Reviewer 2

The authors incorporated a sub-grid topographic parameterization in the E3SM Land Model (ELM) to quantify the effects of sub-grid topography on solar radiation flux, which includes the shadow effects and multi-scattering between adjacent terrain. They found that incorporating the sub-grid topographic effects generally reduces the biases of ELM in simulating surface energy balance, snow cover and surface temperature particularly in the high-elevation and snow-cover regions over the TP. Overall, this manuscript is well organized and written. However, there are still a few places that require further clarifications and discussions. Please see my specific comments below.

Thank you very much for these useful suggestions/comments. We have revised the manuscript carefully.

Specific comments

1. I suggest being more specific and accurate about "sub-grid topographic parameterizations". This study actually focused on the subgrid terrain-radiation interactions instead of other subgrid topographic effects.

As suggested, we have revised "sub-grid topographic parameterizations" as "sub-grid topographic parameterizations for solar radiation" throughout the revised manuscript, to more accurately match our study.

2. The authors mentioned that ELM uses a novel topography-based sub-grid spatial structure. How does this new sub-grid spatial structure interact with the implemented subgrid radiation parameterization? Are they coupled?

The spatial pattern of vegetation types generally depends on the topographic distribution, which controls terrestrial water, energy, water, and carbon cycle (Reed et al., 2009). These aforementioned simplifications may affect the accurate representations of the sub-grid topographic effects on solar radiation in ELM at a coarse resolution. Combining the sub-grid topographic parameterizations for solar radiation implemented in ELM in this study with ELM's new sub-grid topography structure (Tesfa et al., 2017) and downscaling of atmospheric forcing (Tesfa et al., 2020) is anticipated to further improve the representations of the land surface processes at different spatial scales (Ke et al., 2013). We stated these in Line 457-463 of the revised manuscript. We will further couple them in the future study, but this is out of the scope of this manuscript.

3. I suggest providing a schematic figure showing different flux components (Section 2.2) for the parameterization.

As suggested, we have added a schematic diagram for different flux components as Figure 1 in the revised manuscript.

4. Section 2.2: the original parameterization includes a coupled flux term, which however was not included in the implementation (e.g., Eqs 10-11). Any specific reasons? How much impact would this missing of the coupled term have on simulation results?

We did not include the coupled component in the current parameterization because:

1) The impact of the coupled component on the total radiation is not significant in many cases because the magnitude of the variation in the deviation of the coupled flux is only about 0.5 W/m^2, while the deviations in the total surface solar flux are on the order of 100 W/m^2 (Lee et al., 2011).

2) The coupled flux is more complicated because it contains photons experiencing multiple scattering and reflection, and is not linearly proportional to surface albedo. We found that the regression analysis was less satisfactory in cases of low albedo values and we plan to include the coupled term using higher resolution data in future work.

We clarified these in Line 164-165 of the revised manuscript.

5. The implementation adjusts albedo to account for the subgrid radiation effect. What is the rationale and justification to make this assumption? In theory, the surface albedo is a land surface intrinsic property, and by accounting for the additional subgrid terrainradiation fluxes (e.g., reflected from neighboring terrain), the change should be in the incoming solar radiation instead of surface albedo.

For the offline simulations of the land model, the adjustments of incoming solar radiation and land surface albedo are identical theoretically, which motivated the idea to adjust albedo instead of downward radiation. However, for coupled simulations of the land and atmospheric models, only adjusting the surface downward/upward flux will lead to inconsistencies between the surface and the first level of the atmosphere above the surface. This is because the atmosphere model takes land surface albedo as the lower boundary condition rather than the upwelling solar radiation flux computed by the land model. Thus, we need to modify land surface albedo for consistency in fully coupled simulations.

Specifically, in the structure of a global climate model, the land surface model computes the surface albedo, taking into account land types, snow cover, soil moisture, and other factors. This albedo is then employed as a boundary condition in the global climate model for radiative transfer calculations. We can use the sub-grid topographic parameterization for solar radiation to adjust the land surface albedo, i.e. the ratio of the upward flux to the downward flux, such that the downward flux adjustment remains unchanged. In this manner, a balance of the total energy flux at the surface would be ensured, which is critical for long-term climate simulations (Lee et al., 2015). We clarified these in Line 153-155 of the revised manuscript.

