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 have clarified the motivation of our study in the introduction section and add some discussions about our plan for atmospheric modeling in the summary and conclusion section as elaborated above.

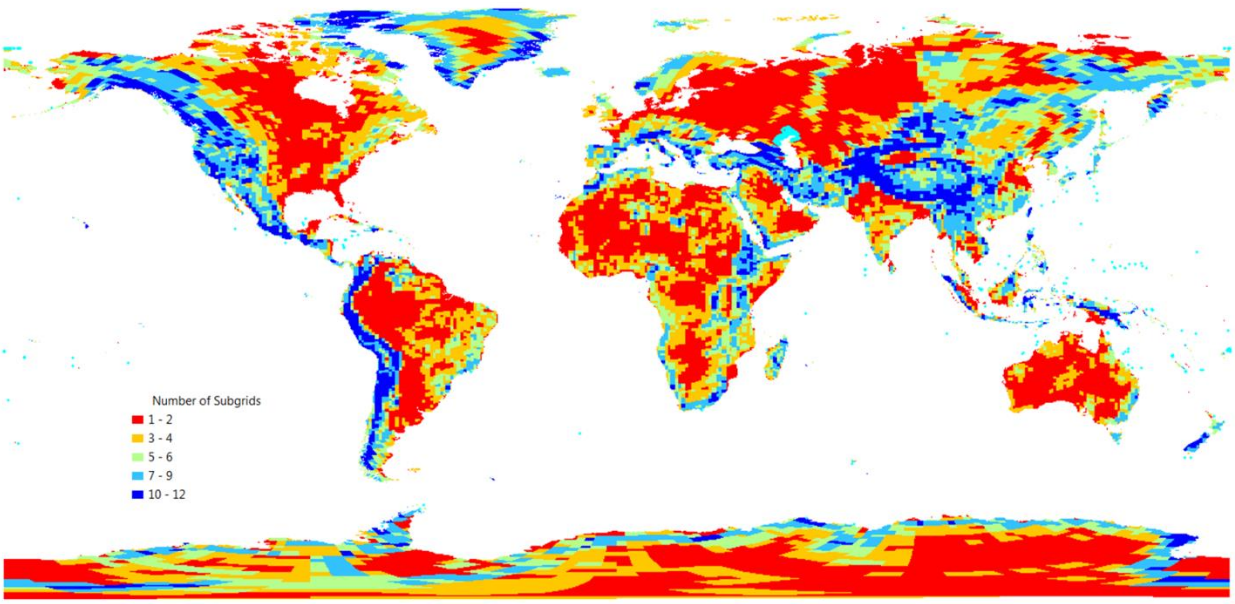


Figure 1: The spatial distribution of the number of subgrid unites per atmospheric grid (ne30np4) at global scale.

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 have included the following table in the revised manuscript and updated 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 have added 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 have stated more clearly 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 values has been included in section 3.2.

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 have addedcorrelation coefficients between the two using values of elevation range within the subbasins for for both 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 have included 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 have been 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.

Response to 2nd Reviewer's comments

We would like to thank the reviewer for the constructive comments on our manuscript. We will revise the manuscript accordingly to address all the comments. Detailed responses to the reviewer's comments and revisions planned are listed below.

Overall Comment:

Current land surface models lack of addressing topographic information in their subgrid structures. In this study, the authors give two types of subgrid structures (geo-located and non-geo-located) over the topographically diverse Columbia River basin in the Northwest Untied States using two topography-based methods (Local and Global) for watershed discretization, and the research topic is interesting and valuable. Generally, the methods are sound and have potential being used in land surface modeling. Therefore, the manuscript can be accepted be published in the Journal Geosci. Model Dev. before some concerns given below have been addressed.

Response:

We thank the reviewer for the constructive comments. The manuscript will be revised accordingly to address all the comments.

General comments:

1. *The first concern is about the evaluation method. When comparing the Local and Global methods, as well as the geo-located and non-geo-located structures, the authors tended to choose the options that are less sensitive to the values of area threshold because it can provide more robust subgrid structures for representing subgrid topographic heterogeneity. The sensitivity may be a key criterion to evaluate the subgrid structures. In reality, before simulation, we will set a certain area threshold based on the computational resources, the advantage of the discretization methods and subgrid structures should be evaluated under that certain area threshold. A more robust (or less sensitive) subgrid structure cannot ensure a better performance in a given area threshold. For example, in the Figure 8c and 8f, the standard deviations in subgrid structures size are lower for geo-located structure than non-geo-located with 1% area threshold, and to the other thresholds, the situations are quite reverse.*

Response:

We thank the reviewer for the comments. We agree with the reviewer that a less sensitive subgrid structure to threshold does not ensure better performance in a given area threshold. However, the purpose of the comparison in Figure 8 is only to show the sensitivity of the two types of subgrid structures (geo-locate and non-geo-located) to the values of area threshold; it is not intended to compare the performance of the two methods. The performance of the subgrid structures in capturing topographic heterogeneity and climate and vegetation variabilities are evaluated using the results shown in Figures 4, 5, 6, 10, 11 and 12.

Regarding the area threshold, the geo-located subgrid units discretize the study domain into geographically contiguous units, while the non-geo-located subgrid units divide the area into geographically non-contiguous subgrid units. This means, before applying area threshold values to merge the units with values of percentage area less than the threshold, for a given study domain, the following relationship always holds true:

$$numGeo >= numNonGeo \quad (1)$$

where, numGeo and numNonGeo are the number of geo-located and non-geo-located subgrid units, respectively. However, this may not be true after area threshold values are applied to merge the smaller subgrid units with the neighboring larger units. Compared to the geo-located subgrid units, the non-geo-located subgrid units tend to have a smaller number of units with size less than the area threshold values because many small subgrid units that are not spatially contiguous but with the same topographic characteristics are grouped into one subgrid unit and their combined area tends to become larger than the area threshold value. Thus, for a given area threshold, more subgrid units are merged with the neighboring units in the geo-located type than those of the non-geo-located subgrid units. Therefore, as the value of area threshold increases, the number of geo-located subgrid units can be less than the number of non-geo-located subgrid units for a given study domain. Please see the example watersheds provided in our response to comment #3 for more clarification.

2. *Also, using the standard deviations in subgrid structure size to judge the performance of the Local and Global methods seems not reasonable (Figure 9). When applying Local method to discrete the subbasin, the size factor is implicitly included by dividing RA into several quasi-equal parts. However in the Global method, the size factor is not considered. So it is natural that the standard deviation in subgrid structure size of Local method is lower than Global method. Moreover, the standard deviation in subgrid structure size is also not directly linked to the performance of each method or structure. It is better to define other criteria to judge the performance for each option or at least remove this unfair comparison from the manuscript.*

Response:

We thank the reviewer for the comment. We agree that the performance of the methods (Global and Local) is not linked with the standard deviation in subgrid structure size. Similar to Figure 8, the results in Figure 9 only aim to compare the sensitivity of the non-geo-located subgrid units to the values of area threshold when derived using the Global and Local methods. Performance of the two methods (Global and Local) in capturing topographic, climatic and vegetation heterogeneity are evaluated in Figures 10, 11 and 12. The results in Figure 9 clearly show that the non-geo-located subgrid structures from the Local method are less sensitive to the values of area threshold as compared to those of the Global method. We also agree with the reviewer’s comment that, taking advantage of the hypsometric analysis, the Local method divides the subbasin into quasi-equal parts resulting in non-geo-located subgrid structures that are less sensitive to the values of area threshold.

In the revised manuscript, we have clarified the purpose of the results compared in Figures 8 and 9 as elaborated above.

3. *When we compare two methods or two structures for subgrid for subgrid scheme, the performance of each option under same computational task (number of subgrid structures) is expected, while an appropriate area threshold is pre-prescribed. In this study, there is no such comparison. Therefore, I think at least the author should find a threshold at which the two methods (or subgrid structures) share*

the same number of subgrid structures, and do the comparison (for the standard deviation in elevation, precipitation and temperature in this study) under this area threshold. From the Figure 8a, 8d and Figure 9a, I do believe such area threshold exists. However, to the Figure 8a, it is also very curious that why the number of subgrid stuructures in non-geo-located structures can be more than it in the geo-located structures when area threshold is set to 4% and 5%. Intuitively, the number of SUs in non-geo-located structure should be always fewer because different subgrid structures (but the same elevation characteristics) in geo-located structure are combined to a same subgrid structures in the non-geo-located. The author should explain clearly about this abnormal effect.

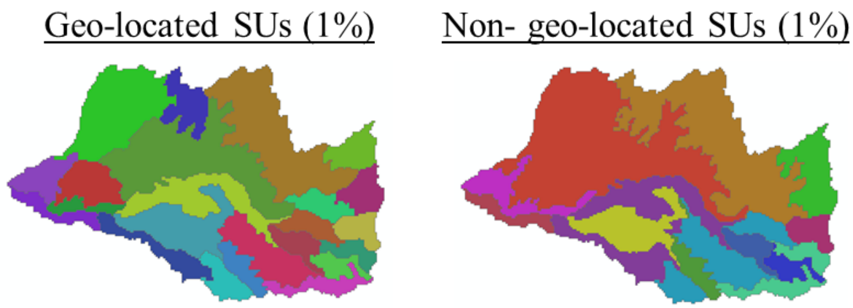
Response:

We thank the reviewer for the constructive comment. The comment can be divided into two parts. First, the reviewer suggests finding a threshold value that gives the same number of subgrid structures in both methods to repeat the comparison of the performance of the two methods at that threshold. Although this is doable, we think that the comparison is already in the manuscript. Figure 9a shows that the area threshold value resulting in the same number of non-geo-located subgrid units from the two methods (Global and Local) lies between 1% and 2%. Figure 10, on the other hand compares the non-geo-located subgrid units from the two methods across different values of area threshold (1%, 2%, 3%, 4%, and 5%) for their capability to capture topographic heterogeneity. The result for the area threshold value resulting in the same number of subgrid units in both methods is implicitly included in Figure 10 between area threshold values of 1% and 2%. Therefore, we think the first part of the reviewer's comment has been already addressed in the manuscript and we have added some discussions for such a comparison.

The second part of the comment is the concern why the number of non-geo-located becomes greater than that of the geo-located at thresholds of 4 and 5 percent. Since this comment is similar to comment #1, the reasons are described in our response to comment #1. However, for more clarification, the condition is demonstrated using one example subbasin from the study domain, as described below

To clarify why the number of non-geo-located subgrid units becomes greater than the number of the geo-located units as we increase the values of area threshold, we derived geo-located and non-geo-located subgrid units for one of the subbasins selected to represent extreme classes of elevation ranges in Figure 1 in the manuscript. The figure below shows the subbasin discretized into geo-located (left) and non-geo-located (right) subgrid units using area threshold of 1%. The colors represent the identification numbers of the units; thus, areas of the same color in the non-geo-located subgrid units belong to the same unit. In this example, the Global method was applied for six values of area threshold (1%, 2%, 3%, 4%, 5%, and 6%) to discretize the subbasin into both geo-located and non-geo-located SUs. The numbers of subgrid units are then compared before and after applying values of area threshold. Note that area threshold values are used to merge all units less than the threshold to the neighboring larger units.

As shown in the results below, the number of geo-located subgrid units is greater than those of the non-geo-located units before applying the area threshold values. However, after using the area threshold values to merge all the small subgrid units with their neighboring larger units, the number of the geo-located subgrid units decreases with increasing threshold faster than those of the non-geo-located subgrid units. As explained in our response to comment #1, geo-located subgrid type tends to have more subgrid units with size smaller than the threshold than those of the non-geo-located type, resulting in more subgrid units being merged as the threshold values increase.



Threshold	No of initial SUs		No of final SUs	
	Geo-located	Non-geo-located	Geo-located	Non-geo_located
1	808	699	23	13
2	808	699	11	8
3	808	699	7	8
4	808	699	6	6
5	808	699	5	5
6	808	699	3	4

Figure 1: Comparison of the number of geo-located and non-geo-located subgrid units derived using the Global method across different values of area threshold.

Specific comments:

1. *L144 – 146: the model code (Table1 and Table2) should be moved to the supplementary material, and instead give a brief description about the procedure of what this code expresses in the manuscript.*

Response:

We thank the reviewer for the suggestion. In the revised manuscript, Tables 1 & 2 have been moved to the supplementary material and the manuscript has been updated with the description of the procedures used in the code.

Tables 1 & 2 have been moved to the supplementary materials. The manuscript has been updated with brief description of the procedures utilized in the code.

2. *L165 – 179: Please add another member that using Global method, geo-located structure and including the topographic slope in these comparisons to show that how the performance of Global method can be improved when the slope effect is considered.*

Response:

We thank the reviewer for the constructive suggestion. Subsection 3.5 of the manuscript aims to evaluate the two methods (Global and Local) using geo-located subgrid structures derived based on elevation classification only. We agree with the reviewer on the importance of showing how the performance of the Global method can be improved when slope effect is considered. However, to keep the story smooth and the manuscript concise, we think such comparison should be placed in the supplementary materials.

In the revised manuscript, we have included the figure shown below in the supplementary material, which compares the number of geo-located subgrid units per subbasin derived using the Global method based on combination of topographic elevation and slope against the average slope of the subbasins to show how the Global method performs when effect of slope is considered. The result and discussion section has also been updated to discuss the comparison.

