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Comment on "A simulation analysis of the advective effect on evaporation using a two-phase heat and mass flow model" by Yijian Zeng, Zhongbo Su, Li Wan, and Jun Wen

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1. Introduction

[1] *Zeng et al*. [2011a] (hereafter referred to as Z11) recently proposed a Representative Elementary Volume (REV) scale two-phase heat and mass flow model and then used the developed model to investigate the usually ignored advective airflow effect on soil evaporation. The proposed model, consisting of balance equations of water (liquid and vapor), dry air, and heat, together with corresponding constitutive equations, is developed mainly on the basis of *Thomas and Sansom*'s [1995] model by additionally accounting for thermal liquid film flow [*Kay and Groenevelt*, 1974; *Milly*, 1982], water vapor dispersion [Z11], dry air diffusion and dispersion [Z11], and heat of wetting [*de Vries*, 1958; *Milly*, 1982]. Subsequently, the model was calibrated using the field measured soil temperature and soil moisture content collected from the Badain Jaran Desert, representing an extremely dry climate condition. The simulated soil temperature agreed reasonably well with the measured soil temperature at five depths (Z11, Figure 2), however, this is not the case for soil water content, particularly at depths of 20, 30, and 40 cm (Z11, Figure 3). Z11 ascribed the mismatch between simulated and measured soil water content to two possible reasons: one is the likely incorrect assumption of homogeneous soil hydraulic parameters along the 5 m simulation soil profile, the other is the possible low sensitivity of soil moisture sensor in measuring water content in extraordinarily dry environment. While we agree with the above two possible explanations, however, to our knowledge, other mechanisms such as adsorption component of the soil water retention which was ignored in Z11 could also be responsible for the mismatch between simulated and measured soil water content in desert soils (discussed later in section 4.1). Z11 then used the calibrated model to study advective airflow effect on evaporation in both low and high permeability soils and found that neglecting soil airflow could result in an underestimation of evaporation by 8.85% and 6.4% in low and high permeability soils, respectively, during the 6 day period. This underestimation error was more significant on the day right after a precipitation event (Z11, Figure 4) because the fine sand was moderately dry (not very dry) after this small rainfall event which occurred at the end of the first day. After systematically analyzing driving forces (soil air pressure gradient, soil matric potential gradient, and soil temperature gradient) and conductivity fields (mainly thermal and isothermal hydraulic conductivity), Z11 concluded that the underestimation error of evaporation was mainly caused by underestimation of isothermal hydraulic conductivity (which we agree with) by neglecting airflow (which we doubt). We commend Z11 for creatively investigating this often neglected advective airflow effect on soil evaporation and finding such insightful phenomena, however, it seems to us that the advective vapor flux on increasing isothermal hydraulic conductivity (hereafter denoted as K_{Lh}) is overestimated in Z11 analysis. In addition, the negligence of rainfall influence on discussing advective airflow effect and the neglect of extending the water retention function and K_{Lh} to oven-dry condition is unwarranted.

2. Advective Flux on Increasing Isothermal Hydraulic Conductivity is Overestimated

2.1. Conductivity Normalized Scale Index Should Have "Sign Effect"

[2] When defining normalized scale index (NSI) for conductivity (Z11, equation 21), Z11 claimed that "there is no positive or negative sign before the ratio of $\mathrm{Cond}_{\mathrm{no\_air}}$ to $\mathrm{Cond}_{\mathrm{air}}$ because the conductivity is always positive." In this way, the NSI for conductivity was calculated by ignoring its "sign effect" corresponding to gradient. For instance, in Z11, Figure 7C at hours 0 (midnight) to 8 (early morning), the K_{Lh} with airflow in high permeability soils is very large compared to that without airflow (i.e., the NSI for K_{Lh} is large for this nighttime). However, during this nighttime period, the soil matric potential gradient is downward (Z11, Figure 7A), which means that the isothermal liquid flux (product of soil matric potential gradient and isothermal hydraulic conductivity) is also downward. This indicates that during and after rainfall in the evening, the moisture infiltration and redistribution processes occurred in the soil [*Zeng et al*., 2009]. This is the reason why the

