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Discussions

Development of an efficient coupled model for soil–atmosphere modelling (FHAVeT): model evaluation and comparison

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Abstract

In agricultural management, a good timing in operations such as irrigation or sowing, is essential to enhance both economical and environmental performance. To improve such timing, predictive software are of particular interest. An optimal decision making software would require process modules which provides robust, efficient and accurate predictions while being based on a minimal amount of parameters easily available. This paper develops a coupled soil–atmosphere model based on Ross fast solution for Richards' equation, heat transfer and detailed surface energy balance. In this paper, the developed model, FHAVeT (Fast Hydro Atmosphere Vegetation Temperature), has been evaluated in bare soil conditions against the coupled model based of the De Vries description, TEC. The two models were compared for different climatic and soil conditions. Moreover, the model allows the use of various pedotransfer functions. The FHAVeT model showed better performance in regards to mass balance. In order to allow a more precise comparison, 6 time windows were selected. The study demonstrated that the FHAVeT behaviour is quite similar to the TEC behaviour except under some dry conditions. An evaluation of day detection in regards to moisture thresholds is performed.

1 Introduction

In agriculture a good timing of management operation as tillage, sowing, irrigation or yielding is an important issue for both economical and environment points of view. Inappopriate irrigation scheduling may lead to water and/or crop losses whereas using heavy engines on wet soil condition may compact soils that reduces oxygen and water flows. The decision making is multifactorial, involving work organization, meteorological forecast or soil moisture. Even if progresses have been made in soil moisture probe development, their implementation remains difficult in operational context as for capturing the spatial soil variability or handling in situ probes together with management

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operation. Modelling the soil moisture dynamic is therefore an alternative to support decisions.

As explained in the review on decision making by Ascough et al. (2008), an optimal decision making software would require process modules which provide robust, efficient and accurate predictions while being based on a minimal amount of parameters easily available. Moreover, a decision making software should allow the representation of the major processes occurring in the studied object. In regards to decision based on soil moisture for agricultural management, some important processes are the soil water and heat transfers as well as the energy balance at the soil surface.

For irrigation purposes, capacity-based models are generally used (Bergez et al., 2001; Chopart et al., 2007; Lozano and Mateos, 2008). Such conceptual models represent soil through its water storage capacity and vertical fluxes that are governed by an overflow of a compartment towards the one just below. In general, additional processes are required to better represent infiltration and upwards fluxes involving empirical parameters that are site specific and need to be calibrated since they are not measurable. In her work, Blyth (2002) compared a conceptual model to a physically based model. The physically based model showed better performances and more versatility than the conceptual model.

In the unsaturated zone, a well-known physically based description of the mass balance, in regards to water flow, is the Richards equation. The Richards equation allows a well detailed description of soil water content distribution evolution as well as water fluxes inside the soil domain. It is based on physical parameters which may be obtained through experimentation such as the retention curve and the hydraulic conductivity. Moreover, pedotransfer functions of these two curves are widely developed (Cosby et al., 1984; Rawls and Brakensiek, 1989; Wosten et al., 2001) and allow description of the parameters necessary for the resolution of Richards equation using very easily available soil characteristics such as the soil texture and bulk density. Moreover, Chanzy et al. (2008) demonstrated that pedotransfer functions may allow a good approximation for agricultural soil water representation even though the adequacy of pedotransfer functions close to the surface is still under discussion (Jarvis et al., 2013). However, the Richards equation is highly non-linear and consequently requires a rather high computing time and low mesh resolution for an accurate solving. Efforts have been made to enhance the time efficiency of the Richards equation solving. For instance, Short et al. (1995) compared resolution using finite difference scheme with the Green–Ampt infiltration model, showing that a well-chosen numerical scheme could significantly improve the performance of the Richards equation calculation. Zhang et al. (2002) studied efficient methods for modelling the unsaturated zone under prescribed infiltration and proposed an evolution of the non-linear solver, improving computing performance. Caviedes-Voullieme et al. (2013) evaluated in their work the efficiency of finite volume models, demonstrating the stability of the implicit scheme and showing that the studied model performances are dependent of soils model and mesh size. Another issue with the Richards equation is that it leads to numerical difficulties in some specific conditions such as the wetting of a dry medium. Therefore, the physically based Richards equation is rarely used for decision making software.

Ross (2003) proposed in his paper a fast resolution of Richards equation. This method demonstrated an accurate, robust and efficient behaviour on a variety of case studies. The fast resolution developed by Ross (2003) has been used in different situations in the latest years, proving its efficiency against models based on the classic resolution of the Richards equation. Varado et al. (2006) tested the solution to evaluate its efficiency and demonstrated that the model shows improved robustness and accuracy compared to analytical solutions and the model SiSPAT. In his work, Crevoisier et al. (2009) proposed a comparison of the solution with the Hydrus software in unfavourable conditions, demonstrating an improvement in efficiency and robustness. In his paper, Ross (2003) developed his method using Brooks and Corey representation of the soil retention and hydraulic conductivity curves. Manus et al. (2009) used the Ross resolution to model the impact of soil characteristics on hydrological response due to extreme events (heavy rain). They compared different pedotransfer functions

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under flooding conditions and demonstrated the importance of soil hydraulic characteristics.

To have a decision tool based on soil moisture estimation, it is important to drive the model with a climate forcing and to be able to have a wide range of soil hydraulic functions (retention curve and soil hydraulic conductivity) in order to take profit of the existing pedotransfer functions to use the model implementation with available information. Crevoisier et al. (2009) allowed the use of Van Genuchten–Mualem curves under certain conditions. In order to allow the use of a wider set of pedotransfer functions, it is important to develop further sets of retention–hydraulic conductivity curves that can be used.

Furthermore, since the model is driven by climatic forcing, a soil energy balance should also be considered. The tightly coupled equation developed by De Vries (1963) may be used. Haverd and Cuntz (2010) actually coupled the Ross solution with an energy and vapour transport equation in an analogy of the De Vries (1963) model. In such a tightly coupled model, there is a strong dependence between soil moisture, heat and vapour transport. Due to this tight coupling, more parameters and a more complex problem resolution is required. Another possibility is to consider a more loosely coupled model. In such a model, the different balances (surface energy, heat transport and moisture transfers) are evaluated sequentially. In such models, vapour transport is neglected.

