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A Field Experiment to Assess the Influence of Heat and Mass Transfer at the Soil Surface on Shallow Ground Heat Exchanger Performances

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ABSTRACT

Prediction of soil thermal regime is still a difficult task for design of ground-coupled heat pump system units (GCHP). A Field experiment was carried out to study the near-surface and moisture transport effects on soil temperature distribution. Energy balance components at the soil surface was monitored using a meteorological station, that included a pyrgeometer and a pyranometer to measure short and far infrared radiation, and using two heat flux plates installed in the soil at a depth of 0.08 m to measure ground heat fluxes. A 2.5 m deep trench has been dug in order to (i) characterize soil hydraulic and thermal properties at different depths and (ii) install tensiometers and thermocouples allowing continuous measurements of soil water tension and soil temperature. We observed that variations of soil properties along the profile as well as compaction influenced soil thermal properties. Results showed that temporal variations of soil heat flux at 8 cm depth closely followed those of available energy (net radiation), vertical turbulent heat fluxes (latent and sensible fluxes) near the soil's surface.

1. INTRODUCTION

Shallow geothermal energy sector is continuing to grow at a higher than expected rate: more than 66.000 ground-coupled heat pump system units (GCHP) are installed worldwide annually. 80 % of these installed units are domestic (Lund et al.., 2011). Knowledge of ground temperature distribution is a key parameter for design of GCHPs, such as to define the possible geometrical configurations, and also for their performance enhancement (Florides, et al. 2007). Prediction of soil thermal regime is still a difficult task. This is mainly because that soil temperature near the surface is a property that changes spatially and temporally in response to numerous factors. For this, a test facility has been carried out in Orleans, France since 2008 to optimize performance of shallow geothermal energy systems (Philippe et al., 2010). The test facility was equipped with GHE of various geometries: horizontal ground heat exchangers (HGHE), coil-shaped GHE and borehole heat exchangers (BHE). The Scientific objectives of this facility are to improve understanding interactions with the surrounding soil (e.g. climatic parameters, geological properties, soil cover) and to determine the performances of new types of ground heat exchangers.

*Near-surface and moisture transport effects on soil temperature distribution are usually neglected or have been addressed by relying on extreme simplifications during the design and sizing of shallow ground heat exchangers such as horizontal ground heat exchangers (*HVAC&R Research, 2011). The present study aims to investigate at field scale, near-surface processes related to ground temperature variation during soil wetness and dryness to allow a better design of shallow ground heat exchangers

2. EXPERIMENTAL SET UP

Soil temperature is governed by two kinds of processes: (a) energy exchange/transfer at earth-atmosphere boundary (b) heat propagation within the soil which can vary substantially with moisture content. The former one determines the energy quantity stored in the soil, the latter one control how energy is distributed once inside the soil (Saito et al., 2009; Smits et al., 2010).

For this, continuous measurements of parameters needed to fully evaluate energy and moisture balance were carried out in situ at the geothermal energy test facility to investigate energy transfer between soil and atmosphere and study the thermal and moisture regimes. Figure 1 shows the test facility where these measurements have been processed.

Energy balance components at the soil surface were monitored using a meteorological station and heat flux plates (Figure 2). The net short radiation is measured with an albedometer composed of two pyranometers, mounted back-to-back, model LP PYRA 05, one looking upward (sky) and one downward (earth). The upward pyranometer measures the incident global radiation (direct radiation + diffuse radiation) striking the ground, while the downward one, measures the global radiation reflected from the ground. The incoming far infrared radiation is measured with Pyregeometer, model LP PIRG 01 (DeltaOHM S.R.L.).The outgoing longwave radiation was measured using the soil surface temperature $Ts(\varepsilon\sigma(T_S + 273.16)^4)$ measured at 0.03m, where ε is the emissivity of grass cover (e =0.9) and σ is Stefan Boltzmann's constant (σ = 5.67x10-8 WK-4m-2)

Soil heat flux is measured by two heat flux plates Hukseflux Self-Calibrating plates (Campbell Sci, type HFP01SC) installed in the soil at a depth of 0.08 m. The self-calibration corrects the errors due to thermal conductivity differences between the sensor and the surrounding medium, temperature variations, and slight sensor instabilities.

