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Evaporation enhancement in soils: a critical review

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Temperature gradients in the top layer of the soil are, especially during the daytime, steeper than would be expected if thermal conduction was the primary heat transfer mechanism. Evaporation seems to have significant influence on the soil heat budget. Only part of the surface soil heat flux is conducted downwards, increasing the soil temperatures, and part is used for evaporation, acting as a sink to the soil heat budget. For moist soils, the evaporation is limited by the transport of water molecules to the surface. The classical view is that water vapor is transported from the evaporation front to the surface by diffusion. Diffusion is mixing due to the random movement of molecules resulting in flattening concentration gradients. In soil, the diffusive vapor flux and the resulting latent heat flux are generally small. We found that transport enhancement is necessary in order to sustain vapor fluxes that are large enough to sustain latent heat fluxes, as well as being large enough to explain the observed temperature gradients.

Enhancement of vapor diffusion is a known phenomenon, subject to debate on the explanations of underlying mechanism. In an extensive literature review on vapor enhancement in soils, the plausibility of various mechanisms was assessed. We reviewed mechanisms based on (combinations of) diffusive, viscous, buoyant, capillary and external pressure forces including: thermodiffusion, dispersion, Stefan's flow, Knudsen diffusion, liquid island effect, hydraulic lift, free convection, double diffusive convection and forced convection. The analysis of the order of magnitude of the mechanisms based on first principles clearly distinguished between plausible and implausible mechanisms.

Thermodiffusion, Stefan's flow, Knudsen effects, liquid islands do not significantly contribute to enhanced evaporation. Double diffusive convection seemed unlikely due to lack of experimental evidence, but could not be completely excluded from the list of potential mechanisms. Hydraulic lift, the mechanism that small capillaries lift liquid water to the surface where it evaporates, does significantly contribute to enhanced evaporation from soils, also from dryer soils. The experimental evidence for and the theoretical underpinnings of this mechanism are convincing. However, we sought mechanisms that both explain enhanced evaporation and steep temperature gradients in the soil during the daytime. These often observed gradients consist of a sharp decrease of temperature with a depth up to the depth of the evaporation front. Hydraulic lift cannot explain this because the evaporation front is located at the surface. One remaining mechanism is forced convection due to atmospheric pressure fluctuations, also referred to as wind pumping. Wind pumping causes displacement and flow velocities too small for significant convective and too small for significant dispersive transport, when steady state dispersion formulations are used. However, experiments do indicate significant dispersive transport that can be explained by dispersion under unsteady flow conditions. Forced convection due to pressure fluctuations seems to be the only mechanism that can explain both enhanced evaporation and the steep temperature gradients.