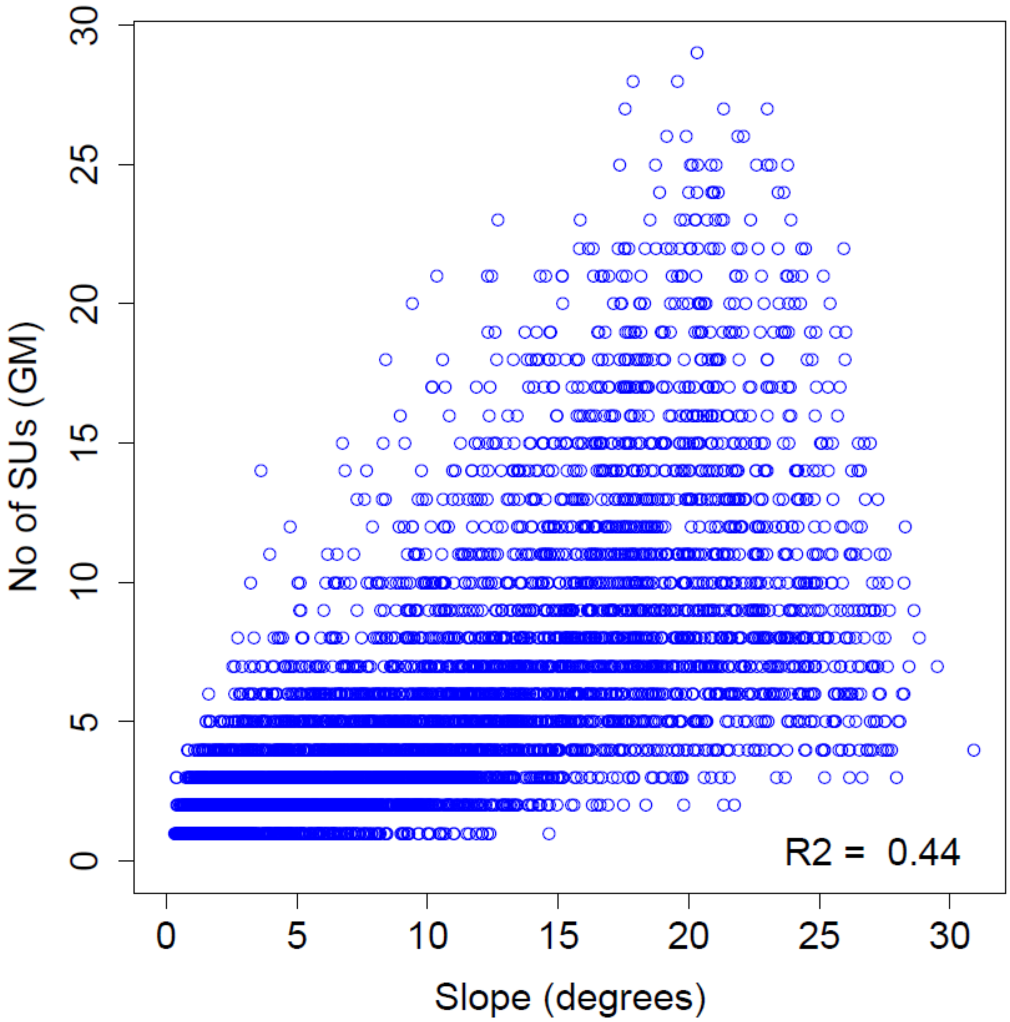


Figure 2: Number of geo-located subgrid units per subbasin from the Global method based on the combination of topographic elevation and slope at area threshold value of 1% compared against values of average slope of the subbasins

3. *L195: The title is not appropriate. NO Land surface processes were shown here, only precipitation and temperature.*

Response:

We thank the reviewer for the comment. The title has been changed to "Exploring New Topography-based Subgrid Spatial Structures for Improving Land Surface Modeling".

4. *L195 – 211: Some important information missing here. How do the authors interpolate the precipitation (or temperature) from subbasin-level to subunits-level, or how can we get the Figure 14b from 14a? Much more detail information about proceeding method should be added.*

Response:

The PRISM climate dataset has a spatial resolution of 800m. Both precipitation and temperature values for each subbasin/subgrid unit are computed as the average of the corresponding values from all the source PRISM grids that intersect with the subbasin/subgrid unit.

In the revised manuscript, more detailed description of the mapping approach has been included.

5. *L195-211: I think beside results from the option of Local method and non-geo-located structures, results from other options (Local method and geo-located stuructures, Global method and non-geo-located structure, Global method and geo-located strucutres) are also expected to be displayed in Table 3, Figure 13, and Figure 14.*

Response:

We thank the reviewer for the comment. The manuscript has been designed to evaluate the two methods (Global and Local) and two types of subgrid structures (geo-located and non-geo-located) in a more orderly manner. For this purpose, first the two methods (Global and Local) are compared using the geo-located subgrid units for their capability to capture topographic heterogeneity and to demonstrate the benefits of using hypsometric analysis in the Local method in capturing variability of topographic slope implicitly (Figures 4, 5, 6 , and 7). The geo-located subgrid structures are then compared against the non-geo-located (Figure 8). The two methods are then compared for their sensitivity to the values of area threshold (Figure 9). Furthermore, the two methods (Global and Local) are compared using the non-geo-located subgrid structures for their capability to capture topographic, climate and vegetation heterogeneity (Figures 10, 11, and 12). Finally, the method and subgrid structure type with more pronounced advantages are compared against the subbasin-based representation to evaluate potential improvements of the new subgrid structures (Figures 13 and 14). We think including the results from Local method and geo-located, Global method and non-geo-located subgrid structure, and Global method and geo-located subgrid structure would make the manuscript too long. To address the reviewer's comments without making the manuscript too long, in the revised manuscript, a table comparing results from the Global method against the subbasin-based and the original PRISM grids in the supplementary materials. Furthermore, maps similar to Figures 13 and 14 for the non-geo-located subgrid structures from the Global method have been included in the supplementary materials.

6. *L195 – 211: Please add spatial distribution for NDVI as it does to the precipitation in Figure 13. Also, the statistics about NDVI should be added in Table 3.*

Response:

We thank the reviewer for the comment. Since statistical metrics are generally more informative than maps, to address the reviewer's comments without making the paper too long, we have included a separate table (Table 3) comparing statistical metrics of NDVI of the non-geo-located SUs from the Local method against the subbasin-based and the high resolution NDVI grids in the revised manuscript. Further comparison of statistical metrics of the non-geo-located SUs from the Global method against the subbasin-based and original high resolution NDVI grid has been included in the supplementary materials.

7. *Figure 7, Figure 8 and Figure 9: These bar plots are not clearly displayed. Please redraw figures to make them discernible enough.*

Response:

We thank the reviewer for the comment. In the revised manuscript, the figures have been updated as recommended to improve the quality of the figures.

Exploring New Topography-based Subgrid Spatial Structures for~~to~~ Improvinge ~~Representation of Land Surface Processes for~~ ~~in~~ Land Surface ~~Modeling~~Modeling~~s~~

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Abstract

Topography exerts a major control on land surface processes through its influence on atmospheric forcing, soil and vegetation properties, river network topology and drainage area. Land surface models with spatial structure that captures the spatial heterogeneity influenced by topography may improve representation of land surface processes. Previous studies found that land surface modeling using subbasins instead of structured grids as computational units improves scalability of simulated runoff and streamflow processes. In this study, new land surface spatial structures are explored by further dividing subbasins into subgrid structures based on topographic properties including surface elevation, slope and aspect. Two methods (Local and Global) of watershed discretization are applied to derive two types of subgrid structures (geo-located and non-geo-located) over the topographically diverse Columbia River basin in the Northwestern United States. In the Global method, a fixed elevation classification scheme is used to discretize subbasins. The local method utilizes concepts of hypsometric analysis to discretize each subbasin using different elevation ranges that also naturally accounts for slope variations. The relative merits of the two methods and subgrid structures are investigated for their capability to capture topographic heterogeneity and their implications on representations of atmospheric forcing and land cover spatial patterns. Results showed that the Local method reduces~~d~~ the standard deviation of subgrid surface elevation ~~over~~in the study domain by 17% to 19% ~~as~~ compared to the Global method, highlighting the relative advantages of the Local method ~~over the Global method~~for capturing subgrid topographic variations. Comparison between the two types of subgrid structures showed that the non-geo-located subgrid structures are more consistent across different area threshold values than the geo-located subgrid structures. Overall the Local method and non-geo-located subgrid structures effectively and robustly capture topographic, climatic, and vegetation variability important for land surface modeling.

1 Introduction

Topography exerts a major control on land surface processes through its influence on atmospheric forcing, soil and vegetation properties, and river network topology and drainage area. Consequently, accurate climate and land surface simulations in mountainous regions cannot be achieved without considering the effects of topographic heterogeneity (Leung and Ghan, 1998; 1995; Ghan et al. 2006). Mountain water resources are particularly sensitive to global warming (e.g., Leung and Ghan 1999; Ghan and Shippert 2006; Mote et al. 2007; Kapnick and Hall 2012). The amplified warming at high elevation due to the lapse-rate effect and snow albedo feedback has large impacts on snowpack accumulation and melt, with consequential effects on runoff and water supply (Leung et al. 2004; McCabe and Clark 2005; Rasmussen et al. 2011).

Topography has dominant control on the spatial pattern of atmospheric forcing including surface temperature, precipitation, incoming and reflected solar radiation. Regions characterized by heterogeneous topography generally exhibit diverse hydroclimatic conditions. For example, stable moisture-rich air lifted by the mountains can produce orographic precipitation that dominates the spatial distribution of cold season precipitation in the western United States (Leung et al. 2003). In mid and high latitude regions topography also influences the partitioning of precipitation into snow and rainfall. In addition, incoming and reflected solar radiation is highly dependent on the orientation of landscapes, which can also have significant impacts on surface hydrology through the effects of radiation on cloud, precipitation, and snow processes (Lee et al. 2015).

Topography is also one of the factors of soil formation, exerting dominant control on the spatial patterns of soil properties over watersheds, e.g., soil depth (Tesfa et al., 2009 and references there in). Soils are generally deeper and finer in texture over valleys compared to the shallower and coarser texture over ridges of watersheds. Through its influence on direct and diffuse solar radiation and consequent effects on soil moisture and evapotranspiration, topography affects spatial pattern of vegetation on a landscape. Different vegetation types grow on different parts of a landscape depending on their water demand and resistance to water stress. In semiarid regions, vegetation types that have high water demand or less resistant to moisture stress grow near streams, while vegetation types resistant to moisture stress can grow further from streams (Tesfa et al., 2011). Topography also determines topology of river network and drainage area, which in turn control surface and subsurface flows (Beven, 1997; Chen and Kumar, 2001). Overall, catchment ecohydrology is strongly influenced by the topography-mediated interactions among vegetation, soil, and river network (Thompson et al. 2011).

Improving representations of land-atmosphere and surface-subsurface interactions influenced by fine scale topography and vegetation has been identified as a grand challenge, motivating the need for hyper-resolution land surface modeling (Wood et al., 2011). While hyper-resolution modeling approaches are being tested at regional (Singh et al. 2015) and continental scales (Maxwell et al. 2015), improving the spatial structures of land surface models to capture the effects of topographic heterogeneity could be crucial to advancing modeling of land-atmosphere interactions in earth system models. Tesfa et al. (2014a; 2014b) demonstrated improved scalability of simulated runoff and streamflow processes when subbasins instead of structured grids are used as computational units in the Community Land Model. The improvements of the subbasin-based land surface modeling in scalability come from its important conceptual advantages in capturing atmospheric forcing and runoff generation processes, both strongly influenced by topography that defines the boundaries of the subbasins.

Discretization of the subbasins to capture spatial heterogeneity influenced by topography may further improve the representation of land surface processes. Ke et al. (2013) evaluated several classification methods to account for subgrid variability of surface elevation and vegetation cover for land surface models with structured grids. To the best of our knowledge, development of subgrid structures for the subbasin-based land surface modeling has not been attempted. The purpose of this paper is to explore subgrid structures that capture topographic heterogeneity and its influences on land surface processes for land surface modeling. Such subgrid spatial structures ~~are expected to~~may provide a more realistic spatial distribution of surface properties and their influence on climatic variability with more reasonable computational requirement compared to discretizing the domain into fine resolution grid-based representations reported in the literature (e.g., Singh et al., 2015).

Motivated by the significant influences of topographic heterogeneity on land surface processes, we explore new topography-based spatial structures by further dividing subbasins into subgrid structures or subgrid units (also hereafter denoted as SU) to take advantage of the emergent patterns and scaling properties of atmospheric, hydrologic, and vegetation processes in land surface models. For this purpose, two methods (Global and Local) of subbasin discretization are applied to derive two types of SUs (geo-located and non-geo-located) over the topographically diverse regions of the n~~N~~orthwestern United States. In the Global method, the subbasins are discretized into multiple SUs following the surface elevation classification scheme employed in Leung and Ghan (1998; 1995), combined with classifications of topographic slope and aspect. The local method utilizes concepts of hypsometric analysis (Willgoose and Hancock, 1998; Sinha-Roy, 2002) combined with classification of topographic aspect to discretize each subbasin into multiple SUs. We evaluate the two discretization methods and spatial structures for their capability to capture topographic heterogeneity and their implications on the representation of the spatial patterns of atmospheric forcing and land cover. For Earth system modeling, the atmospheric model will adopt the subgrid topographic precipitation scheme of Leung and Ghan (1998) and Ghan et al. (2006) to provide subgrid atmospheric forcing for coupling with the topographic SUs of land surface models to represent topographic effects on atmospheric and land surface processes and land-atmosphere interactions.

The remainder of the paper is organized as follows: Section 2 describes the study area. Development of the new subgrid structures is discussed in Section 3. The strategy used to evaluate the methods of subbasin discretization and the subgrid structures are discussed in Section 4. Section 5 presents the results and discussion and finally Section 6 closes with conclusions and recommendations.

2 Study Area

To investigate the importance of various watershed discretization methods, the Columbia River basin located in the U.S. Pacific Northwest is used as a case study. Figure 1 shows the topographic patterns, subbasins with average size equivalent to 1/8th degree grid, elevation ranges of the subbasins, and two subbasins representing extreme topographic properties. The Columbia River basin encompasses both mountainous and low-lying regions. Climatically, the mountainous regions are characterized by low temperature and higher precipitation dominated by snowfall, while, the low-lying regions have warmer temperature and lower precipitation mainly in the form of rainfall. The basin encompasses the largest river in the Pacific Northwest region of North America, and is the fourth largest river in the United States by discharge volume. Water resources in the basin are dominantly controlled by the high precipitation and snow cover in the mountainous areas.

3 Development of new SUs for land surface modeling

Two methods of subbasin discretization are implemented to develop land surface subgrid structures that capture the spatial heterogeneity influenced by topography. Both methods are applied to derive two types of subgrid units (SUs): geo-located and non-geo-located. The following subsections describe the input data, the two discretization methods and the two types of SUs.

3.1 Input data

To derive the subgrid units, the study domain is first delineated into subbasins. We utilize the subbasins equivalent to 1/8th degree grids delineated in Tesfa et al. (2014a; 2014b) using ArcSWAT (Soil and Water Assessment Tool; Neitsch et al., 2005) with the 90m Digital Elevation Model (DEM) and the 15-arcsec river networks from the Hydrological data and maps based on Shuttle Elevation Derivatives (HydroSHEDS) (Lehner et al., 2008). Although DEMs at resolutions of 30m or finer are available from the United States Geological Survey (USGS), we use DEM from a global database (i.e., HydroSHEDS) because the main goal of this study is to develop subgrid structures for global land surface models and Earth system models. Along with the delineation of the subbasins, topographic attributes such as slope and aspect are derived for the study domain to be used as inputs for the subbasin discretization methods.