At a 2 m height, the air relative humidity and temperature (Figure 2a) are measured respectively with capacitive humidity and a Platinum temperature sensors (100Ω @0°C) (Delta-OHM, model HD9008TRR).

A 2.5 m deep trench has been dug in order to (i) characterize soil hydraulic and thermal properties at different depths and (ii) install tensiometers and thermocouples allowing continuous measurements of soil water tension and soil temperature (Fig. 2). Tensiometers (two at each depth) were installed at the 20, 45, 100 and 140 cm depths. Soil temperatures, T, are measured by

thermocouples type T at depths of 00.3, 0.06, 0.14, 0.2, 0.3, 0.5, 1 and 1.5m (two thermocouples for each 0.03 and 0.06 m depth). Measurements are recorded every ten minutes

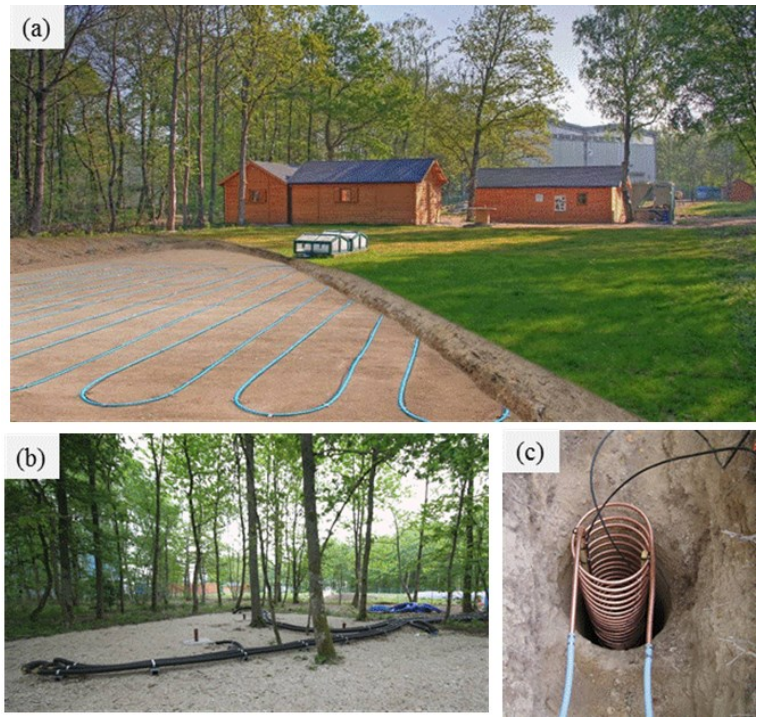


Figure 1: (a) Overview of the test facility in France with horizontal ground heat exchangers (HGHE), (b) Three borehole heat exchangers (50 m deep double-U, coaxial exchanger and 100 m deep double-U exchanger) used to understand the influence of hydro-thermal soil properties on heat transfer (c) Coil-shaped GHE made of copper

