Climatic effects on the soil temperature and water content changes

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ABSTRACT

This paper analyzes the results of a series of numerical analyses aiming to predict temperature, water content, and pore-water pressure changes due to climatic effects in a soil profile during a long term period by considering the soil atmosphere interface interactions. A soil-atmosphere interface model is used to calculate the evaporation rate and heat flux on the soil surface; the water transport equations (liquid - Darcy's law and vapor - Fick's law) coupled to heat flow equation (de Vries 1963) are solved to determine the profiles of soil temperature, water content or pore water pressure. A sensitivity analysis was also carried out to study how the variations of the soil albedo value (i.e., the ratio of reflected to incident solar radiation), the saturated hydraulic conductivity, and the initial temperature profiles (ITP) can influence water content, suction and temperature changes. It was considered the heterogeneous soil column consisted of two different soil layers in a total soil depth of 5 m. The results suggest that the variation of 5^{o}C in ITP affects the temperature profiles but its influence on the suction and water content profiles is very small. During the cold season, precise albedo values are not very important nor very sensitive in influencing the water balance. The simulations show that climatic effects are limited to a shallow depth, which results from the low soil hydraulic conductivity. Calculated and direct measurements values of soil temperature profiles were compared and satisfactory results were obtained.

RÉSUMÉ

Une série d'analyses numériques a été effectuée pour étudier la sensibilité des variations de la teneur en eau, de la pression d'eau et de la température aux profils de température initiale (PTI). Le modèle sol-atmosphère est utilisé pour calculer le taux d'évaporation et du flux de chaleur en surface du sol ; les équations de transfert d'eau (liquide – loi de Darcy et vapeur – loi de Fick) couplées à l'équation du flux de chaleur (de Vries 1987) sont résolues pour déterminer les profils de température, de la teneur en eau ou de la pression d'eau. Les résultats montrent qu'il est important de connaître le bilan d'eau dans l'atmosphère pour déterminer différents profils dans le sol. Les résultats suggèrent également que le PTI peut influencer sur les profils de température mais son influence sur la pression d'eau et sur le teneur en eau volumique est faible. Au cours de la saison froide, précise albédo valeurs ne sont pas très important ni très sensibles à influencer l'eau équilibre. Les simulations montrent que les effets climatiques sont limitées à une faible profondeur, qui résulte de la faible sol conductivité hydraulique. Calculé et des mesures directes valeurs de la température du sol profils ont été comparés et des résultats satisfaisants ont été obtenus.

1 INTRODUCTION

Many geotechnical engineering problems involve unsaturated soils (i.e., the construction of embankments or earth dams, roads and railways, excavations around construction sites, slope stability, and clay liners in waste containment) and, it is accepted the importance of understanding and predicting soil water content (or suction) and temperature profiles in the unsaturated region. The spatial variation of soil water content (suction) in a drying soil sample is mainly dependent on the local environmental conditions, initial water content and temperature, hydromechanical properties of the soil, and on the boundary conditions at the soil-atmosphere interface.

The purpose of this paper is to simulate in situ water content, suction and temperature changes due to climatic effects in a soil profile during a given period by considering the interaction between the ground and atmosphere. It is applied the principle of mass and energy conservation to describe one-dimensional water (liquid and vapour) and heat flow in unsaturated soil and the surface energy balance approach to evaluate the evaporation fluxes from a soil surface.

For accurate numerical analyses of the simultaneous flow of water and heat, the boundary condition at the soil-atmosphere interface is critical. The evapotranspiration process has been widely studied in the field of meteorology and agronomy. Evaporation is referred to as the combination of two separate processes: evaporation (liquid water is converted to water vapour) and transpiration (vaporization of liquid water contained in plant tissues and the vapour removal to the atmosphere). Evaporation and transpiration occur simultaneously and there is no easy way of distinguishing between the two processes. Very often, the potential evapotranspiration (i.e., the amount of water that could evaporate and transpire from an evapotranspiration surface without restrictions other than the atmospheric demand) is calculated to obtain a first estimate. The most common methods used for potential evapotranspiration (PET) calculation are the Penman method, the Penman-Monteith method and the Turc radiation method (Federer et al. 1996). The actual evapotranspiration (ET) can be determined by either field measurement based on water balance or energy balance, or numerical analysis using standard meteorological data. For the numerical analysis, Choudhury et al. (1986) and Xu and Qiu (1997) developed different models allowing the calculation of ET in the case of bare soils (without vegetation) or homogenous canopy (grass, crops etc.).