Consequently and in order to keep a limited amount of input parameters, we prefer to develop a model based on the original Ross approach, which was widely tested in a large range of soil and water flow conditions. This requires combining it to soil heat transfer models and a surface energy balance through loose coupling. We take profit of the Virtual Soil[1] platform (developed at INRA) which offers coupling environment that makes the coupling of different models very easy. At longer term, the interest would be

[1]All informations about the platform and how to use it and contribute can be found in the dedicated web site: http://www.inra.fr/sol_virtuel

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to enlarge the scope of the soil water and heat transfer model to other processes such as root uptake, solute transport, biogeochemical reaction or soil properties dynamic.

The aim of this paper is to present the evolution of the Ross model development from Crevoisier et al. (2009). This evolution concerns the introduction of a climate forcing, new soil hydraulic functions as well as a loose coupling between soil mass balance, soil energy balance and surface energy balance. Then, the hypotheses of the model, specifically the loose coupling between processes which implies a lack of vapour transport, will be studied. The impact of errors induced by such hypotheses will be evaluated by considering both soil moisture accuracy and the timing in taking decision based on a moisture threshold. To do so, a comparison between the developed and the tightly coupled model TEC (Chanzy and Bruckler, 1993) used as a reference will be made.

2 Model description

The model FHAVeT (Fast Hydro Atmosphere Vegetation Temperature) consists in the coupling of a surface energy balance, a soil energy balance and a soil mass balance module. Simulations have been performed using the INRA Virtual Soil platform. The platform provides an easy way to use and couple numerical modules representing processes occurring in soils. A scheme of the model is presented in Fig. 1. The model consists of three main modules computed sequentially in the following order: Surface Energy Balance – Soil Water Transfer – Soil Heat Transfer. As shown in Fig. 1 the surface energy balance is driven by climatic forcing, soil surface temperature and soil surface potential and it computes evaporation/rainfall and soil surface heat flux. The soil water transfer module is driven by evaporation/rainfall and computes soil potential, water flux and moisture content. Finally, the soil heat transfer module depends on water flux, moisture content and surface heat flux and evaluates soil temperature.

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2.1 Surface energy balance

The surface energy balance module is based on a double source model as used in SiSPAT (Braud et al., 1995). An equation of energy budget (Eq. 2) at the soil surface is used to obtain the soil surface heat flux G ($\mathrm{W\,m^{-2}}$) and the soil evaporation flux E_g ($\mathrm{kg\,m^{-2}\,s^{-1}}$).

$$\mathrm{Rn_g} = H_\mathrm{g} + L_\mathrm{v}(T_\mathrm{s})E_\mathrm{g} + G \tag{1}$$

$$= -\rho_\mathrm{a} c_p \frac{(T_\mathrm{a} - T_\mathrm{s})}{R_\mathrm{aH}} - L_\mathrm{v}(T_\mathrm{s})\frac{\rho_\mathrm{a}(h_\mathrm{a} - h_\mathrm{s})}{R_\mathrm{av}} + G \tag{2}$$

In this equation, $\mathrm{Rn_g}$ ($\mathrm{W\,m^{-2}}$) is the net radiation, L_v ($\mathrm{J\,kg^{-1}}$) is the latent heat of vaporization and H_g ($\mathrm{W\,m^{-2}}$) is the sensible heat flux. The aerodynamic resistances for heat and vapour R_aH and R_av are calculated using the formulation by Taconet et al. (1986). T corresponds to the temperature and h to the specific humidity (mass of water in air over mass of humid air), subscripts "a" relates to the air and "s" to the soil surface level. Moreover, ρ_a ($\mathrm{kg\,m^{-3}}$) is the air density and c_p the specific heat at constant pressure. Solving Eq. (2) requires climatic observation parameters, as well as the soil surface temperature and soil surface water potential calculated from the soil heat and water transfers at the previous time step and input parameters as described in Table 2.

2.2 Soil mass balance

Ross' fast solution for Richards equation is described in Ross (2003) and Fast Hydro, the upgraded implementation of Ross method used in this study is described in Crevoisier et al. (2009). It solves the Richards equation by a non-iterative approach. Ross' fast solution may be written as in Eqs. (4) and (5) with w representing the saturation degree ($S = (\theta - \theta_\mathrm{r})/(\theta_\mathrm{s} - \theta_\mathrm{r})$) in unsaturated conditions and Kirchhoff potential ($\phi(h) = \int_{-\infty}^{0} K(\tilde{h})\mathrm{d}\tilde{h}$ in $\mathrm{m^2\,s^{-1}}$) when soil is saturated. θ ($\mathrm{m^3\,m^{-3}}$) is the volumetric soil

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moisture content.

$$(\theta_{si}-\theta_{ri})e_i\frac{\Delta S_i}{\Delta t} = -\left(q^{\sigma}_{i-1}-q^{\sigma}_{i}\right) \quad \text{if } S_i<1 \tag{3}$$

$$0 = -\left(q^{\sigma}_{i-1}-q^{\sigma}_{i}\right) \quad \text{if } S_i=1 \tag{4}$$

$$q^{\sigma}_{i} = q^{0}_{i} + \sigma\left(\left[\frac{\delta q_i}{\delta w_i}\right]^0 \Delta w_i + \left[\frac{\delta q_i}{\delta w_{i+1}}\right]^0 \Delta w_{i+1}\right) \tag{5}$$

K represents the hydraulic conductivity ($\mathrm{m\,s^{-1}}$), θ_r and θ_s ($\mathrm{m^3\,m^{-3}}$) the residual and saturated water contents, e_i (m) the cell i thickness, q^{σ}_{i} ($\mathrm{m\,s^{-1}}$) the darcian flux at time $t+\sigma\mathrm{d}t$ between cells i and $i+1$ when cell $i+1$ is deeper than cell i. Detailed description of the fluxes and fluxes derivative may be found in Crevoisier et al. (2009). Similarly to the code developed in Crevoisier et al. (2009), a water surface layer and time step optimization are used. Different analytical representations of the hydraulic properties may be used (Table 1).

2.3 Soil energy balance

The soil energy balance is modelled using a simple convection diffusion model (Eq. 6) with convection being limited to the liquid phase.

$$\rho C_\lambda \frac{\partial T}{\partial t} + \rho_\mathrm{w} C_\mathrm{w} \boldsymbol{q}^{\sigma}\cdot\nabla T = \nabla\cdot(\lambda\nabla T) \tag{6}$$

where ρ (ρ_w) ($\mathrm{kg\,m^{-3}}$) is density of the medium (of water) and C_λ (C_w) ($\mathrm{J\,kg^{-1}\,K^{-1}}$) is the specific heat of the medium (water) and λ ($\mathrm{W\,m^{-1}\,K^{-1}}$) is the soil heat conductivity. Heat transport parameters are dependent on soil moisture. The soil medium heat capacity (density) is calculated as the mean of water and solid capacities (densities) weighed by volume. The soil heat conductivity has a linear dependence on soil water content

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following Eq. (7).

$$\lambda = (1/0.654(\Lambda_s + 2300\theta - 1890))/C_\lambda \tag{7}$$

Moreover, impact of the rain on fluid transport is considered with rain having a constant temperature of 283 K.