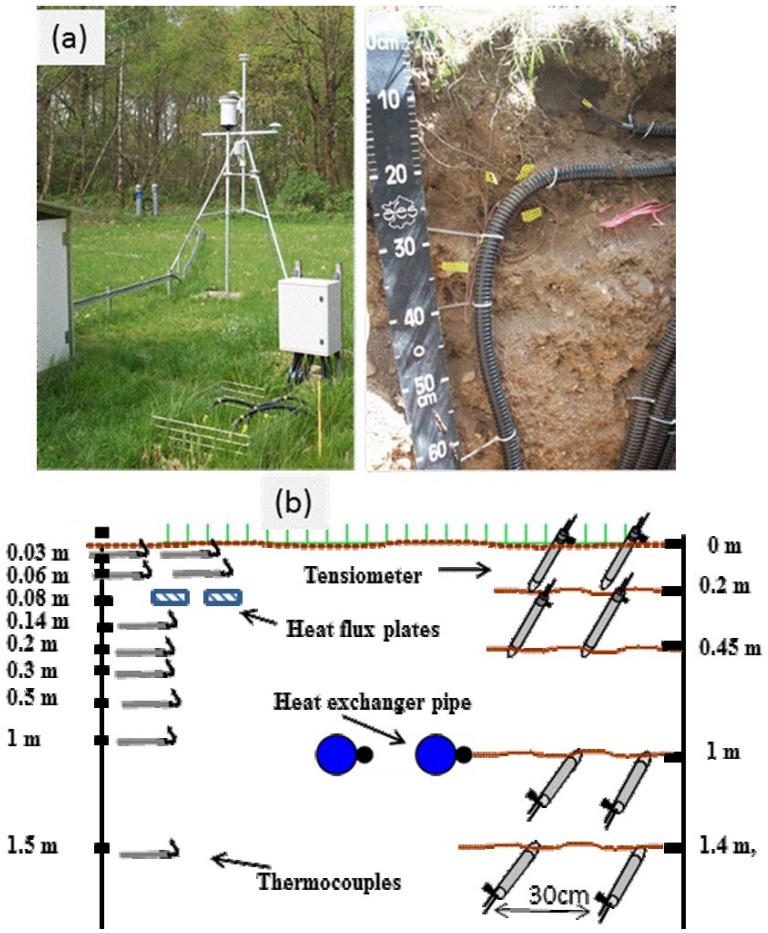


Fig. 2: (a) Overview of field experiment, and (b) Locations of thermocouples probes, heat flux plates and tensiometers

Soil hydraulic and thermal properties and soil physico-chemical characteristics were measured at the time the thermocouple probes and tensiometers were installed. Soil samples were extracted at 4 depths: 10-20cm, 40-50 cm, 90-105 cm, 145-155 cm and 195-205 cm, coinciding with soil distinct horizons. Three replicate profiles were taken for each measurement to provide a better idea of the within-plot variability.

Soil water retention curves of the soil were measured with the pressure plate apparatus using 50 cm3soil cores. Average bulk density profiles were measured by sand replacement method (AFNOR, 1996 - NF P 94-061-3) using soil cores of 5 cm by 8.4-cm diameter. The hydraulic conductivity – water potential relation was measured with a disc infiltrometer at different matrix potentials from -10 cm up to -0.5 cm (using the multipotential method of Ankeny et al. (1991)) (Coquet et al., 2000).

Undisturbed soil samples (10 cm length by 11 cm diameter; with three replicates per depth) were taken at different depths (10-20cm, 40-50 cm, 90-105 cm, 1145-155 cm and 195-205 cm) to determine the soil thermal properties. Volumetric heat capacity (Cv, MJ.m-3.°C-1), thermal conductivity (k, W.m-1.°C-1) and gravimetric water content were determined for each sample. The given measurements were conducted using an ISOMET 2114 thermal conductivity instrument (Applied Precision Ltd., Slovakia), portable measuring apparatus, and by means of a surface probe at room temperature and according ASTM D 5334-08 et ASTM D 5930-09 methods. Three measurements were made at each depth. The grass cover is mowed regularly, has a mean weight of 0.12 m and a mean leaf area index, LAI, 2.88 (FAO, with LAI=24*0.12).

3. RESULTS

The monitoring data were used to investigate the interactions between heat transfer and saturated/unsaturated moisture transport caused by solar radiation, rainfall, evapo-transpiration and water table so as to determine the key processes controlling ground temperature and moisture distribution.

Based on particle size distribution, the soil is sandy; the main physico-chemical characteristics are described in Table 1. Low organic matter contents ranging from 1 to 2 %, were found in the middle and deep layers. Soil contained large proportion of gravels (between 33 and 46%) then we classify it at “gravelly soils” (Poesen and Lavee, 1994). Higher concentrations of gravels at the soil surface compared to the soil horizons below (between 33 and 46%).