A one dimensional explicit finite difference program developed by Gao (2006) is used for doing the numerical simulations. The program models the coupled water flow and heat flow in unsaturated soil and uses an energy estimation method for determining the evaporation rate of water from a wet soil (Choudhury et al. 1986 or Xu and Qiu 1997). The model was validated with several data sets and able to satisfactorily predict the behaviour and volumetric water content profiles for non-cohesive and cohesive soils by Gao (2006) and Cui et al. (2005, 2010).

This paper discusses the ability of the method to predict evaporative fluxes over extended periods of drying between rainfall events. The predicted values are compared with direct measurements of an extensive data collection covering both atmospheric and soil data at a site in Mormoiron located between the Mont Ventoux and the Vaucluse plateau in France. In order to model the changes in soil temperature and water content (or suction) due to climatic effects in a soil profile during a given period, it is necessary to determine the soil albedo value (i.e., the ratio of reflected to incident solar radiation). Albedo is a key parameter which controls surface energy exchange. It is a function of several surface parameters including soil color, water content, roughness and vegetation cover. Since the soil albedo value is not known, the sensitivity of predicted temperature changes due to ground-atmospheric interactions to the variations of the soil albedo is investigated. It is also discussed the influence of the initial soil temperature profile and saturated hydraulic conductivity on the predicted soil temperature and water content (or suction) profiles.

2 SOIL-ATMOSPHERE INTERFACE MODEL

The model computes the evaporation rate from soil by solving a coupled water (liquid and vapour) transport equations (Darcy's law and Fick's law), heat flow equation (de Vries 1987) analysis, and the surface energy balance used for defining a reliable boundary setting method for extended periods of evaporation simultaneously.

2.1 Soil heat and mass flow models

Similar one-dimensional model was also used by Wilson et al. (1994) and Cui et al. (2005, 2010) to describe the heat and groundwater flow in unsaturated porous media. In this model, the transient equation of liquid water and water vapour is given by:

$$\frac{\partial(h_w)}{\partial t} = C_w \frac{\partial}{\partial z}\left(k_w \frac{\partial(h_w)}{\partial z}\right) + C_v \frac{\partial}{\partial z}\left(D_v \frac{\partial P_v}{\partial z}\right) \quad [1]$$

where t (s) is the time, z (m) the elevation, h_w(m) the total hydraulic head (the sum of capillary head and elevation head z), P_v (kPa) the vapour pressure, C_w (m) and C_v (m^4 kg^{-1}) the modulus of volume change with respect to liquid phase and vapour phase respectively, D_v (kg m kN^{-1} s^{-1}) the diffusion coefficient of water vapour through soil. P_v may be related to the hw by Kelvin's equation. kw is the water hydraulic conductivity depending on capillary head.

The calculation of the vapour pressure P_v in Eq. (1) depends on the saturated vapour pressure P_{vs} and the soil temperature T (°C). Hence, the temperature profile of the soil must be determined simultaneously. The heat flow due to both conductivity and latent heat diffusion is (Wilson et al. 1994):

$$c_h \frac{\partial T}{\partial t} = \frac{\partial}{\partial z}\left(\lambda \frac{\partial T}{\partial z}\right) + L_v \frac{P + P_v}{\partial z} \frac{\partial}{\partial z}\left(D_v \frac{\partial P_v}{\partial z}\right) \quad [2]$$

where C_h(J m^{-3} $°C^{-1}$) is the volumetric specific heat capacity, representing the thermal storage capacity of the volume element considered, λ(J $s^{-1}m^{-1}$ $°C^{-1}$) is the thermal conductivity of soil, L_v(J kg^{-1}) is the latent heat coefficient of vaporisation of water ($4.186\times10^3(607-0.7T)$).

2.2 Soil-atmosphere interface boundary condition

The energy balance equation expressing the net radiation flux, R_n *(Wm^{-2})*, for the surface is (Blight 1997):

$$R_n = LE + H + G \quad [3]$$

where LE *(Wm^{-2})* is the latent energy transfer (positive for evaporation and negative for condensation), H *(Wm^{-2})* is the sensitive heat flux for the air (positive when energy is used to warm the air and negative when the air loses energy due to cooling), and *G (Wm^{-2})* is the ground heat transfer (positive when energy is transferred to the subsurface and negative when energy is transferred to the atmosphere).

