Development and evaluation of a variably saturated flow model in the global E3SM Land Model (ELM) Version 1.0 [MS no. gmd-2018-44]

RC1: 'Review of the manuscript by Bisht et al.', Anonymous Referee #1

Bisht et al. developed and evaluated a one dimensional variably saturated flow model (VSFM) and calibrated spatially heterogeneous subsurface drainage parameters for ELM. They were able to significantly improve water table depth prediction using this model. I believe the major contribution of this work is the calibrated drainage parameters.

Overall, the manuscript is not quite well organized or written. I couldn't find a motivation in the manuscript why one wants to spend extra 30% computation time using VSFM.
Why is the new model justified given 30% computational cost?

Response:

We have updated sections 2.2.1, 3.4, and 3.5 to highlight the features of the VSFM model and justified the increase in 30% computational cost. Here is a summary of those modifications:

- The modular software design of VSFM allows it to be built independently of the ELM code. This flexibility of the VSFM build system allows testing of the model's physics without any influence from the rest of ELM's physics formulations. Additionally, the modular software design of VSFM does not limit its application to a problem with only a fixed boundary and source-sink conditions. VSFM can be easily configured for a problem with different types of spatial grid resolutions, material properties, boundary conditions, and source-sink terms. The previous version of ELM did not allow for this flexibility.
- VSFM uses PETSc's DMComposite capability that adds flexibility for solving tightly coupled multi-component problems (e.g., transport of water through the soil-plant continuum) and multi-physics problems (e.g., fully coupled conservation of mass and energy equations in the subsurface). The previous version of ELM was unable to solve these types of problems without extensive modification.
- The relative computational cost of the land model in a fully coupled global model simulation is very low. Dennis et al. (2012) reported computational cost of the land

model to be less than 1% in ultra-high-resolution CESM simulations. Thus, the increase of 30% computational cost of ELM is expected to be not very significant within fully coupled E3SM simulation, and we argue the enhancements described in the current paper far outweigh the modest increased computational cost.

The existing flow formulation was described, but the model was only compared against PFLOTRAN. How does it compare to the existing formulation in ELM?

Response:

ELMv0 code for subsurface hydrologic processes only supports two vertical mesh configurations and a single set of boundary and source-sink conditions. The mesh configurations and boundary conditions required for solving benchmark problems is unsupported by ELMv0. Moreover, the monolithic ELMv0 code does not allow for testing of individual process representations against analytical solutions or simulation results from other models. We have updated text in Section 2.3 to include these reasons why comparison of VSFM was not performed against ELMv0 for the multiple benchmark problems. One of the abilities of the new model is its easy configurability for benchmarking across a wide range of problems. We have added extensive notes on how to run the VSFM for all benchmark problems and compare results against PFLOTRAN at https://bitbucket.org/gbisht/notes-for-gmd-2018-44. Additionally, we have updated the code availability section to include the above-mentioned notes for reproducing our results for the benchmark problems.

Would ELM perform equally well using the existing flow formulation with the new drainage parameters?

Response:

ELM's existing saturated zone flow formulation, which is based on the unconfined aquifer model of Niu et al. (2007), is only setup to simulate a maximum WTD of 42.1 [m]. Thus, ELM's existing saturated zone flow is incapable of accurately simulating WTD for the ~13% of global grid cells that have a water table deeper than 42 [m] (Fan et al. (2013). While extending the Niu et al. (2007) unconfined aquifer model for grid cells with WTD greater than 42 [m] and estimating optimized drainage parameters is beyond the scope of this work.

Specific comments:

1. There is a great deal of efforts describing different models and the importance of groundwater system in the introduction, but no justification of why a new model is in need.

Response:

The introduction has been updated to include reference to the Clark et al. (2015) study that summarized the lack of unified treatment of soil hydrologic processes in current generation LSMs and identified incorporation of a variably saturated Richards' model in future LSMs as a key modeling development opportunity.

2. Eq. (6), missing "z" in the term after the second "=".

Response:

Equation 6 has been updated to include the missing term.

3. Eq. (10, "P" in the second if should be "Pc".

Response:

Equation 10 has been updated to use P_c instead of P.

4. Eq. (14), missing dV in the last term. I didn't go through all the equations, but the authors should check for correctness/completeness of each one of them, including the appendix.

Response:

The missing dV in the third term of equation 14 has been added.

5. Make sure every variable in the equations is defined. For example, what's T in Eq.(13)?

Response:

We have updated the description on line191-192 to include the definition of T (i.e., soil temperature). We have also gone through the entire manuscript to ensure that all variables are defined in the text.

6. Page 10, line 223: correct the conversion as -0.75 m is not equivalent to 9399.1 Pa.

Response:

We corrected the equivalent head of -0.75 m to 93989.1 Pa.

7. Table 1 mentioned on page 10, line 225 is missing.

Response:

The missing table containing parameters for the benchmark problems is included now.

8. Figure 1 – where is the green line?

Response:

The figure has been updated to include the initial pressure profile by a green line.

9. Figure 4 – which one is a,b,c,or d?

Response:

The title of subplots in Figure 4 do include a, b, c and d.

References

Clark, M. P., Fan, Y., Lawrence, D. M., Adam, J. C., Bolster, D., Gochis, D. J., Hooper, R. P., Kumar, M., Leung, L. R., Mackay, D. S., Maxwell, R. M., Shen, C., Swenson, S. C., and Zeng, X.: Improving the representation of hydrologic processes in Earth System Models, Water Resources Research, 51, 5929-5956, 2015.

Dennis, J. M., Vertenstein, M., Worley, P. H., Mirin, A. A., Craig, A. P., Jacob, R., and Mickelson, S.: Computational performance of ultra-high-resolution capability in the Community Earth System Model, The International Journal of High Performance Computing Applications, 26, 5-16, 2012.

Fan, Y., Li, H., and Miguez-Macho, G.: Global Patterns of Groundwater Table Depth, Science, 339, 940-943, 2013.

Niu, G.-Y., Yang, Z.-L., Dickinson, R. E., Gulden, L. E., and Su, H.: Development of a simple groundwater model for use in climate models and evaluation with Gravity Recovery and Climate Experiment data, Journal of Geophysical Research: Atmospheres, 112, n/a-n/a, 2007.