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Experimental study on evaporation from seasonally frozen soils under various water, solute and groundwater conditions in Inner Mongolia, China

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SUMMARY

Soil freezing and thawing significantly impact water balance in cold regions. To improve estimations of evaporation from seasonally frozen and saline soils, field experiments representing various water and solute conditions were conducted during a 5-month-period in Inner Mongolia, China. A mass balance method was used to estimate evaporation from frost tubes (5.5×300 cm) with treatments combining three solute contents (0.2%, 0.4%, and 0.6% g g^{-1} dry soil) with three initial groundwater table depth (*GWTDs*) (2.0, 1.5, and 1.0 m). The dynamics of water, heat and solute transport in the frost tubes and in field plots were also investigated. Seasonal changes in evaporation rates were observed during soil freezing/thawing periods. Low evaporation rates were maintained when the soil was deeply frozen (e.g., in P3), and relatively higher values occurred at the beginning and the end of the experiments (e.g., in P1 and P5). The cumulative evaporation amount increased with an increase in initial solute content and declined with a lowering of the initial *GWTDs*. Solute accumulation with water in the surface layer during freezing decreased the osmotic potential in soil, resulting in obvious freezing point depressions and higher liquid water contents in the uppermost layer of soil. During the soil thawing periods, no evidence of any control of water availability on evaporation was noticed, although the surface soil contained large amounts of water. This study has led to an improved understanding of the coupled effects of water, heat and solute on evaporation from seasonally frozen saline soils and also has important implications for water and energy balance studies in cold regions.

1. Introduction

Soil evaporation, is an important part of the hydrological cycle because it affects agricultural water-use efficiency and plays a vital role in the ecosystem energy balance (Oki and Kanae, 2005; Trenberth et al., 2009; Hayashi, 2013). Research on soil evaporation can play a vital role in the improvement of water management in arid and semi-arid regions because soil evaporation is a key index of water-use efficiency and soil salinization. Few studies have examined evaporation from frozen soils, although the process is important in understanding the water and heat balance in cold regions. The investigation of water and vapor flow in soil during freezing/thawing processes is difficult because of the complex nature of the transport of water, heat and solute during winter (Miller, 1980; Stahli, 2005; Iwata et al., 2010; Dall'Amico et al., 2011; Jafarov et al., 2012). Kaneko et al. (2006) estimated evaporation from a frozen soil surface in the Yellow River Basin using the aerodynamic method and determined that the total water loss (60 mm) due to evaporation during soil freezing (November to March of the following year) was not negligible. Wright (1991) measured an average daily evaporation rate of 1 mm d^{-1} in winter at Kimberly, Idaho, U.S.A., in lysimeters. Meanwhile, a study in Logan, Utah, U.S. A., showed that the evaporation rate during winter ranged up to 1.5 mm d^{-1} (Wright, 1988).

To quantify soil evaporation in cold regions, some estimation methods that worked well for unfrozen soils have been applied to the estimation of evaporation from frozen soils. The crop coefficient for soil under frozen conditions was estimated to characterize the evaporation from bare, frozen soils (Wright, 1988). The evaporation process in frozen soil conditions is assumed to be similar to that of unfrozen soils in numerical models that simulate water,

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heat and solute transport, such as the SHAW model (Flerchinger and Saxon, 1989), the CoupModel (Stähli and Jansson, 1998; Stähli et al., 1999; Jansson and Moon, 2001), and HYDRUS (Hansson et al., 2004). Therefore, evaporation from frozen soils can be calculated by the energy balance of the surface (Flerchinger and Saxon, 1989) or by empirical methods, such as the Penman–Monteith equation (Allen et al., 2005). However, these methods may have limitations if they are applied to frozen soil during winter, as the surface has little liquid water and few pathways for water transfer and vapor diffusion. Furthermore, evaporation from ice and snow can be substantial. This process can be simulated using the energy balance approach, as is done, for example, in the CoupModel (Gustafsson et al., 2004). In order to test the suitability of numerical models for estimating frozen soil evaporation, it is necessary to measure evaporation from frozen soils during freezing and thawing periods.

In the Hetao Irrigation District, Inner Mongolia, China, agricultural fields are affected by high soil salinity due to insufficient recharge to leach soil salts. Most of the annual precipitation is received during the growing season when evaporation is high. Irrigation is applied to enhance the leaching of solutes and to store water in the soil during the winter prior to the start of the next growing season. However, rapid rises in the groundwater table due to improper irrigation and poor drainage makes this irrigation practice inefficient, because the upward movement of water and solutes under temperature and water potential gradients in the winter counteracts the drainage. This helps facilitate evaporation from soil after soil thawing, resulting in a large amount of water loss as well as accumulation of salt at the soil surface in spring of the next year. This process is contrary to the original intention of autumn irrigation, which is to store water for spring sown crops and remove solutes from the root zone.

The objectives of this study are (i) to experimentally measure evaporation from seasonally frozen soils under different conditions, (ii) to identify the influences of groundwater conditions on soil surface evaporation, and (iii) to discuss the coupled effects of water, heat and solutes on evaporation from frozen soil.

