Soil-Atmosphere Gas Transport Processes Created by Soil Cracks

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Overview

The exchange rate of gas between the vadose zone and the atmosphere is, in practice, a transfer process between two reservoirs. The transfer flux is sensitive to boundary conditions existing at interface between the two reservoirs. This work looks at the effects of soil cracks on soil-atmosphere boundary conditions.

Mass transfer mechanisms are driven by either diffusive or advective processes. Diffusive processes are driven by partial pressure gradients in response to atmospheric conditions, and soil thermal, osmotic and matric potentials. Advective processes usually are driven by atmospheric instabilities that produce pressure gradients within the soil profile.

Soil cracks engender gas transfer that is not taken into account by the processes previously mentioned. Cracks are, in essence, a box that holds a cyclical gas transfer engine, exchanging soil and atmospheric gases advectively at night and diffusively during the day. In fact, soil cracks enhance soil-atmosphere exchange, whether it be heat, water vapor or gas.

Mechanism

- Soil thermal gradient causes an unstable air density gradient within soil cracks at night.
- Unstable air density gradient within the crack leads to thermally-driven free-convection. Air within the soil crack is vented and exchanged with atmospheric air.
- Seasonal thermal signature of the upper vadose zone enhances the thermal gradient and significantly increases the transfer rate in **winter**.

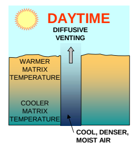
What impact does this mechanism have on soil-atmosphere gas exchange?

- Soil cracks are transient features, generally forming during dry seasons, or in semi-arid settings, or as part of the irrigated agricultural landscape. For soil cracks to form requires specific soil chemical and structural properties (Thomas et al., 2000). Although very common, these features are regionally limited, and thus their impact on atmospheric gas exchange will be equally regionally unique.
- Convective venting of soil cracks enhances evaporation of the soil profile, and increases the exchange of soil moisture and soil air between atmospheric and soil reservoirs.
- Vapor transport:
  - Cracks vent mostly at night, increasing **nighttime** evaporation of the soil profile and have relatively little impact on daytime evaporation.
  - Seasonal variability in vadose zone thermal profile causes much higher vapor transport in **winter**.
- Gas Exchange:
  - Crack venting has a stronger impact on nighttime soil inhalation of atmospheric gases, and a lesser impact on daytime exhalation.
  - Seasonal variability in vadose zone thermal profile result in higher contribution from cracks during **summer**.

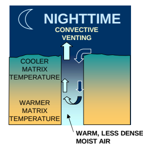
Mechanism Details

Convective instability

- Air movement within a fracture will respond to air density differences.
- At night, soil at depth is warmer than soil near the surface. Density inversion occurs within the fracture with less dense, warm moist air resting below more dense cool dryer air. The density inversion drives convective overturning of air within the crack, which enhances the exchange of air with the atmosphere.
- During the day, no density inversion forms and movement within the soil crack occurs by diffusion.



Daytime: Vapor diffusion rate controls gas motion



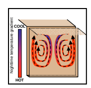
Nighttime: Convection rate controls gas motion

Triggering the instability

Rayleigh-Bernard Instability

Requires: vertical unstable density gradient within the fracture.

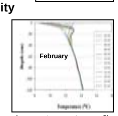
Pattern: Convection cell



Condition for instability

Rayleigh number > 4π

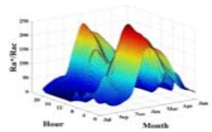
$$Ra_c = \frac{g\beta\,\rho\Delta TkL}{\mu\alpha} > 4\pi$$



Average temperature profile (rock, Negev desert, Israel)

When will a fracture vent?

Convection (Ra/Rac > 1) is expected to occur at night and more prevalent in winter than summer.

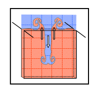


Monthly averages of Ra/Rac, shown hourly for 7/2004-6/2005

Rayleigh-Taylor Instability:

Requires: Sharp air-density contrast at the fracture-atmosphere interface.