2.4 The reference model: TEC

The TEC model (Chanzy and Bruckler, 1993) is a tightly coupled finite element model based on the heat and mass flow theory in unsaturated media (De Vries, 1963). This model solves equations for water transfer, heat and vapour transport using climatic forcing in case of bare soil. This model was used for the evaluation of various pedotransfer functions and implementation strategies were proposed under operational context when only limited information are available to describe the soil system in the work by Chanzy et al. (2008). The major difference between TEC and the FHAVeT lies in the water and heat transfers coupling. Indeed, TEC considers vapour flow, and its impact on heat and liquid water transfers, whereas FHAVeT does not. There are however others differences between the two models. The evolution of soil heat conductivity with soil moisture and the aerodynamic resistances are calculated through different means. Moreover, the numerical spatial discretisations are different.

3 Model intercomparison

The knowledge of soil moisture profile is critical when it comes to agricultural management. Therefore, the prediction capacity in regards to soil moisture of the FHAVeT model is going to be the major focus of the intercomparison even though both TEC and FHAVeT are coupled models. The reference model TEC was moreover evaluated in regards to soil moisture in the top 5 and 30 cm against experimental data in the work of Chanzy et al. (2008). Model intercomparison will thus be done using the data and parameters shown in their work.

The cases studied were chosen so as to offer a variety of climatic and soil conditions that may occur in France and in agronomic context. Two climatic sequences are used. The first one was measured at Avignon (southern France, 43.78° N, 4.73° E) and represents a Mediterranean climate with occasional heavy rains and long periods of dryness (Fig. 2a). Wind velocity also varies strongly. The second climatic sequence was measured at Estree-Mons (northern France, 48.99° N, 2.99° E). It represents an oceanic climate with frequent light rainfalls and short dryness periods (Fig. 2b).

Four soils from the sites of Estree-Mons and Avignon with various textures, rangeing from silty loam to silt clay loam (Table 3) were chosen for the study.

As described Table 1, the model developed uses different methods of integration for the calculation of the Kirchhoff potential. In order to evaluate the impact of the integration method used, three different sets of hydraulic properties were used for each soil. Each set corresponds to an integration method (analytical, beta functions and numerical integration) which allow the use of several pedotransfer functions. The pedotransfer function developed by Cosby et al. (1984) offers parameters corresponding to a Brooks and Corey set of hydraulic properties and therefore requires the use of analytical integration in the software. The pedotransfer function developed in Rawls and Brakensiek (1989) allows deriving of Van Genuchten–Mualem hydraulic properties parameters with the hypothesis of shape parameter η equals 0.5. Therefore integration using beta functions may be used. Finally, the pedotransfer function of Wosten et al. (2001) also derives Van Genuchten–Mualem parameters, but shape parameters η obtained are usually below -1, therefore numerical integration is necessary. Those three pedotransfer functions were consequently used. All three functions require the same parameters, which are the textural characteristics of soils, summarised Table 3.

Thermal characteristics of the different soils were considered dependent on volumetric soil moisture content. The heat capacity is calculated as the mean of soil and water capacities weighed by relative volumes. In the FHAVeT model, the heat conductivity dependence on the soil moisture content is obtained through Eq. (7).

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The thermal inertia at saturation Λ_s ($J\,m^{-2}\,K^{-1}\,s^{-1/2}$) has been tabulated against soil textures by Van de Griend and O'Neill (1986). In the TEC model, the evolution of heat conductivity is obtained through the De Vries (1963) description.

Initial values for soil matric potential and soil temperature used in the FHAVeT model were the ones derived using TEC model from a preliminary climatic sequence (Chanzy et al., 2008). Constant matric potential (−3.33 m) and temperature (293 K) are considered at the bottom of the studied domain for both models as used in Chanzy et al. (2008).

The one-dimensional mesh used in FHAVeT is homogeneous with a cell thickness of 2 cm and a total soil thickness of 80 cm while the mesh used in TEC is refined close to the surface with element thicknesses rangeing from 0.6 cm to 5 cm.

4 Results and discussion

To compare the numerical accuracy of both models, a calculation of mass balance was performed. The mass balance absolute error was computed as the absolute difference between in and outflow of the soil domain and the soil water stock evolution at each time step. As shown in Fig. 3 the TEC mass balances are not always respected (error lower than 1 %) due to strong water potential near the surface in dry conditions. FHAVeT offers improved results in regards to mass balance compared to the TEC model. In most cases the absolute mass balance error was below 0.2 % with only one case being higher. In this particular point, corresponding to the soil AL-SiCL with the Wosten pedotransfer functions and under the Avignon climate, both the computing time and the mass balance (0.8 % error) were unsatisfying. Richard's equation is used under a mixed form in the developed model, meaning that the variables derived are different when a cell is saturated (Kirchhoff potential) or unsaturated (saturation) (see Eq. 5). Therefore, when a cell is going from unsaturated to saturated state (or reversely), the calculation undergoes an error. For the permeability curves from Wosten et al. (2001), there is a very steep non linear variation of permeability close to the saturation. This

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leads to a slow numerical calculation of the permeability close to saturation state as well as a strong discrepancy between the soil saturated and slightly unsaturated state flow characteristics. All these considerations lead to a heightened probability of an "oscillation" to occur between saturated and unsaturated states and the consequent error accumulation. An improvement of the numerical integration method should, however, improve the computation time and allow the use of a more constraining numerical tolerance.

Figure 4 shows the comparison of all cases studied between soil moisture content of both models for the 0–5 cm and 0–30 cm soil layers. The models show generally good agreement. However, divergences between the models are observed.

In order to study the conditions of these divergences 6 time windows (TW) were selected with the objective of studying specific features of the two climatic sequences (Fig. 5). TW 1 and 2 are chosen within the first drying period of the Avignon sequence with TW 1 showing strong wind conditions and TW 2 little wind conditions. Indeed, Chanzy and Bruckler (1993) demonstrated that wind has an influence on vapour transport with lower vapour flow when the convective part of the climatic demand is stronger. TW 3 is selected during the heavy rain period of the Avignon sequence. TW 5 covers the drying conditions of the Estree-Mons climate. Finally, TW 4 and 6 were chosen during wet periods of the Estree-Mons sequence, respectively before and after the dry period. A summary of the averaged climatic conditions during those 6 time periods is shown in Table 4.

