RC1:

This is a review of "Development of Inter-Grid Cell Lateral Unsaturated and Saturated Flow Model in the E3SM Land Model (v2.0)" by Qiu et al.

The authors describe the development of a saturated lateral flow parameterization for between-gridcell water movement. The modified model is compared to a fully 3d subsurface flow model.

Derivation of equations

In general, I thought that the derivation of the moisture movement equations could be improved. Around line 105, the authors reference Oleson et al. [2013], which describes the conservation of mass in one dimension that is used in the CLM model. But their equation 7 is not what is found in Oleson et al., and instead is written in the general 3d form. The authors here use the index n to denote different control volumes, before switching to an index k used to describe the layers of the 1d soil structure. I think it would be more clear to either 1) describe the 3d equations first, then show how the specific 1d case leads to the ELM/CLM equations described in Oleson et al., or follow Oleson et al. and then show how the 3d equations are used to define the new term in equation 14.

Response: Thank you for the suggestions. In the revised manuscript, we updated Section 2.1 and have adopted the suggested option-1. Specifically, we described the general 3-D soil water movement equations first and then introduced the simplified 1-D equation used by ELM/CLM. Please see Equations 1-14 in the revised manuscript. Additionally, we have updated the figure 1 in the revised manuscript to explain the implementation details of the computation of lateral fluxes in the unsaturated and saturated zone.

Regarding the equations describing the lateral flux, e.g. 14 and following, the areas used to convert between fluxes and volumes should be clarified to show whether they are actual surface areas, or projected areas. The appropriate area is the area that is normal to the direction of the flux. This is why I found the description of equation 16 confusing. I don't think describing the fluxes relative to z' (the rotated z axis) make sense. This is still a 1d column model, with the nodes aligned vertically, therefore the fluxes in the column are all in the vertical. Presumably the coupling to the atmosphere also occurs in the vertical. It would be more clear to me to note that a cosine arises in equation 16 due to the projected area of the surface being smaller than the surface area by a cosine factor.

Response: This is a very helpful suggestion. The volumetric flux is the dot product of the flux vector and the area vector which either the flux can be adjusted by the cosine of the angle or using the area that is normal to the direction of the flux. Given the fluxes in the column are all vertical, we applied the cosine to the area, indicating the projected area of the surface. Please see equation (16) in the revised manuscript.

I would also like to know if the presence of z in equation 15 is correct. I understood the gravity term in the modified Darcy equation to be the sin(theta) term.

Response: The presence of z is for reference of elevation. This equation is also used by ParFlow, please see Equation (7) in Maxwell (2013). This equation is originally derived from Childs (1971). We have added this reference in the revised manuscript.

Why does equation 17 not have a similar form as equation 15? Also, I would like to see the calculation of the transmissivity T described here rather than simply referenced.

Response: The reviewer is correct that equation 17 for the lateral saturated flux should follow a similar form as equation 15 for the lateral unsaturated flux. We corrected this mistake in the revised manuscript, as well as in the model code. All simulations were rerun using the corrected model. We found this correction improved the model results while benchmarking against the PFLOTRAN for the three idealized hillslope problems. We also added details of the transmissivity calculation in Appendix A.

What is the size of the contribution of the unsaturated lateral flow term, for both the benchmarking and application simulations? It would be useful to indicate the relative importance of this term, and whether this impacts the simulations significantly. It would seem to be straightforward to turn off this flux to test this issue.

Response: Relative to unsaturated flow, the saturated flow plays a more dominant role in magnitude. We have added the text in the revised manuscript related to the results of the magnitude of the unsaturated lateral flow and saturated lateral flow. Please see Figure 8 for the idealized problems and Figure 14 for the little Washita case. Additionally, we evaluated the change of energy flux results after turning off the unsaturated lateral flux through a rainfall event, please see Figure A8.

Evaluation over lww

A comparison to a LWW PFLOTRAN simulation would have been interesting. Given that PFLOTRAN was used in the benchmarking section, why was it not used in the evaluation section?

Response: While it is tempting to investigate the tradeoffs between the computational cost and simulation accuracy by comparing ELM-PFLOTRAN (i.e.,3D variably saturated subsurface model)and ELM-Lat (i.e., a simplified approach to include lateral unsaturated and saturated flow), such a comparison is beyond the scope of this work. In the LWW application, it can be extremely computationally expensive to drive PFLOTRAN with the prescribed hydrologic fluxes computed by ELM under extremely dry conditions. For example, the ELM-simulated evapotranspiration, which is transient and varies vertically in the soil, could be large for a single drier control volume within the 3D domain, thus resulting in PFLOTRAN to take extremely small timesteps. Therefore a comparison for LWW between the two models is beyond the scope of this study.

The WTD map in figure 8 shows that the addition of lateral flow helps to better resolve the uphill/downhill differences in water table depth, but there are still significant differences relative to the Fan WTD map. The authors note that calibration of the f_d parameter to give a better match to the Fan WTD map may not be fruitful due to differences in climate forcing. But given the relatively large differences, it would be informative to do a sensitivity test for the f_d parameter. For example, is there a value of f_d that further lowers the water table depth, and better resolves the riparian areas as shown in the Fan map?