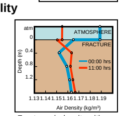
Pattern: invasive finger



Condition for instability

Atwood number > 1

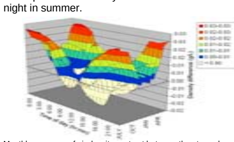
$$A = \frac{\rho_a - \rho_f}{\rho_a + \rho_f} > 1$$



Fracture air density with depth (Negev desert, Israel)

When will a fracture vent?

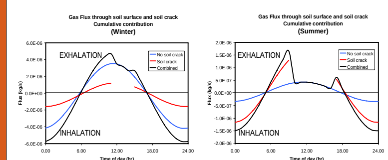
Unstable conditions (red) indicate when atmospheric air is likely to enter the fracture: at night in summer.



Monthly averages of air density contrast between the atmosphere and fracture air, shown hourly for 7/2004-6/2005

Impact on gas transport

- Cracks effectively extend the reach of the atmosphere into the vadose zone.
- Convective air motion whisks away gas diffusing from the deep soil into the crack, and brings atmospheric air deep into the vadose zone.
- Cracks enhance both exhalation (transfer from soil to atmosphere; positive values on graph) and inhalation (transfer from atmosphere to soil; negative values on graph).
- Results of numerical model to assess contribution of crack convection to atmospheric gas exchange are shown (graphs) for a mid-summer and mid-winter day.
- Winter:
  - During nighttime, cracks convect and enhance inhalation by ~50%.
  - During daytime, cracks enhance exhalation by ~50%, except near noon when air convection in cracks is quiescent.
- Summer:
  - The role of cracks in summer is more significant, enhancing exhalation and inhalation processes by 2-4 times over diffusion through the soil surface.



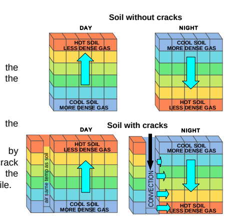
Conceptual model

Daytime:

- Gas diffuses upward through the profile, and upward through the soil crack.

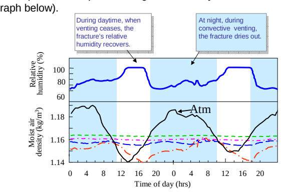
Nighttime:

- Atmospheric air diffuses into the soil through the soil surface.
- Atmospheric air is carried by convection deep into the soil crack and is able to diffuse into the deeper portions of the soil profile.



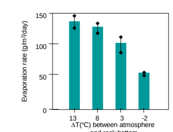
Impact on vapor transport

- Convective motion removes from the crack warm moist air and entrains cool, dry atmospheric air, significantly enhancing evaporation, by up to two orders of magnitude compared to diffusive losses through the crack.
- Diurnal pattern of vapor exchange is shown by the relative humidity data (graph below).

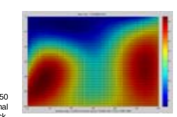


Relative humidity and air density data in a rock fracture, Negev Desert, Israel. Air density values within fracture (colored dashed lines) taken at 10, 40, 80 and 120 cm depth, and atmosphere (black line). Relative humidity (RH) data shows that as soon as density inversion occurs (1800 hrs: $\rho_{ATM} < \rho_{FRAC}$), convection is initiated and the fracture begins to dry out. Field data.

- Evaporation from a fracture strongly depends upon thermal gradient between atmosphere and deep vadose zone (graph below).



Evaporation from a fractured rock (chalk) under 50 cm of tension for different imposed thermal gradients, between atmosphere and bottom of rock. Laboratory data from Kamai et al., 2009.



Typical convective pattern within a fracture. Data shows temperature profile at midnight within a vertical crack 60 cm x 60 cm. Field data from Weisbrod et al., 2009.

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Acknowledgements

This material is based upon work supported by the National Science Foundation under Grant No. 0208384 and 0510825, and the Israeli Science Foundation 70/06.