The energy estimation method proposed by Choudhury et al. (1986) or Xu and Qiu (1997) is used for determining the evaporation rate of water from a wet soil. In this approach, *H* and *LE* are calculated from the turbulent exchange equations by:

$$H = \frac{\rho_a C_{pa}(T_s - T_a)}{r_a} \quad [4]$$

$$LE = \frac{L_v M_w(p_{vz0} - p_{vza})}{RTr_a} \quad [5]$$

where ρ_a is the air density, C_{pa} is the specific heat of air equal to 1.013×10^3 J/(kg.K), T_s is the soil surface temperature, T_a is the air temperature at reference height Z_a, T is the average temperature and $T \approx (T_a+T_s)/2$, p_{vz0} is the vapor pressure at the soil surface, p_{vza} is vapor pressures of in the air at reference height Z_a, r_a is the aerodynamic resistances for the sensible and latent heat fluxes, L_v is the latent heat of vaporization, M_w is the molecular mass of water equal to 0.018 kg/mol, R is the gas constant equal to 8.314 J/(mol.K). These equations take into both account both the soil-atmosphere resistance (r_a), depending on the wind velocity (u_a), the soil-atmosphere temperature (T_s-T_a) or vapor pressure (p_{vz0}-p_{vza}) gradients. The soil heat flux G is then calculated from the energy balance equation.

Aerodynamic resistances r_a is calculate as:

$$r_a = r_{a0}\frac{1}{\left(1+Ri\left(T_s-T_a\right)\right)^{\eta}} \qquad [6a]$$

where η = 0.75 in unstable condition (T_s>T_a), and η = 2 in stable condition (T_s<T_a), R_i is the Richardson Number and r_{a0} is the aerodynamic resistances derived from a logarithmic wind profile:

$$Ri = \frac{5g(z_a-d)}{u_a^2 T_a}\ , \quad \mathrm{r_{a0}} = \frac{\left[\ln\left(\frac{z_a-\mathrm{d}}{z_0}\right)\right]^2}{k^2 u_a} \qquad [6b]$$

where z_0 is the roughness length parameters for momentum (wind) and sensible heat transport, Z_a is the measurement height for wind speed u_a and relative humidity d is the displacement height , and d = 0 for bare soil, k is a constant equal to 0.41. Details of the used method are discussed in Cui et al. (2005, 2010).

2.3 Soil constitutive functions

To solve the governing equations the suction-volumetric water content and suction-unsaturated hydraulic conductivity relationships must be known. The relationships are (Cui et al. 2005):

$$\theta_w = \frac{\theta_{ws}-\theta_r}{1+\left(\frac{\theta_{ws}-\theta_r}{\theta_{w1}-\theta_r}-1\right)\left(\frac{s}{s_1}\right)^{\varsigma}}+\theta_r \qquad [7]$$

$$k_w = \frac{k_s}{1+\left(\frac{k_s}{k_{w1}}-1\right)\left(\frac{s}{s_1}\right)^{\xi}} \qquad [8]$$

where θ_{ws} is the saturated volumetric water content, θ_r is the residual volumetric water content, θ_{w1} is the value of water content corresponding to suction s_1, and ς is the parameter that controls the shape of the s-θ_w curve, k_s is the water permeability at s = 0, and k_{w1} is the hydraulic conductivity corresponding to suction s_1.

The thermal conductivity of soil, λ , is (de Vries 1963):

$$\lambda = \frac{f_s\theta_s\lambda_s + f_w\theta_w\lambda_w + f_a\theta_a\lambda_a}{f_s\theta_s + f_w\theta_w + f_a\theta_a}$$
$$\lambda_a = \lambda_{dry-air} + \lambda_{water-vapor} \qquad [9]$$

