_{eff} = D \cdot \phi_a^{\frac{4}{3}} \tag{2}$$

For example, assuming sandy soil (ϕ_a = 0.35) with the evaporation front at a depth of 1 m below surface, soil pores just above the evaporation front have water vapor concentration of 0.03 kg/m^3, corresponding to 100% relative humidity at 30°C (Ho, 2006). For an atmospheric relative humidity of 50% the vapor concentration is 0.015 kg/m^3, hence ∇C between soil surface and water table is 0.015 kg/m^3 over a distance of 1 m. From Table 1, D for water vapor is 2.82x10^{-5} m^2/s. Using Equation 2 (D_{eff} is equal to 6.95x10^{-6}) and Equation 1, the water vapor flux from the water table toward the atmosphere is 1.04x10^{-7} kg/m^2 s. The constraining effect of pores is removed for the diffusion of gases from the vadose zone towards the atmosphere when the diffusion path is via fractures, caves, karstic holes or animal burrows. In these cases, or the same physical conditions but for diffusion in free air, the vapor flux would be four times higher than vapor flux through the soil, which would be equal to 4.23 x10^{-7} kg/m^2 s.

2.2 Advective gas transport

Non-turbulent advective gas transport in porous media is described by Darcy's law which correlates gas fluxes J_A (m/s) to matrix permeability, K(m^2), gas viscosity, μ (Kg/m s) and pressure gradient, ∇P :

$$J_A = -\frac{K}{\mu} \nabla P \tag{3}$$

Small pressure gradients can result in substantial advective gas fluxes because the resistance to flow is small, due to the low viscosities of gases (Granger, 1995). When comparing advective to diffusive gas mass transport it is convenient to use the Sherwood number (Sh) which is a dimensionless number that gives the ratio of convective to diffusive mass transport. The Sherwood number is defined as: (Weast, 1980),

$$\text{Sh} = \frac{J_A L}{D} \tag{4}$$

where L is the length scale of interest. For Sh>1 advection is the dominant transport mechanism, while for Sh<1, diffusion is the main transport mechanism.

2.2.1 Barometric pumping

One mechanism which can generate pressure gradients between the air within vadose zone pores and the above ambient atmosphere is related to barometric pressure changes at the order of 1 kPa; these pressure changes are caused by diurnal thermal and gravitational fluctuations, and larger fluctuations corresponding to regional scale weather patterns, which cause pressure changes of tens of kPa (Auer et al., 1996; Scanlon et al., 2001; Rossabi, 2006). The penetration depth of barometric pressure fluctuations increases with the permeability of the medium. In very high permeability fractures and boreholes, this mechanism is more

prominent and the pressure wave can penetrate to a large depth, in some cases down to depth of several hundred meters (Nilson et al., 1992; Holford et al., 1993).
Rossabi (2006) presented a comprehensive review of this mechanism. It was shown that the barometric pumping mechanism results in very high mass transfer rates of air through boreholes crossing the vadose zone. For a 32 m deep, 1 inch diameter borehole, and an average atmospheric pressure fluctuation of 1 kPa per day, the maximal measured air flow velocities were in the range of 0.7 m/s, much faster than typical diffusion mass transfer rates. Massmann & Farrier (1992) computed gas transport in the unsaturated zone resulting from atmospheric pressure fluctuations and found that atmospheric "fresh" air can migrate several meters into the subsurface during a typical barometric pressure cycle. Auer et al. (1996) included the effects of barometric pumping in an airflow and transport model and found that as little as 13% of a simulated original contaminant mass remained after 50 years, compared with 49% of the original mass remaining for the case of diffusion only.

2.2.2 Wind effect

Another mechanism which results in ventilation of the vadose zone, and has been explored mainly in connection with fractured media (Fukuda, 1955; Weeks, 1993, 1994) and animal burrows (Vogel et al., 1973; Fenton & Whitford, 1978; Kleineidam et al., 2001), is related to wind flow above the ground surface. It follows naturally from the conservation of energy law that for any fluid (including gas) the balance between its pressure, velocity and elevation on a single stream line is described by the Bernoulli equation: (Schaschke, 1998),

$$P + \frac{\rho V^2}{2} + \rho g h = CONSTANT \tag{5}$$

where V is the gas flow velocity (m/s), ρ is density (kg/m^3), g is gravitational acceleration (m/s^2) and h (m) is height over a reference. The first term in the equation, P, is called the static pressure (kg/m s^2) and is the pressure induced by the gas that can be measured by a barometer. The second term in the equation is known as the dynamic pressure and the third term is the gravitational potential. As can be seen from Equation 5, as gas velocity increases the dynamic pressure increases and induces a static pressure decrease. For a stagnant bulk of air (V = 0 m/s) at sea level (h=0 m), Equation 5 can be written as P=$CONSTANT$=ATM (atmospheric pressure). Now, if this bulk air moves at constant elevation with velocity U (m/s), the static pressure becomes: $P = ATM - \frac{\rho U^2}{2}$.

Therefore, when wind blows over porous or fractured media a pressure gradient is induced between the stagnant air below ground surface and the moving atmospheric air, resulting in advective gas fluxes from the vadose zone towards the atmosphere. As per Darcy's Law (Equation 3), an increase in matrix permeability increases gas fluxes, therefore this mechanism is expected to be most prevalent in fractures and other cavities exposed to atmosphere that have much higher permeability, compared to porous media (Weeks, 1993). Assuming air density of 1.3 kg/m^3 (Evett, 2001) and wind velocity of 0.5 m/s at ground surface (Morgan, 2005), the pressure difference between stagnant air below soil surface and atmospheric air is 0.1625 Pa (Equation 5). Using Equation 3, this pressure difference along a fracture with 0.5 m depth and aperture of 2 cm results in a gas flux of 0.58 m/s towards the atmosphere (values used where k = (2b)^2/12 and 2b is the fracture aperture (Shemin, 1997) and μ=1.85x10^{-5} (kg/m s)).

