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The Relative Importance of Water Vapor Flux from the Perspective of Heat and Mass Movement

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ABSTRACT

Water movement is normally modelled in the soil to quantify spatial and temporal soil moisture distribution. This is important given that soil moisture indicates the amount of water available to plant consumption and also imply the necessity of water sourcing, storage and distribution system to maintain agricultural activities. Modelling soil moisture content in soil is often limited to water mass flux in the mass balance equation. A limited account is given to water vapor contribution to mass flux. Adding to the complexity, the liquid water, and water vapor mass fluxes are influenced by soil heat flux. In this study, five mechanisms driving overall mass fluxes, and seven mechanisms driving overall heat fluxes were quantified based on the published experimental data from Heitman and his co-workers. The study was carried out on silt loam and sandy soil in a drier soil condition at 0.1 and 0.08 $m^3 \cdot m^{-3}$, respectively. The relative comparison between the mechanisms and the soil types clearly shows that water vapor mass flux dominates in the overall mass fluxes, while water vapor heat flux repeatedly ranked second the most important among the seven mechanisms quantified on overall heat fluxes in which there were only three water vapor-heat flux mechanisms exist, the rest four mechanisms are from liquid water-heat flux. Clearly, water vapor flux is a necessary inclusion in heat and mass movement estimation.

1. Introduction

Water movement in soil is modeled by Richards' equation [1]. The equation is based on the principle of a water pressure gradient to guide the flux of water in the soil. The water moves from low to high suction regions. In addition, the liquid water vaporizes to form a gas phase known as water vapor. The density in the vapor phase is in equilibrium with the amount of water present in the liquid phase. The variation of soil temperature in response to incoming sunlight affects the fluxes of liquid water and water vapor in the soil. The energy balance equation governs the heat and predicts the variation of temperature in the soil, while the mass balance equation controls the mass movement and predicts the distribution of soil moisture content in the soil. Solving the mass and

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energy conservation equations simultaneously determines the distribution of soil temperature and soil moisture content, at a given time [2].

Diffusion equation models the water flux in the soil [3]. Under water infiltration conditions in the vertical direction, gravitational pull is adding additional flux to the water movement [4,5]. In the presence of heat flux in or out of the soil, the temperature gradient adds additional term into the mass flux equation [6]. In the gas phase, diffusion equation models the mass movement of water vapor in the soil [7]. Like liquid water, the water vapor moves by temperature gradient. Stationary soil particles, the air in pore space, and water in pore space transfer heat by conduction [8]. A vaporizing liquid phase absorbed a large amount of heat to transform from liquid water to water vapor carries with it a substantial amount of heat in the vapor phase. Furthermore, the water in the liquid and gas phase transport a sensible amount of heat as they moved in the form of liquid water and water vapor, respectively.

Philip and de Vries [9] introduced the mass transport equation with vapor enhancement factor as a multiplier on the temperature gradient-causing vapor flux term. Since then, multiple attempts have been made to uncover the mechanism involved in enhancing the water vapor flux under temperature gradient environments. One of the most noticeable attempts came from Cass *et al*., [10] that found the factor as multiple times the value of vapor flux under temperature gradient conditions, determined using the heat flux density equation by de Vries [8]. Until recently, the work by Lu et al. [11] again reaffirmed the presence of the unknown phenomenon. Multiple hypotheses have been proposed such as air volume expansion-contraction [12], water vapor volume expansion resulting advection due to temperature gradient [13], and the original hypothesis by Philip and de Vries states that (1) liquid island present in the soil pores shorten the flow path by condensation at one site and evaporation at the other side, and (2) the soil temperature gradient used in the calculation of water vapor heat flux is under reporting because in reality a greater air temperature gradient value should be used in the calculation.

Even the highly sought-after phenomenon of vapor enhancement factor remained unknown, the mass and heat transport equations have been widely used in many applications such as a couple with solute transport mechanism [14], coupled with crop growth model [15], and coupled with soil deformation [16]. There is even a simplification toward using only Richards' equation without the vapor flux [17], and also, a report from Mahdavi *et al*., [18] states the contribution of soil vapor flux is around one percent of total soil moisture flux. However, the work of Wang *et al*., [19] has demonstrated the need of including vapor mechanisms to improve their model prediction.