where the thermal conductivity of solid, λ_s = $(k)^q\,(k^*)^{1-q}$ (Johansen 1975), q = the quartz volume fraction, for q = 0, λ_s= 2.0 W/mK and q = 100 %, λ_s = 7.7 W/mK, the thermal conductivity of water λ_w (0.57 W/m ^{0}C), $\lambda_{dry-air}$ (0.025 W/m ^{0}C), $\lambda_{water-vapor}$ (0.608 θ_w), f_s , f_w and f_a are the weight coefficient for solid, water and air respectively and $f_w = 1.0$,

$$f_s = \left[1+\left(\frac{\lambda_s}{\lambda_w}-1\right)\right]^{-1} \qquad [10]$$

$$f_a = \frac{1}{3}\sum_{i=1}^{3}\left[1+\left(\frac{\lambda_a}{\lambda_w}-1\right)g_i\right]^{-1} \qquad [11]$$

where g_i are called shape factors (g_1 +g_2 +g_3 =1) (Gao 2006):

for θ_w > 0.121

$$g_1 = g_2 = \frac{0.333-0.105}{0.236-0.121}(\theta_w - 0.121) + 0.105$$

for θ_w < 0.121

$$g_1 = g_2 = \frac{0.105-0.015}{0.121}\theta_w + 0.015\,)$$

3 NUMERICAL SIMULATIONS

The soil heat and mass flow equations (Eqs. (1) and (2)) were solved using the explicit finite difference method (one-dimensional computer program developed at Ecole Nationale des Ponts et Chaussees by Gao 2006). It is assumed that the soil skeleton is rigid. The input data are θ_{ws} = 0.49-0.4, θ_r = 0.08, θ_{w1} = 0.24, s_1 = 700-200 kPa, and ς =1.1, k_{sat} = 1.2 x 10^{-11}-2.4 x 10^{-10}m/s) and k_{w1} = 1.2

x 10^{-14}m/s, s_1 = 40 kPa, ς'' = 1.25. The thermal coefficients C_w (4.15×10^6 J/m^3 ^oC), C_s (2.24×10^6 J/m^3 ^oC), and q = 50% and λ_s = 3.92.

The climatic data recorded at the Mormoiron site in France from December 2003 to December 2005 (i.e., solar radiation (0.05 to 0.35 *kW.m-*^{2}), energy, precipitation, runoff, wind speed (2 to 14 m/s), air temperature (0 to 25 ^oC), and air humidity) were used to set the soil-atmosphere interface boundary condition (see Figure 1). It is observed that the air temperature changes correlate well with solar radiation. The air relative humidity varies between 30 and 100%, but it does not necessary follow the precipitation pattern. The air relative humidity depends not only on precipitation, but also on air temperature and wind speed (Cui & Zornberg 2008). A water deficit is observed in most of time throughout the studied years (from December, 2003 to December, 2005) except for a brief period in December 2003, October 2004, April 2005 and October 2005. Thus, the years of 2004 and 2005 correspond to drier conditions where the recharge of the water table did not take place.

The analyses performed employed the same values of the depth of the analysis (ZMAX = 5.25 m), the constant spacing (Δz = 0.005-0.05 m), the time step (Δt = 0.5 s), the runtime, TMAX (s), bottom volumetric water content boundary (θ_b = 0.30), bottom temperature boundary (T_b= 14^oC), and initial volumetric water content profile. Sensitivity analysis were made in one dimensional idealised case where the actual land soil cover is replaced by two layers homogeneous soil column.

Since the initial temperature profile (ITP) may change during the day, it is investigated the sensitivity of predicted volumetric water content (or pore-water pressure) and temperature profiles to the variation of 5^oC in the ITP. The dependence of the soil temperature on the soil water retention curve was not considered in the numerical simulations. The Influence of Initial temperature profiles on the volumetric water content profiles was not observed. Figure 2 presents the predicted temperature profiles from January to July 2004 considering cases B and D. As can be seen from this comparison, the value of the ITP can affect the temperature profiles. The influence is more accentuated for the near surface layers, where more extreme variations in temperature occur. The results show that the temperatures increase with the depth during the cold season (January to March 2004) and decrease with the depth during the warm season (April to July 2004).

The results of the simulations using different saturated hydraulic conductivities (case B - k_{sat} = 1.2 x 10^{-11}-2.4 x 10^{-10}m/s; case B4 - k_{sat} = 1.2 x 10^{-9}-2.4 x 10^{-8}m/s) are presented in Figure 3. The insensitivity of the results presented in Figure 3 is visible. Comparisons of the soil temperature and volumetric water content profiles for Cases B and B4 reveals the same insensitivity of the results to the considered changes in k_{sat}. The years of 2004 and 2005 correspond to drier conditions (high suction values) and changes of k_{sat} of this magnitude have not significant effect on the considered suction-unsaturated hydraulic conductivity relationship.