Table 1: Main soil physico-chemical characteristics (average value of 3 sampled profiles ± standard deviation)

	10-15cm	40-50cm	95-105cm	145-155cm	190-200cm
Clay, $g.kg^{-1}$dry wt.	60 (±5)	59 (±7)	72(±10)	56(±6)	38
Silt, $g.kg^{-1}$dry wt.	98 (±10)	89 (±11)	43 (±4)	50(±2)	80
Sand, $g.kg^{-1}$dry wt.	468(±21)	421 (±21)	560 (±73)	508 (±27)	425
Gravel content, $g.kg^{-1}$dry wt.	374(±15)	430 (±25)	325 (±69)	386 (±27)	457
OM[a], %	3 (±0.3)	1 (±0.1)	1 (±0.1)	1 (±0.1)	2
Bulk density, $Mg.m^{-3}$	1.58 (±0.07)	1.94 (±0.27)	2.03 (±0.07)	2.13 (±0.02)	2.02 (±0.02)

[a]OM: organic matter content

Soil characteristics (e.g. bulk density, degree of wetness, soil heat capacity), which govern temperature regime, were monitored at different depths. Bulk density increases with soil depth which can be related to the fact that subsurface layers are more compacted. Subsurface layers are more compacted and have less organic matter, compared to surface layers, therefore contain less pore space. Soil porosity was calculated from measured bulk density. High bulk density is an indicator of low soil porosity (Figure 3a, b) and water holding capacity. The top layer (Figure3b), 10-20 cm, had larger water retention than deep layers mainly in the range of macropores (pF 0 – pF 1.5). The highest mobile water content is observed in the 10-20 cm layer and the lowest in the deep layers.In the range of micropores (pF 2.2 – pF 4.5), the water retention curve of this layer showed changes in the slope tending to converge in the micro pore range. The amount of larges pores decreased with depth, but the volume of fine pores (i.e. the volumetric water content between pF1.2 and 4.2) seems equal along the profile. This is related to the fact that the soil texture did not change with soil compaction, therefore, the amount of micro pores remain constant (Kutilek et al., 2006). As the bulk density increases with depth, the pore volume decreases, resulting in a decrease of saturated hydraulic conductivity (Figure 3c).

Thermal properties measurements (Figure 4) showed that local soil thermal conductivity and heat capacity measured at each depth were slightly variable. Coefficients of variation of local thermal conductivity calculated from the three replicates were between 23 and 3 % respectively for the 10-15 cm and 195 and 205 cm layers. Variation coefficients of local heat capacity were between 1 and 9 %. Variability in local soil thermal properties can be explained by spatial variation of gravel content. The porosity of soil varies spatially in general and in the presence of gravels, the variability increases because of the range and tortuosity associated with gravel fragments (the differences in the behavior of fine earth and gravels during the process of wetting and drying, poor soil contact in gravelly soils) (Poesen et Lavee, 1994).

Variations (increase/decrease) of measured Cv and k properties as function of water content were greater in samples taken from depth of 10-15cm. k varies from 1.15 to 1.83 W/m/K (59% increase) as volumetric water content increases by 12 % (from 17 to 18 cm3/cm3). However, k varies from 2.04 to 2.15 W/m/K (5% increase) as water content increases by 5% (from 14 to 15 cm3/cm3).

No clear trend emerges from the measured thermal properties as how thermal conductivity varies with depth despite the fact that bulk density increases with depth. Our results are not in accordance with pervious investigations that showed that thermal conductivity increases with increasing density as a result of better particle contact with a decrease in porosity and a greater mass of solids per volume unit (Smits et al., 2009; Nidal et al., 2000). Thermal properties data are scarce and incomplete as thermal conductivity and heat capacity are not measured in a continuous manner at varying soil water contents.

