Response to 1st Reviewer's comments

We thank the reviewer for the insightful and constructive comments on our manuscript. The manuscript will be revised accordingly to address the comments. Specific responses to the reviewer's comments and revisions to be included in the manuscript are listed below.

General Comment:

This manuscript evaluated a new approach in representing the spatial heterogeneity of topography and pointed out that the representation based on a more flexible classification using hypsometric analyses (local) and spatially non-contiguous (non-geo-located) subgrid structures is more robust. The manuscript is generally well written and I think it is ready to be published after the major points are answered.

Response:

We thank the reviewer for the constructive comments on our manuscript. We will revise the manuscript accordingly to address all the reviewer's comments.

Major comments:

1. *In the atmospheric science field, the importance of land-surface processes to the evolution of temperature and moisture distribution in the atmospheric boundary layer is generally well recognized. The impact of spatial distribution of topography on the atmospheric motion and precipitation distribution, on the other hand, is a major topic in the field (see, for example, the review paper by Houze 2012). With the new approach in representing subgrid structure of topography, can the atmospheric modeler benefit from the paramters used in the new approach for better representing subgrid scale land-topographic-precipitation processes?*

Response:

As the reviewer pointed out, the impact of spatial distribution of topography on atmospheric motion and precipitation distribution is well recognized. Consequently, atmospheric modelers are actively working to enhance the capability of atmospheric models to capture the impact of topographic heterogeneity on precipitation distribution. This has been most commonly explored by increasing model resolution to better resolve topographic effects on mesoscale flow, cloud formation, and precipitation. Besides increasing model resolution, subgrid parameterizations have also been developed as a more computationally efficient approach. For example, Leung and Ghan [1995, 1998] developed a subgrid orographic precipitation parameterization to represent the impact of subgrid topography on airflow and precipitation for a discrete number of subgrid elevation classes defined using the non-geo-located Global method. They showed that this method produces realistic spatial distributions of precipitation and snow cover in mountainous areas. The subgrid structures presented in this study have been developed to improve the representation of land surface processes in land surface models. However, in a coupled modeling framework, we envision the atmospheric model to adopt a subgrid structure similar to the non-geo-located subgrid units from the Local method, which as shown in the manuscript, capture more spatial heterogeneity of surface topography. The subgrid orographic precipitation scheme of Leung and Ghan will be included in the atmosphere model for coupling with the land surface model. The figure below is a global map of the number of subrid units per atmospheric grid developed as part of this effort described in the manuscript. We believe combining the subgrid orographic precipitation parameterization in the atmospheric model with the subgrid structure of the land model will provide the largest improvement for capturing subgrid variability of land surface processes. In the revised manuscript, we will clarify the motivation of our study and add some discussions about our plan for atmospheric modeling as elaborated above.