In addition, the adjusted land surface albedo in our methods is closer to the apparent land surface albedo, observed by satellite remote sensing.

Lee, W.-L., Gu, Y., Liou, K. N., Leung, L. R. and Hsu, H.-H.: A global model simulation for 3-D radiative transfer impact on surface hydrology over Sierra Nevada and Rocky Mountains, Atmospheric Chemistry and Physics Discussions, 14(22), 31603–31625, doi:10.5194/acpd-14-31603-2014, 2015.

6. Do the fitting parameters (A) in the subgrid radiation parameterizations vary across different scales? What are the values for the fitting parameters? A table listing these values would be good. What is the applicable range of spatial scales for the subgrid parameterization?

As suggested, we have added Tables S1-S2 to list the values of the fitted parameters. In the current parameterization, we used the Shuttle Radar Topography Mission (SRTM) global data set at a resolution of 90 m to perform 3-D Monte Carlo photon tracing simulations to improve parameterization accuracy. The parameterization was developed at a 10 km × 10 km spatial scale, representative of a grid size of traditional weather models. Lee et al. (2013) demonstrated that the parameterization can be applied to various spatial resolutions larger than 10 km × 10 km. We added these descriptions in Line 164-168 of the revised manuscript.

7. Some clarifications and descriptions are needed in Section 2.3. (1) What satellite data is used for LAI? (2) What are the native spatial and temporal resolutions of GSWP3v1 data and how did the authors interpolate the data to different simulation resolutions? (3) Since the authors focused on the analysis on snow and related surface quantities, a description of how ELM handles key snow processes and properties needs to be included.

As suggested, we clarified the above in Line 97-104 of Sections 2.1 and Line 180-190 of 2.3 in the revised manuscript, as below:

1) In Section 2.3, MODIS LAI data was used.
2) The GSWP3v1 data has a spatial resolution of 0.5 degrees and temporal resolution of 3-hourly. The bilinear interpolation technique was used to downscale the GSWP3v1 data to the required spatial resolution, and the coszen (i.e., the cosine of the solar zenith angle)-based, nearest neighbor, and linear interpolation methods were used to downscale the solar, precipitation and other data to the half-hourly temporal resolution, respectively.

3) For the related processes, ELM (Version 1.0) is based on the Community Land Model Version 4.5 (CLM4.5) (Golaz et al., 2019). ELM calculates canopy radiation flux using the two-stream approximation methods, snow albedo using the Snow, Ice, and Aerosol Radiative Model (SNICAR) model (Flanner et al., 2007), and snow cover fraction based on snow water equivalent (Swenson and Lawrence, 2012). ELM also represents snow hydrological processes including accumulation, melt, compaction, aging, and water transfer across layers.

8. The authors used a random forest model to quantify the sensitivity of topographic factors. Why not directly use the physics-based ELM model and vary those topographic factors to do the sensitivity tests? To me, the random forest model itself introduces additional uncertainties in the analysis.

ELM is computationally too expensive to be directly use for performing the global sensitivity analysis covering different atmospheric conditions, soil and vegetation characteristics. Besides, simply varying selected variables in a fixed range may lead to unrealistic combinations of variables deviating from the real world. Therefore, we combined the ELM simulations over the Tibetan Plateau and a random forest model to evaluate the variable importance.

We also further clarified the theory of random forest models used to measure the variable importance in Line 205-209 of Section 2.4 in the revised manuscript as: The random forest model is a regression tree-based bootstrapped non-parametric machine learning model, which allows the calculation of the variable importance by estimating the out-of-bag (OOB) errors (Breiman, 2001). The OOB error represents the mean prediction error for each sample x_i, which uses only the trees that did not have x_i in their bootstrap sample. To measure the importance of the j-th feature for training, the values of the j-th feature are permuted among the training data and the OOB error is computed for each perturbed data set. The importance score for the j-th feature is computed by averaging the difference in the OOB error before and after the permutation over all trees.

In addition, we tested the correlation between different factors and the sub-grid topographic effects based on the ELM simulations. Different factors show different correlations (both sign and magnitude) with the relative difference in land surface albedo between TOP and PP, as shown in the figure below. These demonstrate that different factors have different contributions which vary with seasons and are consistent with the variable-importance analysis based on the random forest model.