Figure 6 show the histogram of the absolute difference distribution between the water content averaged over a defined soil depth (0–5 cm and 0–30 cm) for both models over each time window. The comparison takes into account all pedotransfer functions.

It can be clearly observed that under wet conditions (TW 3, 4 and 6) the two models led to similar results with the absolute difference in averaged water content being lower than 0.01 $m^3 m^{-3}$ for around 80 % of the time in the 0–5 cm soil layer and always below 0.03 $m^3 m^{-3}$ in the 0–30 cm soil layer. However, under dry conditions (TW 1, 2 and 5) the difference between the two models is more consequent. This is especially true

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in TW 5, where there is little rain for a long time (1.5 mm in 12 days), which leads to absolute water content difference going over 0.1 $m^3\,m^{-3}$. This discrepancy between the two models is most likely due to the loose coupling and thus to the effect of vapour transport.

As it may be observed in Fig. 7, the model FHAVeT tends to underestimate the evaporation of soil under drying conditions and consequently leads to a higher soil moisture content in the observed soil layer. The errors are larger in the 0–5 cm layer than in the 0–30 cm layer which tends to demonstrate that the impact of vapour transport is most important close to the surface. Such considerations are further observed in Fig. 8. This figure compares two moisture profiles for each model. Under dry conditions (during TW 5) the profiles are alike below 30 cm and their discrepancy increases when depth decreases with the larger difference being around 8 % at the surface. However, after a rainy period, the profile is almost recovered in TW 6. This may demonstrate that the neglected volume of evaporated water is not very important in regards to the total amount of water.

In decision-support software, it is common to use thresholds as criteria for decision for agronomic purpose such as soil moistening. Therefore, the ability of a model to accurately detect the day when the soil moisture status crosses such thresholds is essential. Figure 9 shows the amount of accurate dates (considering TEC as a reference) at which a given saturation value (for the top 30 cm layer) was detected either from dry to wet conditions (wetting) or from wet to dry conditions (drying) as well as day detection with a one day tolerance.

Due to the little amount of saturation conditions below 50 % the lowest threshold showed in Fig. 9 is 60 %. It can be observed that thresholds are detected at the same date for two thirds of the cases at higher saturation (thresholds 90 and 80 %) and a little over half of the cases for thresholds 70 and 60 % during drying. The success rate is much higher during wetting. Moreover, day detection accuracy with a one day tolerance is quite high with values of 90 %.

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Important day detection delay (or advance) of over three days have occurred in only 0.8 % of the cases and significant day detection misses (when the threshold is crossed for more than three days) in 1.4 % of the cases. The day detection inaccuracy may have different causes. The case where mass balance error is high has lead to an early detection in the FHAVeT model. This is likely due to the numerical error as the discrepancy between soil water volume between the two models and the mass balance error in the FHAVeT model are quite similar. The other cause of day detection miss or delay could be the lack of vapour transport. Indeed, all other day detection misses or delay appear during the drying period and especially TW 5. When the soil is in dry conditions, the hydraulic conductivity is low, thus limiting the transfer of liquid water. However, when vapour transport is considered it allows faster drying of the soil. Therefore, in a tightly coupled model such as TEC, the soil is allowed to dry at a higher pace leading to earlier day detection than in a loosely coupled model such as FHAVeT. Extended dry conditions that allow significant evaporation seem necessary though not sufficient for the FHAVeT model to diverge from the tightly coupled TEC model. Indeed, the dry period in the Mons climate is not well represented but the dry period in the Avignon climate is simulated accordingly to the TEC model. The reason why there is a difference in accuracy between the dry period in the Avignon climate and in the Mons climate remains unclear and further testing is necessary to evaluate possible sources such as the impact of soil moisture history.

5 Conclusions

FHAVeT extends the model developed by Ross (2003) and improved by Crevoisier et al. (2009) by introducing a coupling with the atmospheric conditions and by considering a wider range of soil hydraulic functions in order to take profit of commonly used pedotransfer functions. The coupled model is based on existing process modules and uses the coupling technology offered by the soil virtual modelling platform to make the software development easier. As a consequence, a loose coupling between soil heat

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and mass flow is introduced leading to ignore water vapour flows. Moreover, water and heat flow are computed sequentially. The model demonstrated good efficiency and improved mass balance conservation in comparison to the model TEC with the exception of one particular condition. In that case, the soil characteristic curves (soil water retention and relative permeability) are highly non-linear and lead to an "oscillatory" behaviour between saturated and unsaturated state, accumulating numerical errors.

The loose coupling leads to little error in rainy conditions. Under dry conditions the error is larger, which was to be expected due the more important role of vapour transport. However, the simulated discrepancy is limited to the firsts centimetres and therefore concerns a rather limited volume of water.

Since the developed model is aimed at being a support for decision making software, it is important that it accurately simulates threshold criteria. The FHAVeT and TEC models are in good agreement for around 90 % of the day detections with a one day tolerance. Considering the modelling parameters and initial conditions uncertainties in field application, such a tolerance seems to be acceptable. Moreover, due to the lesser computing time (Crevoisier et al., 2009) required by the Ross solution, the FHAVeT model is a much better candidate than TEC for improvement techniques of parameter and initial conditions description such as data assimilation.

However, under drying conditions, the FHAVeT model may fail to correctly simulate the soil drying, especially close to the surface. In such conditions, wrong decisions may be taken even though the model allowed good recovery of the soil moisture after a rainy period. It is consequently important to fully identify the specific climatic and soil history conditions that lead to inaccurate description of the soil behaviour in regards to moisture content. To do so, a wider evaluation of the model, as well as a comparison with experimental field values require further work. Future improvement of the model include a better numerical integration method in order to deal with highly non-linear soil characteristic functions as well as coupling with water transfers due to vegetation.

