Response to 3rd Referee's Comments

We would like to thank the reviewer's constructive comments on our manuscripts. We will modify the manuscript accordingly, and the detailed responses are listed below.

General Comments

1. The purpose of this manuscript is not clear. First, most of the current LSMs do not represent topography in their parameterization, therefore it is (not) clear to me what is the potential usefulness for the proposed subgrid approach. What is the purpose of this study? Can the authors please demonstrate how the results of this study can really improve the LSM simulations?

Response:

Thank you for your comment. In the revised manuscript, we will further clarify the purpose of the study and the benefit of the new subgrid method as followed.

In climate models, high spatial resolution is needed to accurately simulate precipitation and surface hydrology associated with the heterogeneity in elevation and vegetation. It is straightforward to represent the elevation heterogeneity in land surface models using subgrid elevation classes so that the effects of subgrid topographic variations on precipitation and snow process can be parameterized. The Variable Infiltration Capacity (VIC) model is one example of land surface model that divides a model grid cell into multiple subgrid elevation bands to achieve improved simulations of surface hydrology. It is also straightforward to specify the subgrid fractional coverage of vegetation to resolve more vegetation types to improve the simulations of surface fluxes. The Community Land Model (CLM) is one example of land surface model that divides a model grid cell into multiple subgrid Plant Function Types (PFTs). The purpose of this study is to develop a method that jointly represents both subgrid elevation and vegetation to enhance the simulations of surface fluxes and

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surface hydrology that are influenced by heterogeneities in both elevation and vegetation. While this may be accomplished by dividing a model grid cell into a large number of subgrid elevation/PFT classes, it can greatly increase the computational burden in land surface modeling as land surface processes must be calculated for each subgrid class. This study examines approaches to derive subgrid classification schemes that account for subgrid variability of both surface elevation and PFT without significantly increasing the computation burden of the current land surface models using CLM4 as an example of LSM.

With the new subgrid method, each surface elevation class can be forced by different atmospheric conditions by disaggregating the atmospheric forcing from each model grid cell to the subgrid elevation class based on temperature and precipitation lapse rate or the subgrid parameterization of orographic precipitation described in Leung and Ghan (1995; 1998). Separate calculations of surface processes can be performed for each subgrid PFT within each subgrid elevation class. This allows the interactions between soil, vegetation, and atmosphere to be represented for each subgrid vegetation-elevation class to improve the simulation of land surface processes and feedbacks to the atmosphere. This study focuses on assessing different subgrid classification schemes, which will be implemented in CLM and the effects of representing both subgrid elevation and vegetation on land surface simulations will be discussed in a follow-on study.

2. *Although the authors cited their previous work Leung an Ghan (1998) in which the influences of topography on precipitation was accounted for by a sub-grid approach as the motivation of this study, the issue in the present study, namely the relation between vegetation and topography, does not influence the LSM simulation as long as the vegetation cover is faithfully specified.*

Response:

Leung and Ghan (1998) presented a subgrid precipitation scheme which accounted for the influences of topography on precipitation, as well as a subgrid vegetation scheme

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which considers the topographic distribution of vegetation. The subgrid vegetation scheme took advantage of the framework of subgrid precipitation scheme such that multiple vegetation covers can be described within each elevation band (although only the dominant vegetation cover was used in the study). Our study generalized the idea of their subgrid vegetation scheme.

In this subgrid scheme to represent the subgrid joint distribution of surface elevation and vegetation, the LSM simulation will be influenced because different atmospheric conditions will be assigned to each elevation band. For example, elevation band corresponding to higher elevation will have cooler near surface air temperature and increased precipitation compared to the grid cell mean values. Applying such atmospheric forcing to different PFT classes within the same elevation class will simulate surface fluxes and soil hydrology that reflect the influence of atmospheric forcing for the higher elevation on different PFTs to improve land surface simulations for the specific subgrid elevation/PFT class as well as the overall grid cell averaged conditions.