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soil moisture content at 10 cm depth increased during the nighttime, which reflected the response of soil moisture to the precipitation event at the end of day 1 [*Zeng et al.*, 2011b]. At hours 8 (early morning) to 18 (late afternoon), the difference of K_{Lh} between with airflow and no airflow is not very significant and the resulting NSI for K_{Lh} should be relatively small for this daytime. However, during this daytime period, the upward soil matric potential gradient results in upward isothermal liquid flux and based on Z11, a little smaller upward isothermal liquid flux with no airflow causes the corresponding underestimation error of evaporation induced by neglecting airflow during the daytime of the second day. Similar pattern could also be found in low permeability soils (Z11, Figure 9). This indicates that the NSI for K_{Lh} should also be averaged separately during the different time within one day (e.g., day/night) corresponding to the direction of hydraulic gradient. As such, it is physically unclear to obtain the conductivity NSI results in Z11 (i.e., NSI for K_{Lh} is 4.3 and 57.2 in the high and low permeability soils, respectively) via averaging for the whole second day. These calculations result in Z11 overestimated the advective airflow effect because the larger K_{Lh} with airflow (i.e., larger NSI for K_{Lh}) during the night used for soil water infiltration or redistribution during and after rainfall is also incorrectly used for soil evaporation during the daytime. In addition, similar to soil temperature gradient NSI calculation in Z11, the NSI for soil matric potential gradient calculation should also be averaged for daytime and nighttime explicitly in order to keep its physical meaning.

2.2. Downward Advective Flux is the Smallest on Day 2

[3] Z11 used the generalized form of Darcy's law in two-phase flow theory to calculate advective vapor flux. Neglecting gravitational effect, the advective vapor flux is given by [after Z11]

$$q_v = \rho_v \frac{S_a k_g}{\mu_a} \nabla P_g = \rho_v \frac{\left(1 - \frac{\theta}{n}\right) k_g}{\mu_a} \nabla P_g \qquad (1)$$

where q_v is advective vapor flux, ρ_v is density of vapor, S_a $(=1-\theta/n)$ is the degree of air saturation in the soil, θ is soil moisture content, n is porosity, k_g is intrinsic permeability of porous media, μ_a is dynamic viscosity of air, ∇ is gradient operator, and P_g is soil air pressure. Note that the relative air permeability is denoted as S_a $(=1-\theta/n)$ in equation (1) according to Z11 which is a linear relationship with soil moisture content for simplicity. Figure 5B in Z11 shows that for low permeability soils, the downward soil air pressure head gradient during day 3 to day 6 is larger than that on day 2, however, the soil moisture content (θ) during the same period (day 3 to day 6) should be smaller than that on day 2 (Z11, Figure 3) because of the soil evaporation. Then according to equation (1) shown above, the downward advective vapor flux on day 2 should be much smaller than that during day 3 to day 6. The same is true for high permeability soils. Meanwhile, Z11's logic for how the advective effect works is that the downward advective liquid and vapor fluxes induced by downward soil air pressure gradient during the daytime could moisten the near-surface layer and consequently increase K_{Lh}. If airflow is ignored, the absence of such downward advective fluxes will make the K_{Lh} nearly stable during the day (Z11, paragraph 51). Based on Z11's logic, the advective effect should be more evident during day 3 to day 6 but not day 2 since downward advective vapor fluxes are larger during day 3 to day 6 compared to that on day 2. This means that the underestimation error of evaporation induced by neglecting advective airflow should be larger during day 3 to day 6 and smaller on day 2. However, such reasoning contradicted the results presented in Figure 4 in Z11 which shows that among day 2 to day 6, the underestimation error is most significant on day 2 when the downward advective vapor flux is the smallest. Furthermore, Z11's logic could not explicitly explain the larger K_{Lh} (with airflow) during the nighttime than that during the daytime in both high and low permeability soils (Z11, Figures 7C, 9C). These arguments cast doubts on the advective airflow effect on enhancing isothermal hydraulic conductivity as assumed by Z11 and consequently invalidate Z11's conclusion that "when the soil was very dry (e.g., desert sand) the enhanced vapor transfer induced by the air pressure gradient can increase the hydraulic conductivity tremendously." In the above discussion, the advective liquid flux induced by soil air pressure gradient is ignored mainly because of its small order of magnitude compared to advective vapor flux during the daytime (Z11, Figure 10).