In order to investigate the effects of the thickness of the upper layer (Z) in the two layers homogeneous soil column, Figure 4 shows the results of the numerical simulations of volumetric water content profiles using different thicknesses of the upper layer, i.e., Z= 3.45 m (Case B) and Z= 0.5m (Case B5). The results suggest that the differences between Cases B and B5 are very small. The volumetric water content and pore water pressures at depth > 1.5 m are almost constant.

The changes in soil profiles during a given period depend on the ratio of reflected to incident solar radiation (i.e., the soil albedo value). It is a function of several surface parameters including soil color, water content, roughness and vegetation cover, usually being lower for wet and rough conditions. The albedo value ranges from 0 to 1. The value of 0 refers to a blackbody, a theoretical media that absorbs 100% of the incident radiation. Albedo ranging from 0.1-0.2 refers to dark-colored, rough soil surfaces, while the values around 0.4-0.5 represent smooth, light-colored soil surfaces. The value of 1 refers to an ideal reflector surface (an absolute white surface) in which all the energy falling on the surface is reflected. The sensitivity of predicted temperature changes to the variations of the soil albedo is investigated in Figure 5, where case B (soil albedo = 0.15) and case C (soil albedo =0.05). The insensitivity of the results (Cases B and C) during the cold season (January to March 2005) is shown in Figure 5. Small changes in the soil temperature values (increase) due to the variation (decrease) of the soil albedo (case C) are observed during the warm season (April to August).

The results presented in Figures 3 and 4 indicate that the active zone (where the suction profile is influenced by seasonal environmental changes) is generally about 1.5 m deep in the investigated region. For investigating it, the results of the simulations using the actual climatic input data presented in Figure1 (case B) and the mean month input data (case G) are present in Figures 6, 7 and 8. The results show that the use of mean climatic data (dashed lines, case G) increases the soil temperature and the soil suction values, and the active zone about 3.0 m. However, more data should be investigated before anything very definite can be said about it.

Figure 9 presents the comparison of predicted and measured changes in soil temperature at three different depths (0.5m, 1.5m, and 2.5 m) during 2005 in Mormoiron, France. The results suggest that in the near the surface layers the simulations were less satisfactory due to probably vegetation effects or other mechanical phenomena (i.e., soil cracking). A sensitivity analysis of temperature and water content profiles to the changes to the variations of other unknown parameters (i.e., soil water content that depend on the soil temperature) should also be investigated. Cui et al. (2005) proposed to consider the superficial zone independently, using different values of the soil parameters.