Assuming the fracture is saturated with water vapor, which diffused into it from the surrounding porous media, the induced gas exchange between the fracture and atmosphere will increase water vapor extraction from the fracture, resulting in a net vapor flux into the atmosphere. The Sh number (Equation 4) can give an estimate of the wind effect on mass transfer rates. For example, the ratio between advective velocity of 0.58 m/s to diffusion of H_2O vapor with D=2.82x10^{-5} m^2/s, over a 0.5 m fracture depth results in Sh>10,000, indicating a potential mass transfer for advection that is 10,000 times greater than diffusion, demonstrating the important role of wind in ventilation of the fracture.

Another passive ventilation mechanism, occurring mainly for surface exposed cavities in the ground, is called "viscous entrainment". Viscous entrainment is caused by the resistance of fluids to rapid shear rates and the consequent attraction of stagnant fluid by adjacent rapidly moving fluid. For surface exposed cavities this shear stress develops between the fast moving surface wind and the stagnant air in the cavity (Vogel et al., 1973; Kleineidam et al., 2001). In addition, several works (Kimball & Lemon, 1971, 1972; Ishihara et al., 1992) have shown that turbulent wind above ground surface might result in turbulent diffusion of gases below ground surface, hence increasing the overall gas exchange rates. Apart from this, when wind blows over irregular surfaces, the formed eddies increase pressure on the windward side of an obstruction and reduce pressure in the leeward side (Don scott, 2000). This mechanism is more relevant to flow in high porosity and permeability matrices, with its effect limited to a depth of several cm (Ishihara et al., 1992). Kimball & Lemon (1971) reported an increase of up to 2 orders of magnitude in fluxes of Heptane vapors from 2 cm below surface to the atmosphere due to turbulent winds with an average velocity of 0.65 m/s.

3. Thermal convection mechanism

Besides wind and barometric pumping mechanisms, a third mechanism was recently explored, relevant to increasing gas exchange between vadose zone and atmosphere. Weisbrod et al. (2005) and Weisbrod & Dragila (2006) proposed that thermally-driven convection might be a primary mechanism for venting of surface-exposed fractures and cracks open to the atmosphere. While the above mentioned barometric pumping and the wind mechanisms require specific meteorological conditions to occur, conditions necessary for thermal convections occur every night in fractures and cavities exposed to the atmosphere, in response to daily thermal fluctuations (Weisbrod et al., 2009).

The authors suggested that during cold nights, especially in arid climates, when the ambient air becomes colder and consequently denser than the fracture air, density-driven air convection may develop within the surface exposed fractures. Exchange of warm fracture air with cooler atmospheric air effectively ventilates fracture air. Conversely, during the day, atmospheric air is warmer than fracture air, generating a stable condition in which no appreciable convective movement driven by air-density differences is expected. Theoretical calculations have suggested that convection could markedly increase gas exchange between fractures and atmosphere and increase evaporation rates from fractures with apertures of more than a few millimeters and thermal differences of more than a few degrees Celsius between fracture and atmospheric air (Weisbrod & Dragila, 2006; Weisbrod et al., 2005).

Several experimental studies (Nachshon et al., 2008; Kamai et al., 2009) as well as field measurements (Weisbrod et al., 2009) have demonstrated the validity of this concept and quantified the thermally-driven convection mechanism. A thorough review of this mechanism will be presented in this chapter.

3.1 Density-driven gas fluxes

In contrast to barometric pumping and the wind mechanisms, which are associated with pressure gradients, thermal convection in fractures responds to density differences between fracture and atmospheric air. The fundamental assumption is that because of the high geometric aspect ratio and low heat capacity of air, fracture air temperature is similar to the temperature of surrounding fracture walls. Consequently, the daytime thermal profile of fracture air consists of warm air in the upper parts of the fracture and colder air in the fracture's deeper parts, in accordance with the typical thermal profile of the vadose zone matrix (Don scott, 2000, Weisbrod & Dragila 2006). At night atmospheric air temperature drops dramatically, especially in arid areas and the vadose zone's thermal profile is inverted (Evett, 2001). The ground surface, which is exposed to the relatively cold atmosphere and from where energy is radiated, becomes colder than the deeper parts of the matrix. Thus, the fracture's thermal profile is in an unstable state, with cold, dense air on top of warmer, less dense air.

Unstable thermal gradients of sufficient magnitude lead to buoyancy-driven convection flows. A conceptual model for day and night thermal conditions and their associated mass transport mechanisms are depicted in Figure 1.

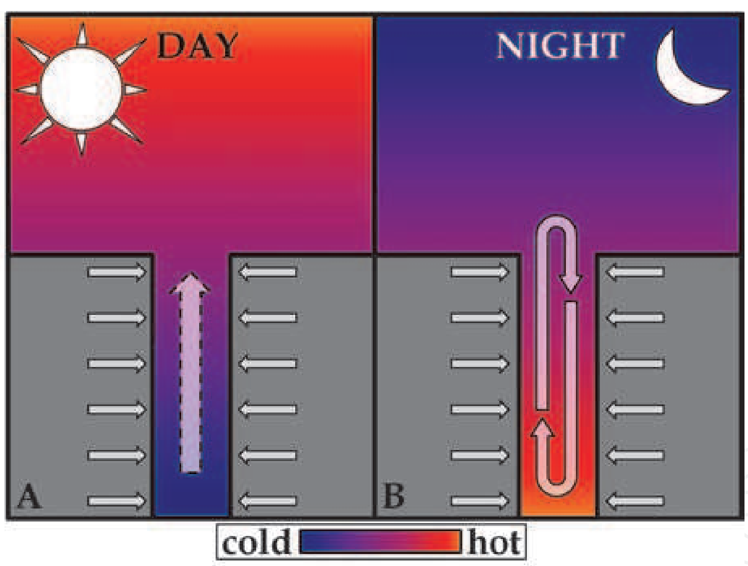

Fig. 1. Conceptual model for fracture venting, consisting of (A) diffusive venting of fracture air during the day; and (B) thermally driven convection at night. Horizontal arrows indicate diffusive gas flux from the porous matrix towards the fracture.

