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Water infiltration and redistribution in Land Surface Models

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Abstract

In this report, we examine the potential of integrated Land Surface Models that are part of Numerical Weather Prediction (NWP) systems to produce surface runoff in case of intense rainfall events. We chose to run two infiltration experiments using the SWAP, JULES and CHTESSEL models. In the first experiment, intensive rainfall was represented as a step function and in the second constant intensive rainfall was considered. These types of problems (with discontinuities) are challenging for the numerical solvers. We performed a mesh dependence study changing the vertical resolution of the soil column. This revealed non-physical oscillations in predicted soil moisture profiles, hydraulic conductivity profiles and surface/subsurface runoff in JULES and SWAP, while CHTESSEL does not present this behaviour due to its approach in computing the hydraulic conductivity. It has been also identified that infiltration representation in JULES does not allow for the gradual increase of surface runoff expected in the experiments and predicted by the other two codes. We recommend future work should consider correcting the maximum infiltration in JULES and investigating the numerical schemes in order to make it high resolution ready.

1 Introduction

The UK Natural Environment Research Council (NERC)-funded Flooding from Intense Rainfall (FFIR) programme was initiated in 2013 with two large multi-institutional projects: FRANC (Forecasting Rainfall exploiting new data Assimilation techniques and Novel observations of Convection) and SINATRA (Susceptibility of catchments to INTense RAinfall and flooding). They address such issues as improvements in hydro-meteorological forecasting, understanding flood response and impacts of flooding from intense rainfall.

NWP models provide distributed information about atmospheric conditions, such as simulating precipitation. The resolution of NWP models is ever increasing and short duration, high intensity convective rainfall events are being captured with increasing skill Richardson et al. (2012). Better understanding of complex hydrological processes representation in NWP models is important in order to improve the prediction of magnitude and duration of flood events. Flood events can be captured by effectively implementing land surface hydrology into the Land Surface Model (LSM) Emerton et al. (2016) and Stephens et al. (2015). This is a key part of the research being undertaken in the part of the SINATRA project dealing with large scale processes representation.

In this study we evaluate how the Land Surface Model components of NWP models cope with rapid surface runoff and infiltration problems. Both in terms of the amount of water infiltrated into the soil storage, the timing and the amount of surface and subsurface runoff generated. The models investigated are SWAP, JULES and CHTESSEL.

We analyse the numerical aspects arising with discontinuities (or sharp gradients) in input (forcing) and/or the model solution (runoff). These types of configurations have been tested in the laboratory (Vachaud (1971)); for some there are semi-analytical solutions (Philip (1955) , Parlange (1972) , Vanderborght (2005)) and reference numerical solutions for model inter-comparison (Haverkamp (1977), Van Dam (2000), Vanderborght (2005)). These studies are useful not only as tests of the stability and diffusivity of numerical schemes, but also may be interpreted as design storms; intense or sudden rainfall causing flash flood events, which is why they were selected for model testing in the SINATRA project. We evaluate the movement of the wetting front in the soil and the timing and the amount of surface and subsurface runoff.

2 Materials and methods

2.1 Land Surface Model (LSM)

The Land Surface Models differ in complexity, from simpler conceptual models which only simulate water balance to more physically-based models which are designed to perform three key sets of calculations at every time step of a weather or climate simulation Kauffeldt et al.(2015):

(i) surface water balance calculations in which precipitation is split into infiltration, interception and surface runoff. The intercepted water is split into evaporation and transpiration. The amount of water infiltrated is then passed into soil moisture recharge and deep drainage (subsurface runoff).

(ii) surface energy balance calculations in which net radiative energy is partitioned into latent heat flux, sensible heat flux, and ground heat storage

(iii) some LSMs compute the carbon cycle, vegetation and snow processes.

In this study we are interested in surface runoff originating from intense rainfall. Accurate estimates of surface runoff require reliable schemes of infiltration and subsequent redistribution of water throughout the soil profile. Therefore we focus on liquid water transport in a column of soil.

In LSMs rainfall (R) has to pass through the vegetation canopy or urban structures, where part of R is intercepted and evaporated, before it reaches the ground. This amount is called throughfall (T). At the resolutions used in LSMs (down to ∼1km) there are a number of types of surfaces that can occur within one gridbox (or fraction of it). For example there might be bare ground, grassland, low level shrubs, crops, trees, urban 'canopy' - each model has its own set of these surfaces that have distinct properties (for example albedo, maximum infiltration factor, etc.). Usually they are called tiles. Each tile has a unique set of parameter constants that are used in parametrisations that describe surface processes such as water transfer through vegetation canopy for each type of surface that may be present in the gridbox.

Only part of the throughfall is allowed to infiltrate into the soil column. Before the soil water transport equations are solved (eq. 1), the throughfall is split into water available to infiltrate - the maximum infiltration, and the surface runoff. The maximum infiltration rate is defined very differently in the 3 models used in this report and will be described later.

Once the maximum infiltration is computed it is used as the top boundary condition for the solution of water redistribution in the soil column below the surface. This is done in one (vertical) dimension z assuming that in unsaturated soil the main movement of water occurs in a vertical direction.

The maximum infiltration into the soil surface I_{max} is in practice dependent on atmospheric conditions, surface type, soil type, soil moisture content θ, and surface orographic factor.

The continuity equation for vertical one-dimensional transient water flow in unsaturated soil is typically described by Richards' equation:

$$\frac{\partial \theta}{\partial t} = \frac{\partial [K(\frac{\partial h}{\partial z} + 1)]}{\partial z} - S(h) \tag{1}$$

where z is depth, t is time, θ is volumetric water content, h is matric pressure head, K is soil hydraulic conductivity and $S(h)$ is the sink/source term (for instance plant root water uptake).

The pressure head h, soil moisture θ and the hydraulic conductivity K are related via soil hydraulic functions. A widely used pair of hydraulic functions are the Mualem-van Genuchten (van Genuchten 1980) equations:

$$\Theta(h) = \frac{\theta(h) - \theta_r}{\theta_{sat} - \theta_r} = \frac{1}{(1 + |\alpha h|^n)^m} \tag{2}$$

$$K(h) = K_{sat}\Theta^{\lambda}[1 - (1 - \Theta^{1/m})^m]^2 \tag{3}$$

Where $\Theta(h)$ is the normalised water content (also known as effective saturation), θ_r is the residual water content (unit m^3/m^3), θ_{sat} is the saturated water content (unit m^3/m^3), α is the inverse value of bubble point potential (unit m^{-1}). λ, n and $m = 1 - 1/n$ are non-dimensional parameters.

Equation 1 is a partial differential equation (PDE) and in order to provide a unique solution it needs the initial and boundary condition of soil moisture θ_i or water pressure head h_i.

2.2 Soil column boundary conditions

The models used in this study differ mainly in Richards' equation boundary conditions definition. Below is the summary of all the surface and bottom boundary conditions available to the user.

2.2.1 SWAP

SWAP (Soil Water Air Plant, Alterra, the Netherlands van Dam (1997)) - is the most versatile in terms of boundary conditions available. It is an established model for lowland hydrology, but not used in NWP or climate modeling. It can reproduce ponding and fluctuating ground water levels. Two methods are available in SWAP to simulate rainfall interception, one for agricultural crops and one for trees and forests. SWAP is generally used on the 'field scale' - with only one type of surface defined in a gridbox.

At the surface one can define the boundary condition that is either:

- flux controlled q or
- head controlled h which is switched on automatically in case the soil at a given timestep becomes saturated allowing the user to obtain the depth of ponding, or in the presence of run-on infiltration.

at the bottom of the soil column the user can choose to run a simulation setting one of the following:

- ground water level
- fixed flux
- calculate bottom flux from hydraulic head of deep aquifer
- calculate bottom flux as function of groundwater level
- prescribe soil water pressure head of bottom compartment
- bottom flux equals zero - bedrock

- free drainage of soil profile
- free outflow at soil-air interface

2.2.2 CHTESSEL

CHTESSEL (Carbon and Hydrology-Tiled ECMWF Scheme for Surface Exchange over Land) is the land surface scheme used by ECMWF in its operational weather forecast system Balsamo (2009). The model evaluates the land surface response to the atmospheric forcing, and estimates the surface water and energy fluxes along with the temporal evolution of the snowpack, soil temperature and moisture. Each grid-box surface is divided into fractions (tiles).

In this study we use a new version of CHTESSEL that introduced a flexible (user defined) number and depth of soil layers in vertical column.

The soil column top and bottom boundary conditions are following:

- At the surface the maximum infiltration is defined as:

$$I_{max} = (W_{sat} - W) + max(0, W_{sat}\{(1 - \frac{W}{W_{sat}})^{\frac{1}{b+1}} - [\frac{T+M}{(b+1)W_{sat}}]\}^{b+1}) \qquad (4)$$

  where W and W_{sat} are the integrated water content and saturated water content of the first 50 cm of soil, defined as the effective depth for surface runoff. T and M are throughfall and snowmelt, and b depends on the standard deviation of orography σ the following way: $b = \frac{\sigma - \sigma_{min}}{\sigma + \sigma_{max}}$

- At the bottom of the soil column there is free drainage

2.2.3 JULES

JULES (Joint UK Land Environment Simulator) Best et al. (2011) is a community land surface model that has been developed in a collaboration between the Met Office and other research institutes. JULES models the exchange of heat and moisture between the Unified Model atmosphere and the land surface and vegetation. It is operational in Met Office forecasting system, but it can also be used offline to estimate the impacts of different climate models on the land surface and hydrology.