Vapor flux is a subset of overall mass flux, however, the range at which vapor flux is significant is not clearly understood, especially under dry soil region. The current study intends to quantify the individual mechanisms describing mass flux and heat flux, and compare their relative importance, using the experimental dataset from Heitman *et al*., [6]. Hence, the objectives of the work are: (1) quantify and compare the mechanisms governing mass flux, and (2) quantify and compare the mechanisms governing heat flux. This work would justify the importance of estimating vapor flux in dry regions.

2. Methodology

2.1 Experimental dataset

The experimental dataset used in the investigation came from the work of Heitman *et al*., [6]. Their work investigates the effects of temperature gradient and the average temperature on the soil moisture content and temperature distribution in a vertical soil column that was carried out on silt loam and sand. Their work did provide the data points for the temperature and soil moisture content distribution and the characteristic curve parameters which allow estimation of the soil hydraulic properties. Parameters needed to estimate heat flux mechanisms were also given.

2.2 Mechanisms driving mass flux

Liquid water flux mechanisms are described by the following terms,

$$\frac{q_L}{\rho_L} = -D_{TL}\frac{dT}{dz} - K\frac{d\psi_m}{dz} - Ki \tag{1}$$

where $\frac{q_L}{\rho_L}$ represents the soil liquid water mass flux ($kg \cdot m^{-2} \cdot s^{-1}$) in a unit liquid water density ($kg \cdot m^{-3}$), $-D_{TL}\frac{dT}{dz}$ is the spatial temperature difference driving liquid water flux ($m \cdot s^{-1}$), $-K\frac{d\psi_m}{dz}$ is the spatial pressure suction difference in soil that creates liquid water flux ($m \cdot s^{-1}$), and $-Ki$ is the effect of gravitational pull causing liquid water flux vertically.

Water vapor flux mechanisms are represented by the following equation,

$$\frac{q_v}{\rho_L} = -D_{Tv}\frac{dT}{dz} - D_{mv}\frac{d\psi_m}{dz} \tag{2}$$

where $\frac{q_v}{\rho_L}$ is the soil water vapor mass flux ($kg \cdot m^{-2} \cdot s^{-1}$) in a unit liquid water density ($kg \cdot m^{-3}$), $-D_{Tv}\frac{dT}{dz}$ is the temperature gradient causing water vapor flux ($m \cdot s^{-1}$), $-D_{mv}\frac{d\psi_m}{dz}$ is the water vapor flux resulting from pressure suction gradient ($m \cdot s^{-1}$).

2.3 Mechanisms driving heat flux

Mechanisms driving heat flux in the soil are given by,

$$\begin{aligned} q_h = &-\left\{\lambda + c_v\left(T-T_o\right)\rho_L C_{Tv} + c_v\left(T-T_o\right)\rho_L D_{Tv}^{'} + c_L\left(T-T_o\right)\rho_L D_{TL}\right\}\frac{dT}{dz} \\ &-\left\{\left[L(T) + c_L\left(T-T_o\right)\right]\rho_L D_{mv} + c_L\left(T-T_o\right)\rho_L K\right\}\frac{d\psi_m}{dz} \\ &-c_L\left(T-T_o\right)\rho_L Ki \end{aligned} \tag{3}$$

where q_h is total heat flux ($J \cdot m^{-2} \cdot s^{-1}$), $-\lambda\frac{dT}{dz}$ is heat conduction ($J \cdot m^{-2} \cdot s^{-1}$), $-c_v\left(T-T_o\right)\rho_L C_{Tv}\frac{dT}{dz}$ is heat flux by vapor enhancement factor when water vapor moves under temperature gradient condition ($J \cdot m^{-2} \cdot s^{-1}$), $-c_v\left(T-T_o\right)\rho_L D_{Tv}^{'}\frac{dT}{dz}$ is heat flux by water vapor movement under temperature gradient ($J \cdot m^{-2} \cdot s^{-1}$), $-c_L\left(T-T_o\right)\rho_L D_{TL}\frac{dT}{dz}$ is heat flux by liquid water movement under temperature gradient ($J \cdot m^{-2} \cdot s^{-1}$), $-\left[L(T) + c_L\left(T-T_o\right)\right]\rho_L D_{mv}\frac{d\psi_m}{dz}$ is heat flux by water vapor movement under matric suction gradient ($J \cdot m^{-2} \cdot s^{-1}$), $-c_L\left(T-T_o\right)\rho_L K\frac{d\psi_m}{dz}$ is heat flux by liquid water movement under matric suction gradient

($J \cdot m^{-2} \cdot s^{-1}$), and $-c_L(T-T_o)\rho_L Ki$ is the heat flux by liquid water movement due to gravitational pull ($J \cdot m^{-2} \cdot s^{-1}$).