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References

Ascough, J., Maier, H., Ravalico, J., and Strudley, M.: Future research challenges for incorporation of uncertainty in environmental and ecological decision-making, Ecol. Model., 219, 383–399, 2008. 8573

Bergez, J.-E., Debaeke, P., Deumier, B., Lacroix, B., Leenhardt, D., Leroy, P., and Wallach, D.: MODERATO: an object-oriented decision tool for designing maize irrigation schedules, Ecol. Model., 137, 43–60, 2001. 8573

Blyth, E.: Modelling soil moisture for a grassland and a woodland site in south-east England, Hydrol. Earth Syst. Sci., 6, 39–48, doi:10.5194/hess-6-39-2002, 2002. 8573

Braud, I., Dantas-Antonino, A., Vauclin, M., Thony, J., and Ruelle, P.: A Simple Soil Plant Atmosphere Transfer model (SiSPAT), J. Hydrol., 166, 213–250, 1995. 8577

Brutsaert, W.: Evaporation into the Atmosphere: Theory, History and Applications, D. Reidel Publishing Co., Dordrecht, 1982 8590

Caviedes-Voullieme, D., Garcia-Navarro, P., and Murillo, J.: Verification, conservation, stability and efficiency of a finite volume method for the 1D Richards equation, J. Hydrol., 480, 69–84, 2013. 8574

Chanzy, A. and Bruckler, L.: Significance of soil surface moisture with respect to daily bare soil evaporation, Water Resour. Res., 29, 1113–1125, 1993. 8576, 8579, 8582

Chanzy, A., Mumen, M., and Richard, G.: Accuracy of top soil moisture simulation using a mechanistic model with limited soil characterization, Water Resour. Res., 44, W03432, 1–16, 2008. 8573, 8579, 8581, 8591

Chopart, J., Mezino, M., Aure, F., Le Mezo, L., Mete, M., and Vauclin, M.: OSIRI: a simple decision-making tool for monitoring irrigation of small farms in heterogeneous environments, Agr. Water Manage., 87, 128–138, 2007. 8573

Cosby, B., Hornberger, G., Clapp, R., and Ginn, T.: A statistical exploration of the relationship of soil moisture characteristics to the physical properties of soils, Water Resour. Res., 20, 682–690, 1984. 8573, 8580

Crevoisier, D., Chanzy, A., and Voltz, M.: Evaluation of the Ross fast solution of Richards' equation in unfavourable conditions for standard finite element methods, Adv. Water Resour., 32, 936–947, 2009. 8574, 8575, 8576, 8577, 8578, 8584, 8585, 8589

De Vries, D.: Thermal properties of soil, in: Physics of Plant Environment, North-Holland Publishing Co., the Netherlands, 210–235, 1963. 8575, 8579, 8581

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Haverd, V. and Cuntz, M.: Soil–Litter–Iso: a one-dimensional model for coupled transport of heat, water and stable isotopes in soil with a litter layer and root extraction, J. Hydrol., 388, 438–455, 2010. 8575

Jarvis, N., Koestel, J., Messing, I., Moeys, J., and Lindahl, A.: Influence of soil, land use and climatic factors on the hydraulic conductivity of soil, Hydrol. Earth Syst. Sci., 17, 5185–5195, doi:10.5194/hess-17-5185-2013, 2013. 8574

Lozano, D. and Mateos, L.: Usefulness and limitations of decision support systems for improving irrigation scheme management, Agr. Water Manage., 95, 409–418, 2008. 8573

Manus, C., Anquetin, S., Braud, I., Vandervaere, J.-P., Creutin, J.-D., Viallet, P., and Gaume, E.: A modeling approach to assess the hydrological response of small mediterranean catchments to the variability of soil characteristics in a context of extreme events, Hydrol. Earth Syst. Sci., 13, 79–97, doi:10.5194/hess-13-79-2009, 2009. 8574

Rawls, W. and Brakensiek, D.: Estimation of soil water retention and hydraulic properties, in: Unsaturated Flow in Hydrologic Modeling – Theory and Practice, edited by: Morel-Seytoux, H. J., Kluwer Academic Publishing, Dordrecht, 275–300, 1989 8573, 8580

Ross, P.: Modeling soil water and solute transport – fast, simplified numerical solutions, Agron. J., 95, 1352–1361, 2003. 8574, 8577, 8584, 8589

Short, D., Dawes, W., and White, I.: The practicability of using Richards' equation for general purpose soil–water dynamics models, Environ. Int., 21, 723–730, 1995. 8574

Taconet, O., Bernard, R., and Vidal-Madjar, D.: Evapotranspiration over an agricultural region using a surface flux/temperature model based on NOAA-AVHRR data, J. Clim. Appl. Meteorol., 25, 284–307, 1986. 8577

Van de Griend, A. and O'Neill, P.: Discrimination of soil hydraulic properties by combined thermal infrared and microwave remote sensing, Proceedings of the 1986 International Geoscience and Remote Sensing Symposium (IGARSS '86), Zurich, Switzerland, 8–11 September, ESA publication SP 254, 839–845, 1986. 8581

Varado, N., Braud, I., and Ross, P.: Development and assessment of an efficient vadose zone module solving the 1D Richards' equation and including root extraction by plants, J. Hydrol., 323, 258–275, 2006. 8574

Wosten, J., Pachepsky, Y., and Rawls, W.: Pedotransfer functions: bridging the gap between available basic soil data and missing soil hydraulic characteristics, J. Hydrol., 251, 123–150, 2001. 8573, 8580, 8581

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Zhang, X., Bengough, A., Crawford, J., and Young, I.: Efficient methods for solving water flow in variably saturated soils under prescribed flux infiltration, J. Hydrol., 260, 75–87, 2002. 8574

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Table 1. Hydraulic properties curves available in FHAVeT and Kirchhoff potential calculation methods.

Retention curve	Hydraulic conductivity curve	Kirchhoff potential calculation
Brooks and Corey $S(h) = (\alpha_{BC} h)^{-\lambda}$	Corey $K = K_{sat} S^{\eta}$	Analytical (Ross, 2003)
Linear $S(h) = \exp(\alpha_G (h - h_e))$	Linear $K = K_{sat} S$	Analytical (Crevoisier et al., 2009)
Van Genuchten $S(h) = \left(1 + \lvert\alpha_{VG} h\rvert^{n}\right)^{-m}$	Mualem $K = K_{sat} S^{\eta}[1 - (1 - S^{1/m})^{m}]^2$	Numerical ($\eta = 0.5$) (Crevoisier et al., 2009)[a] Beta functions ($\eta > -1$)[b] Numerical ($\eta \leq -1$)[b]
modified Van Genuchten $S(h) = \frac{1}{S_M}\left(1 + \lvert\alpha_{VG} h\rvert^{n}\right)^{-m}$ $S_M = \left(1 + \lvert\alpha_{VG} h_e\rvert^{n}\right)^{-m}$	Mualem $k_r = \frac{S_M S^{\eta}}{k_M}\left[1 - (1 - \left(S_M S\right)^{1/m}\right)^{m}\right]^2$ $k_M = S_M^{\eta}\left[1 - \left(1 - S_M^{1/m}\right)^{m}\right]^2$	Numerical ($\eta = 0.5$) (Crevoisier et al., 2009)[a] Beta functions ($\eta > -1$)[b] Numerical ($\eta \leq -1$)[b]
Van Genuchten $S(h) = \left(1 + \lvert\alpha_{VG} h\rvert^{n}\right)^{-m}$	Corey $K = K_{sat} S^{\eta}$	Beta functions[b]

[a] Integration method upgraded.
[b] New feature in the FHAVeT model.