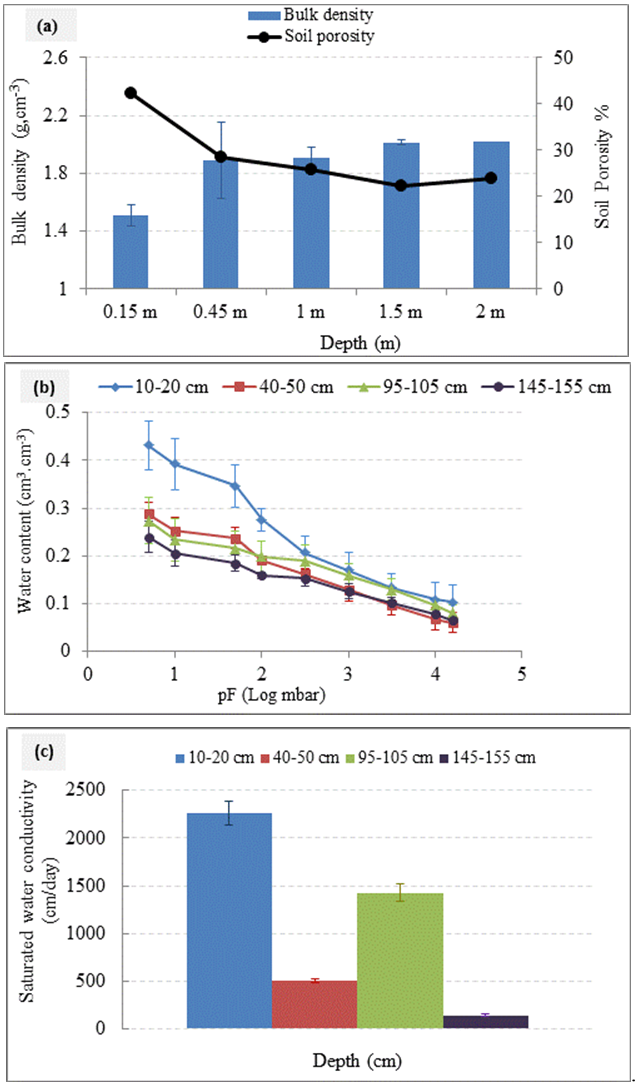


Figure 3: (a) Bulk densities profiles measured at the study site and the percent of total soil volume made up of pore space (Soil porosity (%) = 1-(soil bulk density / 2.65). The default value of 2.65 is the mean particle density of rock with no pore space, (b) and (c) water retention curve and saturated hydraulic conductivity measured at different depths. Water retention curve express the relation between matrix potential and water content.

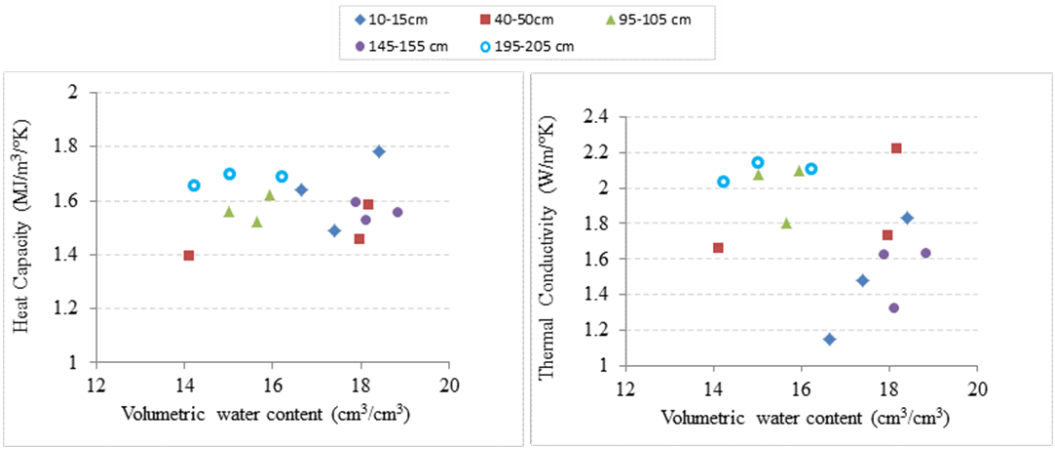


Figure 4: Volumetric heat capacity and thermal conductivity measured in the different layers as a function of water content

Figure 5 showed the temporal evolution of soil temperature at different depths. The soil temperature varies differently with depth; the soil temperature of the surface layer is the most affected by atmospheric variations. Diurnal variations are more important at the soil surface than for deeper layers where there are almost no observed diurnal temperature changes. We note that seasonal variations / fluctuations are more pronounced in deeper layers, meaning that these variations might be more critical for the long-term simulations and cannot be neglected. This might be related to the fact that the measured soil properties differed along the profile (with depth). At a given matrix potential the topsoil has higher water content than deeper depths, and then corresponding k and Cv reach higher values. The top layer (Figure3b), 10-20 cm, has larger water retention than deep layers then, thermal inertia proportionally is higher as well, reducing the diurnal temperature fluctuation in the deep layers.