3.2 Global Method

In the Global method, the study domain is first discretized into 12 elevation classes based on surface elevation extracted from the 90m HydroSHEDS' DEM, following the surface elevation classification scheme employed in Leung and Ghan (1998; 1995) that uses class intervals of 100m for surface elevation below 500m, and gradually increasing to intervals of 500m and 1000m for high surface elevations, resulting in 12 elevation classes (see Figure 2). This method is Global because the same elevation classification scheme is used to discretize all subbasins regardless of the elevation spanned by individual subbasins, which can vary substantially. Since topography influences atmospheric and land surface processes through surface elevation, slope and aspect, the Global method combines topographic slope and aspect with the elevation classes. For this purpose, the study domain is also partitioned into two classes of topographic slope where slope values less than or equal to 20 degrees are grouped as gentle to moderately steep areas, and slope values greater than 20 degrees are grouped as steep to very steep areas following definitions of slope classes by the Natural Resources Conservation Service of the United States Department of Agriculture. Similarly, the study domain is partitioned into two classes of topographic aspect, where areas facing north, northwest, northeast and east are assigned to one class and areas facing south, southwest, west and southeast belong to a separate class. For each subbasin, classes of elevation, slope and aspect are extracted following the subbasin boundary and converted from raster to polygon shapes, resulting in three sets of SUs, respectively, derived based on elevation, slope and aspect separately. The SUs derived from elevation, slope and aspect are then intersected to generate SUs based on the combination of topographic elevation, slope and aspect, resulting in a large number of SUs for each subbasin. Since many of the SUs are extremely small in size, and our goal is to capture topographic heterogeneity with only a reasonable number of SUs for computational efficiency, an area threshold value is used to merge SUs with area smaller than the threshold to their neighboring SUs with size larger than or equal to the threshold value. The area threshold is defined based on~~a value of~~ the percentage of the area of each subbasin. ~~used as a criterion for identifying smaller~~ For s~~s~~ubgrid units that are smaller than the area threshold, they are~~that should be~~ merged to their neighboring larger subgrid units. To enable discretization of each subbasin into a reasonable number of subgrid units, a value of normalized area (SU_{na}) is calculated for each subgrid unit following equation 1 and compared against the area threshold value.

$$SU_{na} = \frac{SU_a}{Sub_a} * 100 \qquad (1)$$

where SU_a and Sub_a are areas of subgrid unit and subbasin, respectively. The Global method has been implemented in Python and utilizes ArcGIS functionalities. In this effort, the Global method is applied to derive both geo-located and non-geo-located SUs.

3.3 Local Method

In the Local method of subbasin discretization, the subbasins for the study domain are first classified into five groups based on values of elevation range using the Natural Breaks (Jenks) classification method in ArcGIS. As an example, to derive the hypsometric curves, the two contrasting subbasins shown in Figure 1 are discretized into 100 elevation contours using elevation data extracted from the 90m resolution DEM from HydroSHEDS. The relative elevation (*RH*) and relative area (*RA*) are calculated for each contour, where, relative elevation (*RH*) is defined as the ratio of the height of the given contour (*h*) from the base plane of the subbasin to the maximum height of the subbasin (*H*), while relative area (*RA*) refers to the ratio of the area above a particular contour (*a*) to the total area of the subbasin (*A*).

$$RA = \frac{a}{A} \quad (~~1~~2)$$

$$RH = \frac{h}{H} \quad (~~2~~3)$$

The hypsometric curves are derived by plotting the relative area (*RA*) along the abscissa and the relative elevation (*RH*) on the ordinate axes. In geomorphology, hypsometric curve is used to characterize the distribution of elevation within a basin. Following Willgoose and Hancock (1998), three parts of the hypsometric curve are identified as the head, body and toe of the subbasin, respectively, and defined as: (1) the upward-concave part of the curve in the upper left-hand side; (2) the downward-concave part of the curve on the right hand side; and, (3) the upward-concave region in the center of the curve between the head and toe. As shown in Figure 3, relative area values of 0.2 and 0.8 are used to discretize the hypsometric curve into the three parts, following Sinha-Roy (2002). Furthermore, the body part of the subbasins is divided at relative area value of 0.5 for more homogenous topography within each class. As a result, each subbasin is initially discretized into four elevation bands with elevation class break values at the minimum and maximum elevation, and at relative areas of 0.2, 0.5 and 0.8. Elevation ranges are calculated between each consecutive class break values. For each elevation band/class, the elevation range is compared against an elevation threshold value of 100 m; ~~and,~~ any elevation class with an elevation range less than 100 m is merged with the neighboring elevation class. The values of elevation range and elevation class break are then updated accordingly and the updated elevation ranges are further compared against the elevation threshold value recursively until the ~~values of~~ final values of elevation class break and ranges are determined. The final values of elevation class break are then utilized ~~The values of elevation ranges and class break are further used in the algorithms in Tables 1 and 2~~ to derive the elevation-based SUs for each subbasin (see Algorithms in Tables 1s and 2s in the supplementary material). This method is Local as the elevation ranges used to discretize the subbasins vary depending on the topographic variations within each subbasin.

Similar to the Global method, classes of topographic aspect are extracted for each subbasin and intersected with the corresponding elevation classes to ~~classifying~~ discretiz~~e~~~~ing~~ the subbasin into multiple SUs, with ~~where~~ some ~~of them are~~ extremely small in size. Since discretizing the subbasins using hypsometric curve is expected to capture slope variation implicitly, topographic slope is not used in the Local method. With the main goal to capture topographic heterogeneity with only a reasonable number of SUs for computational efficiency, similar to the Global method, area threshold is utilized to merge th~~os~~e SUs with area smaller than the threshold to their neighboring SUs with size larger than or equal to the threshold to develop the final SUs. This method has also been implemented in Python and utilizes ArcGIS functionalities. ~~This~~ The Local method is also applied to derive both geo-located and non-geo-located SUs. In this method, ~~T~~the actual number of SUs of each subbasin depends on the variability of surface elevation and topographic aspect within the subbasin boundary.

3.4 Types of Subgrid Units

Two types of SUs are derived using both the Global and Local methods: geo-located and non-geo-located. The geo-located SUs are derived by discretizing the subbasins into spatially contiguous structures. They are characterized with explicit geographical location and a single boundary. In this case, SUs with the same topographic characteristics at different locations of the subbasin are treated as separate units. The non geo-located SUs are developed by discretizing the subbasins into spatially non-contiguous structures. In this case, SUs with the same topographic properties at different locations of the subbasin are treated as a single unit resulting generally in reduced number of SUs compared to the geo-located SUs.

4 Evaluation Strategy

4.1 Analysis using SUs based only on elevation

Because topographic slope is not explicitly used in the Local method, it is logical to ask whether discretizing subbasins using the hypsometric curve is capable of implicitly capturing the variability of topographic slope within the subbasins. To investigate this, geo-located SUs are derived using both Global and Local methods based on elevation classification only. The number of SUs for each subbasin from both methods is compared against the average values of topographic slope of the subbasins in the study area to determine how topographic slope influences the number of SUs needed to capture subgrid topographic variability in each method. In addition, the spatial pattern of the number of SUs for each subbasin derived using each method is compared against the spatial pattern of topographic slope and elevation range within the subbasins for the study region. An effective subgrid method would allow more SUs in subbasins with complex terrain to capture the subgrid topographic variability and use fewer SUs in subbasins with small variations of topography. Finally, the relative capability of the two methods in capturing topographic heterogeneity and their sensitivity to the values of area threshold are evaluated, respectively, based on the standard deviation of the 90m resolution elevation within the SUs and the variation of statistical metrics (the total number of SUs, mean SU size and standard deviation in SU size) calculated for the study domain across different values of area threshold (1%, 2%, 3%, 4%, & 5%). Methods that are less sensitive to the values of area threshold can provide more robust SUs for representing subgrid topographic heterogeneity.

4.2 Analysis using SUs based on elevation, slope, and aspect

The two types of SUs are expected to differ in their ability to capture topographic heterogeneity, the number of SUs, which has important implications to the overall computational burden, and their sensitivity to area threshold values, which is important for defining robust SUs for land surface modeling. Thus, to evaluate the two types of SUs with respect to their applications in land surface modeling, geo-located and non-geo-located SUs for the study area are derived based on elevation, slope and aspect using both Global and Local discretization methods at different values of area threshold (1%, 2%, 3%, 4%, & 5%). The geo-located and non-geo-located SUs of each method are then compared for their sensitivity across values of area threshold using statistical metrics (total number of SUs, average size of SUs and standard deviation in SU size) calculated over the study domain at different values of area threshold.

The Global and Local methods are further investigated for their capability in capturing topographic heterogeneity and consistency across different values of area threshold when using the non-geo-located SUs. The relative capability of the non-geo-located SUs from both methods in capturing topographic heterogeneity is evaluated based on the values of standard deviation in surface elevation calculated at each SU across different values of area threshold. In addition, sensitivity of the two methods (Global and Local) to the values of area threshold when used to derive non-geo-located SUs is evaluated using statistical metrics calculated over the study domain such as total number of SUs, average size of SUs and standard deviation in SU size.

4.3 Implications to representation of land surface processes

Since the main goal of this study is to derive land surface structures capable of improving representation of land surface processes in land surface modeling, it is logical to ask how the new structures impact the representation of land surface parameters. For this purpose, the two methods are first evaluated for their relative capability to capture climatic and land cover variability over the study area using the non-geo-located SUs derived at different values of area threshold. The capability to capture climatic variation is investigated by comparing values of standard deviation in precipitation and surface temperature within the SUs derived using the two methods. In this case, the precipitation and surface temperature datasets for the study area are extracted from the 30 year normal annual precipitation and mean annual surface temperature obtained from the PRISM climate datasets (800m spatial resolution) (http://www.prism.oregonstate.edu/). Similarly, using the Normalized Difference Vegetation Index (NDVI) data as a proxy for land cover, the relative capability of the two methods in capturing land cover pattern over the study domain is investigated by comparing values of standard deviation in NDVI calculated within the SUs from the two methods. For this purpose, the NDVI datasets for the study area are obtained from the enhanced Moderate Resolution Imaging Spectroradiometer (eMODIS) data (250m spatial resolution) portal (http://earthexplorer.usgs.gov/) at the Earth Observation and Modeling Facility (EOMF). Furthermore, to evaluate the relative advantages of the non-geo-located SUs derived using the Local method in capturing climatic variability in the study domain ~~are investigated by~~as ~~comparing~~ compared ~~precipitation and surface temperature represented using the SUs against~~to those of the subbasin-based ~~and original high resolution PRISM grid-based~~ representation~~s~~, the spatial distributions of precipitation and temperature mapped to the subbasins and the non-geo-located SUs from the Local method are compared against the spatial distributions of precipitation and temperature from the original high resolution PRISM grid-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 and streamflow were demonstrated by the subbasin-based approach.

5 Results and discussion

5.1 Global versus Local methods using elevation-based SUs

Since the main differences between Global and Local methods are in the way subbasins are discretized into elevation classes and whether topographic slope is included explicitly, the relative capability of the two methods in capturing topographic heterogeneity is investigated using elevation-based SUs. Figure 4 compares how well the Global and Local subbasin discretization methods capture the topographic slope using elevation-based geo-located SUs derived based on elevation at 1% area threshold. For this purpose, the numbers of SUs per subbasin resulted from both methods are compared against the average topographic slope calculated over the subbasins. The results show the number of SUs per subbasin from the Local method is directly related to the average subbasin slope ($r^2 = 0.47$), so the steep subbasins are generally discretized into more SUs than the flat subbasins. On the other hand, the number of SUs per subbasin from the Global method is not related ($r^2 = 0.07$) to the average topographic slope of the subbasins. From this comparison, it is clear that discretizing subbasins following the Local method (see algorithms in Tables 1s and 2s in the supplementary material) using the hypsometric curve characterization within each subbasin~~s~~ is able to capture topographic slope implicitly, making the Local method superior over the Global method. To investigate how the performance of the G~~g~~lobal method can be improved when the effect of slope is considered, the number of geo-located SUs per subbasin derived using a combination of topographic elevation and slope is~~are~~ compared against the average topographic slope calculated over the subbasins (Figure 1s in the supplementary material). The results show significant improvement of~~in~~ the capability of the Global method in capturing topographic slope ($r^2 = 0.44$) as compared to the Global method using topographic elevation only ($r^2 = 0.07$); however, the performance is still ~~less~~not as good as ~~than~~ that of the Local method ($r^2 = 0.47$).

The Columbia River basin encompasses diverse topography ranging from flat to steep mountainous areas making it an ideal study area for evaluating the relative capability of the two subbasin discretization methods in capturing the spatial pattern of topographic properties. The spatial pattern of the numbers of elevation-based geo-located SUs per subbasin derived using both methods with a 3% area threshold are compared against the spatial pattern of the average topographic slope and elevation ranges of the subbasins classified based on the Natural Breaks (Jenks) classification method in ArcGIS (Figure 5). The results suggest 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 area better than those of the Global method, confirming further the advantages of discretizing the subbasins using the Local method. To quantify the correspondence between the pattern of the surface topography and the pattern of the number of SUs, correlation coefficients are calculated between values of surface elevation range within the subbasins and the number of SUs per subbasin. ~~,~~The correlation coefficients ~~which resulted~~are 0.66 and 0.47 for the Local and Global methods, respectively. Hence, t~~T~~he number of SUs per subbasin from the Local method mimics the topographic pattern better than the Global method, ~~so defining~~as more SUs ~~are defined~~ per subbasin are defined over ~~the~~ mountainous areas and fewer SUs ~~are needed~~ per subbasin are defined over relatively~~the~~ flat areas of the basin. This enables the model to capture the topographic heterogeneity with minimum number of SUs over the study domain, which is essential for computational efficiency in land surface modeling.

Figure 6 shows the relative capability of the two methods in capturing subgrid topographic heterogeneity across different values of area threshold using elevation-based geo-located SUs. For this purpose, values of standard deviation in elevation within the geo-located SUs derived using different values of area threshold (1%, 2%, 3%, 4%, & 5%) from both methods are compared. The results again clearly show that the SUs from the Local method are able to capture topographic heterogeneity, which is reflected in the smaller standard deviation of topography within each SU across different values of area threshold, better than those of the Global method. In addition, the results also show that the Local method can capture topographic heterogeneity more consistently across different values of area threshold than the Global method, suggesting that the SUs derived using the Local method are more robust.

Using the same SUs, the two methods are further investigated for their sensitivity to values of area threshold using the variability of statistical metrics (total number of SUs, mean SU size and standard deviation in SU size) calculated over the whole study domain for different values of area threshold. The results in Figure 7 show that SUs derived using Local method remain more consistent across different values of area threshold than those of the Global method, making the Local method more robust than the Global method for land surface modeling.