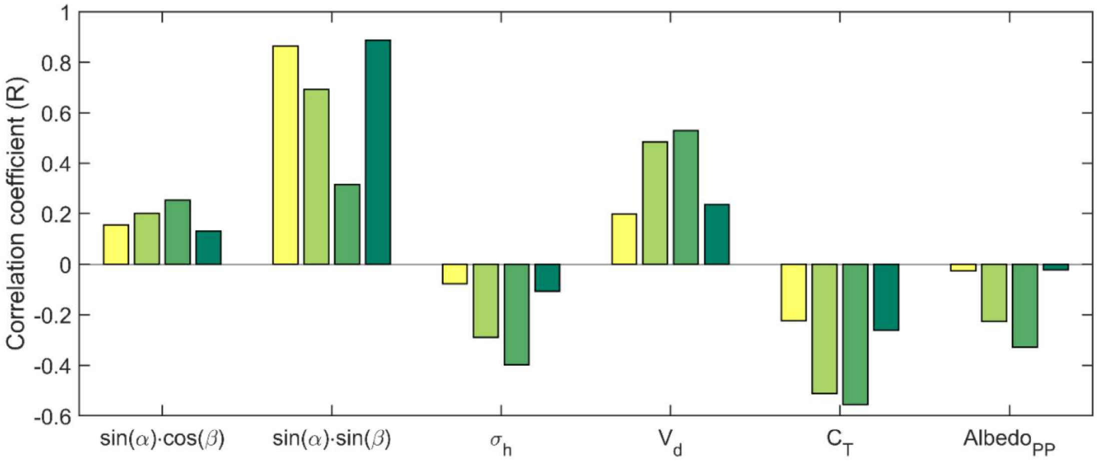

Figure. Correlation coefficients (Rs) between different factors and the relative difference in land surface albedo between TOP and PP for four seasons.

9. I am a little concerned about the evaluation of surface albedo using MODIS albedo data. (1) Note that MODIS data is retrieved through algorithms that only assume planeparallel radiative transfer. So it may not be reasonable to use MODIS albedo as a justification for the subgrid terrain-radiation improvement. (2) Also, it is not clear how much improvement in surface albedo comes from the direct treatment of subgrid radiation and how much comes from the snow cover improvement.

For question (1):

Indeed, there are uncertainties in the MODIS products especially in rugged terrain and we have now expanded Section 4 to include a discussion regarding those uncertainties in Line 422-444. Therefore, we did not use MODIS data as a benchmark and only aimed to compare the ELM simulations with MODIS data to reveal the sub-grid topographic effects in the revised manuscript.

For instance, the operational MODIS albedo algorithms use a semi-empirical kernel-driven model (Schaaf et al., 2012):

$$R(\Omega,\lambda) = f_{iso}(\lambda)\cdot K_{iso}(\Omega) + f_{vol}(\lambda)\cdot K_{vol}(\Omega) + f_{geo}(\lambda)\cdot K_{geo}(\Omega) \quad (1)$$

where f_{iso}, f_{vol}, and f_{geo} are three empirical kernel parameters, and K_{iso}, K_{vol}, and K_{geo} are isotropic, volumetric-scattering, and surface scattering kernels, respectively. Generally, K_{iso} is set to 1, and K_{vol} and K_{geo} are derived from complex radiative transfer and geometric optical models. These radiative transfer and geometric optical models used the plane parallel assumptions. Specifically, the algorithms first calculate the three kernel parameters by fitting the multi-angular reflectance, and then calculate the albedo by the hemispherical integration based on equation (1). Although the kernels K_{iso}, K_{vol}, and K_{geo} don't account for topographic effects, the fitted kernel parameters can be affected by topography because the topography has large effects on the observed reflectance. Therefore, the MODIS algorithms do not account for topography explicitly. We clarified these aforementioned points in the discussion of the revised manuscript.