3. The Effect of Rainfall Should Be Emphasized

[4] Without emphasizing the rainfall influence, it seems inappropriate to investigate the evaporation underestimation caused by ignoring airflow in Z11's analysis. To our understanding, the key to explain the second day's underestimation error of evaporation induced by ignoring airflow is to interpret why the soil moisture content in the upper soil layers with airflow is higher than that without airflow during and after the precipitation event occurring at the end of first day [*Zeng et al.*, 2011b, Figure 9]. One of the possible reasons is that the air viscous resistance effect [*Morel-Seytoux and Billica*, 1985a], which is considered in the Z11's proposed two-phase heat and mass flow model through the air balance equation, to some extent retarded the infiltrated water originated from the rainfall to move into the deeper soil layers and thus kept the near-surface soil layers wetter, particularly during the nighttime of the second day. To this end, the larger soil moisture content in the upper soil layers with airflow (corresponding to larger K_{Lh} with airflow) would cause higher soil evaporation during the daytime on day 2. Air compression effects [*Morel-Seytoux and Billica*, 1985b] or air entrapment effects [*Wang et al.*, 1998], which could also result in the retardation of infiltrated water, are less likely in Z11 case due to the relatively open soil column system (no ponding or surface runoff in the soil surface and bottom boundary is also open) where mobile air cannot be confined. As such, the rainfall influence on discussing advective airflow effect should not be ignored in Z11 case. In other words, without this rainfall event, we could expect that during the entire 6 days, the evaporation rate between with-airflow and without-airflow should be the same just as the first day shows. Furthermore, Z11 did not explicitly explain why the evaporation rate is the largest at the end of the first day but not during the daytime of the

Table 1. Hydraulic Property Parameters Used in the Synthetic Numerical Simulations

Sample	θ_s	θ_r (θ_a)	α (cm^{-1})	n	K_s (cm d^{-1})
Sand (Z11)[a]	0.382	0.017	0.00236	3.6098	172.8
Sand (this study)[a]	0.382	0.037	0.00236	3.8000	172.8

[a]Z11 and this study corresponded to the van Genuchten-Mualem (VGM) model and Fayer and Simmons-Mualem (FSM) model, respectively.

second day (when soil water content is highest among the 6 days) after the rainfall event. We suggest it is probably related to the upper boundary condition adopted in Z11 work.

4. Soil Hydraulic Properties Should Be Extended for the Full Range Saturation

4.1. Extending Soil Water Retention to Account for Adsorption Forces

[5] Z11 used the classical parametric models of *van Genuchten* [1980]-*Mualem* [1976] (VGM) to calculate isothermal unsaturated hydraulic conductivity K_{Lh}. However, the VGM model is typically applicable in the wet to moderately wet range where water is mainly held by capillary forces and is known to underestimate K_{Lh} under moderately dry and dry conditions where isothermal liquid film flow induced by adsorption forces dominates [*Rossi and Nimmo*, 1994; *Tuller and Or*, 2001]. Therefore, a large number of efforts were made to extend the classical capillary force based water retention curve models [*Brooks and Corey*, 1964; *van Genuchten*, 1980] to include the adsorption forces [*Ross et al.*, 1991; *Campbell and Shiozawa*, 1992; *Rossi and Nimmo*, 1994; *Fayer and Simmons*, 1995; *Morel-Seytoux and Nimmo*, 1999; *Webb*, 2000; *Khlosi et al.*, 2006; *Lebeau and Konrad*, 2010; *Zhang*, 2011] in order that these extended models could be used to appropriately simulate soil water movement particularly under dry conditions. For instance, *Andraski and Jacobson* [2000] incorporated the *Rossi and Nimmo* [1994] full-range water retention function in the UNSAT-H numerical model [*Fayer and Jones*, 1990] to simulate coupled water, heat and vapor transport in a layered Nevada desert soil. They found that Rossi and Nimmo (RN) function could improve prediction of not only water potential in near-surface soil layers (particularly under dry conditions) but also temperature throughout the soil profile. Recently, *Sakai et al.* [2009, 2011] also adopted the *Fayer and Simmons* [1995] full-range water retention function in their coupled water and heat modeling.