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Table 2. Model parameters.

Climatic forcing data		
Short-wave incoming radiation RG	$\mathrm{W\,m^{-2}}$	
Long-wave incoming radiation RA	$\mathrm{W\,m^{-2}}$	
Atmospheric temperature at reference height T_a	K	
Atmospheric pressure p_{atm}	Pa	
Air vapour content e_a	Pa	
Wind velocity at reference height U_a	$\mathrm{m\,s^{-1}}$	
General properties		
Water density ρ_w	$1000\,\mathrm{kg\,m^{-3}}$	
Air density ρ_a	$\mathrm{kg\,m^{-3}}$	Function of temperature and pressure
Latent heat of vaporization L_v	$\mathrm{J\,kg^{-1}}$	Function of temperature
Specific heat of dry air at constant pressure c_p	$1004\,\mathrm{J\,K^{-1}\,kg^{-1}}$	
Specific heat of water C_w	$4181\,\mathrm{J\,kg^{-1}\,K^{-1}}$	
Surface energy properties		
Ground surface albedo α_g	0.20–0.30	Function of surface water content
Ground surface emissivity ε_g	0.96	
Roughness length for momentum z_{om}	0.002 m	
Roughness length for heat z_{oh}	m	Calculated with Brutsaert (1982) formula
Soil hydraulic properties		
Saturated volumetric water content θ_s	$\mathrm{m^3\,m^{-3}}$	
Residual volumetric water content θ_r	$\mathrm{m^3\,m^{-3}}$	
Water retention curve parameters		
Hydraulic conductivity curve parameters		
Soil thermal properties		
Soil heat conductivity λ	$\mathrm{W\,m^{-1}\,K^{-1}}$	Function of soil water content
Soil heat capacity C_λ	$\mathrm{J\,kg^{-1}\,K^{-1}}$	Function of soil bulk density

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Table 3. Soil characteristics for comparative study, from Chanzy et al. (2008).

Soil ID	Depth (m)	Texture	Clay %	Sand %	Bulk density ($kg\,m^{-3}$)	Organic Matter %
AL-SiL	0.00–0.10	Silt loam	17.00	34.30	1240	1.50
	0.10–0.40		17.00	29.20	1280	1.50
	0.40–0.80		17.00	29.20	1460	1.00
AL-SiCL	0.00–0.10	Silt clay loam	38.90	5.30	1300	2.50
	0.10–0.40		39.70	4.60	1350	2.50
	0.40–0.80		48.10	2.00	1600	1.00
MO-SiL	0.00–0.33	Silt loam	14.50	5.20	1280	2.10
	0.33–0.80		25.20	3.00	1520	0.90
PO-SiCL	0.00–0.10	Silt clay loam	27.20	11.00	1290	2.40
	0.00–0.25		27.20	11.00	1400	2.40
	0.25–0.80		27.20	11.00	1600	1.00

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Table 4. Climatic forcing summary for the selected time windows (TW).

Case	Site	Start date	End date	Duration	Temperature	Precipitation	Wind velocity
TW 1	Avignon	23 Sep 1997	30 Sep 1997	168 h	14.9 °C	0 mm	$5.14\,m\,s^{-1}$
TW 2	Avignon	30 Sep 1997	05 Oct 1997	120 h	15.3 °C	0 mm	$0.65\,m\,s^{-1}$
TW 3	Avignon	11 Oct 1997	12 Oct 1997	24 h	15.9 °C	55 mm	$1.25\,m\,s^{-1}$
TW 4	Mons	4 Oct 2004	8 Oct 2004	91 h	15.9 °C	16 mm	$4.08\,m\,s^{-1}$
TW 5	Mons	16 Oct 2004	25 Oct 2004	214 h	14.9 °C	1 mm	$3.09\,m\,s^{-1}$
TW 6	Mons	26 Oct 2004	31 Oct 2004	120 h	12.9 °C	11 mm	$3.06\,m\,s^{-1}$

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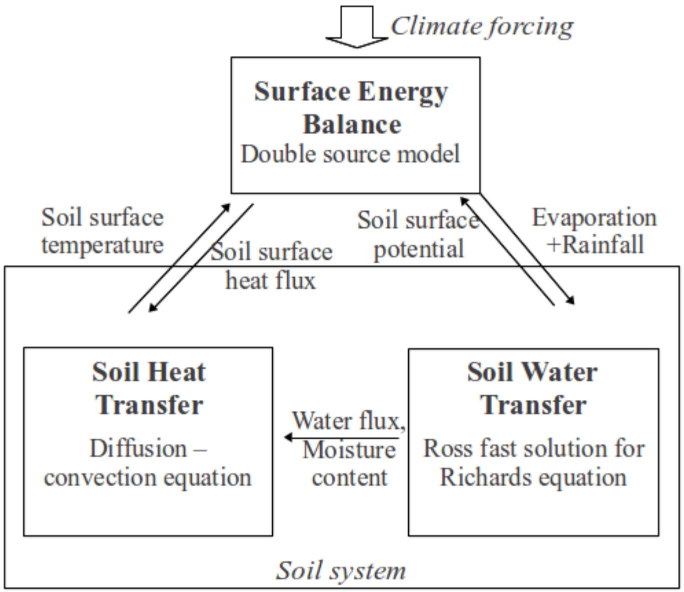

Figure 1. Schematic of the FHAVeT model.