5.2 Geo-located versus non geo-located SUs

To evaluate the robustness of the two types of SUs (geo-located and non-geo-located) for land surface modeling, we compare their sensitivity to values of area threshold. For this purpose, geo-located and non-geo-located SUs are derived based on elevation, slope and aspect using both methods at different values of area threshold. ~~Note that the results in Figure 8 are intended to evaluate how sensitive the two types of subgrid structures are to the values of the area threshold using statistical metrics generated over the whole study domain.~~ The geo-located SUs from each method are then compared against the corresponding non-geo-located SUs derived using the same method based on the statistical metrics calculated over the whole study area. Shown in Figure 8 are comparisons of the variability of the total number of SUs, average SU size and standard deviation in SU size calculated for the geo-located SUs against those of the non-geo-located SUs for both the Global (Figures 8a, 8b, and 8c) and the Local (Figures 8d, 8e, and 8f) methods. In both methods, the results generally suggest that the non-geo-located SUs are more consistent across different values of area threshold than the corresponding geo-located SUs. Thus, in subsequent sections, the two methods of subbasin discretization are evaluated using the non-geo-located SUs only.

5.3 Global versus Local methods using non geo-located SUs

Following the evaluation of the two methods using elevation-based geo-located SUs, it is important to investigate whether the advantages of the Local method over the Global method shown in previous results still apply when the two methods are used to derive non-geo-located SUs based on the combination of multiple topographic properties. Shown in Figure 9 are comparisons of sensitivity of the Global and Local methods to values of area threshold when the two methods are applied to derive non-geo-located SUs using the variability of the statistical metrics (total number of SUs, average SU size and standard deviation in SU sizes) calculated over the whole study domain at different values of area threshold. Note that the results in Figure 9 are intended to evaluate how sensitive the two methods are to the values of area threshold and, ~~that~~ unlike the comparison in Figure 7, the SUs in this comparison are non-geo-located, derived based on a combined classification of elevation and topographic slope and aspect in the Global method and elevation and topographic aspect in the Local method. Similar to the comparisons in Figure 7, the results suggest that the SUs from the Local method are less sensitive to the values of area threshold, yielding more consistent values of the total number of SUs, average SU size and standard deviation in SU sizes over the study domain than those of the Global method.

Shown in Figure 10 are values of standard deviation in elevation within the non-geo-located SUs derived using the Global and Local methods at different values of area threshold, comparing the capability of the two methods in capturing topographic heterogeneity when used for non-geo-located SUs. Similar to the results shown in Figure 6, there is a clear difference in the capability of the two methods in capturing topographic heterogeneity across different values of area threshold. The non-geo-located SUs from the Local method are able to capture topographic heterogeneity much better than those of the Global method across different values of area threshold. The r~~R~~esults in Table 1 show that the Local method reduces~~d~~ the standard deviation of subgrid surface elevation over the study domain by 17% to 19% across different values of area threshold ~~as~~ compared to those of the Global method, highlighting the relative advantages of the Local method over the Global method in capturing topographic heterogeneity. The improved capability of the Local method shown in this comparison comes from the advantage of performing elevation discretization based on hypsometric curve characterization in the Local method (see Figures 6 and 3). The Local method has been designed to minimize computational demand by discretizing mountainous areas into more subgrid units and flat areas into ~~a smaller number of~~fewer subgrid units so~~; thus,~~ its advantages are expected to be more pronounced when it is applied over topographically heterogeneous region~~area~~s as opposed to region~~area~~s characterized by homogenous topography. Furthermore, the results from Figure 9a show that the area threshold value resulting in the same number of non-geo-located subgrid units from the two methods lies between 1% and 2%. Hence the~~; while~~ results from Figure 10 implicitly suggest that the Local method still performs better even when we compare the two methods ~~are compared using~~that produce the same number of SUs. The results also suggest that the capability of the non-geo-located SUs from the Local method in capturing topographic heterogeneity remains more consistent at different values of area threshold than those of the Global method, confirming the superior advantages of the Local method.

From the results shown so far, relative to the Global method, the SUs from the Local method are superior in capturing topographic heterogeneity yielding more SUs per subbasin over mountainous areas and fewer SUs per subbasin over flat areas, which is essential for more realistic representations of the spatial distributions of precipitation and snow cover in mountainous areas and computational efficiency in land surface modeling. Also, the SUs from the Local method are more consistent across different values of area threshold than those of the Global method. Subsequently, it is important to examine whether similar advantages exist for the Local method in capturing climatic and land cover variability as compared to the Global method. The following section focuses on the implications of the non-geo-located SUs in the representations of climatological and land cover variability in the study area.

5.4 Implications to the representation of land surface processes

Topography can influence land surface processes through its impacts on atmospheric forcing and vegetation variability. Consequently, it is essential to examine the implications of the new SUs on representations of climatic and vegetation variability. This is particularly important as our goal is to couple land surface and atmosphere models both with topographic subgrid units to provide the largest improvement for capturing subgrid variability of land surface processes. As an example, the subgrid orographic precipitation scheme of Leung and Ghan (1995, 1998) has been shown to improve simulations of surface temperature, precipitation, and snowpack in mountainous areas by representing the impact of subgrid topography on airflow and cloud processes. Shown in Figure 11 are values of standard deviation of ~~calculated for~~ the 30 year normal annual precipitation (Figure 11a) and mean annual surface temperature (Figure 11b) obtained from the high resolution PRISM dataset calculated within the non-geo-located SUs derived using the Global and Local methods at different values of area threshold~~, comparing the relative capability of the two methods in capturing climatic variability in the study area~~. This comparison is intended to evaluate the capability of the two methods to ~~capture a more climatically homogeneous area~~reduce climatic variability within the SU boundaries. The results show generally lower values of standard deviation in both precipitation and temperature for the SUs derived using the Local method than those of Global method across all values of area threshold. Consistent with the comparison on the capability to capture topographic heterogeneity shown in Figures 6 and 10, these differences reflect the dominant control of topography and the impact of spatial structure on precipitation and surface temperature, suggesting improved capability in capturing climatic variability for the Local method.

Furthermore, shown in Figure 12 are values of standard deviation of NDVI calculated at the non-geo-located SUs from both Global and Local methods at different values of area threshold. In this comparison, the NDVI is used as a proxy for land cover information during spring (Figure 12a) and summer (Figure 12b) extracted from the eMODIS dataset, showing the relative capability of the two methods in capturing land cover variability in the study area. The results generally show lower values of standard deviation for the SUs derived using the Local method than those of the Global method across all values of area threshold, suggesting that the SUs from the Local method have better capability of capturing land cover variation in the study domain, which is essential to representation of land cover in land surface modeling.

In all the results shown so far, the SUs from the Local method have demonstrated clear advantages in capturing topographic heterogeneity and climatic and land cover variation compared to those of the Global method over the study domain. Therefore, we further examined how representation of climatological forcing improves when using the non-geo-located SUs derived using the Local method at 3% area threshold value compared to the subbasin-based representation. This comparison is intended to evaluate the improvement in representing the spatial pattern of precipitation and temperature from the high resolution PRISM datasets when using the non-geo-located SUs from the Local method as compared to those of the subbasins without a subgrid classification. Figure 13 compares the spatial pattern of the 30-~~ ~~year ~~normal~~ mean precipitation ~~when~~ represented based on subbasins at roughly 1/8th degree resolution (Figure 13a), non-geo-located SUs within the subbasins (Figure 13b) and the original grid representation from the PRISM dataset at 800 m resolution (Figure 13c). Note that the Canadian part of the study domain is missing from the map because the PRISM data are only available for the United States. The results show that the SU-based representation yields similar spatial pattern of precipitation to that of the original PRISM grids with no visually discernible difference. The spatial pattern of precipitation for the subbasin-based representation has noticeable differences from those of the SUs and original PRISM grid representations, especially over the mountainous areas. With the ability to better capture the spatial heterogeneity of precipitation, land surface models that use the SU-based representation are expected to produce more realistic distribution of snow cover over the mountains compared to the subbasin-based representation, and it is considerably more efficient computationally compared to modeling land surface processes using hyper-resolution such as the PRISM grids. Further comparison of the three representations of precipitation using statistical metrics (average and standard deviation values) reveals that both the mean and standard deviation values from the SU-based representation are much closer to those of the original PRISM grids as compared to the subbasin-based representation (Table ~~3~~2).

Similar comparisons are also shown in Figure 14 for surface temperature. Similar to the results for precipitation, there is no visually noticeable difference in the spatial pattern of temperature between the SU-based and original PRISM grid-based representations, while the subbasin-based representation misses important variability indicated in the PRISM data. The advantage of the SU-based representation in capturing the spatial pattern of temperature is more pronounced over the mountainous areas. Comparison using statistical metrics of temperature (Table ~~3~~2) confirms the advantages of the new SUs representation. ~~-~~Further comparison of statistical metrics of NDVI for s~~S~~pring and s~~S~~ummer are shown in Table 3, comparing NDVI representations ~~when~~ using the non-geo-located SUs from the Local method generated at 3% area threshold and the subbasins against those of the original high resolution NDVI grid representation. The results ~~generally~~ show some improvement for the SU-based representation in the standard deviation values,~~.~~ w~~W~~hile the mean values of the SUs are generally higher than those of the subbasin and original grid representations. The latter~~is~~ is caused by the fact that ~~in the SUs the~~ mountainous areas are~~, which~~ generally ~~are~~ characterized by higher values of NDVI and they are~~, are~~ discretized into more number of SUs ~~as~~ compared to ~~the~~ flat areas that~~, which~~ generally have lower values of NDVI, ~~making~~so the mean value calculated over the study domain with the SUs is generally higher. Similar behavior is also observed in ~~the comparison of the statistical~~

~~metrics of precipitation in~~ Table 2~~,~~ where the average value of precipitation from the SUs calculated over the study domain is higher than that of the PRISM grid representation.

The advantages demonstrated for the SUs derived using the Local method in representing topographic features are expected to be significant for land surface modeling in mountainous areas such as the Columbia River Basin, where topography has dominant control on precipitation and temperature characteristics that translate to differences in runoff and streamflow characteristics (Tesfa et al., 2014a; Tesfa et al., 2014b).

Also~~,~~ shown in the supplementary materials are similar comparisons of the non-geo-located SU-based representation from the Global method against the ~~s~~subbasin-based representation of meteorological forcing and NDVI (Tables 3s and 4s and Figures 2s and 3s). The results show general improvements ~~due to~~from the use of non-geo-located SUs as compared to those of the subbasin-based representation.

6 Summary and Conclusions

Topography exerts a major control on land surface processes through its influence on atmospheric forcing, soil and vegetation properties, network topology and drainage area. Thus, spatial structure of land surface models that captures spatial heterogeneity influenced by topography may improve modeling of terrestrial water cycle and land-atmosphere interactions. In both land surface and atmospheric modeling, such spatial structures are very much needed for accurate simulations of land surface processes in Earth system models. While there are similar efforts ~~are being exerted~~ to improve representation of the impacts of topography in ~~the~~ atmospheric models, ~~In~~ this study focus~~s~~es exclusively on the ~~, we developed~~ development of new land surface spatial structures to improve representation of land surface processes in land surface models by further discretizing subbasins into subgrid units (SUs) based on their topographic attributes (e.g. elevation, topographic slope and aspect). Two methods of watershed discretization (Local and Global) have been developed and applied over the Columbia River basin in Northwestern United States to derive two types of topography-based subgrid structures (geo-located and non-geo-located). In addition, the two methods have been evaluated for their consistency, capability to capture topographic heterogeneity and climatic and land cover variability of the study domain using both types of subgrid structures.

In the Global method, the study domain is initially discretized into 12 elevation classes following the surface elevation classification scheme employed in Leung and Ghan (1998; 1995). Then, following the subbasin boundary, the elevation classes are intersected with classes of topographic slope and aspect, discretizing each subbasin into multiple subgrid units. The local method utilizes concepts of hypsometric analysis to first discretize each subbasin into elevation classes using algorithms developed in this study, which are then merged with classes of topographic aspect to divide the subbasin into multiple subgrid units. In both methods, values of area threshold are used to merge small subgrid units into the neighboring large subgrid units, yielding reasonable number of subgrid units per subbasin. Both methods are applied to derive two types of subgrid structures: geo-located (spatially contiguous) and non-geo-located (spatially non-contiguous). Furthermore, using both types of SUs, the two methods of subbasin discretization are investigated for their capability to capture topographic heterogeneity, their implications on representations of climatic and vegetation variability in the study area, as well as their sensitivity to the area threshold values.

Using elevation-based geo-located subgrid unit~~i~~s, comparison of the two methods showed that the Local method is able to capture the topographic variability better than the Global method. Taking advantage of hypsometric analysis, the Local method can capture slope variability implicitly so it generally requires fewer SUs to represent subgrid topographic variability. The Local method more effectively captures the topographic pattern across the region ~~better~~ than the Global method by discretizing steep subbasins into more subgrid units and flat subbains into fewer subgrid units. Using the Local method, the standard deviation of surface elevation within the subgrid units is noticeably smaller and less sensitive to the values of area threshold than the Global method. Hence the Local method is clearly more effective and robust for representing subgrid elevation variability for land surface modeling.

Comparing the two types of subgrid structures derived using the Global and Local methods revealed that the non-geo-located SUs are more consistent than the geo-located SUs across different area threshold values. Further investigation of the relative capability of the two methods with non-geo-located subgrid units representing multiple topographic features (elevation, slope, and aspect) based on the standard deviation in surface elevation within the subgrid units and statistical metrics calculated over the whole study domain further demonstrated superior capability and consistency for the Local method compared to the Global method. Similarly, investigation of the relative capability of the two methods in capturing climatic and land cover variability based on the high resolution PRISM precipitation and surface temperature and NDVI data, respectively, reveals that the Local method is generally better than the Global method. Finally, comparing the precipitation and surface temperature over the study area when represented using non-geo-located SUs from the Local method against those of the subbasin-based and original PRISM grid-based generally showed the spatial pattern and statistical values of the subgrid units are much closer to those of the original PRISM grids than those of the subbasins.

In summary, this study demonstrated that adopting the hypsometric curve characterization for discretizing subbasins yields improved capability in capturing topographic heterogeneity and consistency across different values of area threshold. This resulted in improved representation of climatic and land cover variability in land surface modeling. The improved capability to capture subgrid variability of atmospheric forcing, surface topography, and vegetation cover with nominal increase in computational requirement is essential for improving simulations of land surface modeling in mountainous regions. The focus in this paper is the development and evaluation of the methods and new spatial structures. Future efforts will implement the non-geo-located SUs from the Local method in a land surface model based on the Community Land Model subgrid structure to investigate ~~if or~~ how the addition of topographic subgrid units to the subgrid hierarchical structure may translate~~s~~ to improved simulations of evapotranspiration, soil moisture, snowpack, and runoff and streamflow. Coupling land surface models with the non-geo-located SUs to an atmosphere model with a subgrid parameterization of orographic precipitation may further improve modeling of land-atmosphere interactions in topographically diverse regions.

7 Code Availability

The ~~updated code~~code developed to generate the subgrid structures is available upon request. Please contact Teklu K. Tesfa at teklu.tesfa@pnnl.gov.