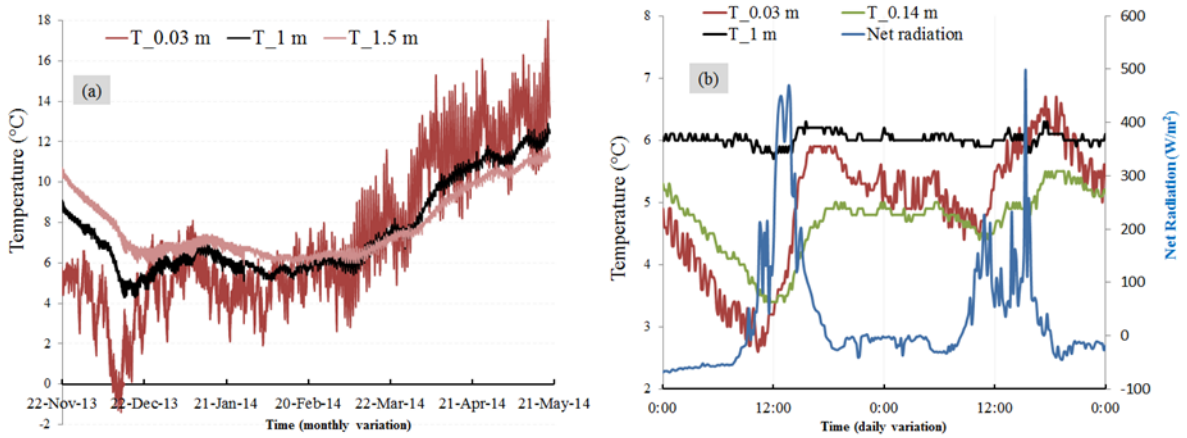


Figure 5: Soil temperature variations with time and depth (a) seasonal variations, and (b) diurnal variations

Figure 6 shows the diurnal variations of the surface energy balance, the largest incoming heat is the absorbed shortwave radiation (solar radiation), and the largest outgoing heat is the heat transfer by convection and evaporation. Incoming solar energy is a maximum when the sun is highest in the sky. But the earth surface warms continuously as soon as the sun rises until the time it sets.