We also compared the typical errors of MODIS data with the differences between TOP and PP in Line 431-440 of the revised manuscript, as below:

However, the topography-induced differences between TOP and PP can be comparable to the errors of MODIS data. For example, Wang et al. (2004) reported that compared to ground measurements, MODIS albedo had a maximum error of 0.036 in a semidesert region on the TP, which is smaller than the maximum difference of 0.1 betweeen TOP and PP (Figure 4). Wang et al. (2007) showed that the mean and maximum errors of MODIS surface temperature were 0.27 K and 2.61 K, respectively at a semi-desert site on the western TP, which is comparable to the maximum difference of 1 K between TOP and PP (Figure 4). Salomonson and Appel (2004) showed that using the Landsat 30 m observations as the benchmark, the mean error of MODIS snow cover fraction was smaller than 0.1, which is comparable to the difference of 0.1 between TOP and PP (Figure 4). Mu et al. (2007) showed that the 8-day MODIS latent heat flux had a mean bias from -5.8 to 39.9 W/m^2, possibly larger than the difference between TOP and PP in our study (Figure 4).

Schaaf, C. B., Gao, F., Strahler, A. H., Lucht, W., Li, X., Tsang, T., Strugnell, N. C., Zhang, X., Jin, Y., Muller, J.-P., Lewis, P., Barnsley, M., Hobson, P., Disney, M., Roberts, G., Dunderdale, M., Doll, C., d'Entremont, R. P., Hu, B., Liang, S., Privette, J. L. and Roy, D.: First operational BRDF, albedo nadir reflectance products from MODIS, Remote Sensing of Environment, 83(1-2), 135–148, doi:10.1016/s0034-4257(02)00091-3, 2002.

For question (2):

It is difficult to directly decouple the contributions of the direct treatment of sub-grid radiation and snow cover evolution. Since there is no snow cover in summer, differences of TOP and PP are caused by the new radiation treatment (Figure 3). The absolute difference in net solar radiation can still be as large as 20 W/m^2 in summer, but the relative difference in summer is smaller than in winter. Generally, direct albedo of TOP shows higher consistencies with MODIS than PP, when snow cover fraction is larger or the snow cover fraction of TOP have higher consistencies with MODIS (Figure 11). These demonstrates that snow cover plays an important role in the improved processes. We added these analysis in Line 404-406 of the revised manuscript.

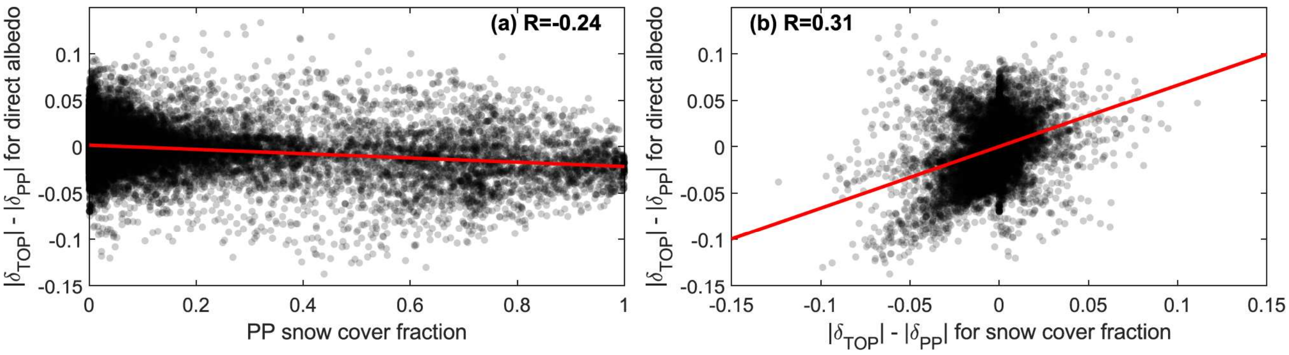

Figure 11. Relationship between the differences in bias for TOP and PP ($|\boldsymbol{\delta}_{TOP}|$-$|\boldsymbol{\delta}_{PP}|$) with respect to MODIS data for direct albedo and PP simulated snow cover fraction (a) or the differences in bias for TOP and PP ($|\boldsymbol{\delta}_{TOP}|$-$|\boldsymbol{\delta}_{PP}|$) for snow cover fraction (b) in winter. Red line is the regression line, and R is the correlation coefficient.