3. Results and Discussion

3.1 Soil Temperature Gradient and Soil Moisture Content Distribution

In this study, the experimental data from Heitman *et al*., [6] were used. Three average temperatures, 15, 22.5 and 30 °C, were used to reflect different ambient temperatures. Also, the temperature gradients, -50 and -150 °C/m, were used to reflect the steepness of the temperature imposed on the soil column. Figure 1 shows the reported temperature distribution in the soil column. Figure 2 shows the imposed average temperature and temperature gradient results in redistribution of soil moisture content on silt loam that a greater water amount accumulates on the cold side than on the hot side. Expectedly, a greater average temperature and temperature gradient, i.e. 30/-150, results in greater water accumulation at the cold side of the column than that of lower temperature, i.e. 15/-50 and 22.5/-150. A similar observation could be seen on sandy soil, just that the soil moisture content would be linearly increased with soil depth than that exponential observed on the silt loam.

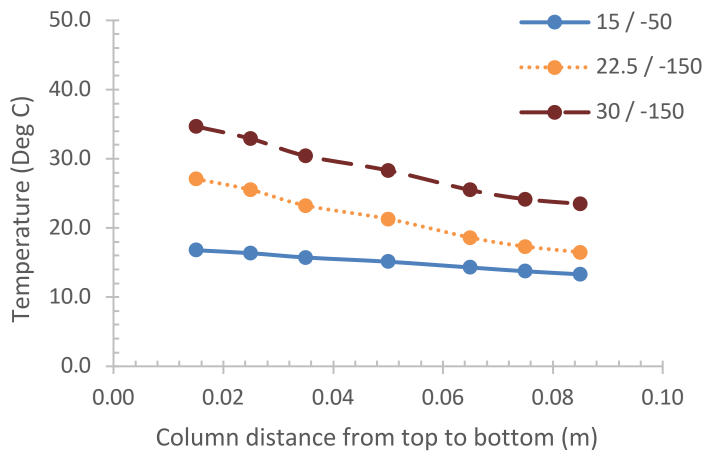


Fig. 1. The temperature gradient imposed on 10 cm vertical soil column. The boundary temperature for each temperature gradient was kept at constant for 96 hours until steady state could be assumed. The soils were silt loam (0.1 $m^3 \cdot m^{-3}$) and sand (0.08 $m^3 \cdot m^{-3}$). Note: 15/-50 refers to 15 deg C as average soil column temperature and -50 °C/m = (17.5 °C - 12.5 °C)/(0 m - 0.1 m). Also, at 22.5 deg C average temperature, the -150°C/m = (30 °C - 15 °C)/(0 m - 0.1 m), while at 30 deg C average temperature, the -150 °C/m = (37.5 °C - 22.5 °C)/(0 m - 0.1 m).

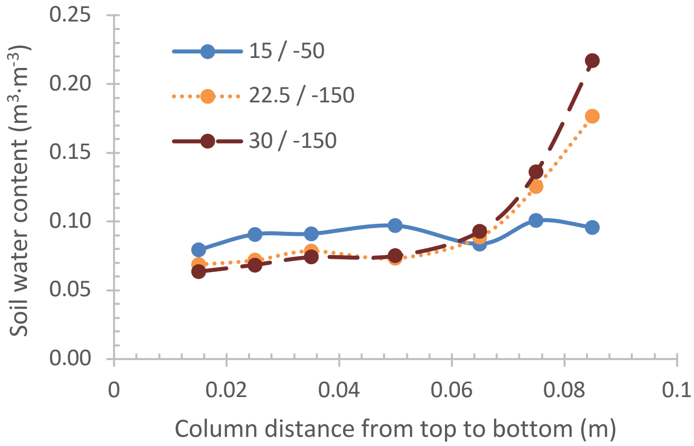


Fig. 2. The soil moisture content distribution in the soil column (silt loam, 0.1 $m^3 \cdot m^{-3}$) at different average temperatures and temperature gradients. Note: 15/-50 refers to 15 deg C as average soil column temperature and -50 °C/m = (17.5 °C - 12.5 °C)/(0 m - 0.1 m). Also, at 22.5 deg C average temperature, the -150°C/m = (30 °C - 15 °C)/(0 m - 0.1 m), while at 30 deg C average temperature, the -150 °C/m = (37.5 °C - 22.5 °C)/(0 m - 0.1 m).