[6] Similar to the work of *Andraski and Jacobson* [2000] and *Sakai et al.* [2009, 2011], a synthetic coupled water-vapor-heat simulation analysis was conducted to investigate the necessity of adopting full-range water retention function under dry conditions. The soil hydraulic parameters employed for the sand are shown in Table 1, in which Z11 and this study corresponded to VGM model and *Fayer and Simmons* [1995]-*Mualem* [1976] (FSM) model parameterization, respectively. HYDRUS-1D code [*Šimůnek et al.*, 2008] was adopted to implement the synthetic simulation, which is similar to the scenario of *Saito et al.* [2006]. Figure 1a shows that the simulated soil water content at 20 cm depth with FSM model is smaller than that with VGM model (the same trend for 30 and 40 cm depths, results not shown). This indicated that if such full-range water retention function was also used in Z11 simulation, the overestimation of simulated soil water content (compared to the measured ones) at 20, 30, and 40 cm depths would probably be reduced. Figure 1b displays that the evaporation rate with FSM model is typically larger than that with VGM model during the daytime of Day of the Year (DOY) 328–DOY 334 when the soil is continuously dry. The assumed rainfall occurred at the beginning of DOY 335 effectively increased the soil water content and consequently enhanced the evaporation rate at the daytime of DOY 335. However, due to this rainfall event, the evaporation rate with FSM model is very similar to that with VGM model during DOY 335–DOY 337 when the soil is not very dry. With the further drying of the soil, the evaporation rate with FSM model is again larger than that with VGM model during DOY 338–DOY 340. Figure 1c shows that during the whole simulation period (DOY 328–DOY 340), the cumulative evaporation with FSM model (0.544 cm) is larger than that with VGM model (0.432 cm). Figures 1b and 1c indicated that without accounting for adsorption component in the soil water retention curve, the evaporation would be underestimated under dry soil conditions. This synthetic simulation results suggest that in Z11 case, although on day 2 (right after the rainfall) when the soil is not very dry, accounting for adsorption component

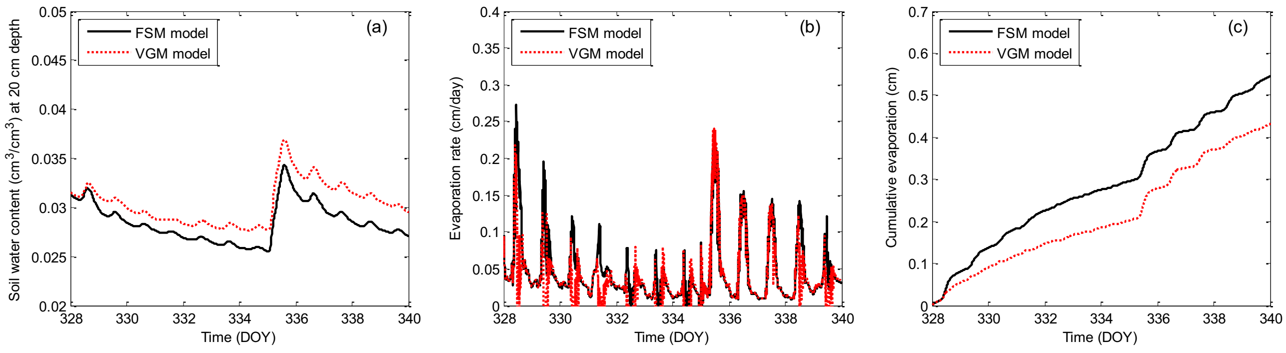

Figure 1. (a) Soil water content at 20 cm depth, (b) evaporation rate, and (c) cumulative evaporation between Fayer and Simmons-Mualem (FSM) and van Genuchten-Mualem (VGM) model during the simulation time period (Day of the Year [DOY] 328–DOY 340).