The soil column boundary conditions in JULES are following:

- At the surface the maximum infiltration is defined as: $I_{max} = \beta K_{sat}$, where β is a constant enhancement factor dependent on the surface tile type, and K_{sat} is the saturated hydraulic conductivity dependent on soil type. There is no dependence on surface orography or the soil moisture content.

- At the bottom there is free drainage, or bedrock in the newest versions

2.3 Numerical solution of Richards' equations

All three LSMs used here discretise the spatial derivative in the Richards' equation ($\partial/\partial z$ in eq. 1) using central finite difference, which is a 2nd order method, that according to the theorem proposed by Godunov (1959) is a non-monotone method and as such it is prone to producing non-physical spurious oscillations in the solution.

The Richards equation 1 is discretised by Finite Difference method to be solved numerically for soil moisture θ in the center nodes of each layer (see dots in figure 1). Hydraulic conductivity K changes non-linearly with θ (example figure 4). $K(\theta)$ is evaluated on the face of computational cells in the middle between the nodes where the soil moisture is being calculated - in so called staggered arrangement. For that reason it needs to be interpolated at the face between the cells. In the cases of intense rainfall n dry soil that are discussed in this paper, we expect high gradients of K at the advancing wetting front.

There are 4 methods of averaging K that are available within SWAP: arithmetic mean, geometric mean, and arithmetic and geometric weighted means. We chose to use the arithmetic mean in SWAP based on findings in Van Dam and Feddes (2000). JULES uses arithmetic means as well. In CHTESSEL the hydraulic conductivity between the cells is computed using the maximum soil moisture of the two cells.

The timestepping in all 3 models is implicit allowing the user to choose relatively big timesteps without the model becoming numerically unstable.

In this study we evaluate the impact of reducing the size of the vertical cells, thereby increasing the resolution and reducing the numerical dissipation that is present when solving with 4 cells resolution, as is standard in global JULES and CHTESSEL.

An LSM can be run in offline mode - meaning it is forced with the driving meteorological variables, but does not feed-back to the atmosphere. This is the way we run the simulations in this study.

3 Intense rainfall infiltration experiments

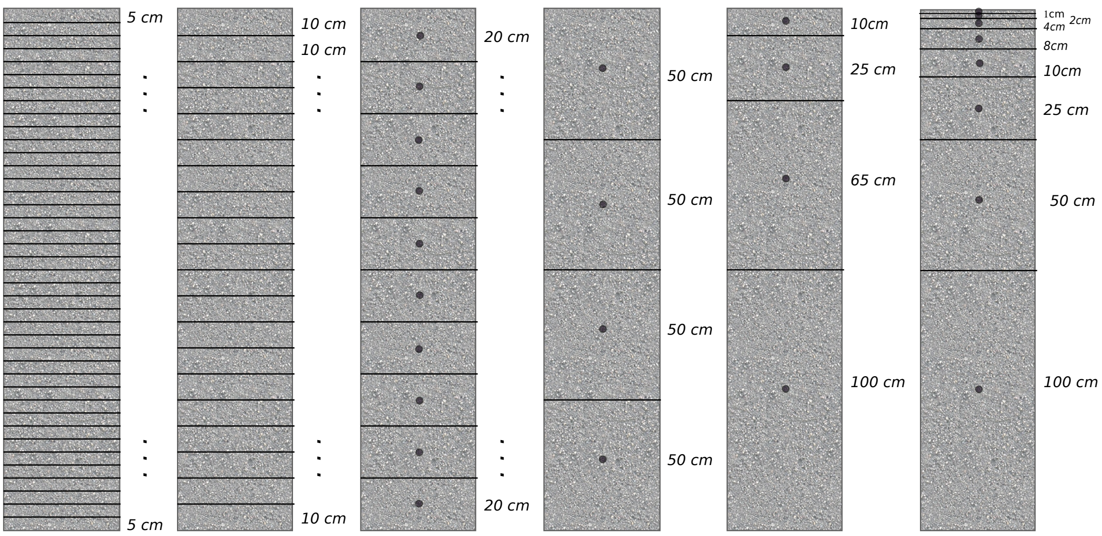


Figure 1: Vertical soil column resolutions used (uniform 1cm resolution not pictured for clarity reasons)

In this study we evaluate the response of 3 different LSMs to a discontinuity in forcing or strong gradients in resulting soil moisture profiles in the case of intense rainfall infiltrating in dry soil. We perform two numerical experiments that are repeatable and controlled. For simplicity we keep the systems in nearly isothermal conditions (long-wave radiation has to be $\neq 0$ in JULES and CHTESSEL forcing) with no wind which reduces the surface evaporation to near zero. We are interested in infiltration and moisture redistribution without sink terms (for example vegetation water uptake), so the surface tile chosen in each model is 100% bare soil. The CHTESSEL standard deviation of orography σ is set to minimum, which sets b in equation 4 to 0.1.

The cell size used to discretise the vertical soil column (figure 1) in our experiments varies from uniform 1cm (not present in figure 1) to, 5cm, 10cm, 20cm, 50 cm and the last case solved is the default telescopic soil cell distribution of 10cm near the surface then 25cm, 65cm and 100cm (as it is standard for JULES, but the bottom layer is 1m shorter). It means that a soil column of 200cm depth (based on Vanderborght et al (2005)) is discretised with 200, 40, 20, 10 and 4 cells respectively. In experiment 2 we added a case with 8 cells (1cm, 2cm, 4cm, 8cm, 10cm, 25cm, 50cm and 100cm) that represents the new multilayer CHTESSEL default resolution (also 100cm shorter).

We run all the simulations over 1 day. The simulations were conducted with a very small timestep of 1s to avoid any numerical instabilities associated with the solvers used by the three models.

3.1 Experiment 1 - infiltration from short duration intense rainfall on dry soil - step function

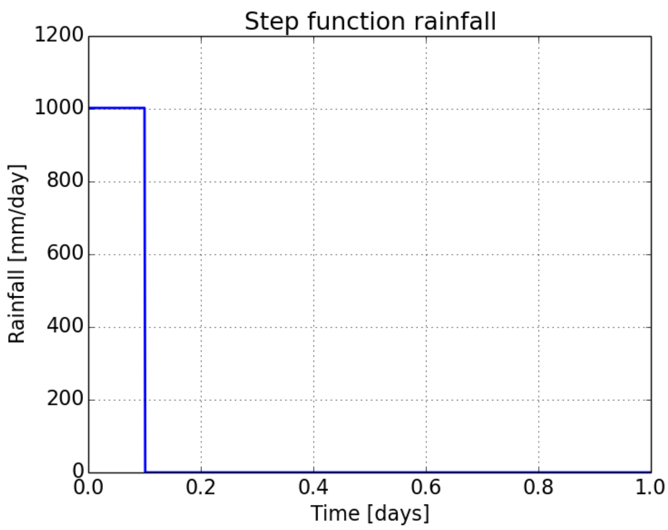


Figure 2: Step function rainfall input in experiment 1.

In this test we simulate the infiltration and subsequent soil moisture redistribution of a short duration, intense rainfall event of 1000 mm/day over 0.1 day (effectively 100 mm of rain) into initially dry sand of $\theta_i = 0.1$ (based on modelling study of Van Dam and Feddes (2000) used also as a reference). After 0.1 day the precipitation is suddenly stopped (see figure 2). The water initially infiltrates into the sand until the infiltration capacity of the soil is exceeded and the remaining water becomes surface runoff. The hydraulic van Genuchten parameter constants (see Eqs 2 and 3) for sand used in this experiment are given in Table 1. The λ parameter that is equal -0.14 in the paper of Van Dam and Feddes (2000) had to be 0.5 as it is hard-coded to that value in JULES.

Figure 3 shows the infiltration rate predicted by SWAP (direct output of flux at the top cell), JULES and CHTESSEL (as water balance at the surface: infiltration = precipitation - evaporation - surface runoff). Lines marked with black symbols represent scanned values from Van Dam and Feddes (2000) for solutions that they obtained using SWAP on 1cm and 5cm meshes (however in their case λ was set to -0.14). Initially all the rainfall infiltrates into the soil and then the surface runoff begins (at 0.008 day for 1cm case in SWAP Van Dam and Feddes(2000)).

	θ_r	θ_s	α	n	K_s	λ
	-	-	cm^{-1}	-	$cm \quad d^{-1}$	-
Sand	0.01	0.43	0.0249	1.507	17.5	0.5

Table 1: Parameters of van Genuchten hydraulic soil functions in eqs. 2 and 3 used in experiment 1, from Van Dam and Feddes (2000)

The SWAP prediction with 1cm and 5cm resolution (red symbols) agrees well with the SWAP result reported in the paper of Van Dam and Feddes (2000) (black symbols), however it is not identical. The cumulative infiltration predicted by SWAP in the study of Van Dam is less than 1% higher than the one in our study (see table 2 columns for 1cm and 5cm). It is due to the different λ in van Genuchten relations (equation 3) and the fact that SWAP was run in this study with the timestep fixed around 1s (to match the other two LSMs), while in the paper of Van Dam and Feddes (2000) the adaptive timestep was allowed to vary between 0.08 and 17280s.