3.1.1 Rayleigh number

In a density-driven gas transport process, two forces oppose one the other: buoyancy and viscosity. The onset of convection in fractures has been theoretically proposed to occur when the Rayleigh number (Ra), which is a dimensionless number that compares buoyant and viscous forces, exceeds a critical value of $4\pi^2$ (Lapwood, 1948; Nield, 1982). Ra is defined as:

$$\mathrm{Ra} = \frac{\Delta\rho g\kappa L}{\mu k} \tag{6}$$

where $\Delta\rho$ is the density (kg/m^3) difference between the air at the top and bottom of the fracture over a length scale L (m), μ is the dynamic viscosity of the air (kg/m s), g is the gravitational constant (m/s^2), κ is the thermal diffusivity (m^2/s), and k is the fracture permeability (m^2) (k = (2b)^2/12, where 2b is the fracture aperture (Shemin, 1997). Within the range of 0 to 80°C, air density can be assumed to be a linear function of temperature and expressed by the thermal expansion coefficient (α = 0.00367(1/°C)). Therefore, Equation 6 can be recast as a function of temperature, which can be measured easily,

$$\mathrm{Ra} = \frac{\Delta T\alpha g\kappa L}{\nu k} \tag{7}$$

where ΔT (°C) is the temperature difference between fracture air at the top and bottom of the fracture over the length scale L, and ν is the kinematic viscosity (m^2/s). As an example, for a discrete fracture of 1 m depth and 2 cm aperture, Ra would predict a minimum necessary temperature difference of 0.01°C. For a 0.5 cm aperture, a temperature difference of 0.17°C is needed. Such thermal differences are much lower than typical thermal differences along a 1 m profile in the vadose zone (e.g., Brady, 1990; Don scott, 2000) and in surface exposed fractures (Weisbrod et al., 2009), which are in the range of 2-15°C, at least for temperate and semi-arid environments. These differences were measured on a nightly basis, thus, theoretically convection flows are expected to be formed in the surface exposed fractures, every night.

3.2 Quantifying thermal convection flows

Weisbrod et al. (2009) and Nachshon et al. (2008) explored and quantified thermal convection *in situ* within a natural fracture and in laboratory experiments. The former used a two dimensional grid of thermocouples to monitor spatial thermal distribution within a natural fracture in the field. The fracture, within a Chalk rock unit, is located in the south of Israel, in a semi-arid environment. The fracture depth is up to 120 cm, with average aperture of 1.5 cm over a lateral width of 150 cm. The installed 25-thermocouple grid occupied part of the fracture, penetrating to a depth of 60 cm and a 60 cm lateral width. Measurements were taken at a spatial resolution of 15 cm every 10 minutes. In addition a vertical line of thermocouples inserted to a depth of 120 cm, measured matrix temperatures (Figure 2).

Nachshon et al (2008) simulated a natural fracture exposed to atmosphere using a 50 cm x 50 cm Hele-Shaw cell with apertures of 1 and 2cm. The Hele-Shaw cell walls were made of glass, enabling viewing of the fracture volume. Thermocouples were installed along the glass walls, as well as a two dimensional grid of thermocouples, similar to the one used in the field that was inserted into the simulated fracture. The entire setup was placed on heating plates in a climate control room. By controlling heating plates and room ambient air temperatures, thermal gradients similar to those measured in nature were imposed. No wind was blowing in the climate control room to eliminate wind effect on convection dynamics. Smoke filled the simulated fracture to enable tracing of air movement. A video camera (24 frames per second) was used to film the migration of smoke within the Hele-Shaw cell and to the atmosphere above. Images were analyzed frame-by-frame to quantify tracer transport.

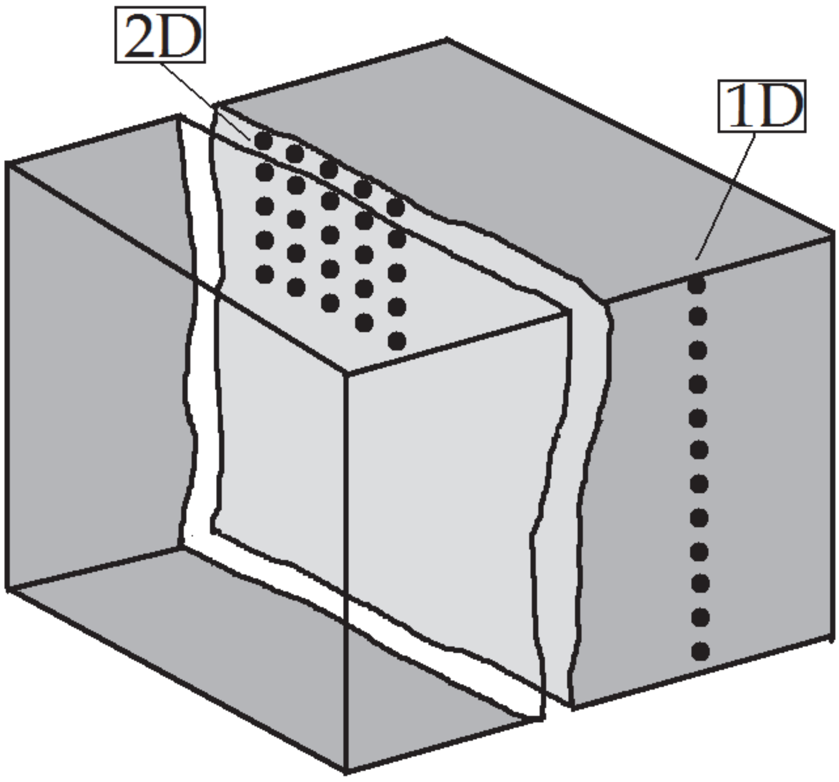

Fig. 2. Schematic of thermocouples installation as two dimensional grid within the fracture and the vertical line within the rock. Two dimensional grid dimensions are 60x60 cm. Fracture aperture is ~1-2 cm.