Acknowledgement

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~~**Table 1**: Algorithm applied to derive elevation-based SUs using the Local method.~~

~~**Algorithm 1**: Local method of subbasin discretization. Array BRK_i = [Elv_{min}, $Elv_{0.2}$, $Elv_{0.5}$, $Elv_{0.8}$, and Elv_{max}] denotes elevation values at the initial class breaks, where Elv_{min}, $Elv_{0.2}$, $Elv_{0.5}$, $Elv_{0.8}$, and Elv_{max} refer to the minimum elevation, elevation values at relative areas of 0.2, 0.5, and 0.8, and maximum elevation of the subbasin, respectively. Array R_i = [R_1, R_2, R_3, R_4] denotes the values of elevation range between consecutive BRK_i. Variables BRK_f denotes the final values of elevation at class breaks. Variable thr denotes the value of elevation threshold (100 m). Variable n denotes the number of Rs with values less than thr. Function GetFinalBRKs() denotes a function used to determine BRK_f by recursively merging Rs less than teh thr with the neighboring Rs recursively.~~

~~For each Subbasin:~~
    ~~Derive a hypsometric curve~~
    ~~Determine elevation values at the BRK_i~~
    ~~Calculate values of R_i between consecutive BRK_i~~
    ~~Determine n~~

    ~~If n == 0 // All values of R_i greater than the thr~~
        ~~BRK_f = BRK_i~~
        ~~R_f = R_i~~
    ~~Else if R1 >= thr and R2 < thr and R3 < thr and R4 >= thr:~~
        ~~If (R2 + R3) >= thr:~~
            ~~BRK_f = [Elv_{min}, $Elv_{0.2}$, $Elv_{0.8}$, Elv_{max}] // Keep the body as separate class~~
        ~~Else:~~
            ~~BRK_f = [Elv_{min}, $Elv_{0.5}$, Elv_{max}] // Split the body into the head and tail~~
    ~~Else if R1 >= thr and R2 < thr and R3 >= thr and R4 >= thr:~~
        ~~BRK_f = [Elv_{min}, $Elv_{0.2}$, $Elv_{0.8}$, Elv_{max}] // Keep the body as separate class~~
    ~~Else if R1 >= thr and R2 >= thr and R3 < thr and R4 >= thr:~~
        ~~BRK_f = [Elv_{min}, $Elv_{0.2}$, $Elv_{0.8}$, Elv_{max}] // Keep the body as separate class~~
    ~~Else:~~
        ~~BRK_f = GetFinalBRKs(BRK_i, R_i, thr) // Call the recursive function~~

    ~~Return BRK_f~~

~~**Table 2**: Algorithm to determine the final class break values (BRK_f) by merging elevation ranges with less than the threshold to the neighboring elevation ranges recursively.~~

~~**Algorithm 2**: To determine the final values of class breaks using recursive function GetFinalBRKs(). BRK_i, R_i, n, thr, denote the same variables as in Algorithm 1 (Table 1). Variables i and nn denote an index values of BRKs and the number of all Rs, respectively.~~

~~Function GetFinalBRKs(BRK_i, R_i, thr):~~
~~Determine n~~
~~Determine nn // number of all Rs~~
~~Determine i // index of Rs with less than thr~~
~~If n > 0 and nn > 1:~~
~~Get the index (i)~~
~~If i == 0: // R is at the beginning of the array~~
~~$R_i[i + 1] = R_i[i + 1] + R_i[i]$ // merge R with the next neighbor~~
~~Update BRK_i~~
~~Call GetFinalBRKs(BRK_i, R_i, thr) // This is a recursive call~~
~~Else if i == nn: // R is at the end of the array~~
~~$R_i[i - 1] = R_i[i - 1] + R_i[i]$ //merge R with the previous neighbor~~
~~Update BRK_i~~
~~Call GetFinalBRKs(BRK_i, R_i, thr) //Recursive call~~
~~Else: // merge with the smaller negibor~~
~~If $R_i[i - 1] > R_i[i + 1]$~~
~~$R_i[i + 1] = R_i[i + 1] + R_i[i]$ // merge R with the next neighbor~~
~~Update BRK_i~~
~~Call GetFinalBRKs(BRK_i, R_i, thr) // This is a recursive call~~
~~Else:~~
~~$R_i[i - 1] = R_i[i - 1] + R_i[i]$ // merge R with the previous neighbor~~
~~Update BRK_i~~
~~Call GetFinalBRKs(BRK_i, R_i, thr) // This is a recursive call~~

~~Return BRK_i~~

Table 1: Comparing the Local and Global methods in capturing topographic heterogeneity when 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

Table ~~3~~2: Comparing the SUs generated using 3% area threshold from the Local method and Subbasin representations against the original PRISM grid representation using statistical summary of- mean annual precipitation and surface temperature calculated over the study domain

Representation	Precipitation (mm)		Temperature (C°)	
	Average	**Standard deviation**	**Average**	**Standard deviation**
Subbasin	669.036	459.479	7.179	2.525
Non-geo-located subgrid units using the Local method	739.05	506.83	6.78	2.66
Original PRISM Grid	717.021	519.523	6.935	2.681

Table 3: Comparing the SUs generated using 3% area threshold from the Local method and Subbasin representations against the original NDVI grid representations using statistical summary of spring and summer NDVI values calculated over the study domain

Representation	NDVI values (spring)		NDVI values (summer)	
	Average	**Standard deviation**	**Average**	**Standard deviation**
Subbasin	5804.00	1735.03	5128.87	1967.29
Non-geo-located subgrid units using the Local method	5924.33	1883.90	5389.01	2109.81
Original NDVI Grid	5810.02	2159.39	5207.00	2342.65

Figures:

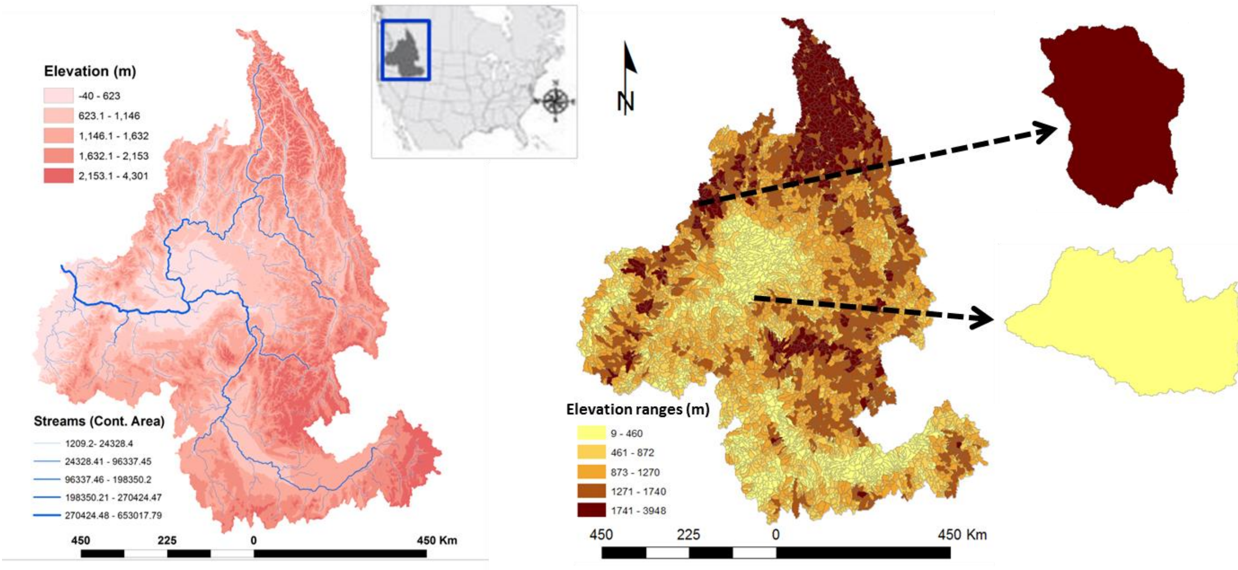

Figure 1: The topographic distribution (left) and subbasin delineation (right) of the study area (Columbia River Basin). Two subbasins selected to represent the extreme classes of elevation ranges are shown on the far right.

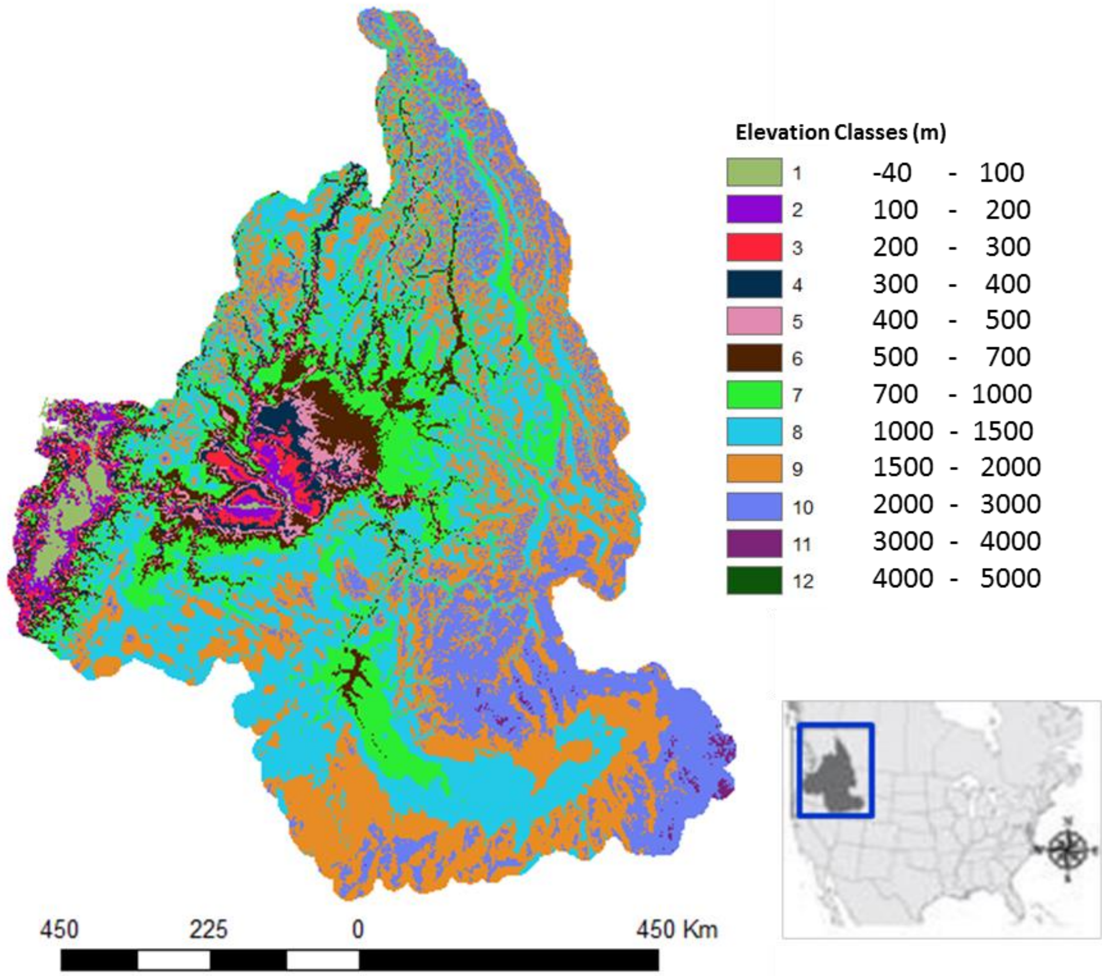

Figure 2: The study area classified into elevation bands used in the Global method, following the approach described in Leung and Ghan (1995; 1998).

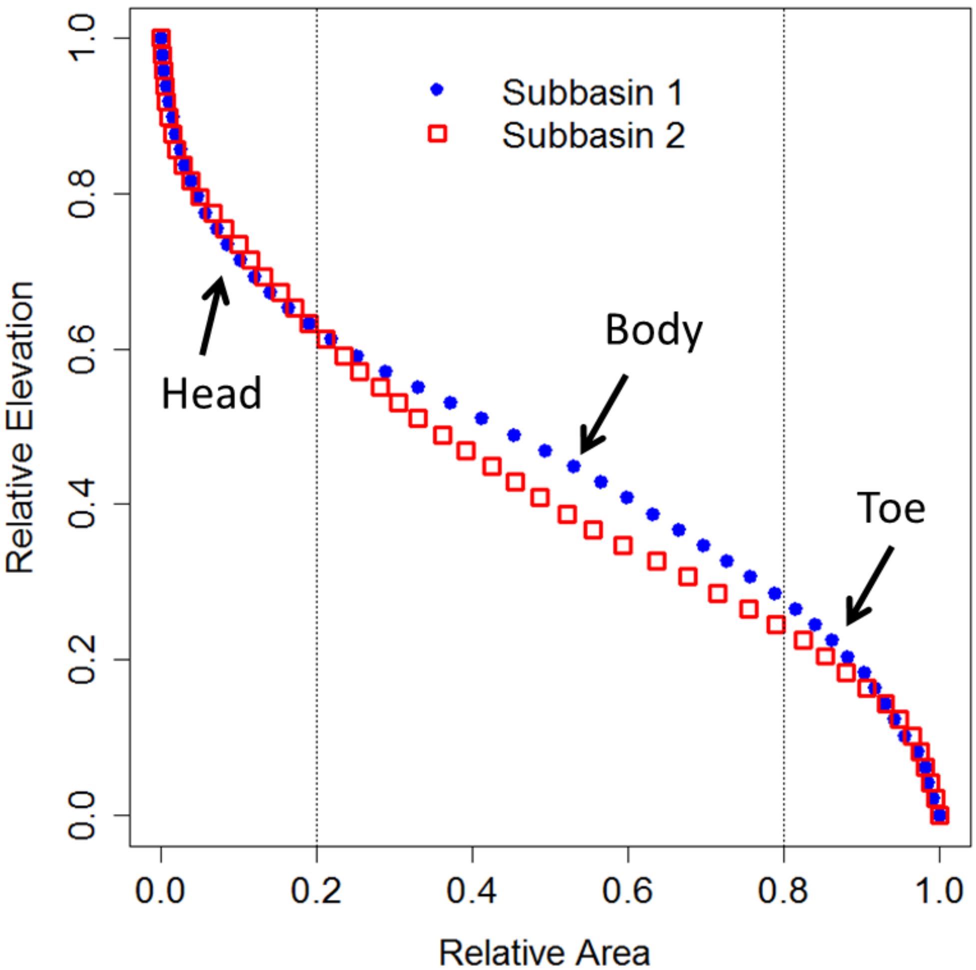

Figure 3: Hypsometric curves of two subbasins with extreme contrast of elevation variability discretized into three parts following Willgoose and Hancock (1998) and Sinha-Roy (2002): the head, body and toe, as used in the Local method.