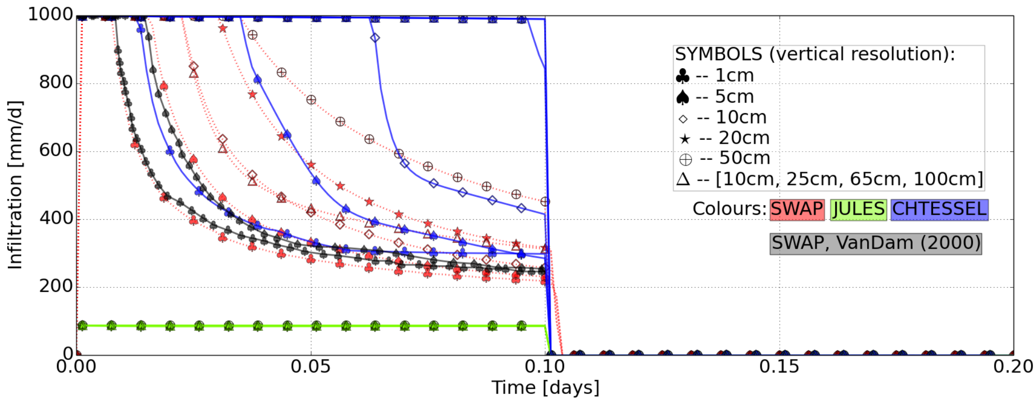


Figure 3: Experiment 1. Infiltration rate in sand. Rainfall is supplied by a step function. Colours represent different models, symbols represent different resolutions.

With increasing cell size (reducing the vertical resolution), the cumulative infiltration is increasing (see fig. 3 and table 2) and the surface runoff is starting later. It is interesting to see that the SWAP case with uniform 10cm resolution (red diamonds in figure 3) and the non-uniform 'JULES resolution' (red triangles in figure 3) with a top cell of also 10cm show similar results of timing and amount of surface runoff. The same is true for JULES (see table 2). Increasing the top layer to 20 and 50cm delays runoff further (both in SWAP and CHTESSEL).

JULES cases allow for an infiltration in the range of $7\% - 8\%$ of the rainfall water (figure 3 and table 2), the rest of the rainfall instantly becomes runoff. The constant βK_{sat} infiltration condition does not allow the water flux at the soil surface to change over time.

In case of CHTESSEL, 98% of rainfall is infiltrated and the surface runoff is near 0 when discretising with cells that are greater than 20cm. The cumulative infiltration calculated with CHTESSEL is larger than the other two models for all resolutions used (table 2).

	Cumulative infiltration [mm]					
Resolution	1cm	5cm	10cm	20cm	50cm	[10cm,25cm,65cm,100cm]
SWAP	37	45	54	64	75	55
JULES	7.4	7.4	7.6	7.9	8.2	7.7
CHTESSEL	45	63	81	98	98	98
Van Dam (2000)	40	47	-	-	-	-

Table 2: Experiment 1. Cumulative infiltration integrated over 1 day.

3.2 Experiment 2 - infiltration from constant intense rainfall on dry soil

In this experiment we model the redistribution of intense, constant rainfall (1000 mm/day) in initially dry soil and the production of runoff after the soil infiltration capacity has been reached. We base our study on the paper of Vanderborght et al (2005). They tested several models (MACRO, HYDRUS_1D, SWAP, MARTHE, WAVE) on 3 soil types (sand, loam and clay) and compared them with the quasi-analytical solution of Philip (1957). One of the models tested by Vanderborght is SWAP, and the current version of the code used here has reproduced the published result at 1cm uniform resolution. We vary the cell size as in experiment 1. The differently to experiment 1, which was forced with a step function rainfall, this experiment is forced with uniform rainfall and produces as a result a step function of subsurface runoff.

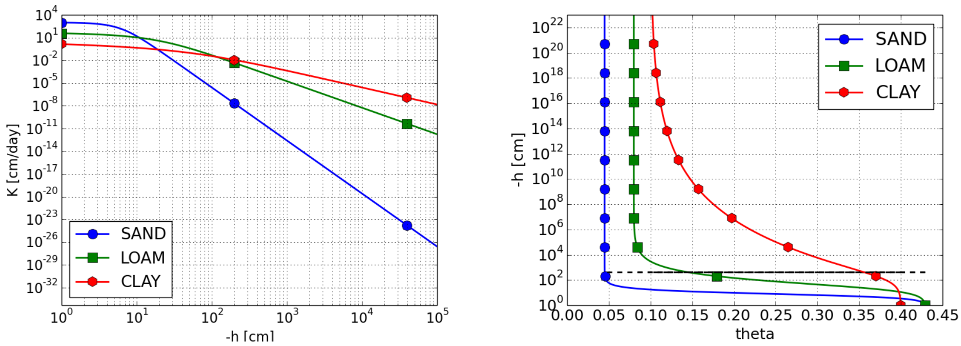


Figure 4: Hydraulic properties of soils used in experiment 2

The parameters of the van Genuchten relations for the three soil types used in this experiment are in table 3 and are the same as in Vanderborght (2005)

Figure 4 shows the van Genuchten hydraulic properties of soils used in experiment 2. We took the values from table 3 (that are based on Vanderborght et al(2005)) and used them in equations 2 and 3.

The initial suction in the soil column is set to $h_i = -400cm$ for all types of soil, this corresponds to

$$\theta_i = [0.045, 0.146, 0.357] \quad for \quad [sand, loam, clay]$$

according to van Genuchten relation (eqn. 2) for $\theta_i(h_i)$ (see black horisontal line marking $h_i = -400cm$ for all soil types in figure 4 right panel).

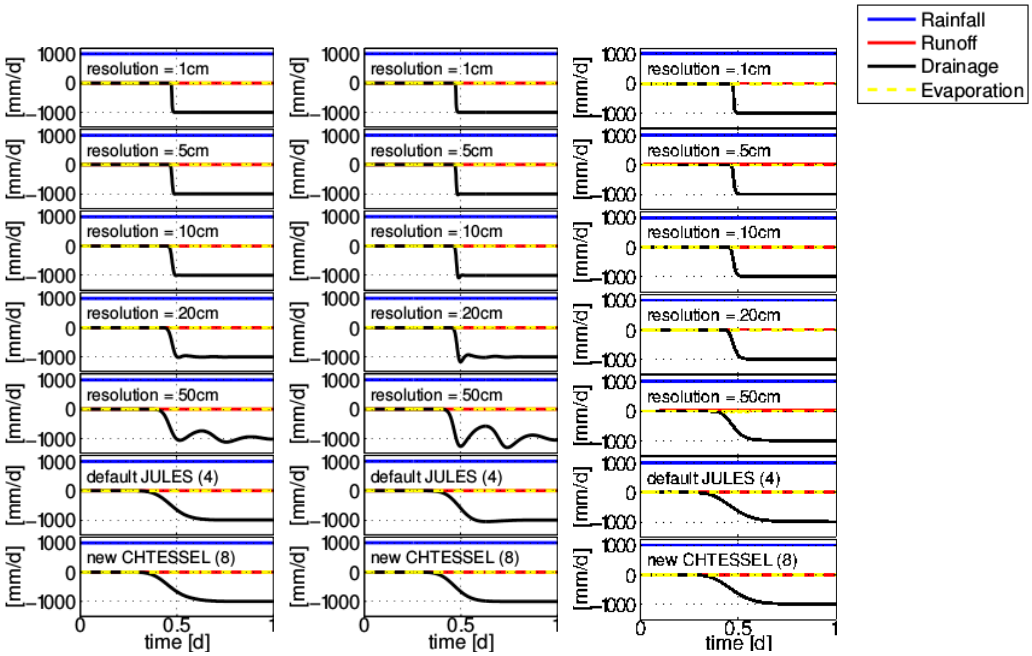
At the bottom boundary, free drainage condition is applied for all three models. Standard deviation of orography in CHTESSEL is set to minimum to match the other two models that do not include subgrid information about surface slopes.

	θ_r	θ_s	α	n	K_s	λ
	-	-	cm^{-1}	-	$mm \quad d^{-1}$	-
Sand	0.045	0.43	0.15	3.0	10000	0.5
Loam	0.080	0.43	0.04	1.6	500	0.5
Clay	0.100	0.40	0.01	1.1	100	0.5

Table 3: Parameters of van Genuchten hydraulic soil functions in eqs. 2 and 3 used in experiment 2, based on Vanderborght (2005)

The results of this experiment 2 can be classified into two groups. The first one is for sand (when the $K_{sat} > Rainfall$) where there is no surface runoff, and the other is for loam and clay ($K_{sat} < Rainfall$) where we expect the saturation excess surface runoff. The results are discussed in the 2 following subsections.

3.2.1 Results for sand, $K_{sat} > Rainfall$



(a) SWAP (b) JULES (c) CHTESSEL

Figure 5: Water balance in the column of sand changing with resolution using SWAP, JULES and CHTESSEL. Drainage is plotted with negative sign.