3.2.1 Field measurements and experimental results

Field measurements indicate diurnal appearance of convection flows every night. The thermal signature of the convection cells was measured by the two dimensional thermocouples grid. It was found that every night, unstable conditions of hot air below cold air develop within the fracture, sustained through the night until the next morning. Calculated Ra numbers for the measured thermal conditions are in the range of few thousands, much larger than the critical Ra necessary for the onset of convection.

3.2.2 Thermal convection patterns

Convection patterns between parallel ducts fall into two categories, Thermo-siphon (Figure 3A; Balaji & Venkatesehan, 1995; Lanchao & Amir, 1998) and finger flow (Figure 3B). For the case of natural convection in natural fractures with apertures in the range of a few cm, it was shown both experimentally and *in situ* in the field that the convection flows form a fingering pattern.

A convection cell is defined as the region which includes one down and one up air stream line. For example; in Figure 3B there are two convection cells. For typical thermal conditions in the field, with a thermal gradient in the range of 2-15°C over a vertical distance of less than 1 m, convection cell dimensions ranged from 20 to 50 cm in width, reaching a maximal depth of ~60cm. As the thermal gradient increases, cell aspect ratio increases as cells become taller and narrower, i.e. more convection cells occupied the fracture volume, increasing the effectiveness of the system for mass and energy exchange with the atmosphere.

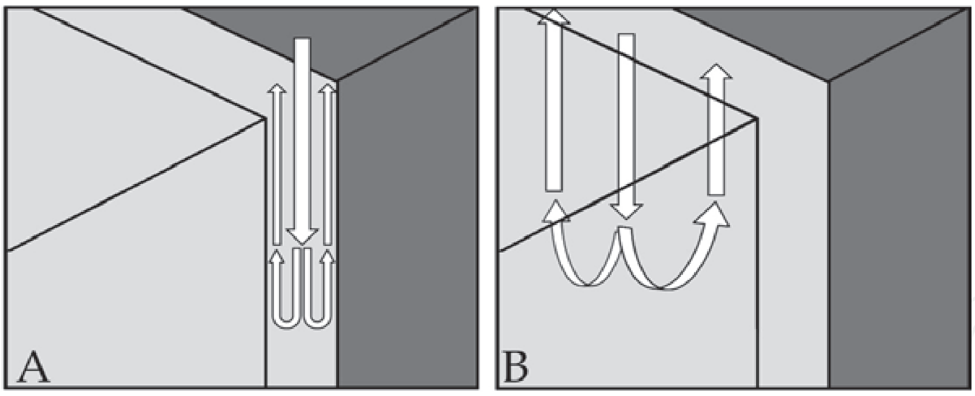

Fig. 3. Convection cell patterns: (A) Thermo-siphon, where the hot air ascends along the hot walls and the cold air descends in the middle; and (B) a fingering pattern, where the ascending hot air and the descending cold air change alternately along the fracture width dimension.

Figure 4 presents examples of the fingering flow pattern within the Hele-Shaw cell (Figure 4A), for a ΔT of 5°C over 50 cm, and thermal signatures of a large and small fingering flow pattern in the natural fracture (Figures 4B and 4C, respectively). Comparison between Figure 4B and 4C demonstrates the effect of an increase in the thermal difference between fracture bottom and upper boundaries on the convection cells' dimensions. In Figure 4B a single, wide convection cell is observed for ΔT of less than 6°C, while for ΔT of 8°C (Figure 4C) two narrow convection cells are observed, enabling more efficient heat removal.

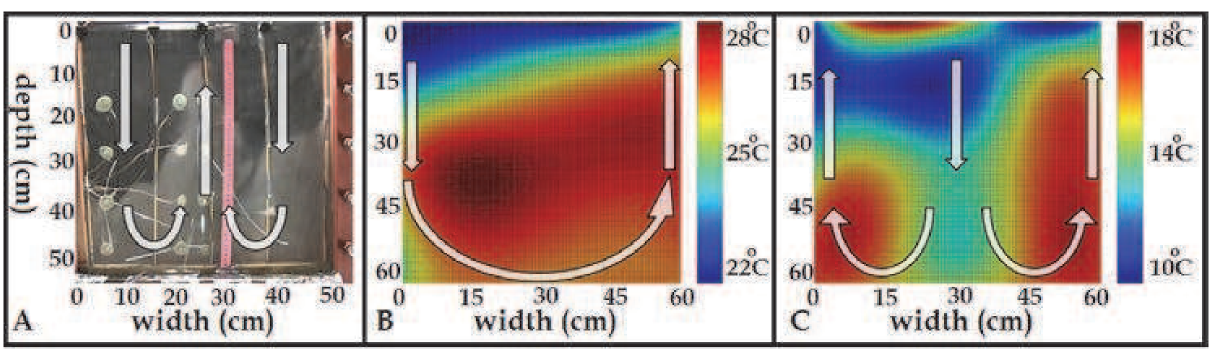

Fig. 4. Experimental and field observations of the fingering flow pattern. Arrows indicate air flow directions. (A) snapshot of the flowing air in the Hele-Shaw chamber, visualized by the smoke, for a thermal difference of 5°C between fracture bottom and atmosphere. (B), (C) thermal measurements from the natural field fracture. The convection cell's thermal footprint is observed. (B) and (C) are for different thermal gradients of 5°C and 8°C respectively.

3.2.3 Thermal convection durations

As observed from the field measurements, the convection flows started as the atmospheric air temperatures started to decline, every evening. The convection cells were observed throughout the night until the following morning. During winter, when the nights are longer and atmosphere is cold the duration of the convection flows were longer than in summer (Figure 5). During December-January the average duration for convection conditions was ~18 hours, starting at ~17:00 and ending at ~11:00 the following day. During July-August, convection started at ~19:00 and lasted until ~07:00 the following day.

A diurnal cycle of thermal distribution, resulting from thermal convection within a natural fracture in the field is presented in Figure 6 (during September 28–29, 2006). At this time, it was observed that the convection cells commenced at 19:00 and ceased around 09:00 the following day.

