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Atmospheric Chemistry and Physics Discussions

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Interactive Comment

Interactive comment on "A WRF simulation of the impact of 3-D radiative transfer on surface hydrology over the Rocky–Sierra Mountains" *by* K. N. Liou et al.

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Dear Professor Fu,

We have carefully studied the reviewers' comments and suggestions on our paper and carried out revisions accordingly. The following is a line-by-line response to each reviewer's general and specific comments. All authors listed on the manuscript concur with the submission in its revised form.

We hope you find the revisions acceptable and our responses adequately address the reviewers' comments.

Thank you for your consideration of this submission.

Sincerely yours,

K. N. Liou

Reviewer 1

We would like to thank the reviewer for the comprehensive comments. Below are our responses to these comments.

This study presents results of the topographical impact on surface radiation and hydrology over the Western United States using WRF model simulations. It shows that the topographical impact is significant, and it is important to be included in climate studies using model simulations. To improve the clarity of the paper, the authors might need to consider the following comments/suggestions:

(1) Figure 4 shows the spatial distributions of the impact of topography on the surface solar radiation at three local times. The authors stated that the overall distributions of the topographical impact are locations relative to mountains. For example, "In the late afternoon, . . ., increases in solar flux are located on the southwest of the mountains, while decreases in solar fluxes are found in the northeast region." This statement needs to be clarified. It implies that decreases in solar fluxes in the northeast region are due to the mountains to the south and west. In fact, surface solar radiation cannot be affected by mountains hundreds of kilometers away. Figure 4 does not provide any information on the relative location of a 30-km resolution grid box with respect to surrounding mountains. I suspect that the solar zenith angle should have an impact on the latitudinal distribution of the surface radiation. The small impact at higher latitude in panels (a) and (b) should at least be partially related to a larger SZA.

Response: We thank the reviewer for the useful comments. To improve presentation of the mountain effect on surface radiation flux distributions, we have added terrain-height contours in Figure 4 for a 30 km resolution grid box and incorporated the following dis-

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cussion: “Solar flux deviations at each grid box are affected by surrounding mountains through 3D radiation parameterization using a 1 km subgrid topographic data and the averaged solar zenith angle. For the north-south oriented mountains (e.g., the Sierras: 118-120W, 36-38N), positive/negative deviations are generally located at the mountain’s east/west sides in the morning (Fig. 4a) and its west/east sides in the afternoon (Fig. 4c). These deviations are distributed over the mountains and surrounding regions at noon (Fig. 4b). For west-east oriented mountains (e.g., 112-115W, 44N), positive deviations are primarily located at mountain south slope. Also, the solar zenith angle has an impact on the latitudinal distribution of solar flux deviations. Because less solar fluxes are available at high latitudes, solar flux deviations due to the 3-D mountain effect are smaller. However, positive/negative patters are primarily dependent on mountain orientation and elevation.”

(2) In April and May, the topography-induced impact on the surface sensible heat flux is very large at noon (Figure 5), which is drastically different from the months in and before March. Further, the magnitude of the impact increases systematically throughout the length (Dec-May) of the model simulations. What are the causes?

Response: As pointed out by the Reviewer, sensible heat flux deviations induced by topography (3D – PP) depict very large values in April and May (Figure 6, not Figure 5). These large deviations are directly related to downward surface solar flux deviations shown in Figure 5. We have stated, “Changes in the seasonal sensible and latent heat fluxes, as function of local time and elevation, basically follow the pattern of solar flux presented above.” We have discussed in details variation of the downward surface solar flux deviation in lines 16 – 29, p 19397 and lines 1 – 13, p 19398 (before revision). Nevertheless, to comply with the Reviewer’s comment, we have added the following in the revised text: “The available surface solar flux increases from December to May for a given time of the day, resulting in enhanced deviations (3D – PP) induced by shading and elevation effects.”

(3) Some of the figures are hard to read. Some letters and numbers are illegible.

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Response: Thank you. We have improved the figure presentation. We would like to note that in the discussion version, all the figures are substantially reduced in size and quality, leading to illegible letters and numbers.

Reviewer 2

We appreciate Reviewer 2's constructive comments. Below are our specific responses to these comments.

This study examines how surface topography impacts the radiative fluxes and surface hydrology over Western US mountain regions. As most global circulation models (GCMs) use "plane-parallel" (PP) radiative transfer approach, potential errors may arise due to 3-D interactions between radiation and mountains. By implementing a 3-D radiative transfer code in the WRF model at 30 km horizontal resolution, the authors provide a detailed account of the deviations of the radiative fluxes and snow-water equivalent (SWE) as a function of local time, elevation and time of a year in the 3-D radiation model from those in the PP model. The deviations, up to 40-60 Wm-2 in surface solar flux and 18% in SWE, are quite substantial. The paper is clearly presented. It is publishable after addressing the following comments and suggestions from me.