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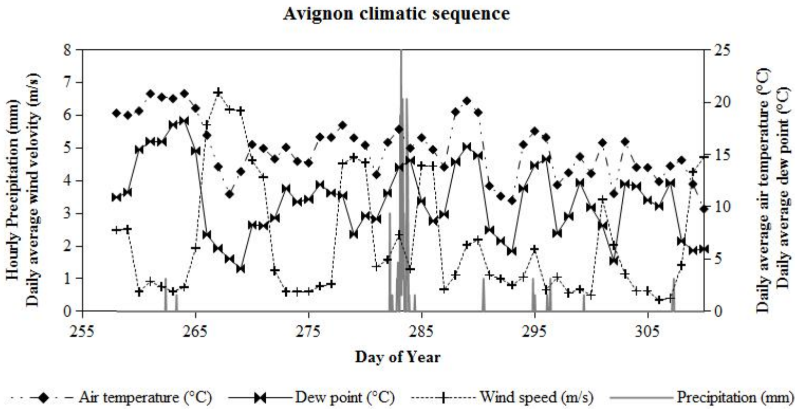
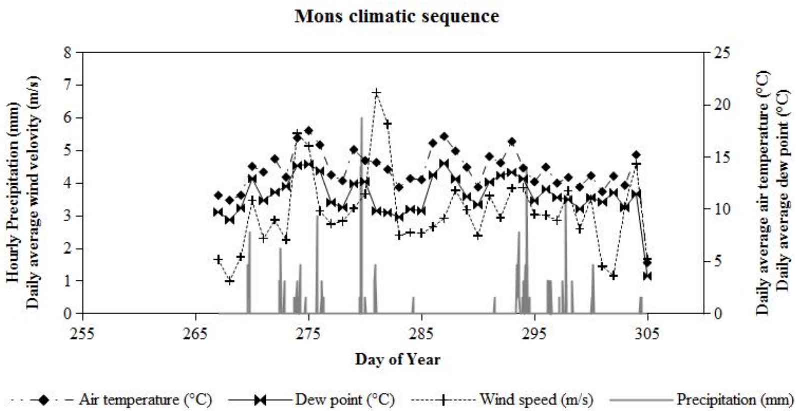


(a) Avignon sequence



(b) Estree-Mons sequence

Figure 2. Climate forcing – precipitation, air temperature, dew point and wind velocity at 2 m height.

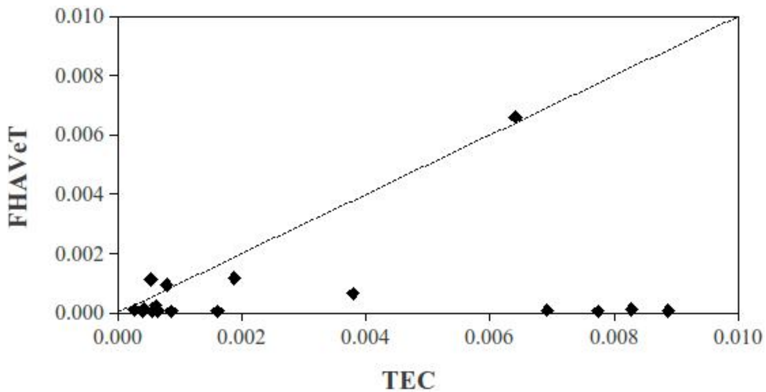


Figure 3. Maximum absolute error in mass balance (in water cubic meter per unit soil surface) – comparison between models.

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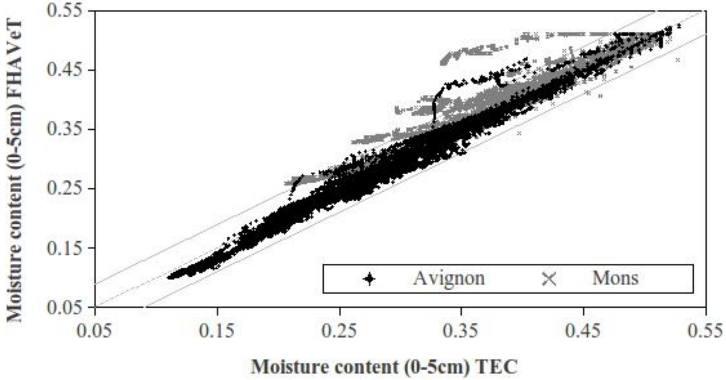
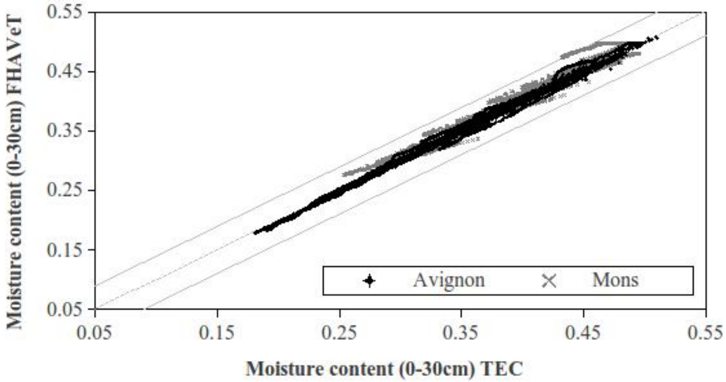


(a) 0-5 cm layer



(b) 0-30 cm layer

Figure 4. Comparison of soil moisture content between models FHAVeT and TEC for all models at time steps of 2 h.

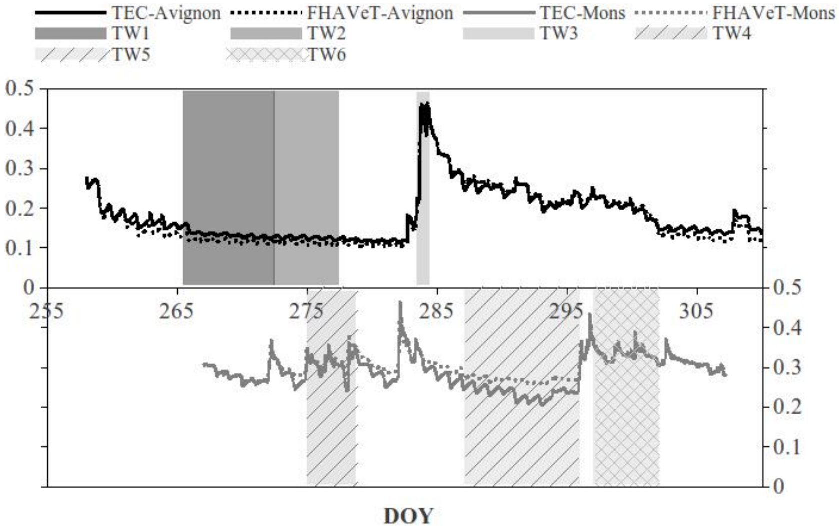


Figure 5. Volumetric soil moisture content evolution in time, for the 0–5 cm layer, comparison between models – soil AL-SiL, PTF – Wosten.

