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## Reply on CC1

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-AC4>, 2021

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We thank Ms de Haan for her careful and thorough review in the form of a community comment. In the following, we will address some of the main points that are raised in the review. We appreciate that Ms de Haan has found our paper to be overall clearly written and thank her for her positive feedback on that matter.

We are not sure if we understood the first major comment correctly: The interaction of rainfall intensities and numerical errors is one of the main points in this manuscript. However, we fully acknowledge that this should be made clearer in the introduction. Indeed, the main problem with numerical errors of Richards' equation in the context of weather and climate models is precisely that precipitation intensities increase in high-resolution setups. This is a consequence of three main factors: First, increasing horizontal resolution decreases the spatial smoothing of precipitation intensities. Second, shorter time steps are required in order to ensure numerical stability as implied by the Courant-Friedrichs-Lewy (CFL) condition, this in turn decreases the temporal smoothing of precipitation intensities. Third, high resolution setups are often run without a parameterization for convective processes in the atmosphere, which also typically leads to higher precipitation intensities (see e.g. Ban et al., 2014). In that sense the 'numerical demons' described in the relatively new paper by la Follette et al. (2021) are also summoned by the recent trend towards kilometer-scale modelling in weather and climate models and there are some interesting parallels between the work of la Follette et al. (2021) and our manuscript. As Ms de Haan mentions, the scope of the paper by la Follette et al. (2021) is on conceptual hydrological models while our manuscript is solely on numerical errors of the Richards equation. We choose this relatively narrow scope because the one-dimensional Richards' equation is extensively used in land surface modelling. We acknowledge that the relationship between numerical errors and precipitation intensities could be investigated more systematically.

We feel that the following three paragraphs may be addressed together. There seems to be some misunderstanding concerning the coupling of precipitation on the one hand and Richards' equation as a part of the land surface model on the other hand. Most modern weather and climate models solve the equations for atmospheric motion on a three-dimensional grid (see e.g. Baldauf, 2011), while the land surface model (mainly providing the lower boundary condition for the atmospheric model) is typically one-dimensional (see e.g. Balsamo et al., 2009). This means that the rainfall from an atmospheric grid cell with horizontal extent of several kilometers is directly coupled to the one-dimensional Richards equation. In that sense, the solution to Richards' equation may be seen as the grid cell

average downward water propagation in the land surface model. Whether or not this is an adequate representation of the underlying physical system is an interesting research question in itself and there are of course good reasons to believe that the Richards equation is not applicable for such large scales (Beven and Cloke, 2012). However, here we solely focus on numerical aspects of Richards' equation in order to keep the scope of the manuscript as clear as possible. When we refer to numerical issues that arise in kilometer-scale modelling, we mainly mean their interaction with high precipitation intensities as such precipitation intensities are simply not present in atmospheric models with a lower resolution. In order for the land surface models to keep up with the trends towards kilometer-scale modelling, these issues must be addressed. On a different note, there are approaches to solve the fully three-dimensional Richards equation on continental scales (Maxwell et al, 2015). However such approaches require a considerable amount of computing power which is also required for other parts of fully coupled weather and climate models. Mainly due to the computational constraints, the weather and climate community is so far reluctant to move towards a three-dimensional representation of water transport in the soil matrix. However, we fully acknowledge that more research is required in order to find suitable approximations for soil water transport on horizontal scales of the order of one kilometer.

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