in the soil water retention curve is probably not highly significant, however, employing full range water retention function is still important for a relatively complete investigation of evaporation underestimation mechanisms in Z11, particularly for day 1 and day 3 to day 6 when the soil is dry.

4.2. Extending Soil Hydraulic Conductivity to Account for Film Flow

[7] Meanwhile, extending the capillary flow based relative hydraulic conductivity model [e.g., *Mualem*, 1976] to include isothermal film flow could be found in the work of *Peters and Durner* [2008], *Lebeau and Konrad* [2010], and *Zhang* [2011]. *Peters and Durner* [2008] simulated an isothermal evaporation scenario and found that the evaporation rate could be underestimated by more than an order of magnitude by neglecting film flow in the hydraulic conductivity model. Similar results also could be found in *Vanderborght et al*.'s [2010] work. Furthermore, the field experimental results in a dry Tanzanian soil by *Goss and Madliger* [2007] also indicated that the evaporation rate would be underestimated due to the underestimation of hydraulic conductivity coefficients caused by neglecting adsorbed water films. Although including isothermal film flow would not induce significant improvement in soil hydraulic conductivity calculation as long as the soil water retention is already extended to oven-dry condition [*Lebeau and Konrad*, 2010, Figure 16 and Table 4], however, for a comparatively complete investigation of the full-range soil hydraulic conductivity parameterization effect on the soil evaporation, it seems still necessary to extend the soil hydraulic conductivity model to include the isothermal film flow processes in Z11 case, particularly for those days when the soil is so dry that the K_{Lh} calculated by VGM model almost approaches zero (Z11, paragraph 49).

[8] Given the importance of employing full range saturation soil hydraulic properties when simulating coupled water and heat transfer under low soil water content environments such as desert [*Scanlon et al*., 1997] or after forest fires [*Massman*, 2012], it is suggested that accounting for adsorption force in water retention curve and isothermal film flow in soil hydraulic conductivity probably should not be neglected in Z11 case. *Smits et al*. [2012] were perhaps the first to take into account full range saturation parameterization of both water retention function and unsaturated hydraulic conductivity in the coupled water-air-heat numerical simulation.

5. Conclusion

[9] In summary, the work presented by Z11 is undoubtedly challenging and intriguing. Whether the enhanced vapor transfer induced by soil air pressure gradient is important or not is still not conclusive. For example, *Rose* [1968] found that the advective vapor flow caused by air pressure gradient only accounted for 0.1% of the total vapor flux under his experimental condition. In Z11's analysis, the authors concluded that the enhanced vapor transfer caused by the downward air pressure gradient could increase isothermal hydraulic conductivity remarkably and thus indirectly leads to the high upward isothermal liquid flux, which will contribute to soil evaporation during the daytime. However, the above discussions indicated that Z11 probably overestimates the advective vapor flux capability on increasing isothermal hydraulic conductivity. Under Z11's unique field experimental condition, the rainfall influence on the advective airflow effect should not be ignored. The infiltrated water originated from the precipitation could probably be retarded by the air viscous resistance effects and this resulted in the higher soil water content in the upper soil layers with airflow during the whole second day, which consequently caused the larger soil evaporation rate with the airflow model. Furthermore, negligence of accounting for adsorptive component of soil water retention and isothermal film flow of unsaturated hydraulic conductivity renders the Z11's analysis incomplete given the overall dry soil condition in Z11.

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