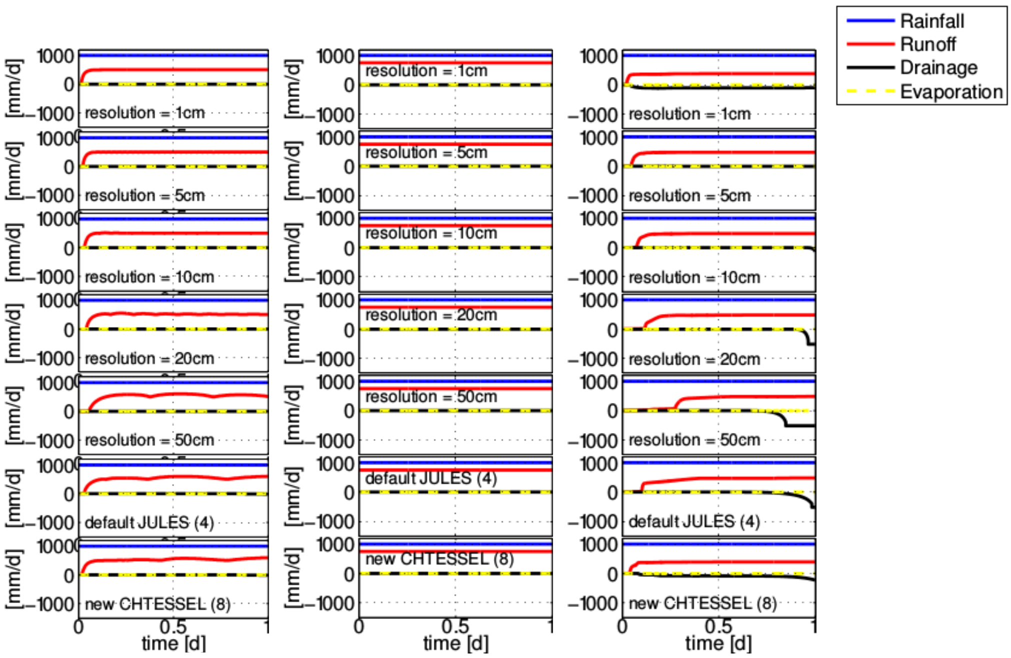
Figure 5 shows the development of subsurface runoff in sand. The surface runoff is identically equal zero, because in this case $K_{sat} > Rainfall$ and the gridbox is considered flat, so all the rainfall is infiltrated in the soil column. The expected step function of drainage in sand was obtained with 1cm resolution with all 3 models used (see top row in figure 5). It is smoothed (diffused) with increasing cell size, and especially with the telescopic distribution of soil layers, marked default Jules (4) and new CHTESSEL (8) in the last 2 rows of figure 5.

Apart from diffuse step, the non-physical, spurious oscillation (wiggle) is present in the time evolution of drainage (subsurface runoff) in sand solved on meshes coarser than 5cm (for JULES) and coarser than 10cm (for SWAP) - see figure 5 (a) and (b). This oscillation is not present in the CHTESSEL solution for all the resolutions used (fig. 5 (c)). This is thanks to the upwind-like treatment of the fluxes between the computational layers used in CHTESSEL, which helps to diffuse the oscillations.

In the appendix there are the detailed plots of the advancing wetting front in the column of sand (figure 10). Every column of figure 10 is showing the instantaneous time shots of moisture profiles for different resolution. The time is increasing downwards - each row is advancing 0.1 day. We can see that the soil moisture never reaches the saturation θ_{sat} line. For 1cm uniform grid, all the solvers produce comparable wetting front sharp gradient function. Figure 10 shows the wetting front in sand with non-physical, spurious oscillations (wiggles) present in uniform discretisations as fine as 5 cm both for SWAP and JULES, whereas the solution of CHTESSEL shows no such oscillations. Those oscillations are also present in $K(\theta)$ plots for sand (fig. 13) when solving with SWAP and JULES. Using the arithmetic mean of K between cells is known to produce this type of oscillation (see Szymkiewicz 2009). The flux limiting approach used in CHTESSEL, which uses K of the layer with higher soil moisture, avoids these oscillations on coarse, uniformly spaced meshes.

CHTESSEL produces an increasingly diffuse wetting front with the increasing cell size, however there is no oscillation in θ and $K(\theta)$ plots, and the soil moisture is bounded.

3.2.2 Results for loam and clay, $K_{sat} < Rainfall$

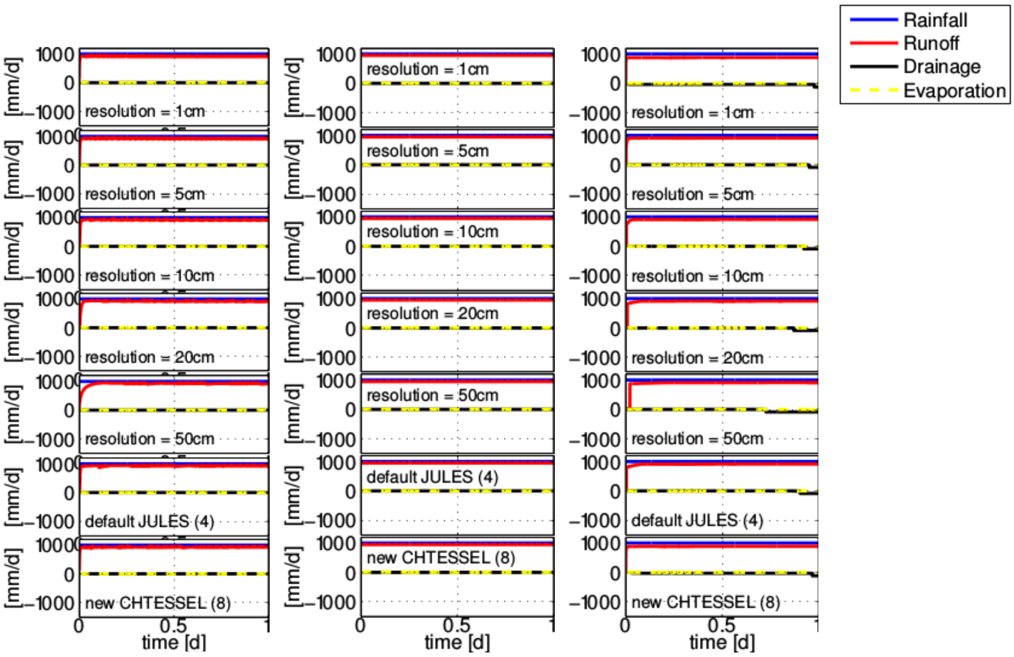


(a) SWAP (b) JULES (c) CHTESSEL

Figure 6: Water balance in the column of loam changing with resolution using SWAP, JULES and CHTESSEL. Drainage is plotted with negative sign.

In case of loam and clay there is the saturation excess surface runoff present in all three models (figure 6 and 7). JULES produces immediate, constant runoff due to the fixed surface boundary condition: βK_{sat} (figure 6 (b) and 7 (b)). It does not include information about the actual soil moisture content which, in fact, is below saturation at the beginning of the simulation. When looking at columns showing SWAP and CHTESSEL (figure 6, 7 (a) and (c)), we see that, when using a model with variable infiltration, there is a gradual increase of the surface runoff with increasing soil saturation. This is especially visible in loam on which we will concentrate the discussion.

The timing of runoff appearance in loam when using CHTESSEL (figure 6 (c)) is delayed when increasing the cell size. It seemingly is associated with the top layer thickness, because the standard JULES discretisation (6th row of the figure 6) is comparable with the uniform 10cm one and the same is true for the new 8 layer discretisation of CHTESSEL (the last row) compared with the uniform 1cm discretisation.