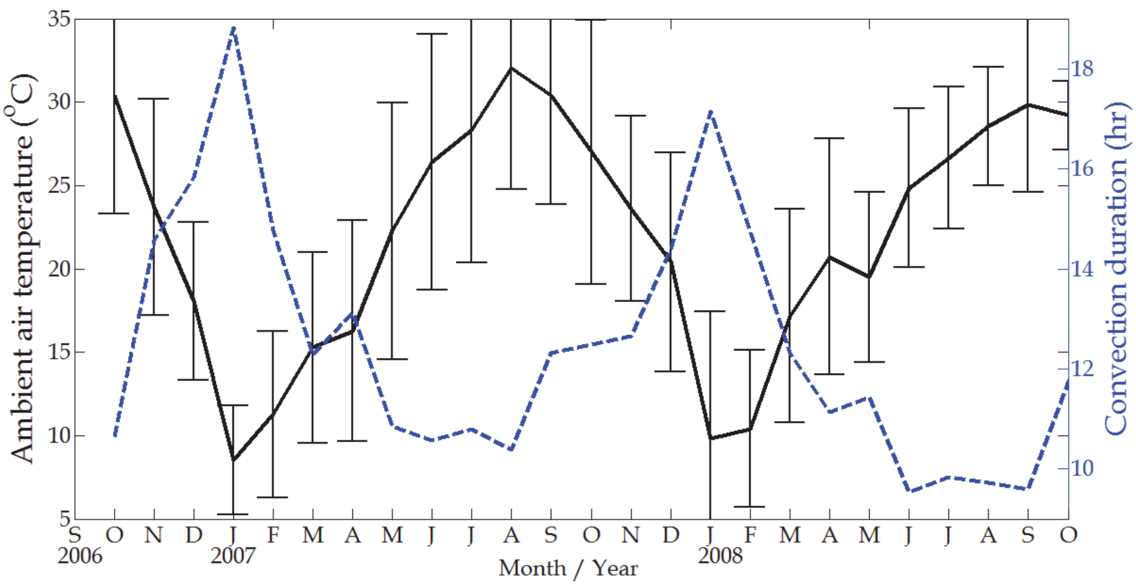

Fig. 5. Variability in daily duration of convective venting. Average monthly atmospheric air temperature (solid line) and monthly average of the daily duration of convection (dashed line) for a 24-month period from October 2006 to October 2008. Vertical bars depict daytime-nighttime temperature range.

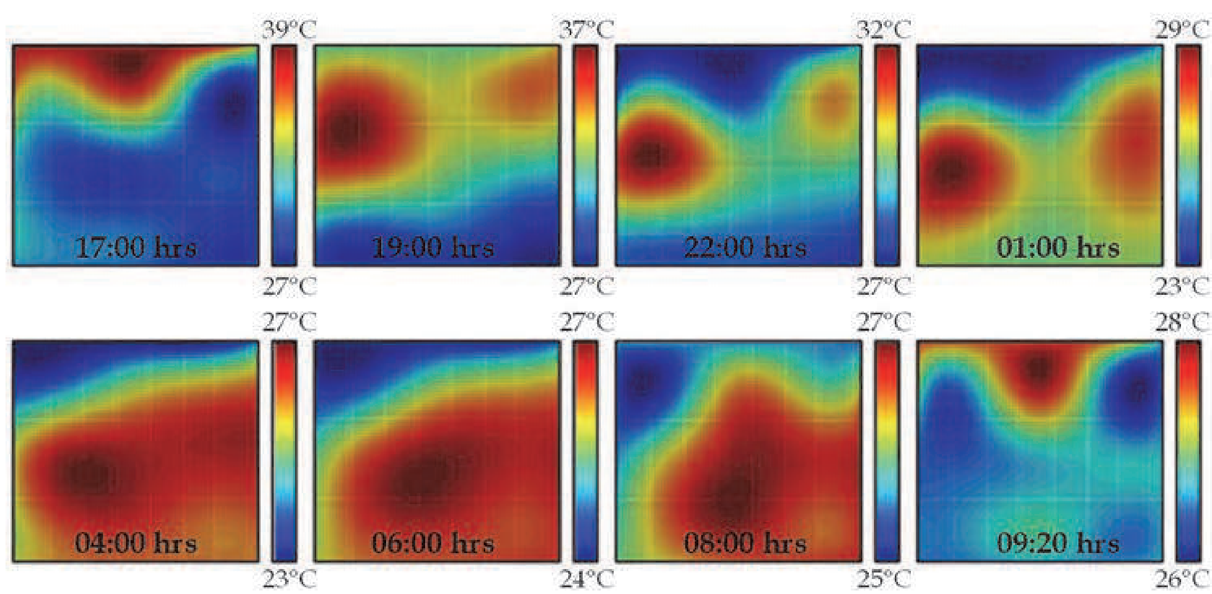

Fig. 6. Thermal map of air temperature within the natural fracture. Thermal convection cells were observed to form in a natural fracture exposed to the soil surface. Note that temperature scale is unique to each map to maximize image range: blue (cool) to red (warm). Dimensions of each map are 60 cm by 60 cm. Time corresponding to each map is shown at each map box. Date: Sep 28–29, 2006.

3.2.4 Mass transfer

Hele-Shaw experiments enabled quantification of the mass transfer rates between the simulated fracture and atmosphere, as well as providing a method for which to measure convection flow velocities for various Ra values which correspond to different thermal gradients and apertures. Nachshon et al. (2008) defined two velocities to describe a convection flow: (1) the maximal velocity at the center of the ascending hot air (U_{max} (m/s)) and (2) the average up flow velocity for the entire fracture (Hele-Shaw) volume (U_{ave} (m/s)). The maximal velocity was measured by analyzing video camera sequences of the smoke flow within the Hele-Shaw cell. The average velocity was calculated based upon the time it took to empty the chamber from smoke. Table 2 presents physical conditions and measured U_{max} and U_{ave} for various Ra values. It is shown that U_{max} is ~50 times faster than U_{ave} for the lower Ra values and only ~15 times faster for higher Ra values. This disparity reflects the linear increase in U_{max} (U_{max}=4x10^{-6}(Ra)) against a logarithmic increase of U_{ave} as Ra increases.