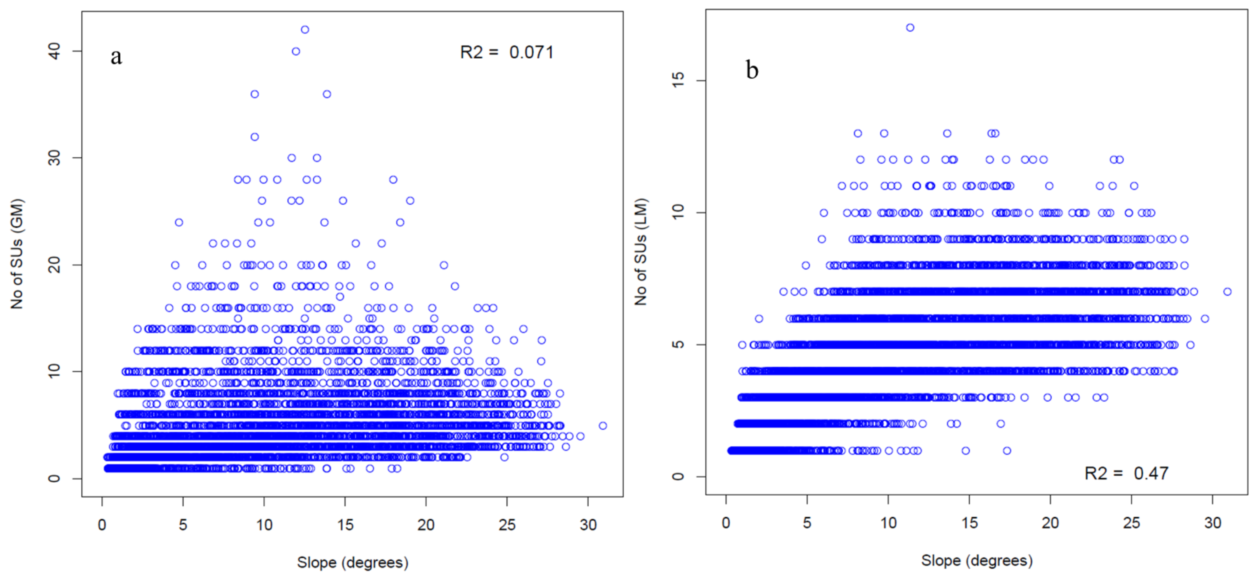

Figure 4: The number of elevation-based geo-located SUs plotted against the average topographic slope for each subbasin derived using the Global (a) and Local (b) methods with 1% area threshold.

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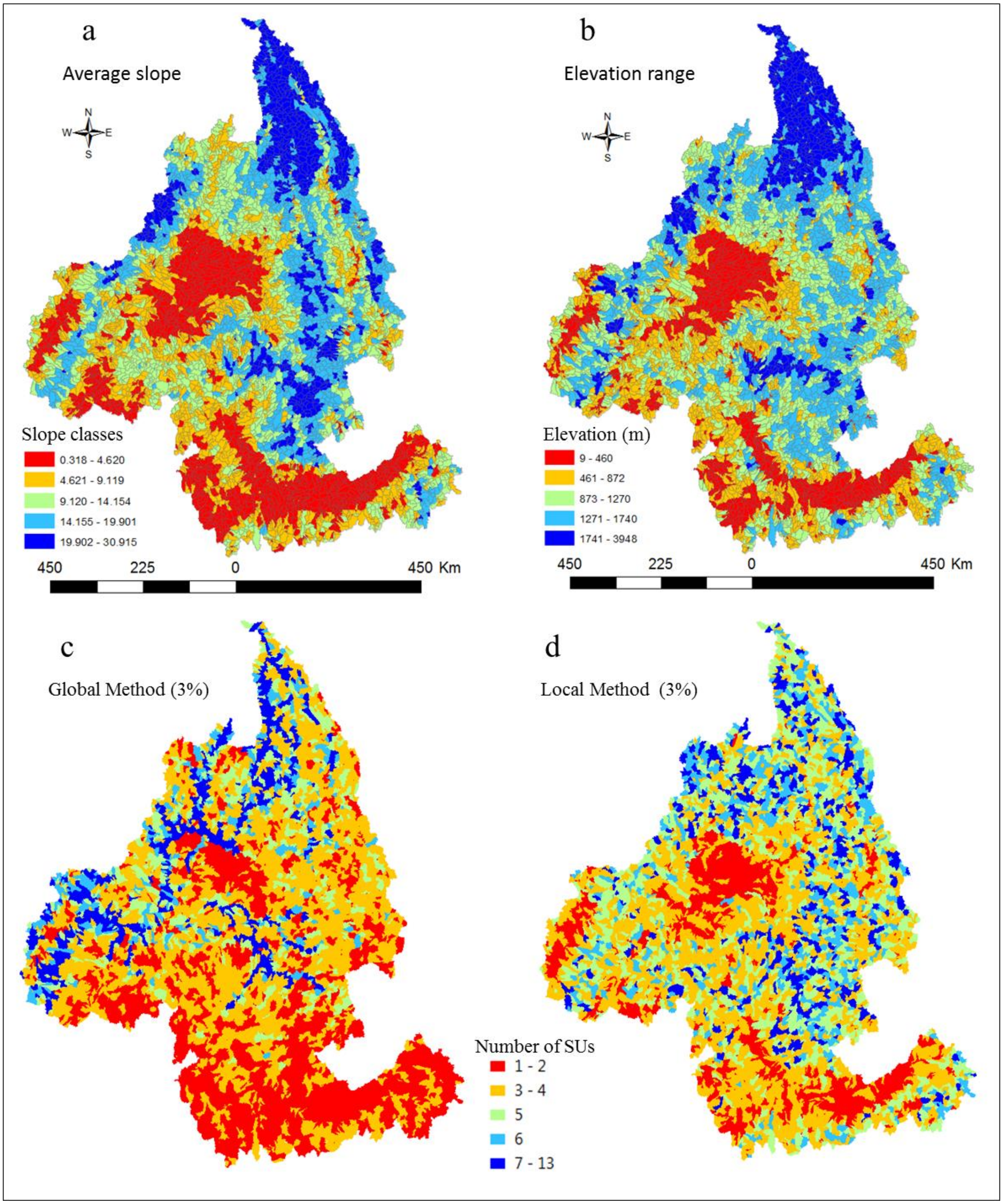


980 **Figure 5:** Spatial patterns of the number of elevation-based geo-located SUs per subbasin derived using the Global (c) and Local (d) methods compared against the spatial pattern of the topographic slope (a) and elevation ranges of the subbasins in the study area.

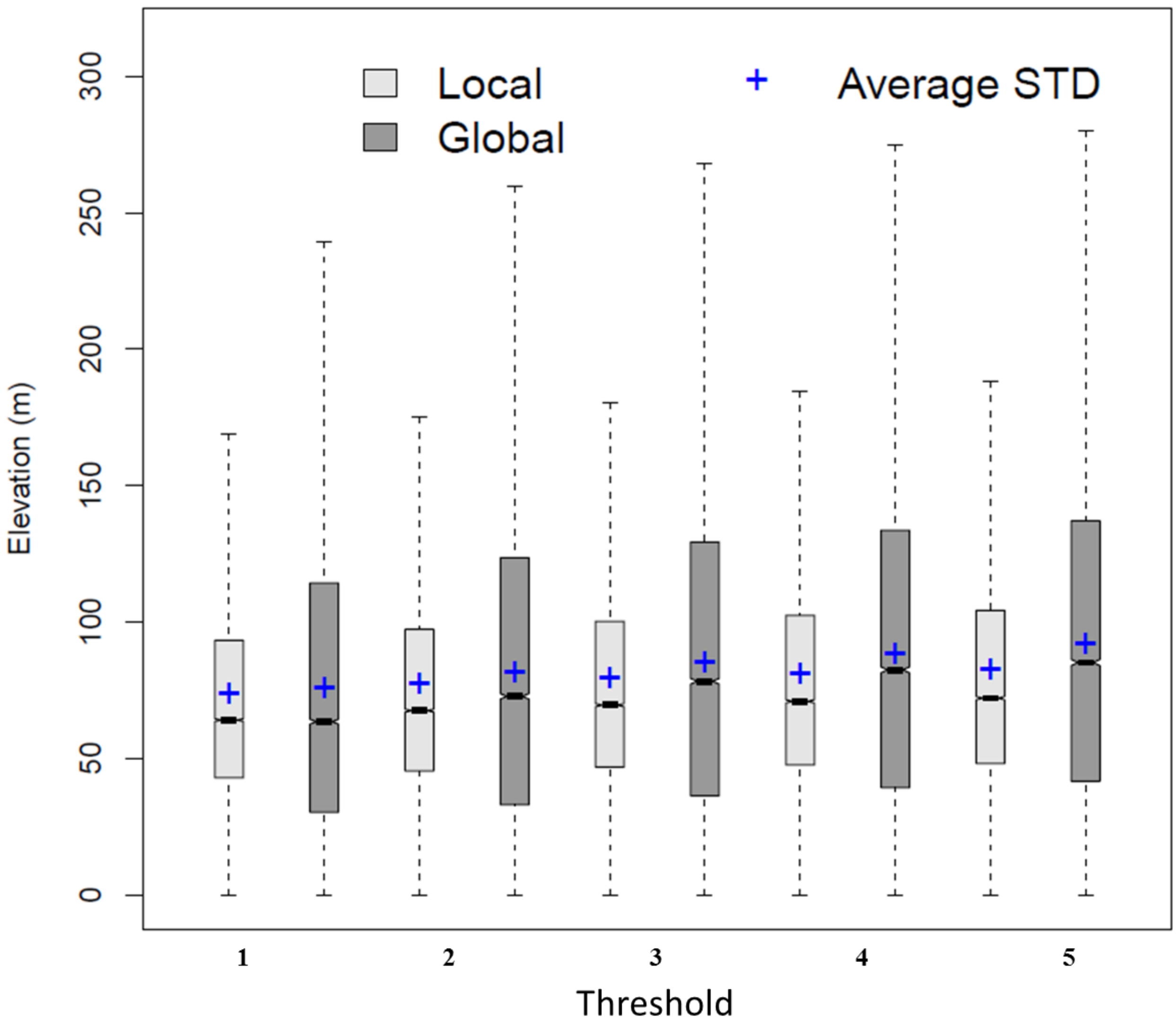
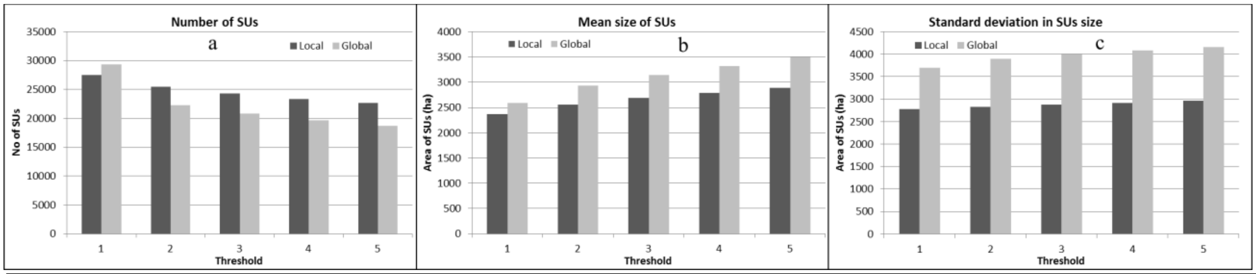


Figure 6: The standard deviation in elevation within the elevation-based geo-located SUs derived using different values of area threshold. On each box, the central mark (notch) is the median (q2), the edges of the boxplot are the 25th (q1) and 75th (q3) percentiles, and the whiskers extend to the most extreme data points (q3 + 1.5 x interquartile range (q3 – q1) and q1 – 1.5 x interquartile range (q3 – q1); outliers are not considered.



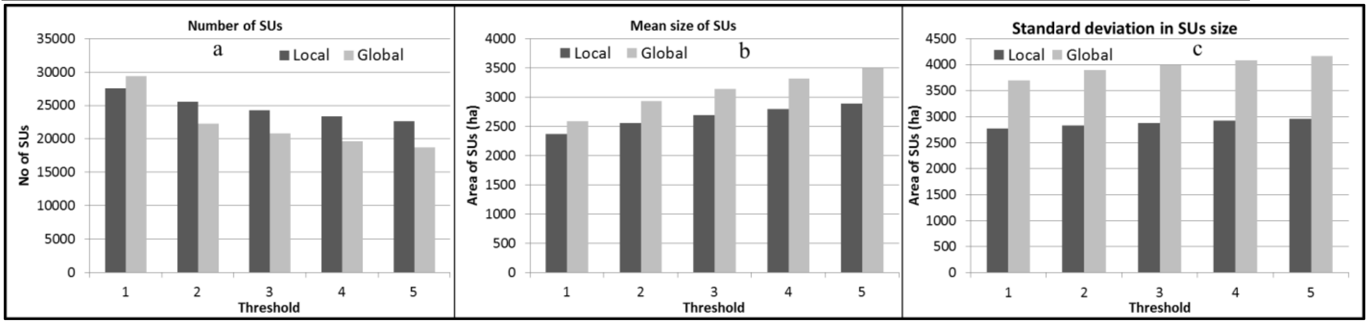
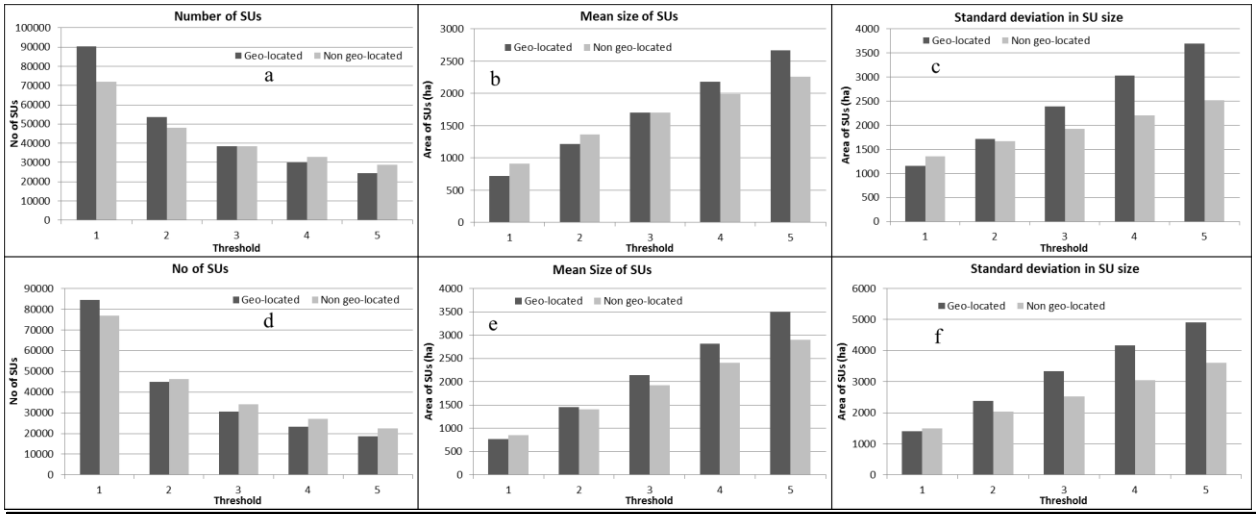


Figure 7: Sensitivity of the Global (grey) and Local (black) methods to different values of area threshold for the total number of SUs (a), average SUs size (b) and standard deviation in SU size (c) of the elevation-based geo-located SUs derived using different values of area threshold.



