Water vapour transport in a soil column in the presence of an osmotic gradient

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ABSTRACT

In arid and semi-arid regions because of water access and soil salinity problems extending of agriculture to a new area has been faced with restriction. Knowledge of the transport process of moisture and energy in subsurface soil is vital to understanding the environmental and economic impact of agricultural practices in these areas. This study was conducted to: (a) assess the relative importance of water vapour movement under moisture, temperature and osmotic gradients on moisture and energy budget in the presence of salts, (b) evaluate the temperature differential method to estimate evaporation in 30 minute interval. The experiment was conducted in a sandy soil column that was buried in the field and irrigated with a pore volume of 50 g/L NaCl solution. Three reference air-dried sandy soil cylinders were buried beside the column. Water content, temperature and electrical conductivity of soil water in depths of 1, 5 and 10 cm of the column as well as surface temperature of soil column and air-dried soil cylinders; and temperature of 5 cm depth in air-dried cylinders were monitored. The result showed that nearly 96% of vapour transfer was due to temperature gradient. Although the osmotic effect on vapour movement was less than 3%, nevertheless still was more than moisture gradient effect in current work. The contribution of the water vapour flux to the total moisture flux was 5%. The heat transported by vapour flux was significant and accounted for 45% of total heat flux in 1–5 cm depth and up to 30% at 5–10 cm depth. The observed difference between estimated cumulative evaporations using the differential method and energy balance equation was less than 5%.

1. Introduction

In arid and semi-arid regions, due to deficit of water sources and problems of access to it, extending of agriculture to new area have been faced with restriction. Moreover, soil salinity problems increased this calamity too. Saline soils occur naturally in arid and semiarid regions, and consist up to 48% of farmland in the world (Noborio et al., 1996a, 1996b). As more land is exposed to irrigation, the salinity problem expands. Water vapour transport can occur in unsaturated soils when differing solute concentrations exist across a gas-filled pores separating soil solution (Nobel, 1983). The first effort to evaluate osmotic effect on soil moisture movement was carried by Wheeting (1925), where salts were added to the column of unsaturated soil, demonstrating the significant water movement from the unsaturated salt free soil toward unsaturated salinized soil. The gradient in osmotic pressure can induce significant flow of water in these soils under conditions of high solute concentrations and low water content. This has been verified by several researchers (Scotter and Raats, 1970; Scotter, 1974; Nassar and Horton, 1989; Nassar et al., 1992b; Kelly et al., 1997; Kelly, 1998; Kelly and Selker, 2001; Fujimaki et al., 2002). The importance of soil moisture and heat, has resulted in a very large number of numerical models, which simulate water transport in both liquid and vapour phases within the uppermost soil layer. Various authors have examined the significance and magnitude of the water vapour flux as it affects either the mass or energy balances in experimental studies. One of the first field-scale tests of the coupled effects of soil heat and moisture transport was done by Rose (1968a, 1968b). Several studies reported that there is a significant effect of vapour movement on soil mass and energy budget (Antonopoulos, 2006; Bittelli et al., 2008; Novak, 2010; Zhang, 2012; Mahdavi et al., 2017). These are based on theories that describe the coupled flow of energy and mass (Mahdavi et al., 2016; Shein et al., 2009; Shein and Troshina, 2012), but few evidence points to couple transfer of heat and moisture in subsurface unsaturated salty soils. (Noborio et al., 1996a; Noborio et al., 1996b; Kelly and Selker, 2001). Estimation of evaporation from bare soil has been explored by many authors (Brutsaert and Chen, 1995; Ventura et al., 2001; Bittelli et al.,

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2008). Theoretical questions regarding parameter estimations are not completely solved; one example is the estimation of the aerodynamic resistance. Qiu et al. (1999) proposed temperature differential method to estimate evaporation from the soil surface that eliminated the challenge of calculating aerodynamic resistance. In their experiment they used mean daily temperatures of soil and air; and ignored the monitored values after sunset. Also, they did not apply this method in term of salinity resistance which can usually affect evaporation in arid and semi-arid saline soils. This study was focused in two major steps. First, the relative importance of vapour movement and its involvement components on moisture and energy budget in salty column will be evaluated by deriving equations. Second, we evaluated estimation of the evaporation amount by a differential method in 30 minute interval with respect to soil salinity resistance during the experiment.

2. Theoretical consideration

2.1. Energy equation

The transport of heat in soils based on Fourier's law described as

$$C\frac{\partial T}{\partial t} = -\frac{\partial q_h}{\partial z} = -\frac{\partial G}{\partial z} - L\,S_e = -\frac{\partial}{\partial z}\left(k_h\frac{\partial T}{\partial z}\right) - L\frac{\partial q_v}{\partial z} \tag{1}$$

where C is the heat capacity of the soil ($W/cm^3\,K$), T is the temperature (K), t is time (s), q_h heat flux density (W/cm^2), z is the depth below the soil surface (cm), G is the convective heat flux density (W/cm^2), L is the latent heat of vaporization (2.45×10^3 J/g), S_e is the vapour flux per unit of soil depth, k_h is the thermal conductivity ($W/cm\cdot K$), q_v is the water vapour flux ($g/cm^2\cdot s$).