3.2 Water Vapor Heat Flux Mechanisms in Comparison to Others

Figure 3 shows that the higher average temperature and temperature gradient results in greater heat flux under a temperature gradient, and matric suction gradient than the heat flux under the unfluence of gravity. The negative heat flux demonstrated by matric suction gradient indicates heat flux in the opposite direction of that of heat flux by a temperature gradient, as observed in Figures 3(a) and 3(b). The heat flux by gravity appears relatively low compared to the other two mechanisms. The temperature gradient and matric suction gradient terms each are presented by a few mechanisms.

Figures 4(a) show the heat flux in silt loam was dominated by heat conduction. Followed by heat flux by vapor flux under matric suction gradient, the vapor enhancement factor, and the temperature gradient. Then only the heat flux by liquid water flux under matric suction gradient, temperature gradient, and gravity. In sand soil, Figure 4(b), heat flux by water vapor flux was observed in domination after heat conduction. The vapor flux resulting in heat flux by matric suction gradient appeared to be less dominant, which could be due to a lower isothermal vapor diffusivity (D_{mv}) than that of silt loam. The gravity-driven heat flux appeared high and close to the liquid flux-heat flux by temperature gradient. The higher gravitational flow of water in sand than silt loam could imply a greater hydraulic conductivity (K) and lower suction pressure of sand particles. Overall, the vapor flux resulting in heat flux is important when compared to other mechanisms in relatively dry soils.

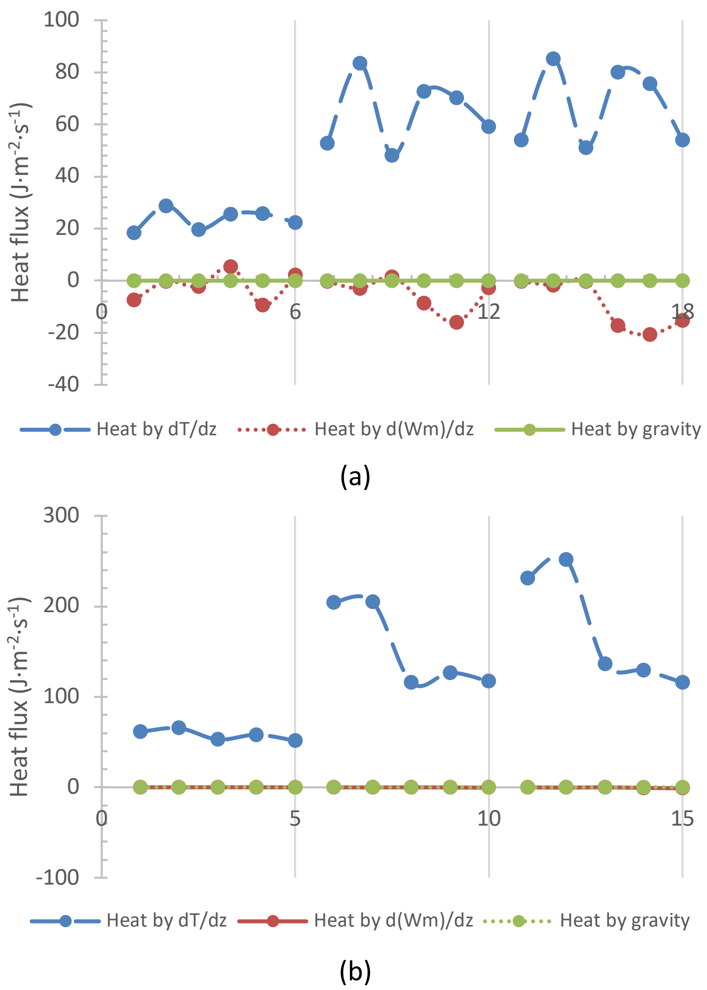
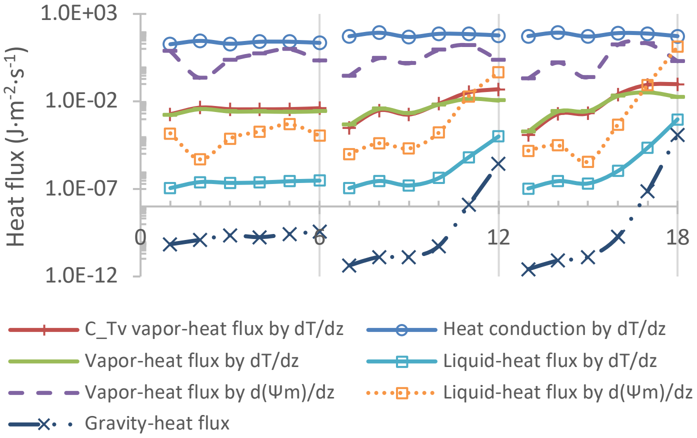