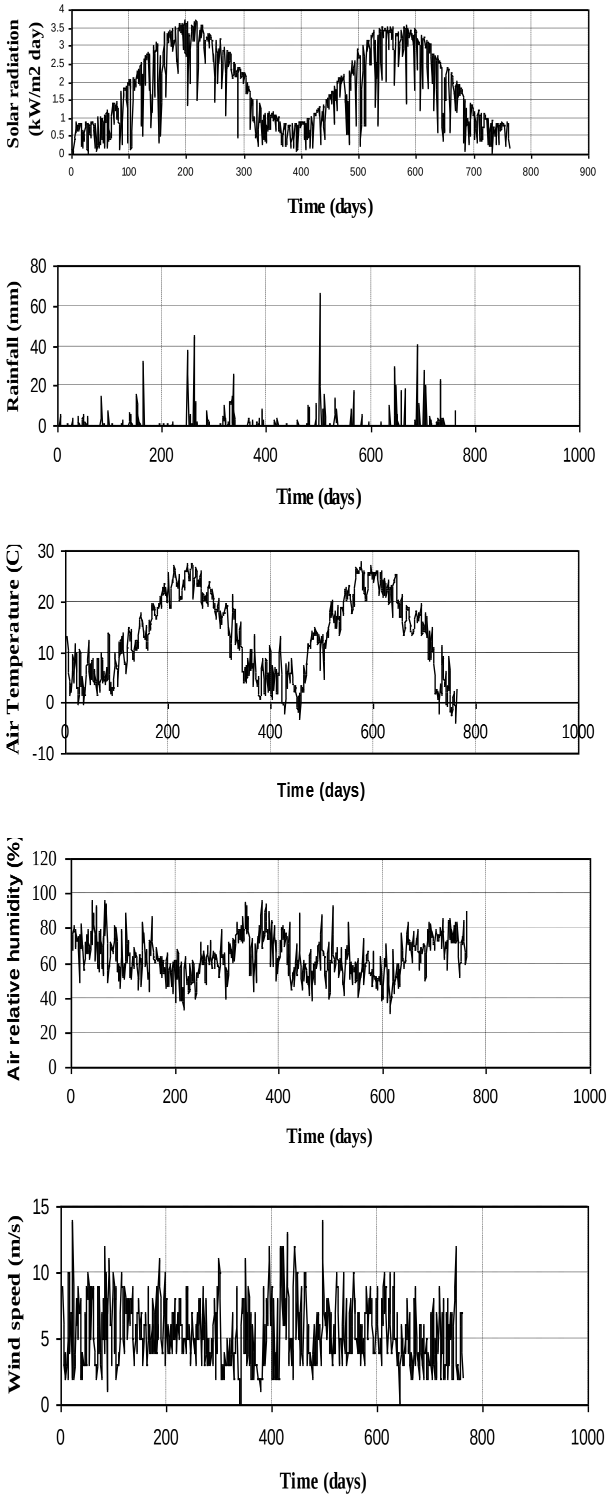

Figure 1. Distribution of the (a) daily Solar Radiation (10 kW/m^2), (b) Rainfall (mm), (c) Air Temperature (^{o}C), (d) Air Relative Humidity (%), and (e) Wind speed (m/s)

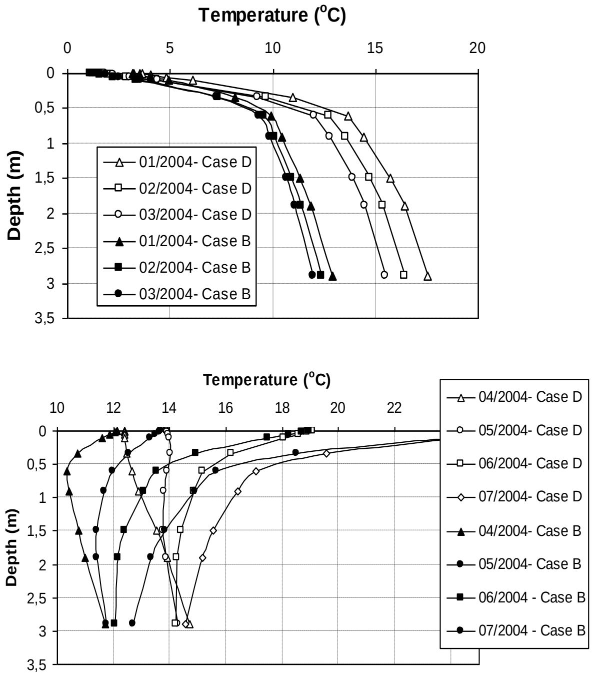

Figure 2. Influence of Initial temperature profiles on the temperature in 2004 (a) cold season, (b) warm season