2.2. Mass equation

The one-dimensional mass equation for liquid water and water vapour within the soil is described as

$$\frac{\partial\theta}{\partial t} = -\frac{\partial q_m}{\partial z} = -\frac{\partial q_l}{\partial z} - \frac{1}{\rho_w}\frac{\partial q_v}{\partial z} \tag{2}$$

where ρ_w is the water density (g/cm^3), θ is the volumetric water content (cm^3/cm^3), q_m is the total moisture flux, which is simply equal to the sum of the liquid and vapour flux (de Vries and Peck, 1958). q_l is the liquid water flux (cm/s).

The liquid water flux is defined as

$$q_l = -D\theta_l\,\nabla\theta - D_{Tl}\,\nabla T - K \tag{3}$$

where $D\theta_l$ is the isothermal liquid diffusivity (cm^2/s), D_{Tl} is the thermal liquid diffusivity ($cm^2/s\cdot K$) and K is the hydraulic conductivity (cm/s) (Philip and de Vries, 1957). The isothermal liquid diffusivity is

$$D_\theta = K\frac{\partial\psi_m}{\partial\theta} \tag{4a}$$

where ψ_m is the matric potential (cm). The thermal liquid diffusivity arises from the flux because of changes in surface tension driven by changes in temperature

$$D_{Tl} = K\,\gamma\psi_m \tag{4b}$$

where $\gamma(\frac{1}{\sigma}\frac{d\sigma}{dT})$ is the relative change in surface tension σ with respect to temperature.

The relationship between soil hydraulic conductivity (K), and viscosity of soil solution can be expressed as

$$K = \frac{\mu_0}{\mu}K_0 \tag{5}$$

where μ is the viscosity of the soil solution, ($g/cm^2\cdot s$), while the subscript 0 indicate reference values. In this study, we did consider the dependence of μ on solute concentration. The value of K may also depend on the exchangeable sodium percentage (ESP) and salinity (Hillel,

1998). Since we used a coarse-textured soil, we neglected the dependence of the hydraulic conductivity on ESP and salinity.

The theory of vapour movement in isothermal condition is described as follows (Jackson, 1964):

$$q_v = -K_v\,\nabla P_v \tag{6a}$$

where K_v is the first order transport coefficient for vapour flow (cm/s), P_v is the vapour pressure (g/cm^2). The defined equation for vapour flux based on Fickian diffusion and isothermal term can be expressed as (Philip and de Vries, 1957).

$$q_v = -D_a\,\nu\,\alpha\,\varphi_g\,\nabla\rho_v \tag{6b}$$

where D_a is the molecular diffusivity of water vapour in air (cm^2/s), ν is a mass-flow factor taken to be unity, α is the volumetric air content of the medium (cm^3/cm^3), φ_g is a tortuosity factor.

The isothermal vapour transport coefficient is driven from the Eqs. (6a) and (6b) as

$$K_v = D_a\,\nu\,\alpha\,\varphi g\frac{d\rho_v}{dP_v} \tag{7}$$

The relationship between vapour pressure and vapour density is

$$P_v = \frac{\rho_v\,R\,T}{M_w g} \tag{8}$$

where R is the universal gas constant 8.314×10^7 (erg/mol·K), M_w is the molecular weight of water 18 (g/mol) and g is the acceleration due to gravity 980 (cm/s^2). Hence, the vapour transport coefficient can be rewritten as

$$K_v = D_a\,\nu a\alpha\,(M_w g/RT) \tag{9}$$

The vapour pressure gradient is defined as

$$\nabla P_v = h\,\nabla P_0 + P_0\,\nabla h \tag{10}$$

where P_0 is the saturated vapour pressure, h is the relative humidity with the respect to following relationship (Edlefsen and Anderson, 1943):

$$h = \exp\left(\frac{\psi_t\,M_w\,g}{R\,T}\right) \tag{11}$$

where ψ_t is equal $\psi_{m}+\psi_s$, (cm), and ψ_s is the osmotic potential because of solutes (cm). Regarding non-isothermal condition the first right part of Eq. (10), can be derived as

$$h\,\nabla P_0 = h\frac{dP_0}{dT}\,\nabla T \tag{12}$$

where $\frac{dP_0}{dT}$ is the slope of saturation vapour pressure curve an temperature T. Using the equation of Buck (1981) for the saturation vapour pressure at temperature T.

$$\frac{dP_0}{dT} = \frac{1}{100\,g} \times \frac{4098}{(T+237.3)^2} \times \left(0.611\exp\left(\frac{17.27T}{T+237.3}\right)\right) \tag{13}$$

The second right part of Eq. (10) is rewritten as

$$P_0\,\nabla h = P_0\frac{dh}{d\theta}\,\nabla\theta \tag{14}$$

The term, $\frac{dh}{d\theta}$, can also be defined from the following equation:

$$\frac{dh}{d\theta} = \frac{dh}{d\psi_t}\frac{d\psi_t}{d\theta} \tag{15}$$

The first right part of Eq. (15) is derived as follows:

$$\frac{dh}{d\psi_t} = \frac{h\,M_w\,g}{R\,T} \tag{16a}$$

The second right part of Eq. (15) can be rewritten as