Aperture (cm)	ΔT	Ra	Total width of upward flow (cm)	U_{ave} (m/s)	U_{max} (m/s)
1	5	2973	10	0.00038	0.019
1	10	5947	12	0.00055	0.0231
1	13	7731	15	0.00065	0.0265
2	5	11893	10	0.00093	0.051
2	7	16658	--------	0.00119	--------
2	8	19037	--------	0.00152	--------
2	9	21417	--------	0.00333	--------
2	10	23796	20	0.00439	0.0678
2	12	28556	--------	0.00556	--------
2	13	30923	25	0.00725	0.124

Table 2. Hele-Shaw experimental conditions and results (Nachshon et al., 2008).

The mass transfer rate of air from the fracture to the atmosphere is comprised of two components: (1) the upward air velocity; and (2) the fraction of the fracture which participates in the upward flow. As can be seen from Table 2 and from the convection cell pattern, as Ra increases, more fracture areas participate in upward flow. Therefore, even though U_{max} increases linearly, the overall mass transfer rates and the subsequent U_{ave} both increase exponentially. Figure 7 displays U_{max} and the mass transfer rates for various Ra values, showing a linear increase in U_{max} and the exponential increase in the mass transfer rate of ≈ 4.3x10^{-9}(Ra)^2. Figure 8 displays the Sh number for various Ra values, indicating the importance of thermal convections to gas exchange between vadose zone fractures and atmosphere. Thermal convections increase mass transfer rates by almost two orders of magnitude for the higher Ra values and by an order of magnitude for lower Ra values. The thermal conditions in the range of these Ra values were measured every night in the natural fracture.

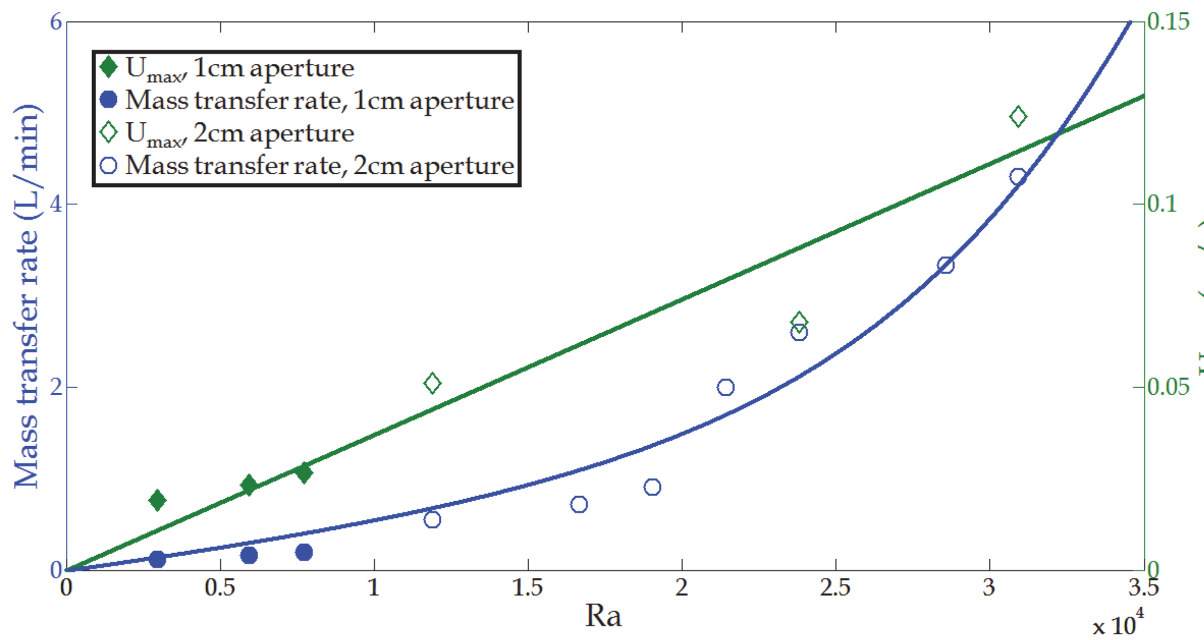

Fig. 7. Mass-transfer rates (blue symbols) from the smoke-replacement experiments increase exponentially with Rayleigh number (Ra) (mass transfer ≈ 4.3 × 10−9(Ra)^2, R^2 = 0.97), while maximum velocity (U_{max}) (green symbols) increases linearly (U_{max} = 4 × 10^{-6}(Ra), R^2 = 0.94). Full and empty polygons represent data from the 1 and 2 cm apertures, respectively.