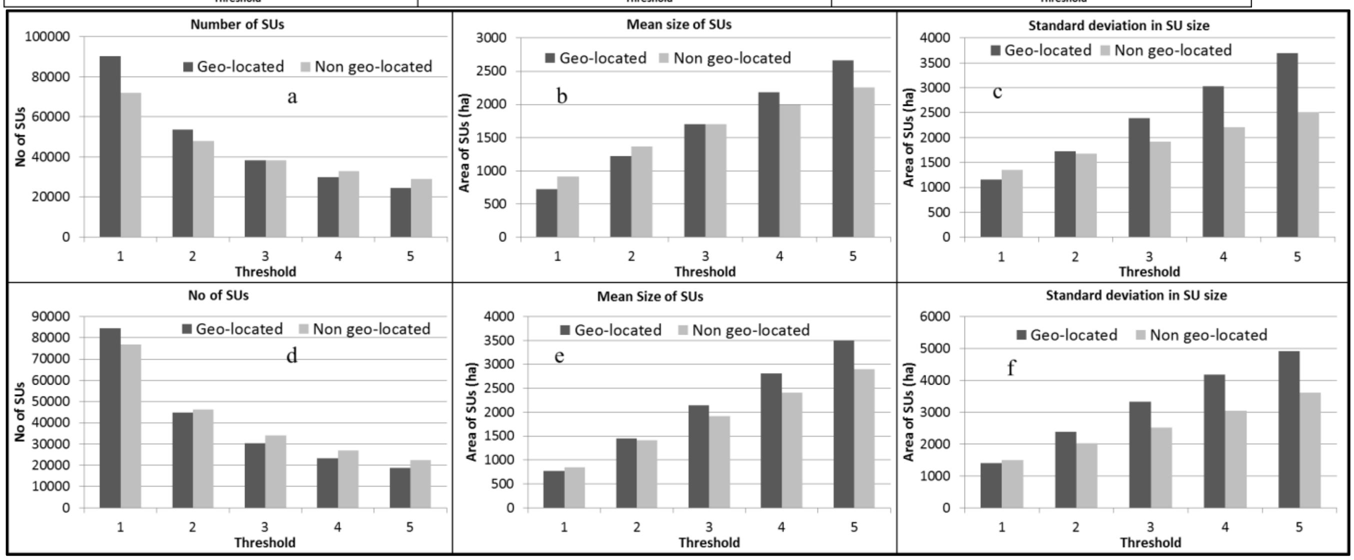
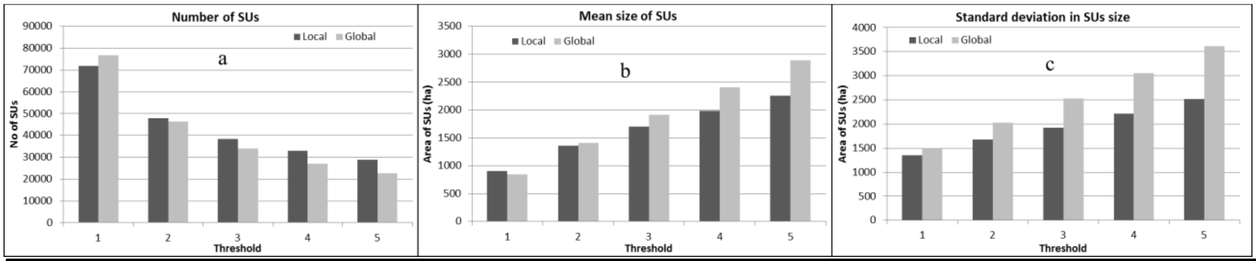


Figure 8: Comparison of the geo-located (black) versus non-geo-located (grey) SUs derived based on elevation, slope and aspect using the Global (a, b, and c) and Local (d, e, and f) methods, in terms of their sensitivity to different values of area threshold for the total number of SUs, average SU size and standard deviation in SU size over the study domain.



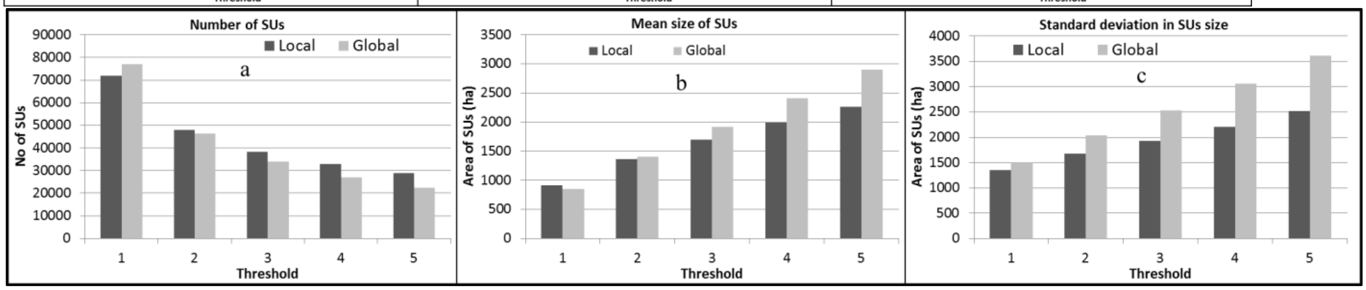


Figure 9: Comparison of the two methods (Global and Local) using non-geo-located SUs in terms of their sensitivity to different values of area threshold for the total number of SUs (a), average SU size (b) and standard deviation in SU size (c) over the study area. SUs are constructed based on elevation, slope, and aspect.

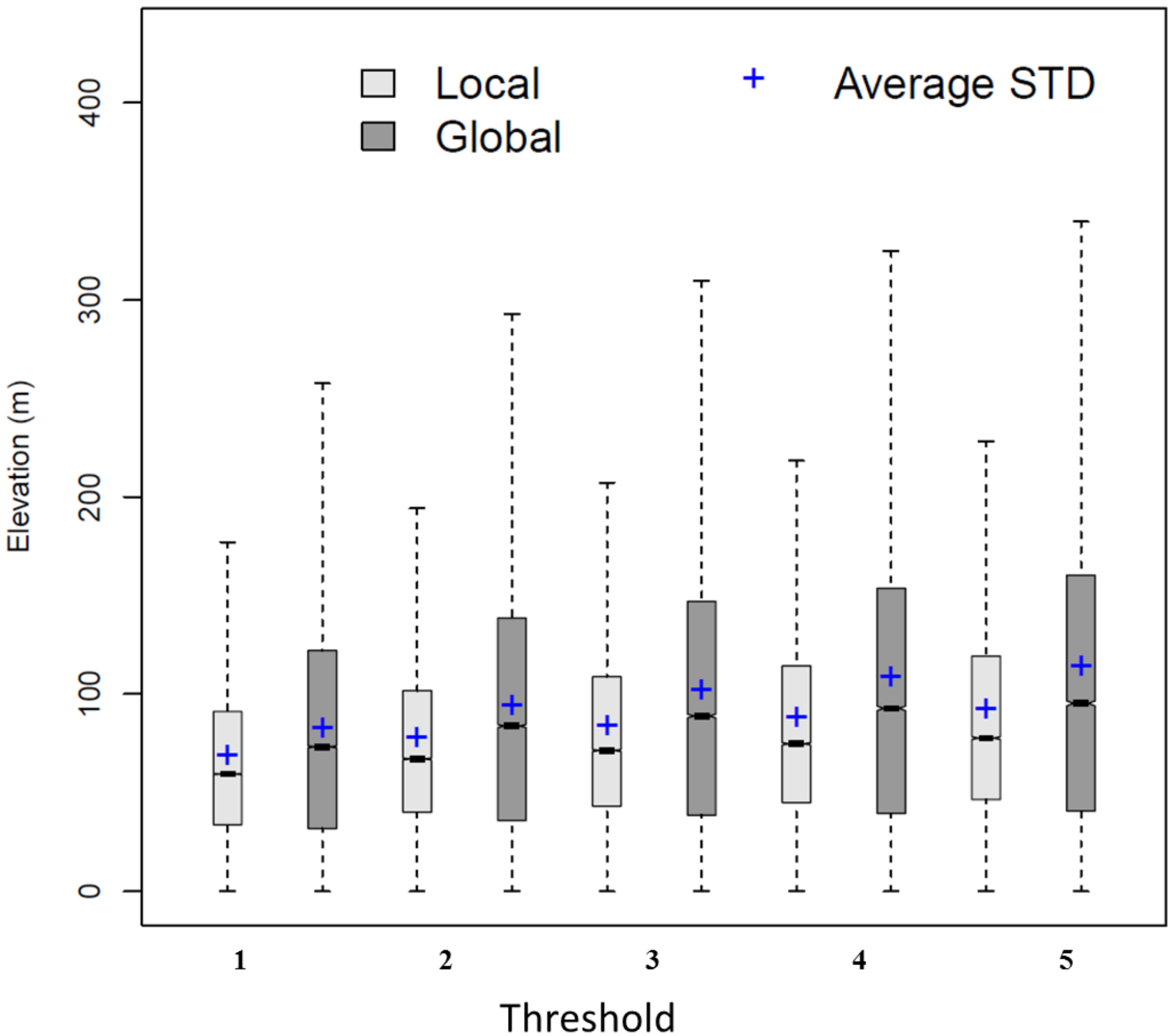
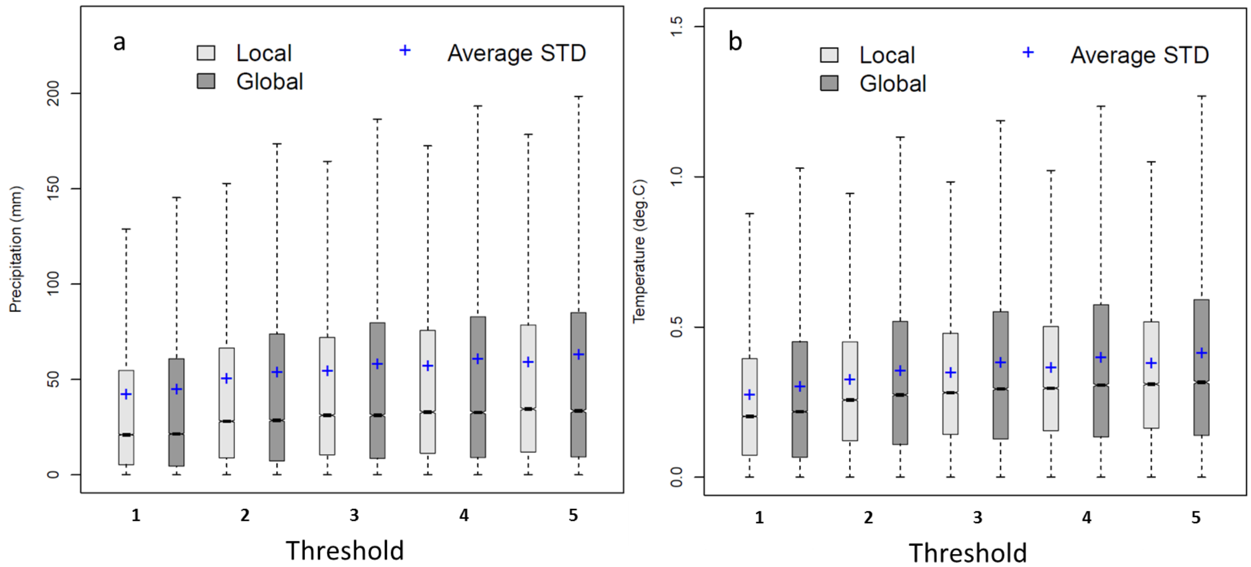


Figure 10: Similar to Figure 6, but for capability of the Global and Local methods to capture topographic heterogeneity based on the standard deviation in elevation within the non-geo-located SUs derived based on elevation, slope and aspect using different values of area threshold.


a
Local
Global
Average STD
Precipitation (mm)
0
50
100
150
200
1
2
3
4
5
Threshold
b
Local
Global
Average STD
Temperature (deg.C)
0.0
0.5
1.0
1.5
1
2
3
4
5
Threshold