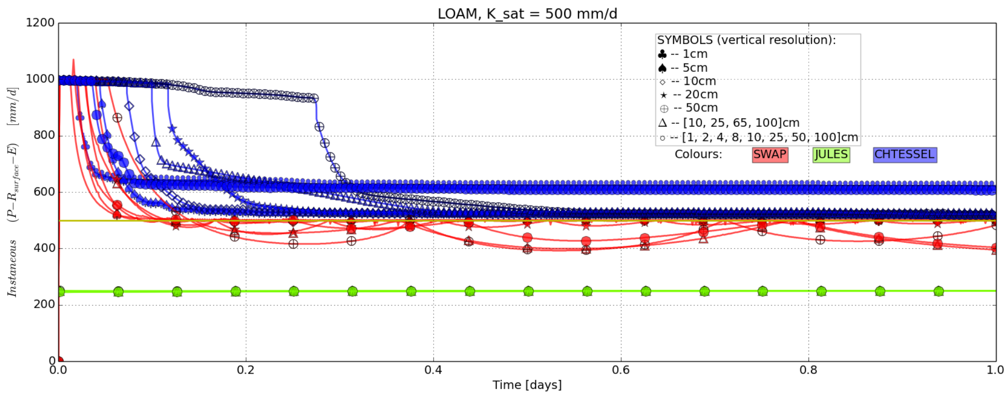


(a) SWAP (b) JULES (c) CHTESSEL

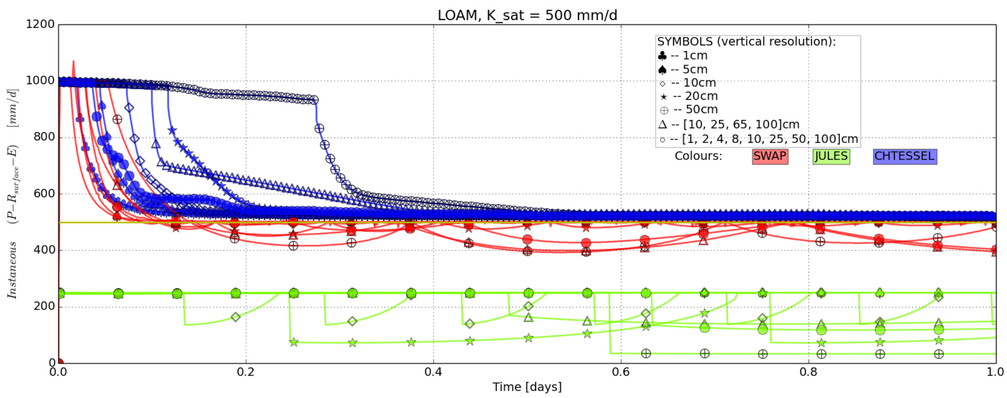
Figure 7: Water balance in the column of clay changing with resolution using SWAP, JULES and CHTESSEL. Drainage is plotted with negative sign.

In the cases discussed in this section, there was no drainage present in the first day of simulation when using SWAP and JULES (figure 6 (a) and (b)). However there is drainage present in the CHTESSEL solution (figure 6 (c)), which appears earlier when the cell size is increased. As it was mentioned before, the hydraulic conductivity K between the layers is taken as the maximum one in CHTESSEL, this way speeding the wetting front. It is visible also in detail in appendix figure 11, where we can see that the soil is getting gradually saturated, and it is happening faster when using CHTESSEL. The surface water fluxes balance, I = Rainfall - Evaporation - Runoff, is plotted in figure 8 and we assume it is equal to what is actually infiltrating in the soil column. Constant rainfall and free drainage at the bottom face lead to a steady state solution once the column is filled up with water - the infiltration at the surface should converge to $I \leq K_{sat}$. However, as it can be seen in figure 8, 2 cases solved with CHTESSEL - the uniform 1cm and the 8 layer new CHTESSEL resolution (with 1cm top layer) both produce a surface flux balance larger than $K_{sat} = 500mm/d$. This gives an information on how the surface and subsurface water balances are treated in the presence of saturation excess runoff.

In both loam and clay, where $K_{sat} < Rainfall$, all the three models reached the supersaturation in at least



(a) Excess water pushed down



(b) Excess water pushed up

Figure 8: Experiment 2. Surface balance in loam. Constant 1000 mm/day rainfall infiltrating in initially dry soil. Colours represent different models, symbols represent different resolutions.

one layer.

The supersaturation is treated differently in each of the models:

- SWAP - the top boundary condition is switched from the flux one to pressure head one and the excess water is either runoff or allowed to pond for the next timestep (depending on roughness). This explains the overshoot in figure 8 where the infiltration is more than the rainfall, because there was a non-zero ponding layer that was added to rainfall.
- JULES - there is a logical switch (l_soil_sat_down) which, when set to true pushes excess water from supersaturated level to a level below, and when set to false (default setting) the excess water is pushed up to the soil layer above the supersaturated one. In this example we set it to true.
- CHTESSEL - if a supersaturation is happening, then the excess water is added automatically to the drainage, bypassing the soil column and not modifying the soil moisture. This is happening when we used the 1cm top layer in the case of loam. It can be visible also in figure 6 (c) (top and bottom resolution) - there is approximately 100 mm/day drainage present in those 2 cases - it is the water that actually did not infiltrate, but was added directly into the drainage. It means that in this case a simple surface balance: Rainfall - Runoff - Evaporation, is not equal to infiltration.

4 Conclusions

We performed two experiments that test the behaviour of soil moisture and runoff predictions by three LSMs (SWAP, JULES and CHTESSEL) in conditions of intense, sudden or prolonged rainfall. The analysis did not take into account the effect of orography or vegetation. The operational, global LSMs (JULES and CHTESSEL) were applied using very fine vertical and temporal discretisations and compared to SWAP model and semi-analytical solutions. That allowed to explore the numerical properties of the Richards equation solvers and the influence of top boundary condition when moving potentially into hyper-resolution in vertical direction and simulating the runoff from extreme rainfall.

Oscillatory Richards equation solutions on coarse grids in un-saturated soils All the models use the central 2nd order finite difference scheme to discretise the Richards equations. When the soil is characterised with hydraulic conductivity that is higher than the rainfall, the solution on coarse uniform mesh using SWAP and JULES is prone to non-physical oscillations. The interpolation of K between the soil layers may cause the oscillations in the solution. Literature studies (Szymkiewicz (2009), Hyunuk An (2014)) have shown that simple averaging methods such as arithmetic or geometric may produce unacceptably large errors on coarse grids owing to the high non-linearity of the hydraulic conductivity. The arithmetic mean is one of the most popular averaging methods. It is used in JULES and SWAP and often suffers from the drawback of numerical oscillations on coarse grids. There are methods of averaging K based on Darcy's law (Szymkiewicz (2009)), however they are reported to be computationally expensive. On the other hand, the upwinding approach used in CHTESSEL, which computes K using the higher soil moisture content of the two adjacent cells avoids oscillations on the coarse grid while providing a similar solution to the other models in finer grids. It would be advised to review the numerical scheme implementation in JULES in order to limit the oscillations in drainage and soil moisture in cases of unsaturated soil moisture redistribution and drainage when discretising with uniform meshes.

Spatial and temporal resolution The spurious oscillations are not present when sufficient numerical dissipation is provided by the telescopic default 4 layers' vertical discretisation (or the proposed new CHTESSEL layer distribution). However, the usual 4 layers diffuse the sharp gradient and the timing of the onset of the runoff and might be unsuitable for flash flood prediction even when applied on highly resolved latitude and longitude 2D map.

This study was performed using unusually short timestep, that provided accurate solution for the range of spatial resolutions and sharp gradients present in the physics of this problem. The authors performed a limited study of the influence of the timestep length. The initial results indicate, that the oscillations present in JULES can be suppressed with longer timesteps. A detailed study of timestep length with changing spatial resolution, soil property, and rainfall intensity is needed.

Infiltration boundary condition Top boundary condition in JULES needs updating to take into account the soil moisture content and orographic factor. The infiltration rate should represent the gradually developing runoff in case of a rainfall on initially unsaturated soil. Under natural field conditions, the infiltration gradually decreases until ponding/runoff occurs when infiltration capacity has been exceeded.

Supersaturation When the saturation excess runoff is generated, it is possible for the JULES and CHTESSEL solvers to reach a supersaturation in the soil layers. Both solvers have ways of eliminating it, however they seem to be ad-hoc and not compatible with fully distributed multi-scale approach.

	JULES	CHTESSEL
Surface runoff	Immediate **constant** surface runoff when $K_{sat} < Rainfall$. Timing and the amount of possible runoff not adequate in extreme rainfall events on unsaturated soil.	**Gradual increase** of surface runoff thanks to variable infiltration dependent on soil moisture and gridbox orography.
Soil moisture solver	Spurious **oscillation** in uniform coarse grids when $K_{sat} > Rainfall$, when $K_{sat} < Rainfall$ possible **supersaturation**: excess water moved layer up or down	No oscillations. Moisture **advancing faster** than in the reference (max K between layers). Increasing cell size ⇒ the sharp gradients more **diffuse**. When supersaturated, the excess water **bypasses** the soil ⇒ added directly to drainage
Subsurface runoff	When the soil moisture solution is oscillatory, drainage is also oscillating	Drainage appearing faster due to increased flux between layers. Supersaturation causes spurious 'drainage' caused by solver correction.

Table 4: Global LSMs - JULES and CHTESSEL summary.

It is worth investigating the approach used in SWAP, which is not allowing soil supersaturation by adjusting the type of infiltration boundary condition. However this might be expensive and not compatible with the scale of application of the LSMs.

The user should be aware, that in JULES, the excess water is kept within the soil column, changing the soil moisture before it is runoff. The supersaturation does not affect the soil moisture in CHTESSEL, as it is automatically added to the drainage. When routing surface and subsurface runoff to produce river discharge one should be aware of that and adjust the wave speeds accordingly. At the moment the solvers do not produce a supersaturation warning flag for the user.