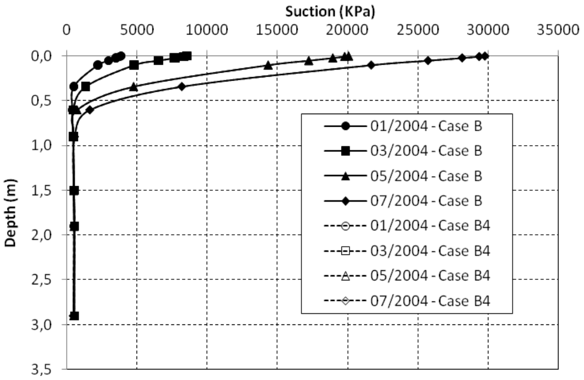

Figure 3. Influence of the k_{sat} on the suction profiles

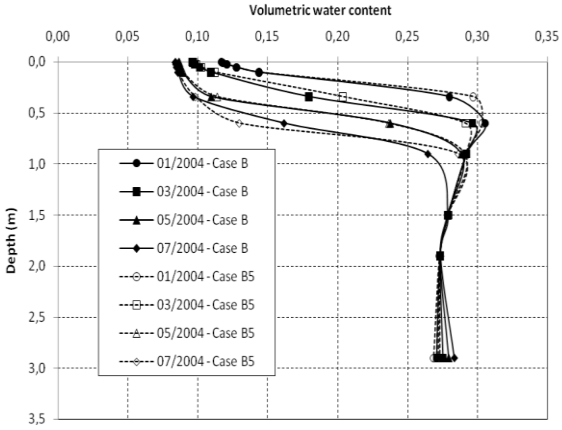

Figure 4. Influence of Z on the water content profiles

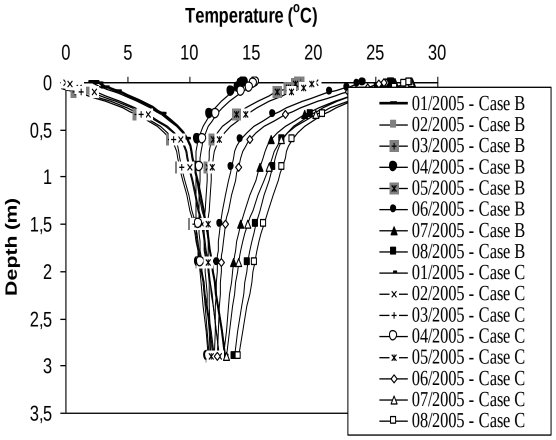

Figure 5. Influence of the soil albedo values on the temperature profiles (2005)

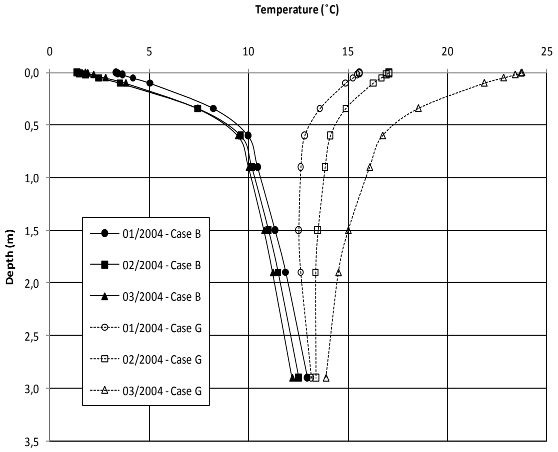

Figure 6a. Influence of climatic input data on the soil temperature profiles (months 01,02 and 03, 2004)

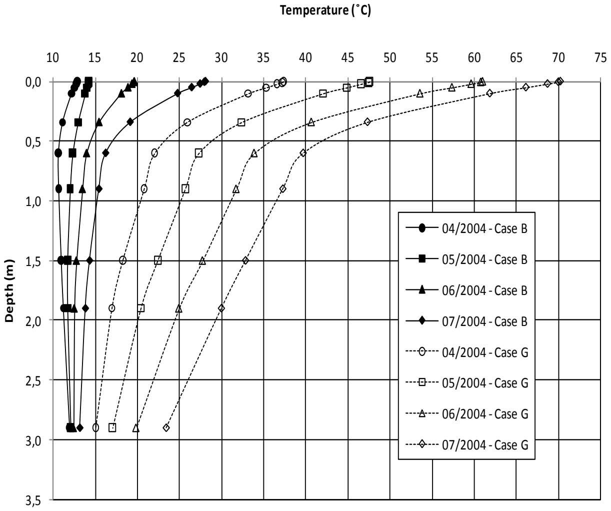

Figure 6b. Influence of climatic input data on the soil temperature profiles (months 04, 05, 06, 07, 2004)