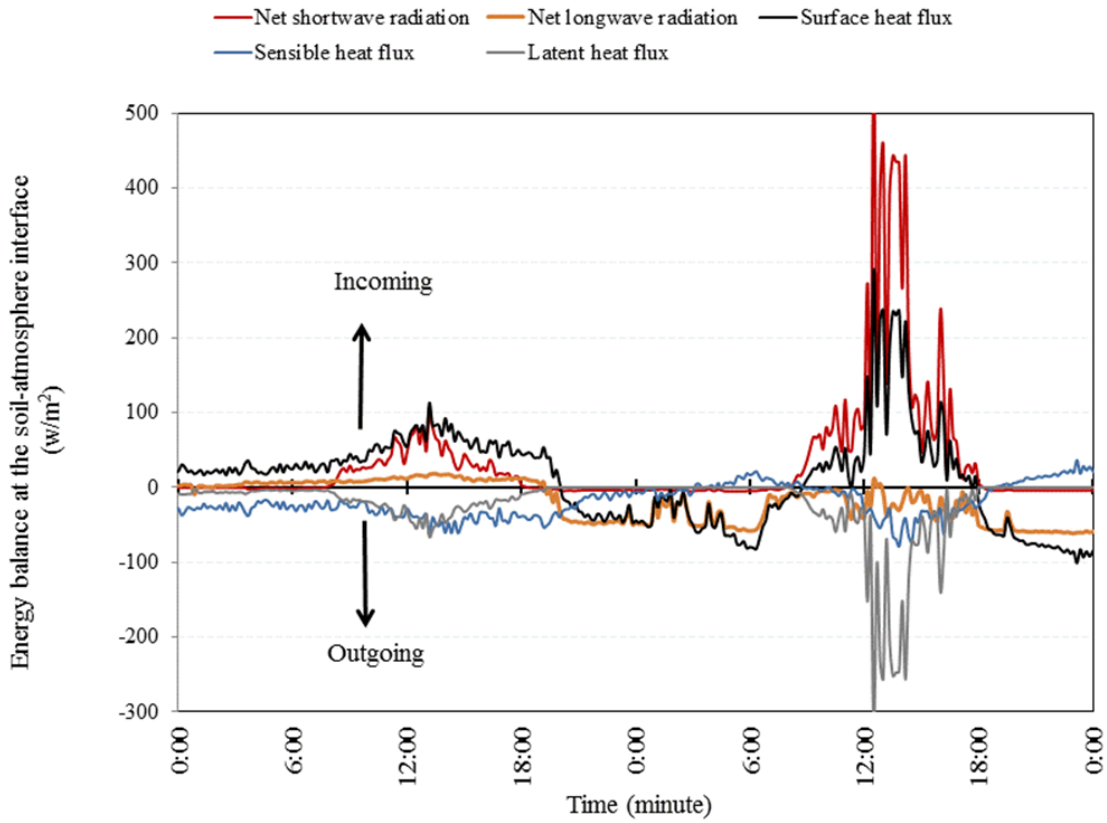


Figure 6: Diurnal variation in energy balance at the soil-atmosphere interface for the 20th and 21th of February 2014.

A positive correlation (R^2 =0.198) was observed between net radiation and soil heat flux at 8 cm depth (Figure 7a). Soil heat flux is better described when plotted versus net radiation and convective terms (latent and sensible heat flux (R^2 increases from 0.198 to

0.3512), meaning that temporal variations of the soil temperature follow those of available energy, vertical turbulent heat fluxes near the soil's surface being thus not insignificant.

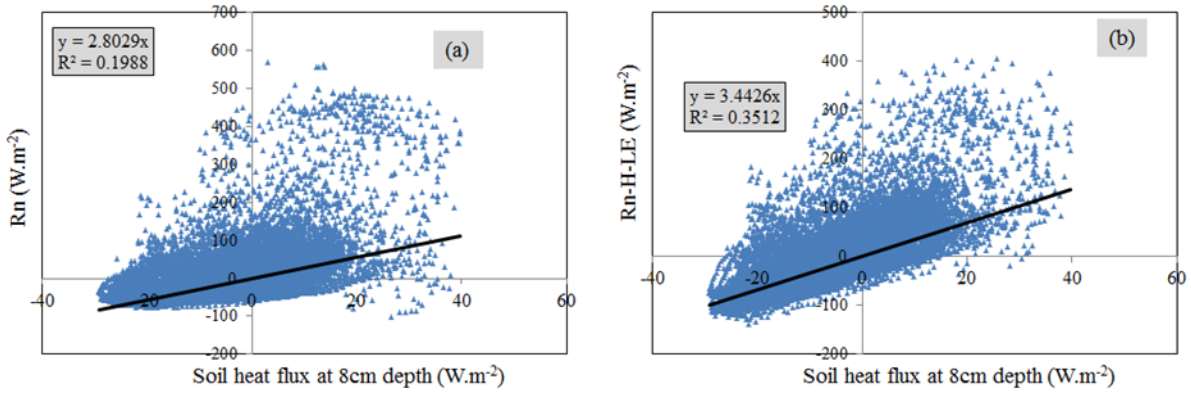


Figure 7: Scatter graph of the net radiation (Rn) versus the soil heat flux measured at 8cm depth, (b) net radiation minus sensible heat flux (H) and latent heat flux (LE) versus soil heat flux at 8 cm depth.

4. CONCLUSIONS

We can conclude that different soil characteristics along the profile as well as compaction rate influence soil thermal properties. The topsoil layer (with high porosity and high water content) can store more heat, and, as a result of different soil properties, the atmospheric variations do not affect the soil thermal regime in the same manner along the profile. The thermal properties, conductivity and volumetric heat capacity, increase with water content. We observed that soil heat flux at 8 cm varies in response to changes in radiant, thermal and latent energy exchange processes that take place at the soil-atmosphere interface. Data analyses are still in progress. In the future, recommendations will be proposed to improve the design of shallow ground heat exchangers (e.g. modification of the soil cover, adaptation exchanger implantation depth).

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