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A Experiment 2 results (uniform rainfall on dry soil) - advancing soil moisture

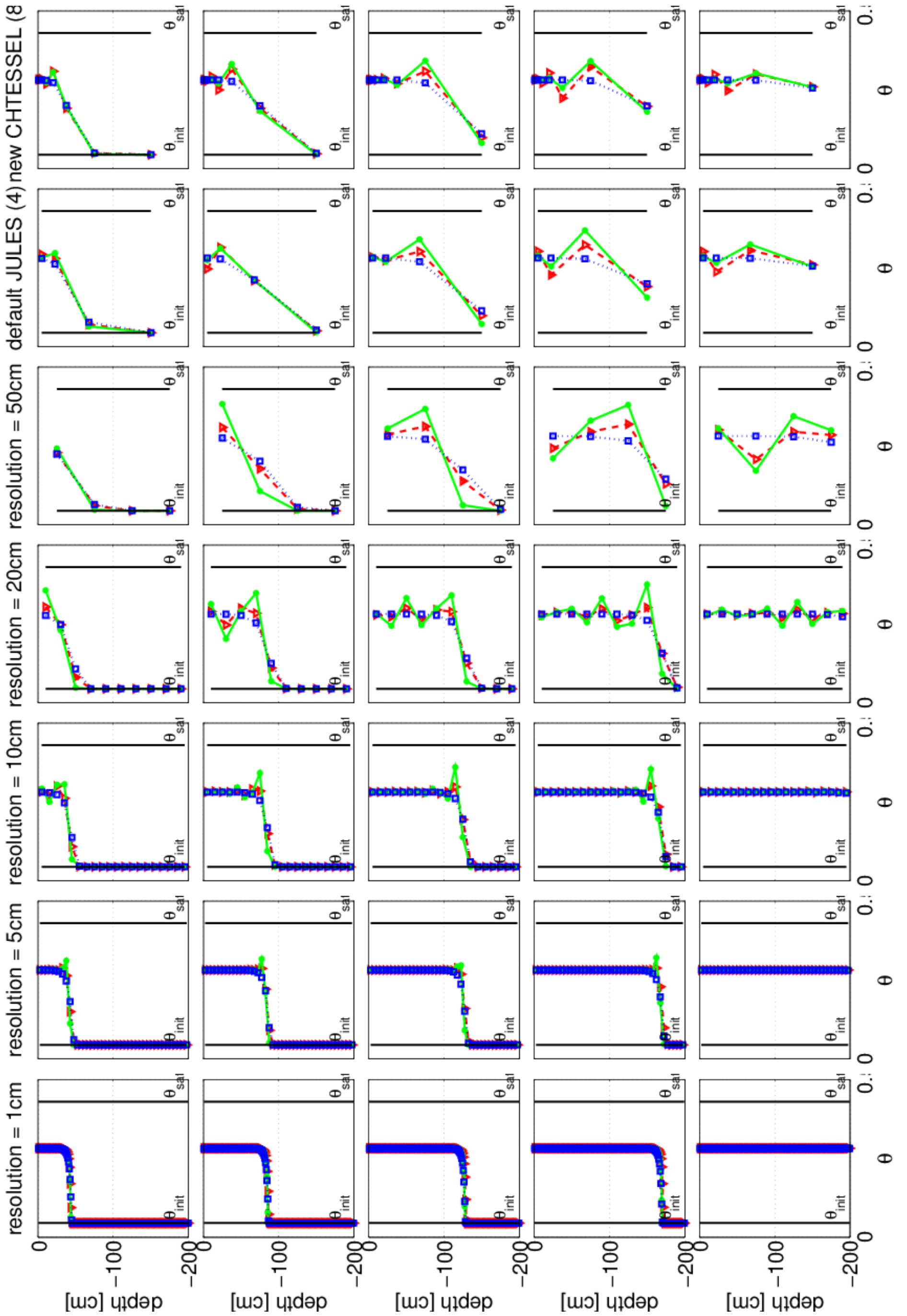

Figure 9: Here is a caption of the figure which is so long that it has to be wrapped over multiple lines, but should not exceed the width (height after the rotation) of the image.

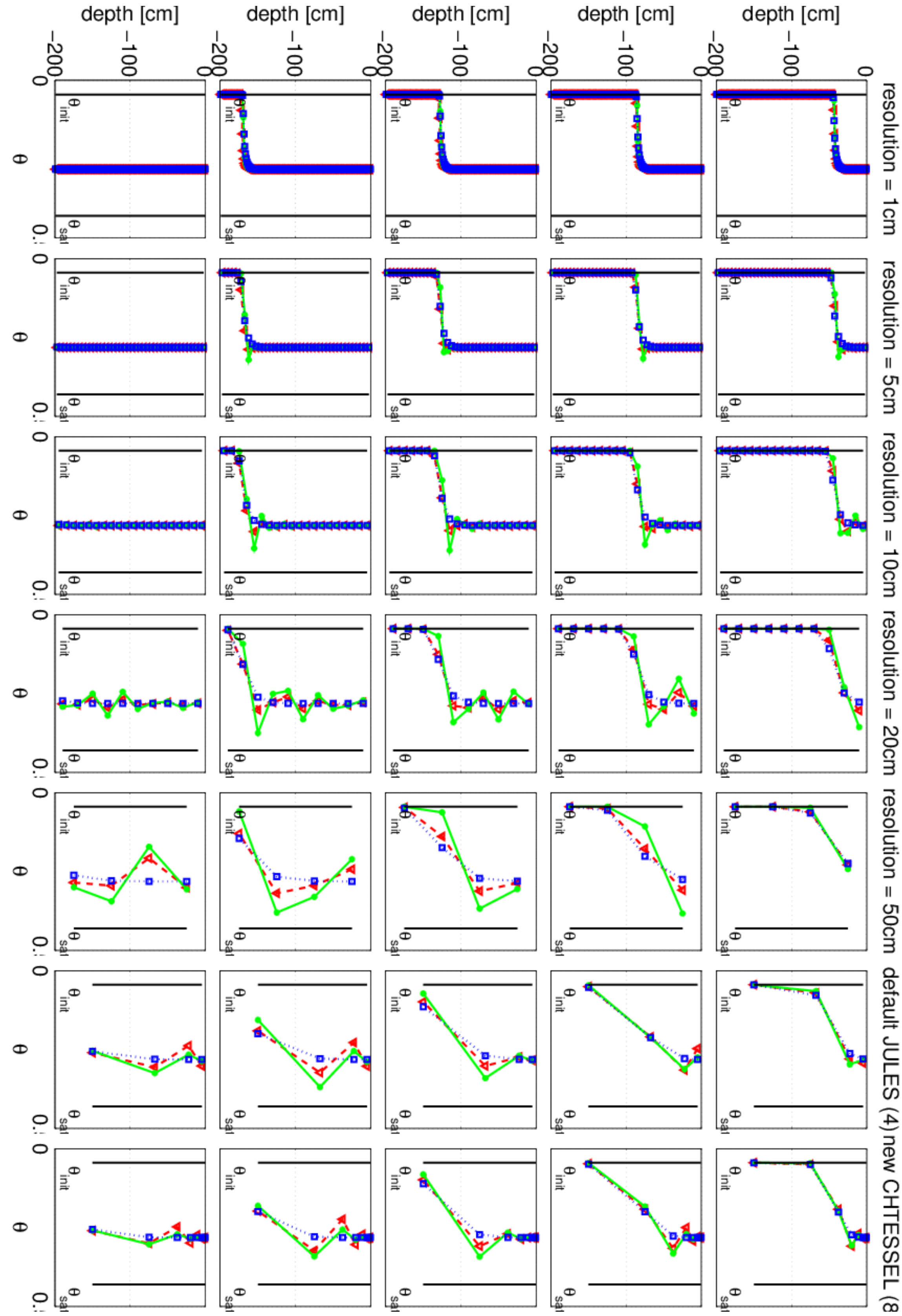

Figure 10: Advancing water front infiltrating in the SAND column. Each column has different soil resolution. Solved with JULES (green circle), SWAP (red triangle) and CHTESSEL (blue square). Every 0.1 day