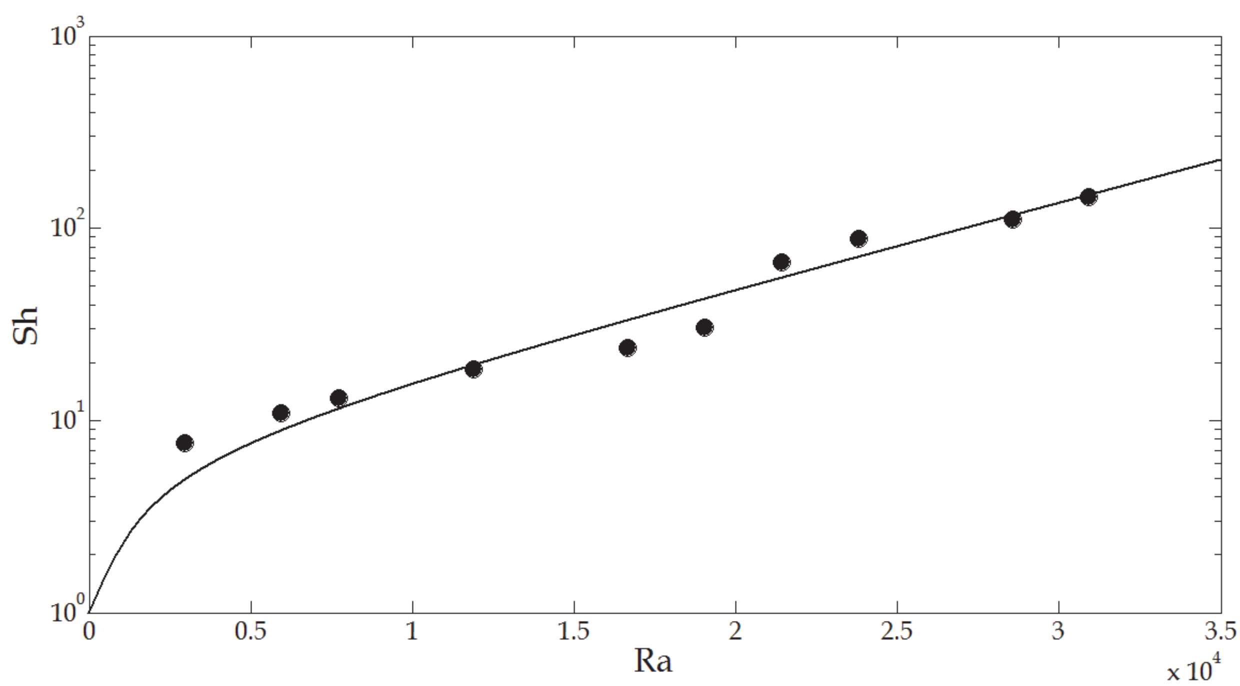

Fig. 8. Sherwood number (Sh) as a function of Rayleigh number (Ra). Black marks are calculated from the smoke-replacement experiment. Black line is a numeric fitting of the results: Sh ≈ 1.5E^{-7}(Ra)^2 + 1.

4. Conclusions

Both barometric variability and surface winds drive gas and vapor exchange between the vadose zone and the atmosphere. However, these two mechanisms are infrequent and depend upon the capriciousness of local weather patterns. On the other hand, thermally driven free convection, occurs on a nightly basis and should therefore be considered as a primary transfer mechanism in areas where the surface is cracked or fractured.

Evidence presented here categorically shows that convective venting of cracks and fractures is a natural and pervasive process that may have a pronounced impact on earth-atmosphere gas exchange in areas where surface cracks and fractures prevail (e.g. desert playas, cracked soils in agricultural regions or rock fractures). Soil cracks and fractures on the Earth's surface are not rare; they are ubiquitous features that can be commonly found in arid, moist and frigid climatic settings. However, thermally driven convection may also prevail in the fractures and cracks of karst systems, boreholes, and animal burrows. Karstic systems provide almost 25% of the world's potable groundwater supply (Ford & Williams, 1989), demonstrating their importance and abundance and subsequently the potential impact of advective gas flux to Earth-atmosphere gas and vapor exchange rate. Preliminary measurements within an ancient borehole (52 m deep, 3.5 m in diameter, Negev Desert, Israel) indicated unstable thermal conditions to a depth of 40 m throughout most of the year nights (data not shown) suggesting the deep reach of the mechanism into the vadose zone.

The studies reviewed herein have shown the diurnal cycle appearance of thermal convection flows in surface exposed fractures. On a yearly scale it was shown that during winter, duration of convection flows is longer compared to summer time, in accord with winter cold atmospheric temperatures and long nights. Velocities of thermal convection flows were found to increase linearly with increasing thermal gradient and fracture aperture (higher Ra). In addition, as Ra increased, convection cells' geometry changed. For high Ra values, convection cells were narrower and taller, resulting in more convection cells per unit fracture volume. Consequently, as Ra increased, the mass transfer rates between the fracture and ambient air increased with a quadratic relationship, reflecting the combined effect of the linear increase in velocity and changes in convection cell geometry. It was shown that for the natural thermal conditions under which measurements were made, surface exposed fractures with aperture in the range of 1-2 cm will accommodate gas transport due to the thermal convection that is two orders of magnitude greater than non convective conditions. These findings demonstrate the importance of the thermal convection in fractures to atmosphere gas exchange processes and hence, vadose zone ventilation.

It is vital to understand gas transfer mechanisms between vadose zone and atmosphere, particularly with respect to greenhouse gases emissions, since vadose zone gas composition is in many cases markedly different than atmospheric gas composition (having high concentrations of greenhouse gases such as H_2O, CO_2, CH_4 and N_2O) (Reicosky et al., 1997; Hillel, 1998; Brady, 1999; Scanlon et al., 2001). Convection can lead to large mass exchange rates of the subsurface and atmospheric air via fracture and other discontinuities of the porous media. Nevertheless, vadose zone ventilation may be limited by gas diffusion through the matrix, as gases need to diffuse through the porous media toward fractures. Since diffusion fluxes are several orders of magnitude lower than convection fluxes within fractures, the diffusion rate from the matrix to the fracture will be the limiting factor in vadose zone-atmosphere gas exchange rates. Yet, even with this limit, fracture and other discontinuities in the porous media ventilation by thermal convection have an important effect on gas emission from the vadose zone as they expose deeper parts of the vadose zone to fresh atmospheric air, increasing the total atmospheric-matrix boundary area, consequently increasing overall diffusion fluxes.

