Journal of Hydrology 396 (2011) 215–220

Contents lists available at ScienceDirect

Journal of Hydrology

journal homepage: www.elsevier.com/locate/jhydrol

Dynamics of water vapor flux and water separation processes during evaporation from a salty dry soil

Meritxell Gran [a,b,*], Jesús Carrera [a], Jordi Massana [c], Maarten W. Saaltink [b], Sebastia Olivella [b], Carlos Ayora [a], Antonio Lloret [b]

[a] GHS, Institute of Environmental Assessment and Water Research (IDAEA), CSIC, Jordi Girona 18, 08034 Barcelona, Spain
[b] Dept. Geotechnical Eng. and Geosciences, Universitat Politecnica de Catalunya, UPC-BarcelonaTech, Jordi Girona 1-3, 08034 Barcelona, Spain
[c] Users Water Community of Llobregat Delta (CUADLL), Verge Montserrat 133, 08820 El Prat de Llobregat, Barcelona, Spain

ARTICLE INFO

Article history:
Received 26 November 2009
Received in revised form 5 November 2010
Accepted 12 November 2010

This manuscript was handled by
Philippe Baveye, Editor-in-Chief

Keywords:
Unsaturated flow
Heat flow
Vapor flow
Salinization
Dilution
Column experiment

SUMMARY

Evaporation from a salty soil generates salt accumulation near the surface with the subsequent deterioration of the soil quality. Salinization mechanisms are poorly understood despite their global impact. Vapor flux and solute transport were studied under evaporation conditions. Laboratory experiments consisted of open sand and silt columns initially saturated with epsomite ($MgSO_4{\cdot}7H_2O$) or halite (NaCl) solutions. Salt precipitation occurred only above the evaporation front, which occupied a very narrow region. Vapor flowed both upwards and downwards from this front. The downward vapor flow condensed further down the column, diluting the solution. This gave rise to two areas: a high salinity area above the evaporation front, and a diluted solution area below it. The effects of thermal, suction and osmotic gradients on water fluxes were studied in order to better understand the underlying mechanisms of this phenomenon.

1. Introduction

Evaporation under very dry conditions may cause salt precipitates, leading to land degradation and desertification. Since dry conditions can be found in most arid and semiarid regions it is not surprising that soil salinization is a major global environmental problem (Van-Camp et al., 2004). Evaporation from dry soils plays a role not only in the salinization of irrigated lands but also in the weathering of mine tailings (Hammarstrom et al., 2005). The phenomenon is complex because heat, water and solute mass transport occur simultaneously during evaporation. Therefore, suction, temperature and osmotic gradients are expected to interact and to control the multiphase system which explains why the detailed mechanisms of soil salinization are poorly understood.

Evaporation is usually conceived by dividing the soil into two zones separated by an evaporation front: above, the soil is dry and water vapor flows upwards, below, water also flows upwards but in liquid phase (Gowing et al., 2006). Konucku et al. (2004) broadened this description by adding a transition zone where water flows in both the liquid and vapor phases while excluding the possibility of a sharp evaporation front.

Still, water vapor is viewed as flowing upwards. Actually, this is not always the case. Scanlon (1992) studied water vapor fluxes in desert soils using ^{36}Cl and ^{3}H distributions. Chlorine 36 flux is restricted to the liquid phase, while tritium can flow in both the liquid and vapor phases. Differences between ^{36}Cl and ^{3}H distributions suggested the existence of a downward vapor flux driven by thermal gradients. Scanlon and Milly (1994), Milly (1996) corroborated these observations by a numerical model. Boulet et al. (1997) obtained similar results.

Soluble salts (chlorides and sulphates of sodium, calcium and magnesium) are commonly present (Abrol et al., 1988) and evaporation leads to high solute concentrations. Therefore, the osmotic effects must also be taken into account. This has motivated numerous experimental studies on the effect of thermal and osmotic gradients. Wheeting (1925) conducted closed horizontal experiments on columns divided into three zones: unsaturated soil with a high salinity solution, unsaturated soil with a diluted solution and an air gap that separates them. Interpreting Wheeting's experimental results, Kelly and Selker (2001) concluded that water activity was reduced in the saline portion, leading to a drop in vapor pressure that drove vapor flux. The air gap diminished this

* Corresponding author at: GHS, IDAEA, CSIC, Jordi Girona 18, 08034 Barcelona, Spain. Tel.: +34 0647543800.
E-mail address: meritxell.gran@idaea.csic.es (M. Gran).

0022-1694/$ - see front matter © 2010 Elsevier B.V. All rights reserved.
doi:10.1016/j.jhydrol.2010.11.011

vapor flux. Therefore, they concluded that these processes should be studied in a continuous soil medium. In fact, Scotter (1974) had placed crystalline salts at one end of a sealed tube of initially uniformly wet soil under isothermal conditions. He obtained an increase in the water content in the salt zone owing to vapor transport by osmotic effects. The join effect of temperature and salinity gradients was studied by Nassar and Horton (1989a), who found that solute concentration affects unsaturated soil water transport also under nonisothermal conditions. A temperature gradient in horizontal closed columns was imposed by Nassar and Horton (1989a), Nassar and Horton (1989b). They observed a liquid water flow from the cold to the hot end, which offsets a water vapor flow in the opposite direction. These data were used by Yakirevich et al. (1997) to test their mathematical model. They highlighted the osmotic effects and proposed a salt crust formation. In fact, Olivella et al. (1996), modeled porosity variations induced by salt precipitation.

In summary, matric potential, temperature and osmotic gradients can drive vapor and liquid water fluxes, often in opposite directions. One may conjecture that evaporation in bare, dry and salty soil will be controlled by the superposition of these effects, but it has never been studied in detail. The aim of this paper is to determine how all these factors interact between them and their impact on water vapor flow and salt concentration. To this end, an open soil column experiment was performed.