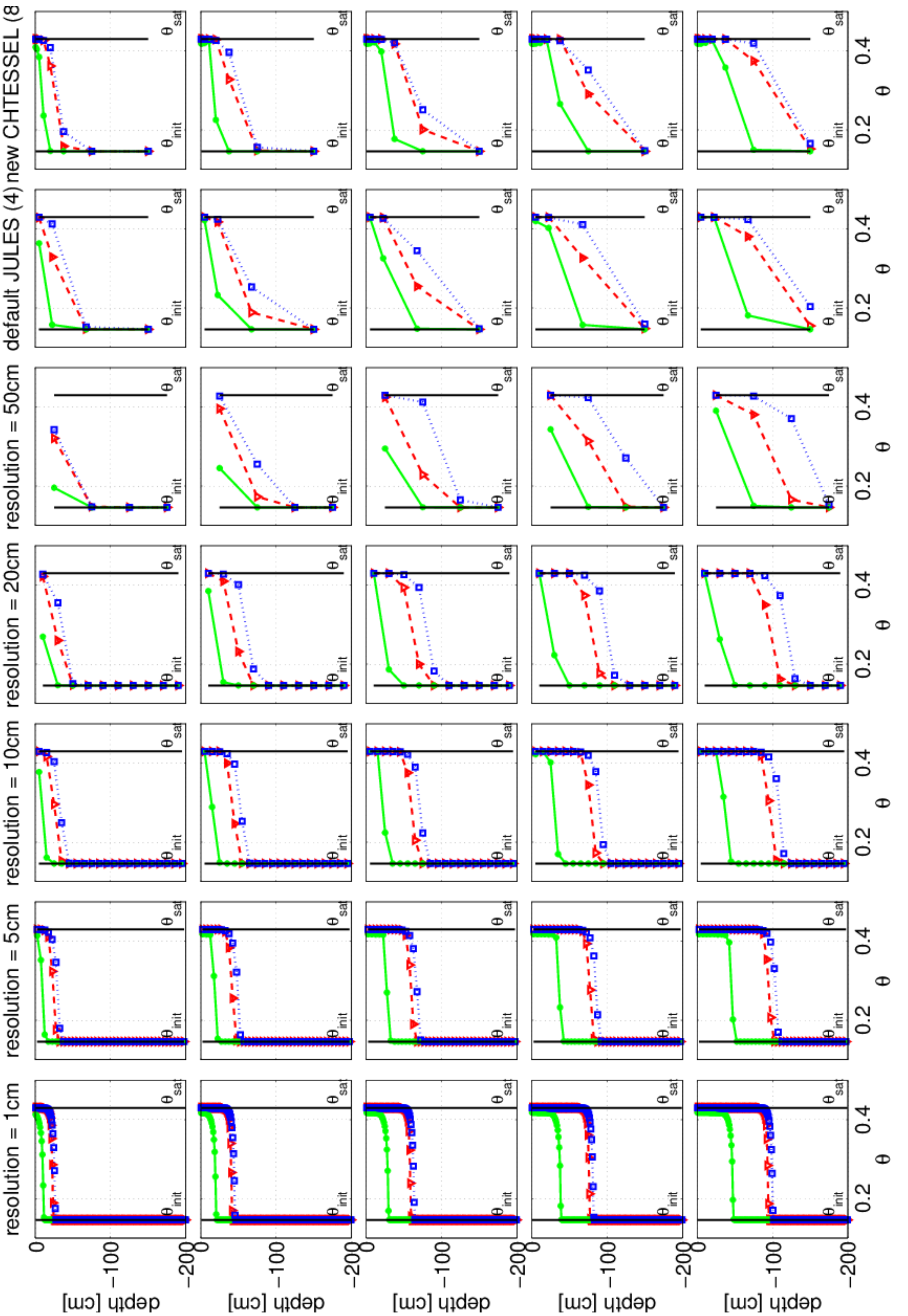

Figure 11: Advancing water front infiltrating in the LOAM column. Each column has different soil resolution. Solved with JULES (green circle), SWAP (red triangle) and CHTESSEL (blue square). Every 0.1 day

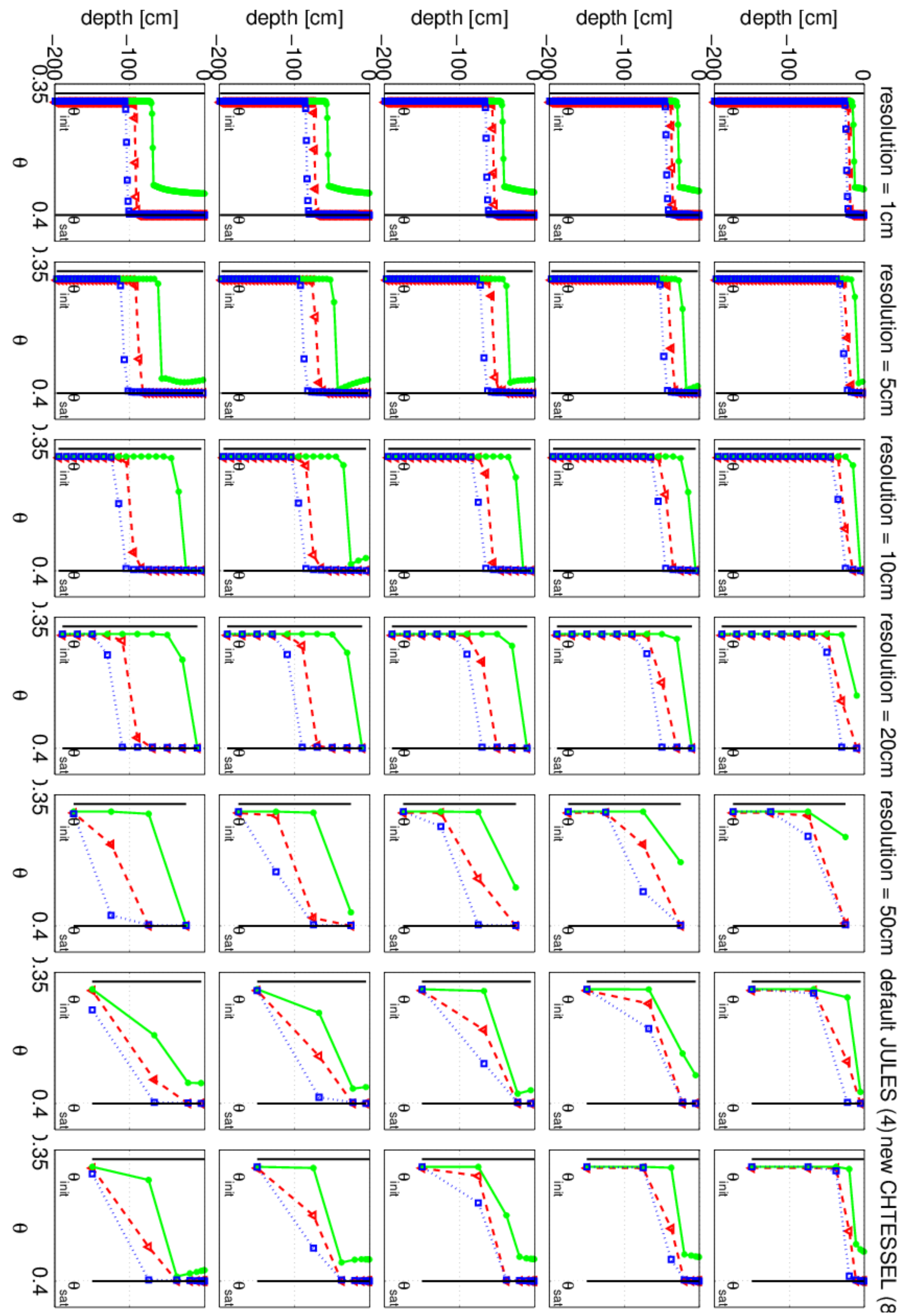

Figure 12: Advancing water front infiltrating in the CLAY column. Each column has different soil resolution. Solved with JULES (green circle), SWAP (red triangle) and CHTESSEL (blue square). Every 0.1 day

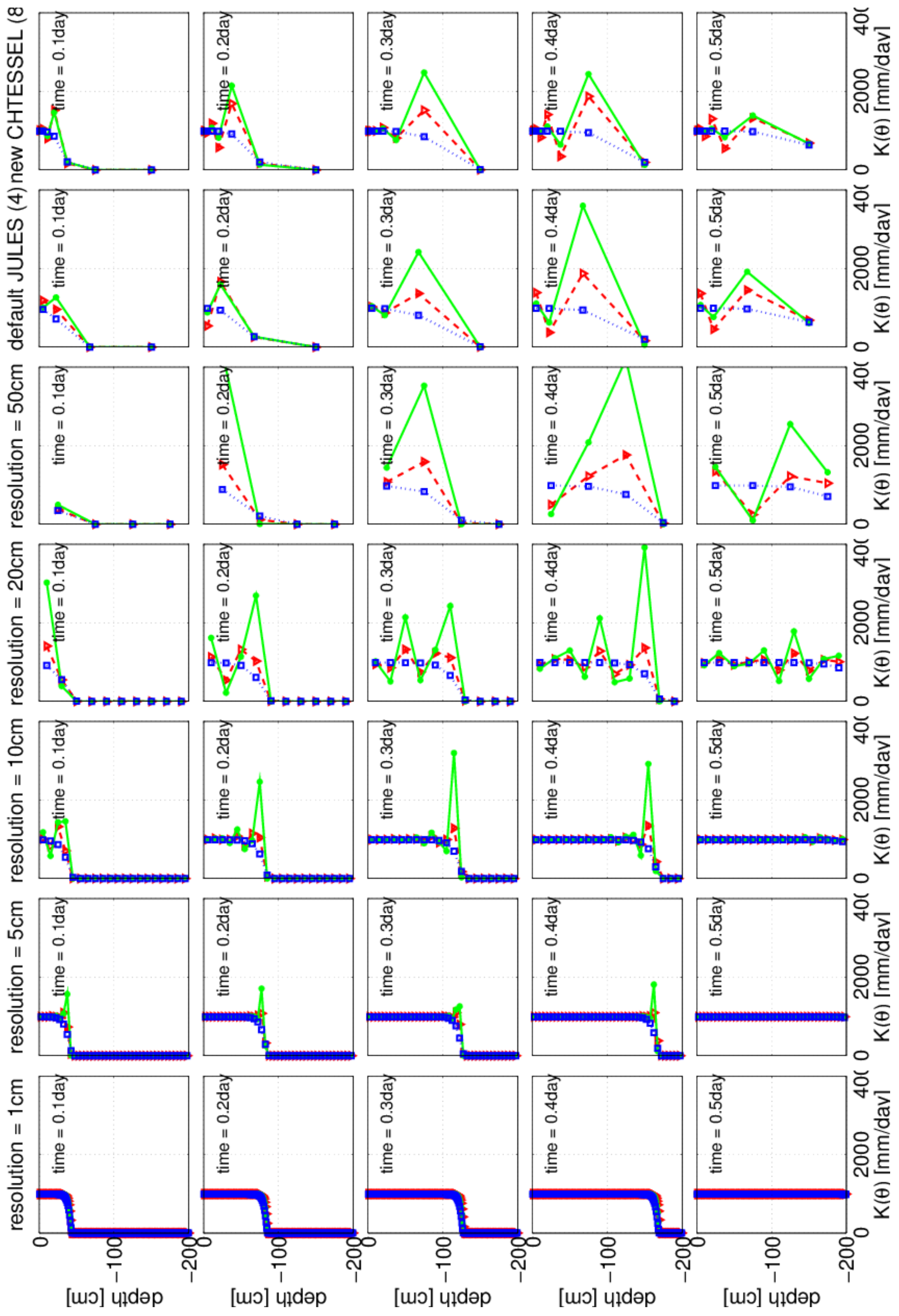

Figure 13: Hydraulic conductivity in SAND column. Each column has different soil resolution. Solved with JULES (green circle), SWAP (red triangle) and CHTESSEL (blue square). Every 0.1 day

