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## Reply on RC1

Daniel Regenass et al.

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Author comment on "It rains and then? Numerical challenges with the 1D Richards equation in kilometer-resolution land surface modelling" by Daniel Regenass et al., Hydrol. Earth Syst. Sci. Discuss., <https://doi.org/10.5194/hess-2021-426-AC1>, 2021

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We thank Jan Hopmans for his review and the suggested literature on modelling vadose zone processes. In particular, we read with great interest the article on recent developments in the HYDRUS software package by Šimůnek et al. (2016) as it gives us a good insight on what is considered state-of-the-art in the vadose zone community.

We believe that the reviewer (along with reviewer 3) might have misunderstood the aim of this paper and we would greatly appreciate feedback on how to reformulate the manuscript to make its aim more clear. It is not the intent of the authors to suggest a novel numerical method to solve the Richards equation. In particular, the solver presented here has already been introduced by Schlemmer et al. (2018) and it is based on the solver used in the TERRA ML land surface model (LSM) (Heise, 2003) and we hope that this has been made transparent in sections 1 and 2 of our paper. The LSM community and (as part of it) the authors are aware of the progress that has been made in the numerical solution of the Richards equation in the last twenty years. As an example, we explicitly mentioned the recent implementation presented in Lawrence et al. (2019) based on the method introduced by Kavetski et al. (2001), which is comparable to what is used in the HYDRUS model (Šimůnek, 2009). We also referenced publications that address a three-dimensional implementation (Maxwell et al. 2015, Mastrotheodoros et al. 2020).

Note that the current version of the CLM model (Lawrence et al., 2019) is a noteworthy exception. In its most recent implementation, the numerical solution of the Richards equation uses an adaptive time step. In contrast, virtually all European centers and modelling consortia use a solver that is similar to the one found in the TERRA ML LSM (Heise, 2003), and use the same time step as in the atmospheric model. This paper is an attempt to raise awareness in the weather and climate modelling community that the numerical methods in the corresponding LSMs are often insufficient to achieve numerical convergence of the Richards equation given high precipitation intensities. This is an urgent matter, as higher precipitation intensities are a natural consequence of the transition in weather and climate modelling to the kilometer scale (see e.g. Ban et al., 2014).

Clearly, LSMs should be adapted to face this challenge and one evident way forward would be to 'catch up' with the progress made in vadose zone physics in the last twenty years. While this is certainly a reasonable and valid approach, we will in the following take the HYDRUS 1D model as an example to highlight potential issues that would arise when using a comparable model as a module inside a weather/ climate model. Eq. 7.1 in Šimůnek et al. (2009) is solved with a Picard iterative solution scheme. Following the notes on

discretization (Šimůnek, 2021) this means in practice that up to 10 iterations per time step are required to achieve convergence in the presence of sharp gradients in hydraulic head (which is the case during the infiltration process, in particular during convective events in summer). Moreover, again following the notes on discretization (Šimůnek, 2021), in the presence of sharp gradients, the vertical discretization should be in the order of cm and the 'stretch factor' between two vertical layers should not exceed 1.5. Note that these recommendations are pretty much in line with the findings presented for the Schlemmer et al. (2018) solver investigated in our manuscript in a clear and systematic manner -- with the exception that a stretch factor of 1.5 would probably be too high for the scenarios presented, as it would roughly correspond to the grid layout with 11 layers. We are concerned with the application of such a solver in fully coupled weather and climate models. For convection resolving simulations, implementing an iterative solver for the Richards equation would on average probably increase the time to solution of the hydrology module by a factor of three to five at most as the time steps in these models are usually shorter than one minute. Compared with the overall time to solution of the fully coupled model this would probably be acceptable but not optimal as variations in the time to solution are largely unwanted in time-critical applications such as numerical weather prediction, especially in operational contexts. More issues would arise due to the higher vertical resolution as this would not only increase time to solution but also the memory footprint of the model. Given our results and the fact that most soil models have soils deeper than 2 m, it seems unlikely to achieve an acceptable convergence with less than 30-40 vertical layers. As highlighted in the manuscript, this is roughly a factor 3-4 more than what most LSMs use as a standard setup. Given that, it is uncertain, whether the Richards equation captures the relevant physics on the scales of interest (Beven and Cloke, 2012) it is not evident whether the weather/ climate modelling community would be willing to invest that amount of resources on the solution of the Richards equation. In this context, our manuscript could serve the weather/ climate modelling community as a starting point for a discussion on potential ways forward.

It is also worth pointing out that the same modeling framework is often used for horizontal resolutions ranging from  $O(100 \text{ km})$  to  $O(1 \text{ km})$ , increasingly also in global climate models (Stevens et al. 2020). This wide range of resolutions implies significant challenges both on conceptual and computational levels.

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