2. Materials and methods

Laboratory experiments were performed on initially saturated soil columns. Sand and silt columns with varying concentrations of epsomite ($MgSO_4{\cdot}7H_2O$) and halite (NaCl) were used. In order to achieve controlled and uniform conditions, evaporation was forced by an infrared lamp simulating the effect of the sun. Columns were periodically weighed to monitor evaporation loss.

To study the soil under very dry conditions, the experiment continued until the overall saturation fell to 0.32 and the evaporation had diminished. At this stage, the columns were dismounted to measure temperature, salinity and water volume content versus depth.

2.1. Materials

The columns consisted of methacrylate cylinders, 24 cm long and 14.4 cm in diameter enveloped in a thermal insulator (*Termoflex*, 2 cm thick). These cylinders were filled either with silica sand of 0.4–0.8 mm grain size and 2.65 g/cm^3 density or with aluminous silt (Eijkelkamp) of particle size about 73 μ and 3.96 g/cm^3 density. Four different salt solutions were employed, two with epsomite (40 g/kg for a high solute concentration and 14 g/kg for a low solute concentration) and two with halite (20 g/kg for a high solute concentration and 7 g/kg for a low solute concentration). It should be noted that solute masses of the two salts are comparable because half of the epsomite molecular weight is water. Evaporation was forced by an infrared lamp (Philips PAR38 IR 175R) located 38 cm above the column surface (Fig. 1) so that radiation at the soil surface was designed to be approximately 90 mW/cm^2, similar to the summer radiation at mid-latitudes.

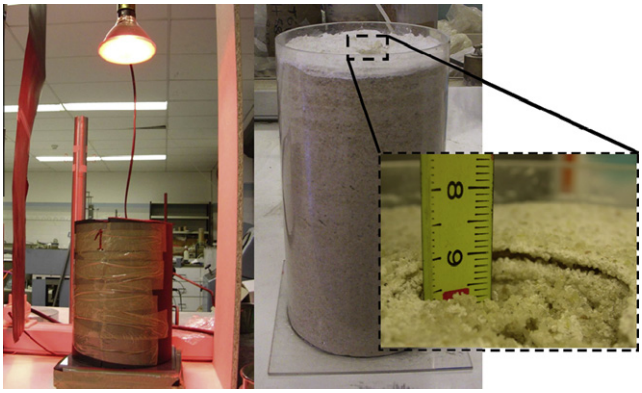

Fig. 1. Experimental set up. Left, initial setting under the infrared lamp with the column enveloped in a thermal insulator. Right, the column at the end of the experiment, when the sand is dry and an epsomite crust has formed at the surface. Note the detail of this crust where we can observe its width and an air gap between the top of the sand and the salt crust. Consequently the salt crust grows upwards.

2.2. Column set up

A synthetic initial solution was created by adding the salt to distilled water. The material (sand or silt) was first mixed with this salt solution and columns were filled with layers that were compacted (≈0.01 kg/cm^2) to eliminate air bubbles. The column weight was monitored daily for weight loss due to evaporation. Relative humidity (*RH*) and temperature (*T*) in the laboratory were recorded ($RH \approx 52\%$ and $T \approx 24$ °C). Profiles of state variables versus depth were collected at the end of the experiment. In order to obtain the time evolution we also set up a group of identical sand columns (four with a low epsomite concentration and four with a low halite concentration), which were dismantled at different stages of the experiment. These columns were dismantled sequentially after reaching average saturation degrees of 74%, 50%, 40% and 32%. This procedure was duplicated to test its repeatability.

2.3. Column dismantling

The temperature profile was measured prior to dismantling. To this end, we perforated the soil and introduced a thermal sensor, recording the temperature from top to bottom while the columns were still under the lamp. Thereafter, the salt crust was removed from the surface. Soil samples were then collected by means of a beveled iron ring (3 cm in diameter and 1.5 cm long) every 2.5 cm, approximately. All the samples including the salt crust, were weighed, dried in an oven at 110 °C for 24 h and weighed again. The water content along the column was derived from the weight difference. Next, each sample was diluted by adding a mass of water five times that of the sample mass and the electrical conductivity (EC) of its solution was measured. The salt concentration was obtained from a specifically calibrated EC-concentration relationship. The total mass of dissolved salt was deduced from electrical conductivity measurements after calibration with a given salt concentration solution.

The resulting mass concentration includes both the dissolved and precipitated salts. The salt concentration was calculated by dividing the total mass of salt and the water content by weight. The salts are assumed to be dissolved when the concentration before dilution is lower than the solubility of the salt. Should the dilution be higher, the excess is regarded as a salt precipitate. In the case of epsomite, this task is complicated by the high hygroscopy of $MgSO_4$. Magnesium sulphate presents six different mineral phases depending on its degree of hydration: epsomite ($MgSO_4{\cdot}7H_2O$), hexahydrite ($MgSO_4{\cdot}6H_2O$), pentahydrite ($MgSO_4{\cdot}5H_2O$), starkeyite ($MgSO_4{\cdot}4H_2O$), sanderite ($MgSO_4{\cdot}2H_2O$) and kieserite ($MgSO_4{\cdot}H_2O$). These phases are rather unstable (hydrated phases evolve rapidly to dry phases and vice versa) with the result that they are not easy to analyze. Therefore, the ratio between $MgSO_4$ and H_2O molar masses (M and W, respectively) was used to distinguish the mineral phases. If W:M = 4, the mineral phase is considered to be starkeyite, if W:M = 5, it is pentahydrite, if W:M = 6, it is hexahydrite and finally, if we have W:M = 7, the precipitate is eps-