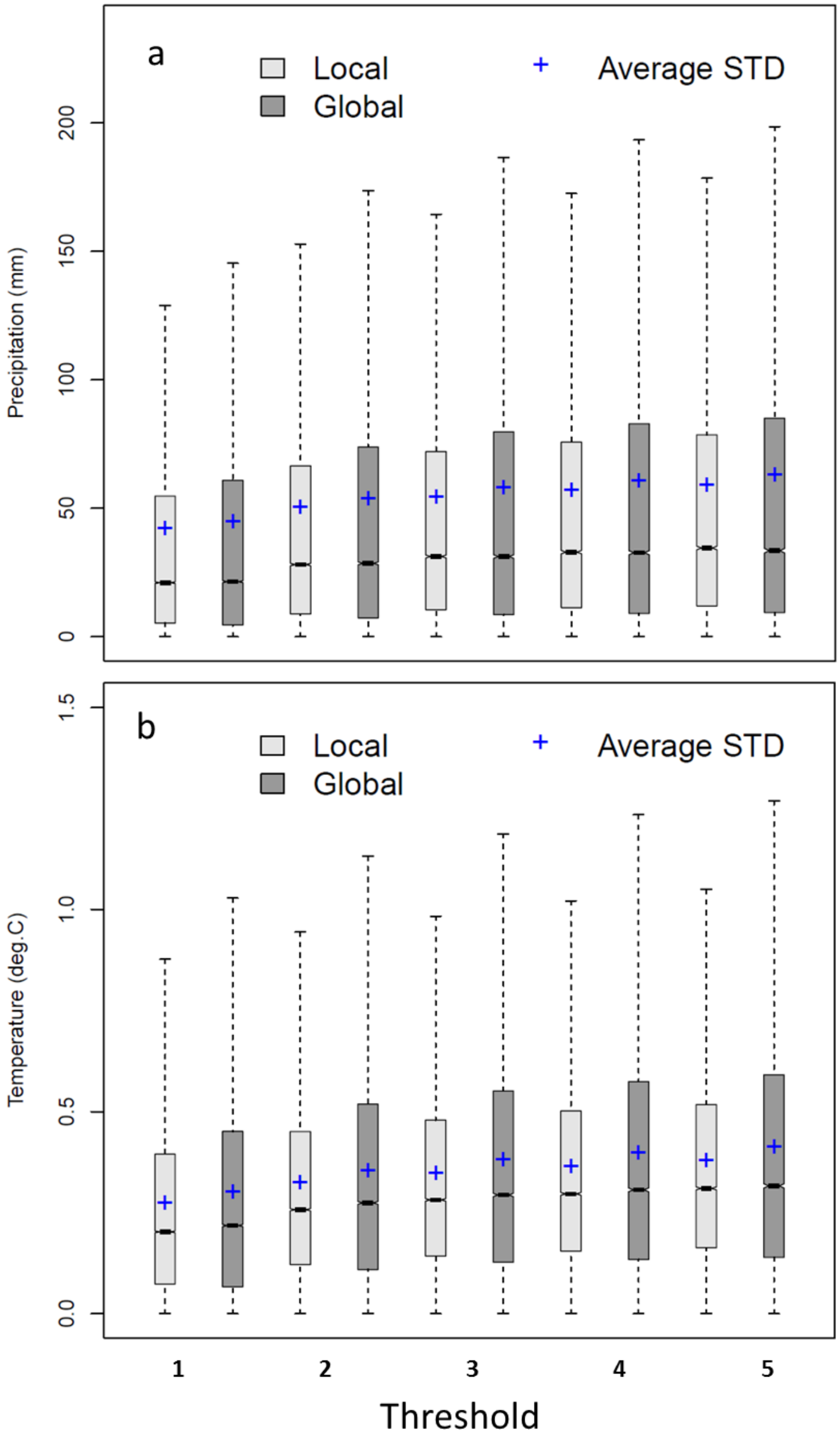
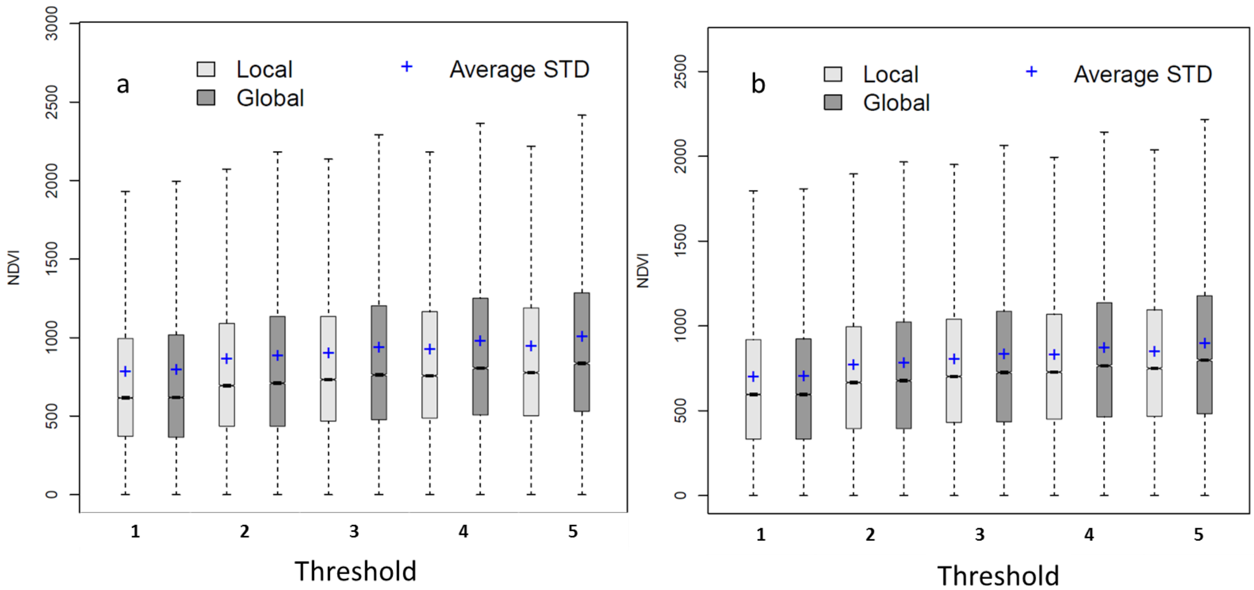


Figure 11: Similar to Figure 5, but for capability of the Global and Local methods to capture climatic variability based on standard deviation of the PRISM 30 year normal precipitation (a) and surface temperature (b) within the non-geo-located SUs derived based on elevation, slope and aspect across different values of area threshold.


a
Local
Global
Average STD
NDVI
0
500
1000
1500
2000
2500
3000
1
2
3
4
5
Threshold
b
Local
Global
Average STD
NDVI
0
500
1000
1500
2000
2500
1
2
3
4
5
Threshold

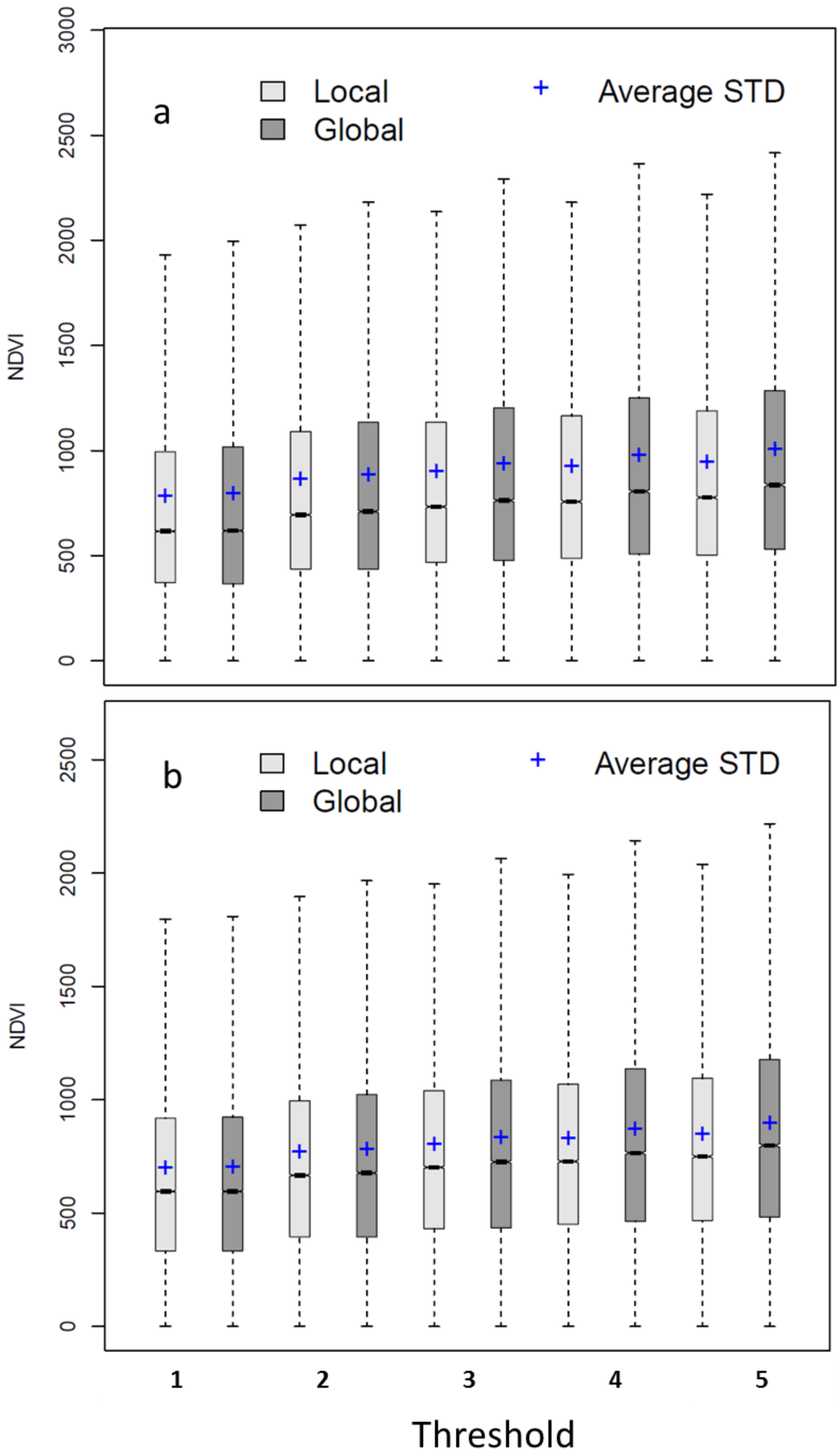


Figure 12: Similar to Figure 6, but for capability of the Global and Local methods to capture land cover variation based on standard deviation values of eMODIS NDVI during Spring (a) and Summer (b) within the non-geo-located SUs based on elevation, slope and aspect across different values of area threshold.

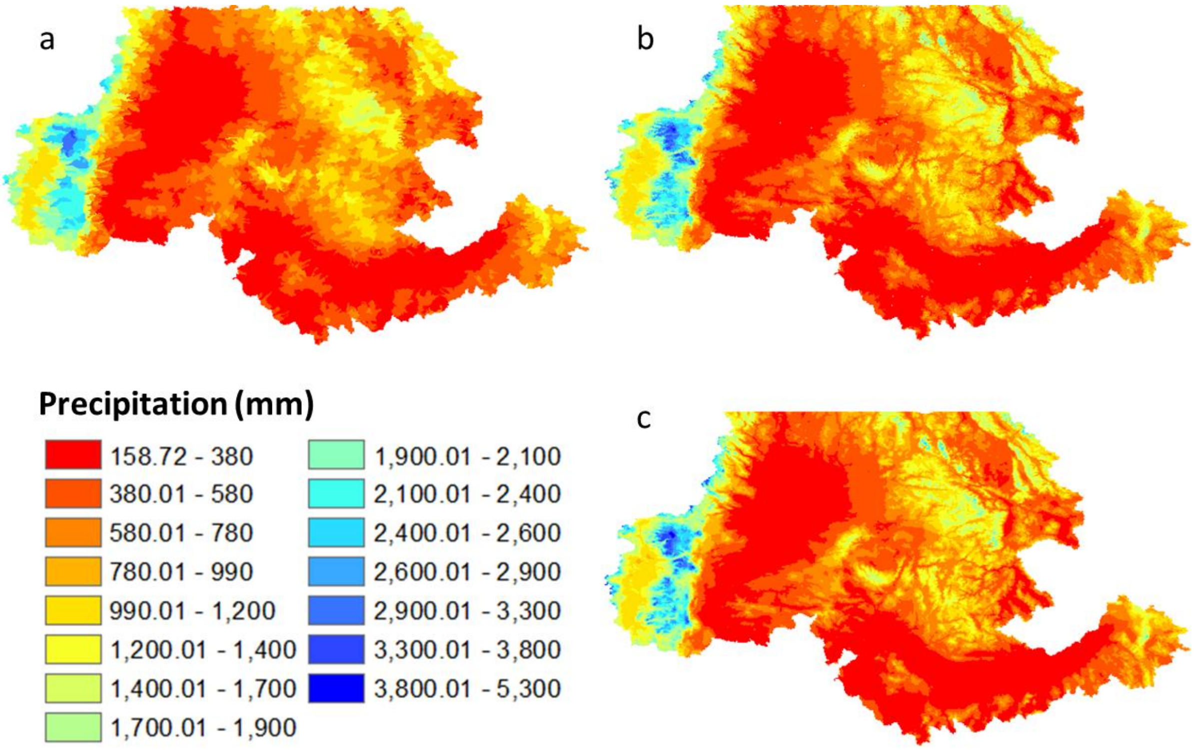
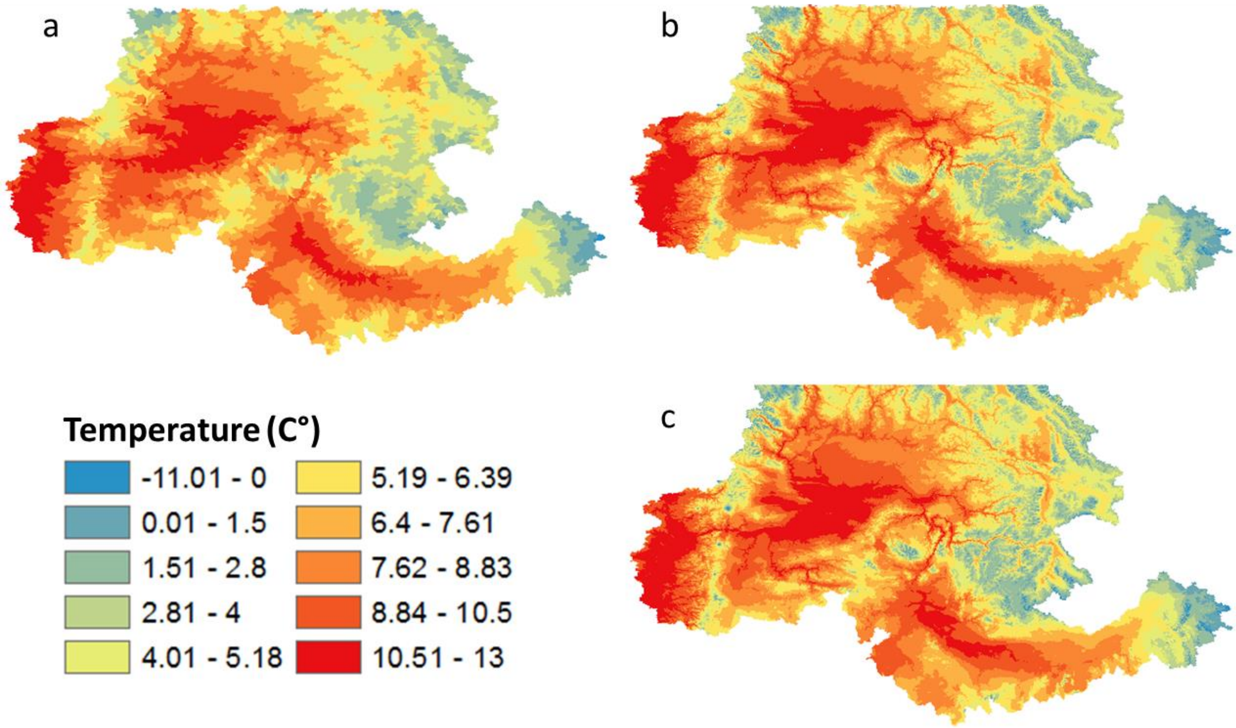


Figure 13: PRISM 30 year normal precipitation represented using the subbasins (a) and non-geo-located SUs ~~based on elevation, slope and aspect~~ from the Local method using 3% area threshold (b) compared to those of the original PRISM grids (c). The Canadian territory of the study area is not represented in the PRISM dataset.



1045 **Figure 14:** Same as Figure 13, but for temperature.