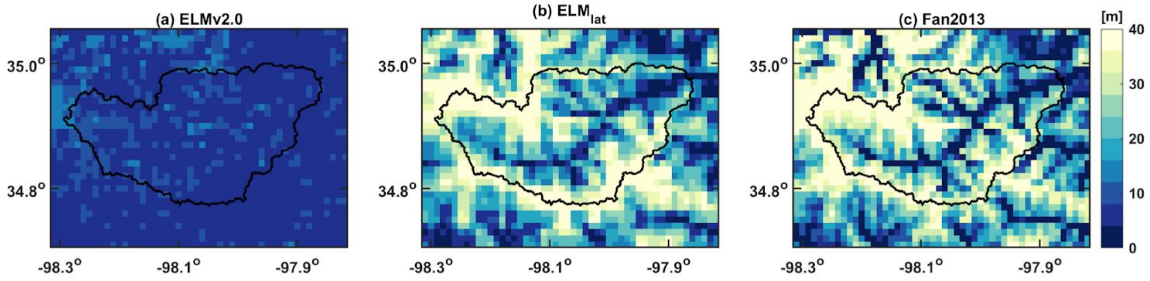
Response: In the revised manuscript, we calibrated f_d values for each grid cell instead of using a spatially homogeneous f_d value. According to our sensitivity analysis of f_d, smaller f_d leads to a deeper groundwater level because the subsurface runoff increases. The updated f_d values led to a significant improvement of the WTD simulations when compared to the Fan2013 WTD map. We found the default ELM_v2.0 also showed spatial WTD variations while using heterogeneous f_d values, but the spatial variations are very small to have a clear pattern.

Statements such as "The effects of WTD changes on the energy fluxes were more pronounced at low elevation cells, especially at the stream and its surrounding cells. The delivery of the groundwater through the lateral flow to the valleys supported higher LH while reducing the SH compared with ELMv2.0 which has little spatial WTD variations" do not appear to be well supported by figure 9. Instead of highlighting the differences between the uphill and downhill areas apparent in figure 8, figure 9 shows spatial patterns having broad domain-wide patterns. Why do the water table patterns in figure 8 show much more structure? For example, larger LH values do not appear consistently in the riparian areas. Similarly, the patterns in the difference maps only show scattered points rather than a clear riparian pattern. Why is this?

Response: The water table patterns shown in figure 8 are primarily driven by the terrain. The hotspots shown in the difference maps are mostly located at low elevation areas, where the influence of the WTD changes is more prominent. That's the reason we made the statement "The effects of WTD changes on the energy fluxes were more pronounced at low elevation cells, especially at the stream and its surrounding cells. The delivery of the groundwater through the lateral flow to the valleys supported higher LH while reducing the SH compared with ELMv2.0 which has little spatial WTD variations." However, the energy fluxes can be determined by many different factors, including the land use type, soil properties and local climate forcings, etc.. Some of them can be dominant processes which the effect of water table change on the energy fluxes can be relatively small. That could explain why the patterns in the difference maps only show scattered points rather than a clear riparian pattern.

The comparisons to observations (figures 10 and 11) do not seem to add much insight into the relative model behaviors. Given the authors choice to not calibrate the models, I don't think it can be stated that the differences between the observations are due to model structure. For example, the A121 differences in figure 10 might be smaller if the f_d parameter in ELMv2.0 model had been calibrated. The statement that both models "were able to capture the major fluctuations and wetting/drying cycles of soil moisture (SM)" seems over-stated. The rain events are generally captured, but the magnitude of the response, and the dry-down rate is generally poor. What information are the authors trying to give to the reader with these figures? Similarly for figure 12; one does not need to perform a model simulation to be aware that shallower water tables will typically have colder temperatures, higher LH, and lower SH than deeper water tables. Any two model versions having different water table depths would presumably show this behavior. I don't see that this figure adds any additional insight to the results.

Response: In the revised manuscript, we calibrated the f_d value to match the Fan2013 water table map and get improved results, please see Figure 9 and shown as below:



. And we found we plotted the observed soil moisture using the wrong station data in Figure 10(b), we corrected this in the revised manuscript. However, the simulated dry-down rates of soil moisture results still do not show perfect performance in comparison with observations. It should be noted that the simulated results represent the model behavior of the whole 1-km grid, while the measurements are taken at a single point. It is probable that the soil parameters for the 1-km grid couldn't represent the soil property of the single point. Therefore, we add this statement 'However, the dry-down rates of soil moisture results are not perfectly captured by both ELM$_{lat}$ and ELMv2.0.' and add the explanations. Please see line 318-320 .

We agree it may be common sense that shallower water tables will typically have colder temperatures and lower LH in summer, and higher LH than deeper water tables. But as we stated in the introduction section, most state-of-the-art earth system models have not taken lateral groundwater flow into account. It is unknown to what extent the lateral groundwater flow makes a difference and how the difference is manifested in the model results. Especially when the difference is also related to the model resolution. To use LWW as an example, we gain insight at 1 km resolution, the lateral groundwater flow does make a difference in regulating the soil moisture and energy fluxes. However, there are still many associated processes that are not represented. For example, ELM assumes no heat flux boundary condition at the soil bottom, lacks lateral heat diffusion, and does not include advective heat transport. Uncertainties associated with absence of these processes are to be explored in the future based on the results and our understanding at this stage. Therefore, although we are at a relatively nascent stage in comprehensively understanding the effects of lateral groundwater on the energy/water nexus, those results are still meaningful to underscore the importance of including detailed subsurface processes in new generation earth system models, especially in the context of global change.

References:

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