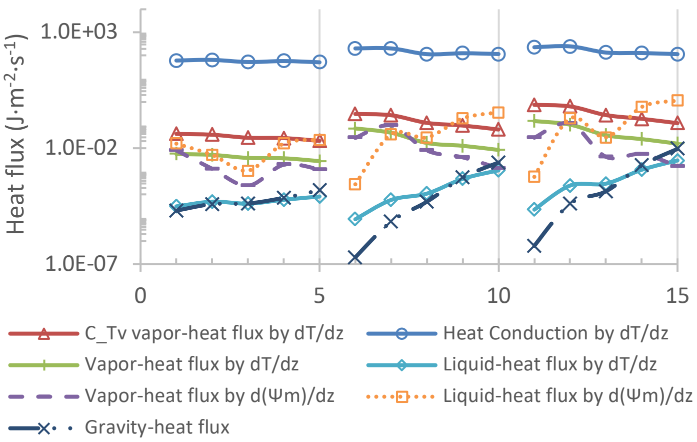
Fig. 3. Soil heat flux is given by temperature gradient, matric suction, and gravity corresponding to the right side of Eq. 3 first, second, and third terms. (a) silt loam at 0.1 $m^3 \cdot m^{-3}$, and (b) sand at 0.08 $m^3 \cdot m^{-3}$. Note: (a) on the x-axis, 1-6 refers to data points from near column top to near column bottom for 15/-50, while 7-12 refers to 22.5/-150, and 13-18 refers to 30/-150. (b) 1-5, 6-10, 11-15 for 15/-50, 22.5/-150, 30/-150, respectively.

3.3 Water Vapor Mass Flux Mechanisms in Comparison to Others

In silt loam, water vapor mass flux by matric suction gradient tops the list of mechanisms. Water vapor mass flux by temperature gradient second, as shown in Figure 5(a). As expected, liquid water mass flux by gravity bottom in the graph was the least important mechanism. Above gravity is the liquid water mass flux by matric suction gradient and temperature gradient. In sandy soil, Figure 5(b), water vapor mass flux remained the dominant mechanism among others. However, the vapor mass flux by matric suction gradient becomes less significant which could be due to the low isothermal vapor diffusivity (D_{mv}) in the dry region of sandy soil. The gravity-driven mass flux remained insignificant, and the temperature gradient resulting in liquid water mass flux appears relatively comparable to the flux of gravity. The liquid water mass flux by matric suction gradient maintained its importance came after the water vapor mass flux by temperature gradient. Overall, water vapor mass flux dominates in both silt loam and sandy soils.

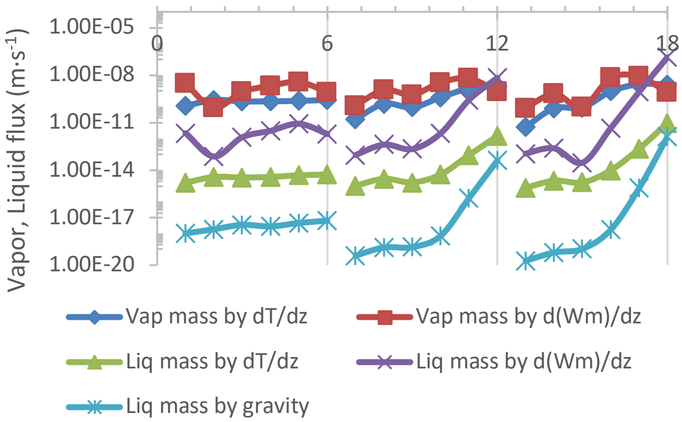


(a)