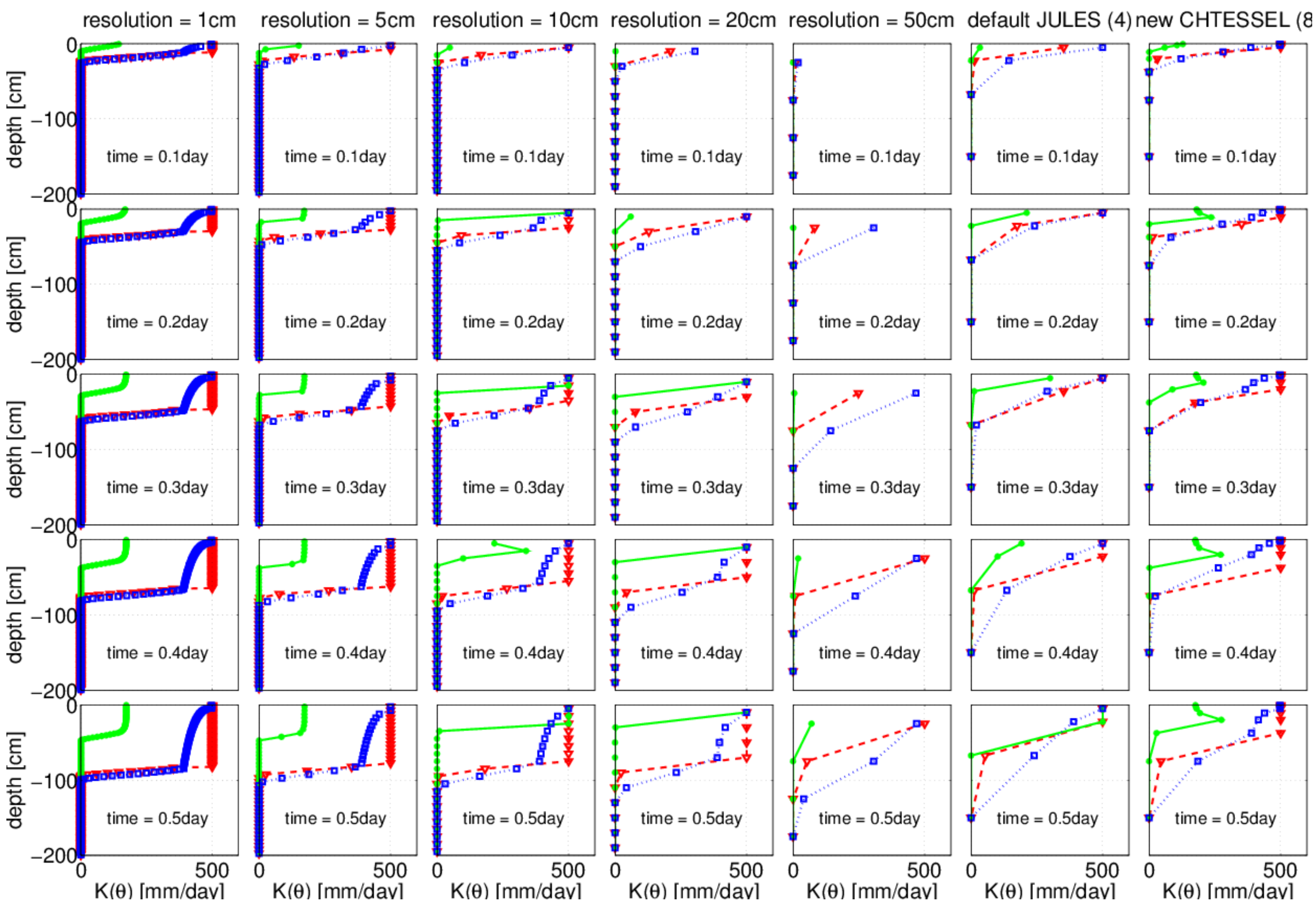

Figure 14: Hydraulic conductivity in LOAM column. Each column has different soil resolution. Solved with JULES (green circle), SWAP (red triangle) and CHTESSEL (blue square). Every 0.1 day

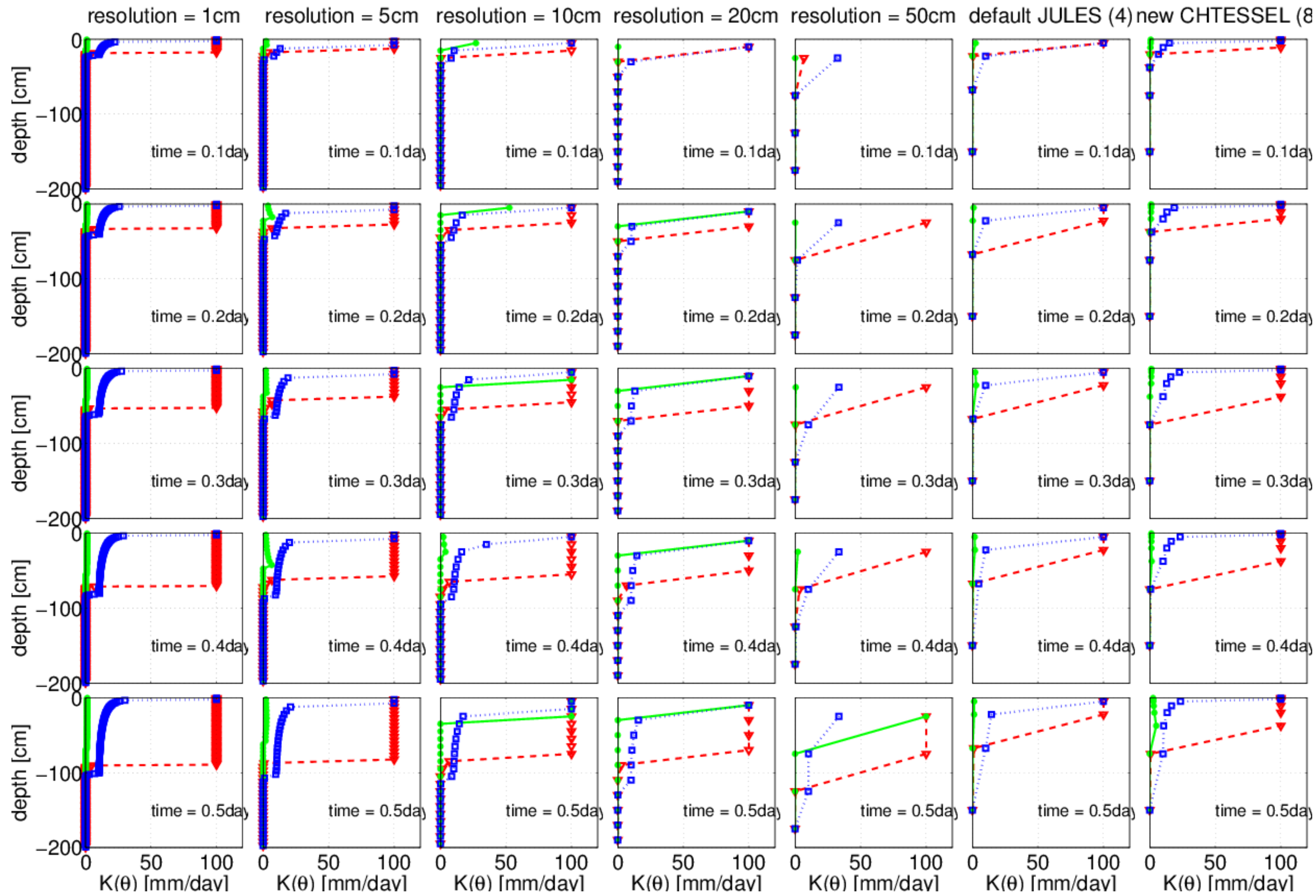

Figure 15: Hydraulic conductivity in CLAY column. Each column has different soil resolution. Solved with JULES (green circle), SWAP (red triangle) and CHTESSEL (blue square). Every 0.1 day

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