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3. I suggest much more clear explanations on the following rather vague statements - (Page 2080, lines 16-19) "...This representation mainly focused on the fractional coverage of each PFT..... The location of the PFTs, however, has seldom been explicitly described (Niu et al., 2011)". But, why it is important to know the exact locations of each PFT in LSM simulations? Can the knowledge of that improve the quality of simulation? Can the authors provide the evidence? Why need explicit information on the spatial location of topography and vegetation? Without any explicit representation of topography in LSMs, can the identified sensitivity to different vegetation classification be attributed to the "strong" correlation between vegetation and topography?

Response:

We thank the reviewer's suggestion. We will revise the statements in lines 16-25, page 2080 to clarify the benefits of representing topographic distribution of vegetation

types. We will modify “the location of PFTs” into “topographic distribution of PFTs” to avoid confusion. Leung and Ghan (1998) provided the evidence that the consideration of topographic distribution of vegetation did improve surface temperature simulation. In their study, the atmospheric forcing was applied to each elevation class, and the LSM simulations for each land cover type were “mapped to geographical locations according to the high-resolution surface elevation dataset. If more than one surface type is prescribed within an elevation band, the high-resolution vegetation dataset is also used to perform the mapping”. Therefore, the explicit location of topography and vegetation provided more spatial details of simulated surface processes.

We recognized that there is no simple relationship between vegetation distribution and topography since vegetation cover depends not only on elevation but other environmental factors such as slope/aspect and soil also play an important role in determining vegetation distribution. However, climate exerts important control on vegetation, and elevation is an important factor determining climate conditions. Thus, in our study we developed the vegetation-topography relationship for each model grid cell, and the topographic distribution of each vegetation type was explicitly represented within each model grid cell. Note that our goal is not to explicitly model the specific location of different vegetation type within a model grid cell, but rather to statistically aggregate vegetation type by surface elevation to represent the subgrid joint distribution of elevation and vegetation. This allows a much more computationally efficient way to represent subgrid land surface heterogeneity compared to a subgrid tiling approach in which a model grid is broken up into a large number of subgrid tiles each assigned different vegetation and surface elevation require a large number of computations to simulate the land surface processes of each tile.

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4. On page 2182, line 10-12, "The method developed in this study assigned a flexible number of elevation bands and PFTs for each model grid and optimized to explain a maximal amount of elevation and vegetation variations in a computationally

efficient manner". Why need to be "flexible"? any advantages from being flexible in the number of classes? Not explain at all...

Response:

In the new subgrid method, each subgrid vegetation-elevation class is a computational unit. To avoid high computation intensity, we require the number of total subgrid classes within each model grid cell (i.e. the number of elevation bands (*M*) multiplied by the number of vegetation types (*N*), namely *N_class*) to be a reasonable number (e.g., similar as the number of total PFTs in CLM, *N_class*=18). The advantage of assigning flexible *M* and *N* values as long as *N_class* = 18 is that the variation of both elevation and vegetation can be optimized with the restriction of a fixed number of *N_class*. For example, in flat area with rich vegetation diversity, this method assigns a small *M* (e.g., *M*=2) so that a large number of PFTs can be represented (*N*=18/2=9) while elevation variation is still well represented. On the contrary, in topography-complex area, the method assigns a larger *M* (e.g., M=6) and a smaller *N* so that elevation variation can be reasonably explained. Based on our analysis using high resolution DEM and vegetation data, we find that this classification is feasible because in topography-complex area, elevation has a dominant influence on vegetation through its effects on climate, so assigning a small number of PFT classes within each elevation class is able to capture the dominant subgrid variations of PFT within the model grid cells.

In the revised manuscript, we will clarify the purpose and the advantage of *M* and *N* being flexible.

5. Finally, this paper is way too lengthy. It is indeed a paint o read through it from the beginning to the end (but the English writing is not the problem). I wish the authors can re-organize the key points of this study concisely (because the idea behind this work is not complicated at all, so really no need to repeat many similar arguments and figures, and cut the length and the number of figures 50%.

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Response:

We thank the reviewer for the suggestion. We will follow the suggestion and make the manuscript more concisely. For example, we will simplify sections “Introduction” and “Results and Discussion” to avoid repeat of similar arguments.