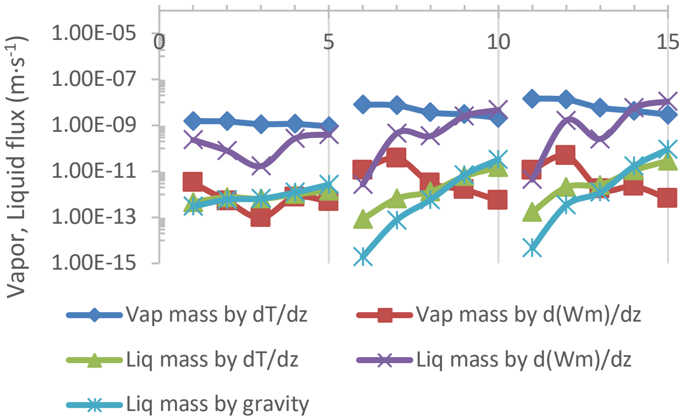


(b)

Fig. 4. The soils are (a) silt loam at 0.1 $m^3 \cdot m^{-3}$ and (b) sand at 0.08 $m^3 \cdot m^{-3}$. Soil heat flux, Eq. 3, given by vapor flux in vapor enhancement factor, temperature gradient, matric suction gradient terms correspond to the $-c_v\left(T-T_o\right)\rho_L C_{Tv}\dfrac{dT}{dz}$, $-c_v\left(T-T_o\right)\rho_L D'_{Tv}\dfrac{dT}{dz}$, $-\left[L\left(T\right)+c_L\left(T-T_o\right)\right]\rho_L D_{mv}\dfrac{d\psi_m}{dz}$. The soil heat flux by pure heat conduction is represented by $-\lambda\dfrac{dT}{dz}$. The soil heat flux by liquid flux in a temperature gradient, matric suction gradient, and gravity terms are $-c_L\left(T-T_o\right)\rho_L D_{TL}\dfrac{dT}{dz}$, $-c_L\left(T-T_o\right)\rho_L K\dfrac{d\psi_m}{dz}$, $-c_L\left(T-T_o\right)\rho_L Ki$, respectively. Note: on the x-axis, 1-6 refers to data points from near column top to near column bottom for 15/-50, while 7-12 refers to 22.5/-150, and 13-18 refers to 30/-150. (b) 1-5, 6-10, 11-15 for 15/-50, 22.5/-150, 30/-150, respectively.



(a)



(b)

Fig. 5. The soils are (a) silt loam at 0.1 $m^3 \cdot m^{-3}$ and (b) sand at 0.08 $m^3 \cdot m^{-3}$. Soil mass flux, Eq. 2, water vapor mass flux driven by temperature gradient and matric suction correspond to $-D_{Tv}\frac{dT}{dz}$ and $-D_{mv}\frac{d\psi_m}{dz}$. Soil mass flux, Eq. 1, liquid water mass flux due to temperature gradient, matric suction gradient, and gravity are $-D_{TL}\frac{dT}{dz}$, $-K\frac{d\psi_m}{dz}$, and $-Ki$, respectively.

Note: on the x-axis, 1-6 refers to data points from near column top to near column bottom for 15/-50, while 7-12 refers to 22.5/-150, and 13-18 refers to 30/-150. (b) 1-5, 6-10, 11-15 for 15/-50, 22.5/-150, 30/-150, respectively.

4. Conclusions

The experimental data from Heitman *et al.*, [6] that studied on silt loam and sandy soils in soil column imposed with temperature gradient resulted in redistribution of soil moisture distribution allowed estimation of heat and mass fluxes in steady state. From the seven mechanisms driving heat fluxes in the soil, three of the mechanisms were from water vapor flux driving heat flux. The water vapor resulting in heat flux appears relatively important after heat conduction. In mass flux, from the five mechanisms, two mechanisms were from water vapor flux resulting in mass flux. Water vapor mass flux dominates the overall mass flux for both silt loam and sandy soils. Hence, this study concludes that in the dry soil regions, silt loam (0.1 $m^3 \cdot m^{-3}$) and sand (0.08 $m^3 \cdot m^{-3}$), the water vapor flux is an important mechanism for inclusion in the mass and heat budget estimation.

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