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

RC2: 'Confidential Review A review for Development and evaluation of a variably saturated flow model in the global E3SM', Anonymous Referee #2

Strength 1. The simulations derived from ELMv1-VSFM is compared with the different dataset and other simulations so that the performance of the model is expressed well. 2. They developed a method for subsurface drainage parameterization and its performance in estimating WTD in global scale is analyzed.

Weakness

1. Given that ELMv1-VSFM is ~30% more expensive than the default ELMv1 model, the advantage of using a unified physics formulation is not clearly indicated in the paper.

Response:

As discussed in our responses to Reviewer #1, we have updated sections 2.2.1, 3.4, and 3.5 to highlight the features of VSFM model and justified the increase in 30% computational cost. Please see above for a summary of those modifications.

1.1 The reason why they intended to unify the treatment of soil hydrologic processes should be stated. (c.f. Distinct representation for different flow domains, unsaturated zone, and aquifer, is more useful to represent dynamic interactions between the flow domains)

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. They use variably saturated Richards' equation to estimate WTD using the relationship of soil moisture-pressure head. Assuming proper soil type for each soil layer is critical for

accurately estimating pressure distribution in the soil column, but their assumption (or investigation) about soil type in the soil column is not indicated.

Response:

We used the same characterization of soil properties that is used in the baseline ELMv0 model. We have added a sentence in section 3.4 describing this soil characterization in VSFM.

3. Lateral movements in phreatic zone (aquifer) is not considered. The variably saturated Richards' equation is the form that can apply to 3-dimensional analysis, but this study uses the equation only for vertical flow in the soil column.

Response:

In section 3.4, we did discuss possible approaches to extend the current 1-dimensional, vertical-only ELMv1-VSFM to include lateral flows with a range of model complexity (i.e. 1D model with source/sink term, 1D model coupled non-iteratively to 2D model or full 3D). Clark et al. (2015) acknowledged that while the need to incorporate lateral flow is well understood, the most effective modeling approach for global LSMs to include lateral subsurface flow is unclear. The development of unified treatment of hydrologic processes in unsaturated and saturated zone in this research is the first step towards incorporating lateral flows in future versions of ELM.

4. Why is a zero-flux boundary condition applied to the last hydrologically active soil layer when the water table is within the soil column? 4.1 Constant pressure head condition could be used as a bottom boundary condition to represent the water table located within the soil column.

Response:

ELMv0 applies a zero-flux boundary condition to the last hydrologically active soil layer when the water table is within the soil column, while VSFM uses a zero-flux boundary condition for the last soil layer. Our first version of the manuscript omitted a description of this lower boundary condition, which we have rectified on line 208 of the revised manuscript.

5. The simulations derived from the newly developed model VSFM are evaluated by comparing with the simulations from PFLOTRAN. As a supplementary basis for model prediction performance, the authors use ILAMB score. For the details of ILAMB metrics and scores are not indicated on the paper, it is difficult to determine the performance of the model prediction skill with ILAMB score (How the ILAMB provides a comprehensive evaluation of predictions of carbon cycle states and fluxes, hydrology, surface energy should be stated).

Response:

To address the reviewer's comment regarding details on ILAMB metrics we have cited two publications describing the ILAMB benchmarking package (Collier et al., 2018; Hoffman et al., 2017). Our intent with discussing the ILAMB benchmarking results in the current manuscript is to indicate that very small differences existed from the baseline metrics used globally to evaluate the hydrological components of the simulations (i.e., surface energy balance, runoff, total water storage anomaly). To clarify this goal, we have revised the text on lines 311-312.

6. The area of each grid-cell of ELMv1-VSFM is 1.90 (latitude) × 2.50 (longitude) and time-step is 30 min. Some indexes could be used to show that the variably saturated Richards' equation is converged well in that spatiotemporal scale (e.g., Peclet number). Plus, if the authors indicate what method (e.g., upwind difference scheme) they use to determine interfacial properties (e.g., hydraulic conductivity), their work will be better understood by readers.

Response:

ELMv0 uses a default tolerance of 10^{-5} [kg m^{-2}] for water mass balance across each time step (30 minutes). VSFM uses an adaptive timestep to ensure solution of the nonlinear equations over the 30 minute timestep is below that tolerance. The permeability at each control volume interface is obtained by a distance weighted harmonic average as mentioned on line 555-556; while an upwind scheme is used for the term k_r/μ as given by equation 31. We have clarified these descriptions in the revised manuscript to address the reviewer's comment.

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.

Collier, N., Hoffman, F. M., Lawwrence, D. M., Keppel-Aleks, G., Koven, C. D., Riley, W. J., Mu, M., and Randerson, J. T.: The International Land 1 Model Benchmarking (ILAMB) System: Design, Theory, and Implementation, in review J. Advances in Modeling Earth Systems, 2018. 2018.

Hoffman, F. M., Koven, C. D., Keppel-Aleks, G., Lawrence, D. M., Riley, W. J., Randerson, J. T., Ahlstrom, A., Abramowitz, G., Baldocchi, D. D., Best, M. J., Bond-Lamberty, B., Kauwe}, M. G. D., Denning, A. S., Desai, A. R., Eyring, V., Fisher, J. B., Fisher, R. A., Gleckler, P. J., Huang, M., Hugelius, G., Jain, A. K., Kiang, N. Y., Kim, H., Koster, R. D., Kumar, S. V., Li, H., Luo, Y., Mao, J., McDowell, N. G., Mishra, U., Moorcroft, P. R., Pau, G. S. H., Ricciuto, D. M., Schaefer, K., Schwalm, C. R., Serbin, S. P., Shevliakova, E., Slater, A. G., Tang, J., Williams, M., Xia, J., Xu, C., Joseph, R., and Koch, D.: International Land Model Benchmarking (ILAMB) 2016 Workshop Report, U.S. Department of Energy, Office of Science, 159 pp., 2017.