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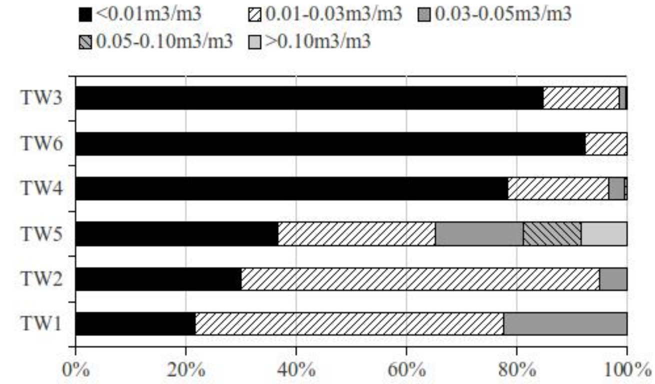
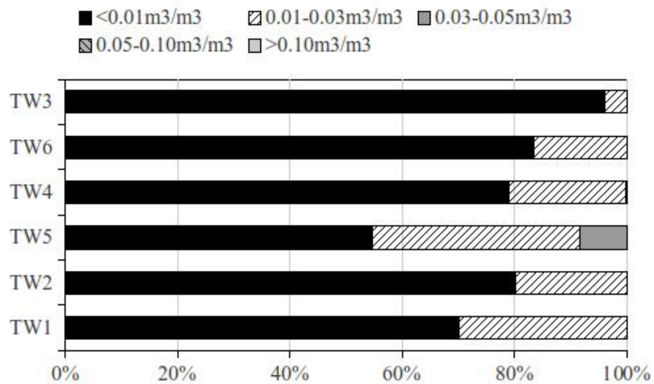


(a) 0-5cm layer



(b) 0-30cm layer

Figure 6. Absolute water content difference distribution between the developed model and TEC for each climatic case study.

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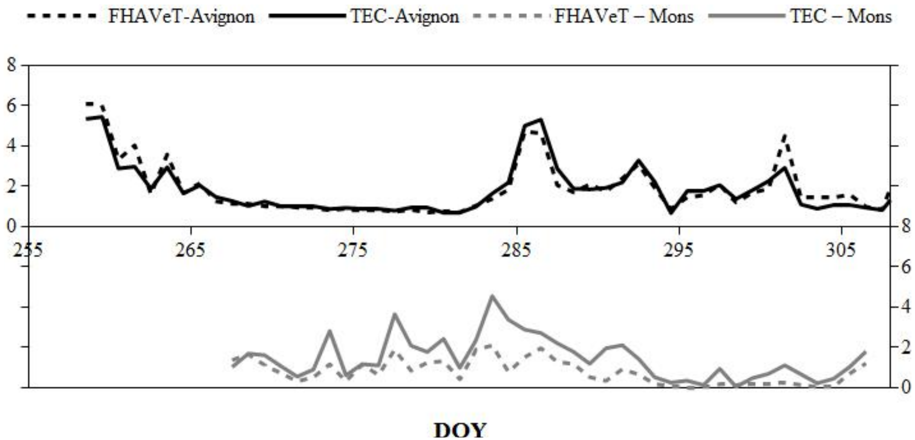

Figure 7. Daily evaporation (in mm) evolution in time, comparison between models – soil AL-SiL, PTF – Wosten.

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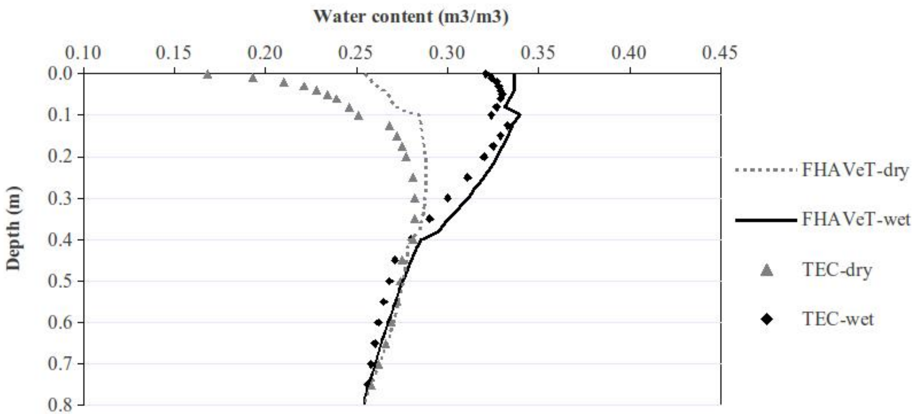

Figure 8. Water content profiles in TW 5 (dry conditions) and 6 (wet conditions) for soil AL-SiL, Wosten pedotransfer function.

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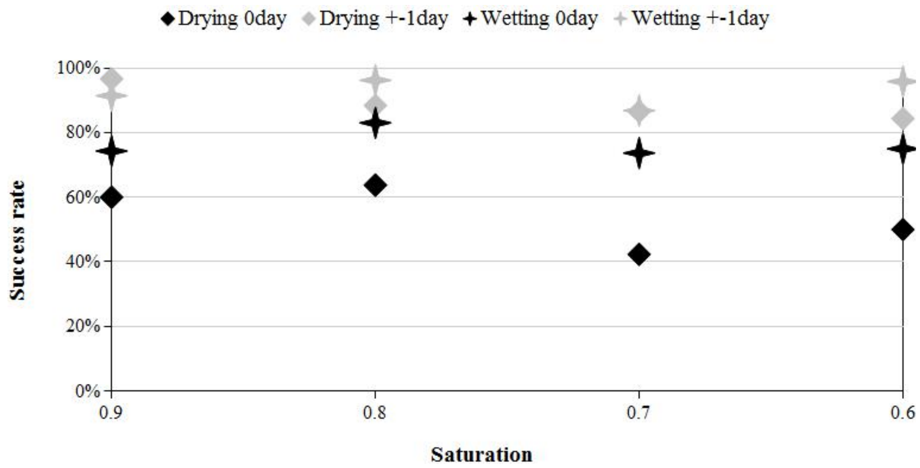

Figure 9. Day detection success rates. Drying0 and Wetting0 show the amount of identical day detection for both models during drying and wetting respectively. Drying ±1 day and Wetting ±1 day show the success rate for day detection when there is less than 1 day difference between the two models.

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