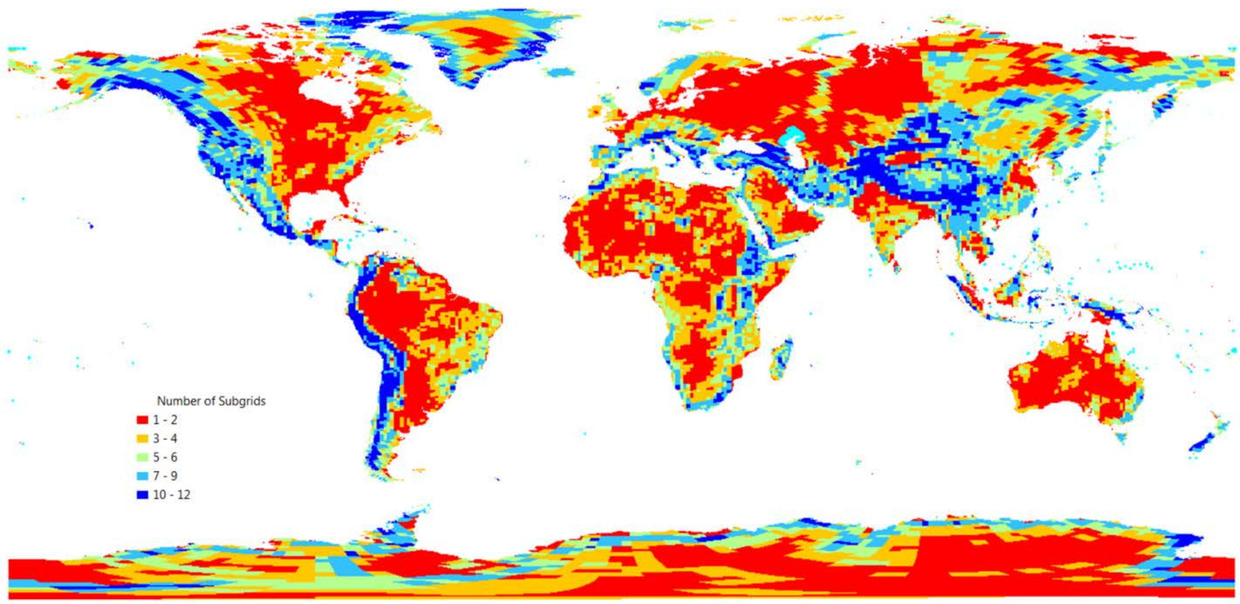

Figure 1: The spatial distribution of the number of subgrid unites per atmospheric grid (ne30np4) at global scale.

2. *The comparisons among various approaches (Global vs. Local, geo-located vs. non-geo-located, etc) in the paper are generally qualitatively rather than quantitative. For example, in line 240, I can understand the local method is better but I cannot understand how much better it is. Judging from the variability of the data, I can also argue that the two methods are roughly the same.*

Response:

We thank the reviewer for the constructive comment. To address this comment, we will include the following table in the revised manuscript and update the abstract, result and discussion, and summary and conclusions sections accordingly. Since the purpose of the subgrid method is to compare different subgrid spatial structures to better capture subgrid variability of topography, the most important metric is the reduction of standard deviation (STD) of subgrid topography within each subgrid landunit (SU). As the table below shows, the Local Method generally reduces the STD of elevation by 17% - 19% compared to the Global Method. This quantifies the effectiveness of the Local Method over the Global Method for capturing subgrid variability of topography.

Table 1: Comparing the Local and Global methods in capturing topographic heterogeneity using non-geo-located SUs

Average STD in elevation			
Area threshold (%)	**Global Method**	**Local Method**	**Difference (%)**
1	80.81	66.82	17.30
2	92.10	75.77	17.73
3	100.03	81.60	18.43
4	106.55	86.20	19.10
5	112.14	90.48	19.32

3. *The purpose of using precipitation in the implications to representation of land surface processes is not clear to me. I think the goal of the new approach is to better capture the subgrid variability of the topography. Precipitation, on the other hand, is the overall results of land-atmosphere-topography interactions. Does that mean the atmospheric model should also have similar grid structure as the land surface model? In addition, I don't understand how the results in Figure 13b are better than Figure 13a.*

Response:

As discussed in our response to comment #1, our modeling objective is to implement a subgrid structure in both atmosphere and land models, together with a subgrid orographic precipitation scheme in the atmosphere model. Hence it is important to use existing precipitation and temperature datasets to evaluate the capability of the subgrid structures in capturing atmospheric forcing variability, as will be represented by the subgrid orographic precipitation scheme. For this purpose, Figure 11 compares the distribution of values of subgrid standard deviation in precipitation and temperature mapped from the high resolution PRISM datasets. Furthermore, in Figures 13 a, b, and c, we evaluate the spatial distribution of precipitation mapped to the subbasins and the non-geo-located subgrid structures from the Local method against the spatial distribution of precipitation from the original high resolution PRISM grid-based representation to determine whether the non-geo-located subgrid structures are able to improve representation of precipitation as compared to the subbasin-based representation. The subbasin-based representation used in this comparison comes from our previous studies (Tesfa et al., 2014a, 2014b), which evaluated the benefits of land surface modeling using subbasin-based approach against the standard regular grid-based land surface modeling approach, where significant advantages in simulations of hydrologic fluxes and streamflow were demonstrated by the subbasin-based approach. However, we agree with the reviewer's comment that without a closer look at the mountainous areas (e.g., in Figure 13), it is not easy to visualize the improvement resulting from the new subgrid structure. Nevertheless with close inspection, it is possible to see the improvement, where the map from the new subgrid structure is more similar to the original PRISM grid representation than that of the Subbasin-based map. In addition, since statistical metrics are generally more informative than spatial maps, we have included statistical metrics in Table 3.

The atmospheric model will use non-geo-located subgrid structures derived based on the atmospheric grid as shown in Figure 1 in our response to comment #1.

In the revised manuscript, we will add more clarifications on how the PRISM climatic data are used to evaluate the subgrid structures.