Figure 9 presents an estimate of diffusive fluxes from a CO_2 point source, at 1 m depth, for conditions of unfractured porous media and fractured media with thermal convection flows. Diffusion rates were calculated using Equations 1 and 2 and Table 2 (for CO_2 diffusion coefficient in free air), for various porosities, ranging from 0 to 50%, to simulate the variation in soil or rock porosity due to texture and/or morphology. CO_2 concentration was considered as 3000 ppm and 400 ppm for the source and atmosphere respectively. For the fracture conditions the following assumptions were made: a spacing of 1 m between fractures, and CO_2 concentration equal to atmospheric concentration, due to the high mass transfer rates between fractures and atmosphere. Figure 9 shows that as porosity increases, diffusion fluxes increase too, due to increase of the effective diffusion coefficient of the porous media (Equation 2). The important contribution of the thermal convection within fractures to the overall diffusion of CO_2 from the vadose zone is thus shown, with total convective mass flux being five fold higher than for unfractured conditions, regardless of porosity. Convective venting, besides increasing gas exchange rates between vadose zone and atmosphere, may also affect greenhouse gases production within the vadose zone. The increase in vadose zone ventilation and subsequently the increase in oxygen supply for deeper parts of the vadose zone may result in increasing biological activity and organic matter decomposition, which are the major producers of CO_2 and CH_4 in the upper parts of the vadose zone (Jenkinson et al., 1991; Ryan & Law, 2005).

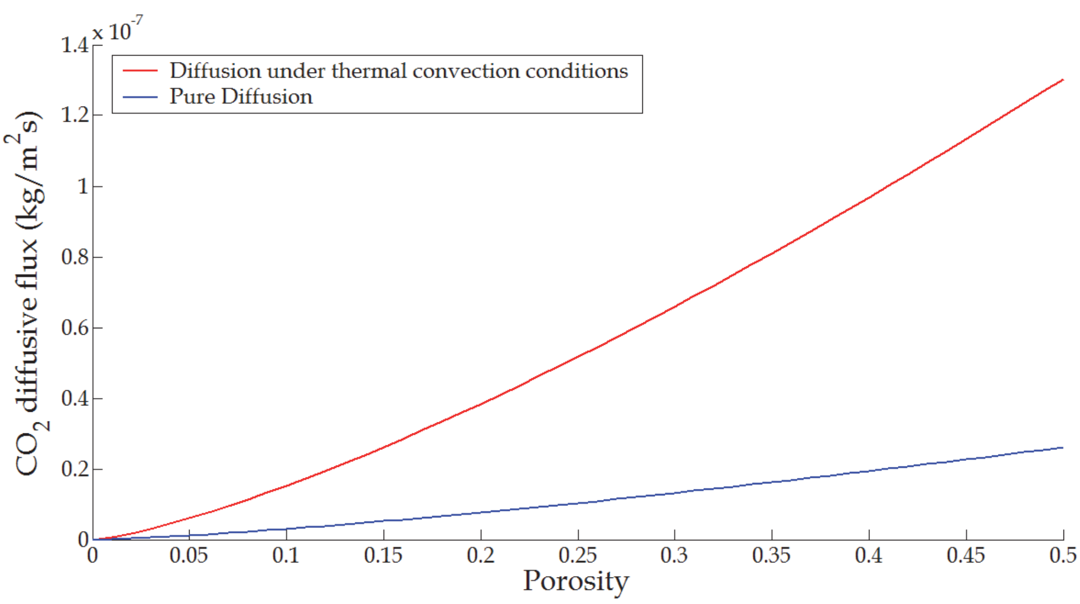

Fig. 9. Calculated diffusive mass fluxes for CO_2 from a point source 1 m deep for fractured-thermal convection conditions (red curve) and unfractured, pure diffusion conditions (blue curve).

Convective venting from cracks and fractures was found to make a marked contribution to vadose zone-atmosphere water vapor flux. Kamai et al. (2009) found that the contribution of nighttime thermal convection to vapor flux from a fractured porous media region, assuming a 1 m fracture spacing, is of similar order of magnitude as the daytime soil evaporative flux observed in field studies (Cahill & Parlange, 1998). Consequently, to ignore this mechanism is to ignore potentially half of the water vapor flux to the atmosphere in regions of cracked soil or fractured rock surface. Salt deposition data also indicate a significant contribution of the thermal convection mechanism for water evaporation. Within a 1 m deep, 2 cm aperture fracture in the arid Negev Desert, Weisbrod & Dragila (2006) calculated an accumulated salt-crust mass corresponding to a vapor venting rate of up to 200 times greater than that which would be predicted by diffusive venting alone. This explains some field observations in the Israeli Negev desert, where enhanced salt-loading inside fractures occurs (Weisbrod et al., 2000). As fractures and cracks are well-known to serve as a bypass for groundwater recharge, enhanced accumulation of evaporates within fractures could pose a risk to groundwater salinization and contamination, especially in arid and semiarid zones with deep vadose zones (Nativ & Nissim, 1992; Scanlon et al., 1997; Weisbrod et al., 2000), hence, advective air fluxes also play a determinant role in groundwater salinization.

In summary, the work presented here demonstrates that advective venting should be incorporated into predictive models in which gas flux across the earth-atmosphere boundary is being considered and quantified. The recently explored ventilation mechanism through thermal convection flows in surface exposed fractures was introduced. It was shown that this mechanism plays an important role in ventilation of fractured porous media. Most likely, it is also very important in other cases where the porous media is contains discontinuities such as karstic systems, shafts, caves, animal burrows etc. It was shown that advective mechanisms can significantly enhance gas flux across this interface. These fluxes, which were briefly mentioned above, have relevance to greenhouse gases migrating into and out of the earth, the water cycle, and soil and groundwater salinization.

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Planet Earth 2011 - Global Warming Challenges and Opportunities for Policy and Practice

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The failure of the UN climate change summit in Copenhagen in December 2009 to effectively reach a global agreement on emission reduction targets, led many within the developing world to view this as a reversal of the Kyoto Protocol and an attempt by the developed nations to shirk out of their responsibility for climate change. The issue of global warming has been at the top of the political agenda for a number of years and has become even more pressing with the rapid industrialization taking place in China and India. This book looks at the effects of climate change throughout different regions of the world and discusses to what extent cleantech and environmental initiatives such as the destruction of fluorinated greenhouse gases, biofuels, and the role of plant breeding and biotechnology. The book concludes with an insight into the socio-religious impact that global warming has, citing Christianity and Islam.