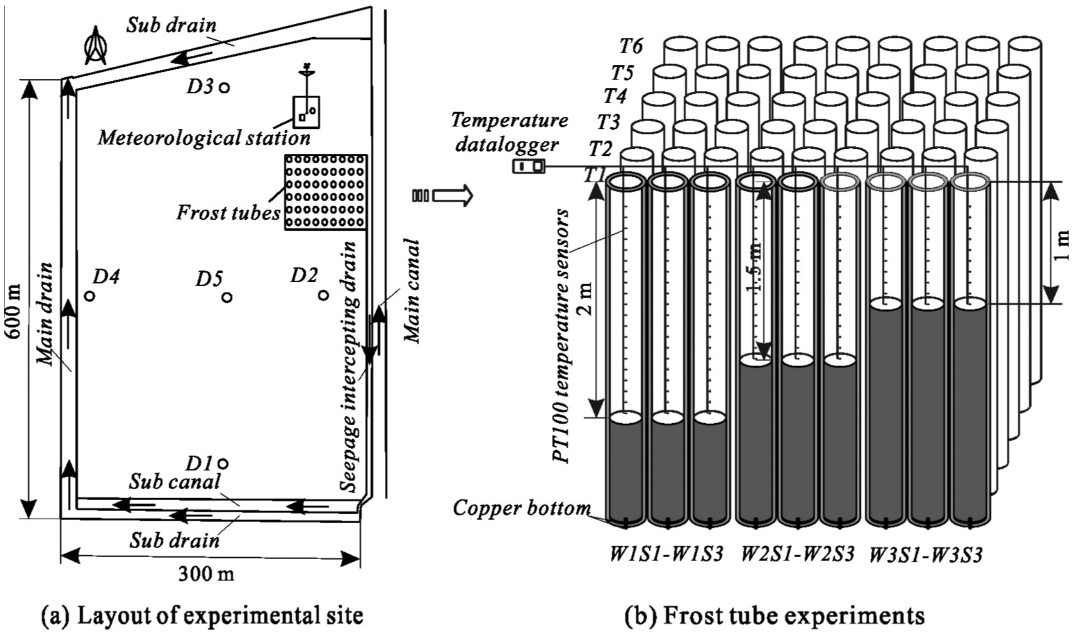
2. Material and methods

2.1. Experimental design

Two experiments were conducted at the Yonglian Experimental Station in the Hetao Irrigation District, Inner Mongolia (41°08′06″N, 108°06′18″E), China, between December 1st 2012, and April 30th 2013. Fig. 1 depicts the experiments conducted at the experimental site, which covered an area of 20 ha, including an agricultural field (western part) and micro-experimental zones (eastern part). The soil at the study site was classified as a silt loam according to the USDA system (USDA, 1938), with saturated hydraulic conductivity in the range of 10.8–54.0 cm d^{-1} and porosity of 0.43–0.55 cm^3 cm^{-3}. The physical characteristics of the soil are shown in Table 1.

The agricultural field was irrigated from November 4 to November 10, with ca. 24 cm. Before irrigation, the field was ploughed to a depth of 20 cm and the soil surface was bare without stubble mulch. Five plots (2×2 m^2, denoted D1–D5, see Fig. 1) in the field were chosen for measurements of water and solute dynamics. One observation well was installed in each plot to detect the depth to the groundwater table. The initial *GWTD*s in five plots of the field ranged from 1.36 m to 1.93 m before irrigation.

Experiments in frost tubes were conducted for 9 treatments combining three water table depths (W_1–W_3, at 2.0 m, 1.5 m, 1.0 m, respectively) with three solute contents (S_1–S_3, at 0.2%, 0.4%, 0.6%, respectively, in g g^{-1} dry soil). For each treatment, six replicates were prepared for sampling at six dates during the winter. In total, 54 (9 treatments × 6 replicates) frost tubes were prepared. The frost tubes were made of polythene pipes, with an inner diameter of 5 cm and a thickness of 0.5 cm. Each frost tube had a length of 3 m, with the bottom sealed with copper cylinder (5 cm in diameter and 0.5 cm in thickness) to conduct heat from deeper soil layers. Before the experiments, 54 polythene pipes (also called outer tubes), with inner diameters of 7.5 cm, lengths of 3 m and copper bottoms, were inserted into the pre-dug holes (the same dimensions as the outer tubes). Soil dug from agricultural field with low salinity (<0.1% g g^{-1}) was air-dried and passed through



(a) Layout of experimental site

(b) Frost tube experiments

Fig. 1. Experimental setup for the various experimental conditions. *T*1–*T*6 denote the six sampling dates during the experiments (i.e. 2012/12/15, 2013/1/10, 2013/2/5, 2013/3/1, 2013/3/25, 2013/4/20); *W*1–*W*3 denote an initial groundwater table depth of 2.0, 1.5, and 1.0 m, respectively; *S*1–*S*3 denote an initial solute content in the soil of 0.2%, 0.4%, and 0.6% g g^{-1} dry soil, respectively. *D*1–*D*5 denotes positions of five field plots.