Minor comments:

1. *Line 61: Does the definition of subgrid affect the results? For example, the subgrid for general circulation model grid size or the cloud resolving model grid size?*

Response:

The approaches described in the manuscript have been exclusively designed for subbasin/watershed based representation. The Local method, for example, utilizes a geomorphologic concept (hypsometric analysis) watershed analysis to derive the subgrid structures capturing the topographic pattern of the study domain. Application of the hypsometric analysis over the general circulation grid is not expected to yield the same behavior as that of the subbasin/watershed grid. However, it is possible to device a variant of the Local method capable to derive non-geo-located subgrid structures for the general circulation model grid size similar to those of the Local method described in the manuscript. For example, as part of our study to improve representation of orographic precipitation in the atmospheric model, we were able to replace the hypsometric analysis (Figure 3 in the manuscript) in the Local method by area-elevation profile curves and discretized each atmospheric grid (ne30np4) into surface elevation-based non-geo-located subgrid structures capable of capturing topographic heterogeneity (please see Figure 1).

2. *Line 83: Does the choice of study area affect results?*

Response:

Yes, the choice of the study area may affect the results. For example, the Local method has been designed to derive the subgrid structures in a way that minimizes computational demand by discretizing mountainous areas into more subgrid units and flat areas into a smaller number of subgrid units. Thus, the advantages of the new subgrid structures from the Local method are expected to be more pronounced when applied over topographically heterogeneous/mountainous areas as opposed to areas characterized by homogenous/flat topography.

In the revised manuscript, we will state that the advantages of the non-geo-located subgrid structures from the Local method are expected to be more pronounced over areas characterized by heterogeneous topography.

3. *Line 175: Can you be more specific on what area threshold means?*

Response:

An area threshold is a value calculated as a percentage of the area of each subbasin to be used as a criterion for identifying smaller subgrid units that should be merged to their neighboring larger subgrid units to enable discretization of each subbasin into a reasonable number of subgrid structures. As it has been demonstrated in our response to the 2nd reviewer's comment #3, both methods (Global and Local) initially discretize each subbasin into many subgrid units. To divide the subbasin into a reasonable number of subgrid units, the normalized area of each subgrid unit, expressed as a percentage of the area of the subbasin, is calculated and compared with the value of the area threshold. All subgrid units with normalized areas smaller than the threshold are then merged to the neighboring larger subgrid units.

In the revised manuscript, more clarification of the area threshold value will be included.

4. *In line 230: "the spatial pattern of the number of SUs per subbasin for the SUs from the Local method follows the topographic pattern in the study area better than those of the Global method". In Fig. 5, it's difficult for me to recognize such point. Is it a result of coloring the number of SUs into 5 categories rather than 13 categories?*

Response:

We thank the reviewer for the comment. However, we think it is quite obvious from Fig. 5c and Fig. 5d that the numbers of SUs used in the two methods are very different. For example, there is a larger east-west gradient in the number of SUs in the mid- and upper-basin in Fig. 5c compared to Fig. 5d. Also in the western basin, the variations of the number of SUs in Fig. 5d correspond much better to the spatial variations of topography than that shown in Fig. 5c. To quantify the correspondence between the pattern of surface topography and the pattern of the number of SUs, we will present correlation coefficients between the two for the Global and Local method in the revised manuscript. We also want to note that the statement in the manuscript that the spatial pattern of the number of SUs per subbasin for the SUs from the Local method follows the topographic pattern in the study domain better than those of the Global method is also supported by the results shown in Figure 4. In Figure 4, the number of the subgrid units per subbasin from the Local method correlated with the values of the average slope of the subbasins much better than those of the Global method.

In the revised manuscript, we will include similar clarifications.

5. *The Y-axis in Figures 7, 8, 9 and 12 is blurry and difficult to read.*

Response plan:

We thank the reviewer for the comment. In the revised manuscript, Figures 7, 8, 9, and 12 will be updated to improve the quality of the figures.

References:

Leung, L. R. and Ghan, S. J.: A subgrid parameterization of orographic precipitation, Theoretical and Applied Climatology, 52, 95-118, 1995.

Leung, L. R. and Ghan, S. J.: Parameterizing Subgrid Orographic Precipitation and Surface Cover in Climate Models, Monthly Weather Review, 126, 3271-3291, 1998.

Tesfa, T. K., Li, H. Y., Leung, L. R., Huang, M., Ke, Y., Sun, Y., and Liu, Y.: A subbasin-based framework to represent land surface processes in an Earth system model, Geosci. Model Dev., 7, 947-963, 2014a.

Tesfa, T. K., Ruby Leung, L., Huang, M., Li, H.-Y., Voisin, N., and Wigmosta, M. S.: Scalability of grid- and subbasin-based land surface modeling approaches for hydrologic simulations, Journal of Geophysical Research: Atmospheres, 119, 3166-3184, 2014b.