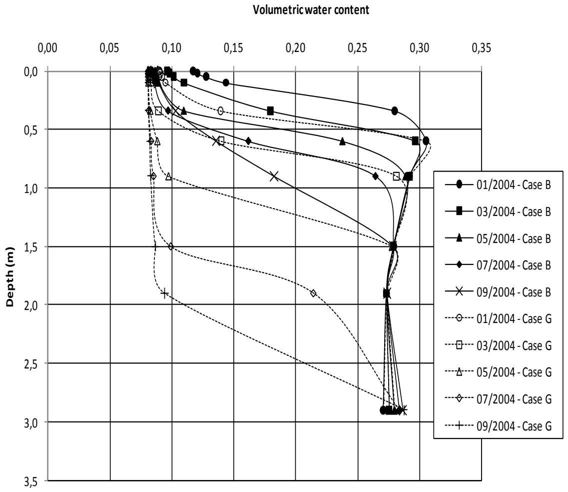

Figure 7. Influence of climatic input data on the volumetric water content profiles (2004)

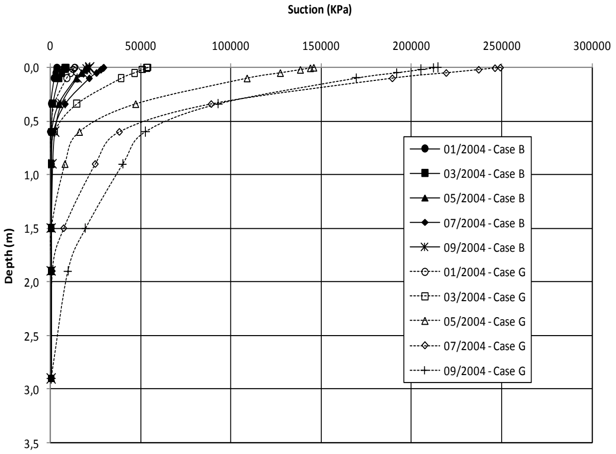

Figure 8. Influence of climatic input data on the soil

suction profiles (2004)

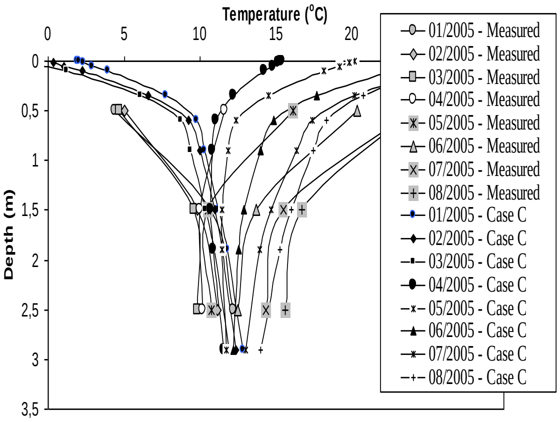

Figure 9. Comparison of predicted and measured changes in temperature profiles during 2005

4 CONCLUSIONS

An approach combining the soil-atmosphere interaction analysis and a coupled heat-water flow model was used to calculate the volumetric water content (or suction) and soil temperature profiles at any time. Based on the work of soil-atmosphere modelling of Xu and Qiu (1997) and Cui et al. (2005, 2010) the changes in soil profiles have been simulated using meteorological data obtained in the field. Estimation based on easily measured climatic data is highly desirable since direct monitoring of the suction and the volumetric water content are known to be difficult.

As all numerical simulation, the main difficulty is the determination of model parameters. In this paper, the numerical analyses carried out to investigate the sensitivity of water content, suction and temperature changes to the variations of the initial temperature profiles (ITP) suggest that the value of the ITP can affect the temperature profiles and the influence of the considered changes (i.e., 5^{o}C) on the suction (or volumetric water content) profiles is very small. In contrast to soil moisture heat enters and leaves the soil surface easier and faster.

The numerical analyses reveal the insensitivity of water content (or suction) and temperature changes to the variations of the saturated hydraulic conductivity k_{sat}. The investigated years (2004 and 2005) correspond to drier conditions (high suction values) and changes of k_{sat} of this magnitude (i.e., 100 times) have not significant effect on the considered suction-unsaturated hydraulic conductivity relationship. For the investigated soils, the changes in the thickness of the upper layer in the two layers homogeneous soil column may only slight affect the soil temperature and water content profiles. The results also show that the active zone (where the suction profile is influenced by seasonal environmental changes) is generally about 1.5m deep in the investigated region and the input climatic data.

During the cold season, precise albedo values are not very important nor very sensitive in influencing the water balance. The comparison of predicted and measured changes in temperature profiles suggest that in near the surface layers the simulations are less satisfactory due to probably vegetation effects or other mechanical phenomena (i.e., soil cracking).

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