(1) The abstract is too long. It should be shortened to emphasize main findings and reduce words on background and implications.

Response: The abstract has been shortened following the reviewer's comment.

(2) The analysis box in Figure 1 should be marked darker and thicker. Figure 2d is of poor quality. The labels are not legible.

Response: Done. Also, the quality of Figure 2d (Fig. 2e in the revised version) has been improved. See also item (3) in the response to Reviewer 1.

(3) Page 19394, why do you choose 30 km resolution? It seems to me that 30 km is too coarse to resolve the topography over the Western US. 4 km would be better. You need to justify the use of 30 km.

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Response: Of course, the effect of the topography on surface radiative flux will be more pronounced as the horizontal resolution increases. However, we submit that the question of appropriate resolutions used in numerical models must be responded to in terms of study objective. In the Introduction (lines 10 – 16, page 19391), we state, "... Quantifying these interactions and reliably determining total surface solar fluxes for incorporation in a land surface model has been a challenging task that has yet to be accomplished in regional and global climate modeling...." Thus our objective has been and continues to be focusing on climate research. We respectfully submit that the selection of 30 km resolution for our study is in line with climate research objective, because the need of long-term simulations would limit the spatial resolution that can be achieved by global and regional climate models. For this purpose, we have built a 3D radiation parameterization using a 10 km grid box as a proto type, which comprises a 1 km resolution topographic data. In the current 30 km simulation, we have already demonstrated a substantial impact of 3D mountain/snow on simulated surface solar flux, sensible and latent heat fluxes, surface temperature, and surface hydrology in association with shading and elevation effects. In response to the Reviewer's question, however, we have incorporated a sentence in the revised text: "We plan to employ the 90 meter topographical data available from the Shuttle Radar Topography Mission (SRTM) to construct an improved radiation parameterization that can be applied to model resolutions higher than 10 km in future studies."

(4) It would be better to add the WRF-PP simulations of SWE together with WRF-3D in Figure 2. I am curious whether the WRF-3D simulates better SWE than WRF-PP.

Response: Following the Reviewer's comments, we have included contours of differences (3D – PP) in the simulated SWE (Fig. 2a). In comparison with CMC observations, WRF model results tend to produce larger SWE values over mountain areas. As shown, the incorporation of 3D radiation parameterization has reduced model overestimation in reference to PP results to certain degree. However, the model overestimation bias involving SWE can come from a number of sources, including snow

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parameterization and precipitation bias, and cannot be solely resolved by 3D radiation parameterization.

(5) Page 19397, Line 6, define “LT”.

Response: The term LT is an abbreviation for Local Time and has been defined in the revision.

(6) The descriptions of diurnal variation of solar fluxes on page 19397 are confusing. My understanding is that the topographical impact to the surface fluxes is related to the distance of the mountains. For example, the decreases in solar fluxes in the northeast region are due to the mountains to the southwest, but the distance of the mountain matters! How does surface flux be affected by mountains a few hundreds kilometers away?

Response: The reviewer is correct in that the distance between mountains is an important parameter. To clarify, we would like to point out that the essence of the present 3D surface solar radiation parameterization for surface solar fluxes in reference to a flat surface (or a unobstructed horizontal surface) has been briefly discussed in the second paragraph of the Introduction (Pages 19391 and 19392). In short, the flux deviations (3D – PP) at each model grid box of 30 km are affected by surrounding mountains through 3D radiation parameterization using the solar zenith angle and a 1 km topographic data as the building block. In the parameterization, the sky view factor and the terrain configuration factor are used to represent the distance and height of nearby mountains with respect to a target point at a given solar zenith angle. An unobstructed horizontal surface will intercept radiation emitted from the sun in all directions. Over mountainous areas, however, the solar fluxes intercepted at a target point are subject to the blocking of surrounding mountains. Consequently, only a portion of the sky dome can be visible at the target point, which is defined by the sky view factor, representing the shadowing effect of mountains on the direct and diffuse solar fluxes reaching the target point. The terrain configuration factor is defined as the area of surrounding

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mountains visible to the target point, which determines the portion of solar fluxes that are reflected to the target point from surrounding mountains. This parameter will affect the direct- and diffuse-reflected fluxes as well as the coupled flux induced by mountain topography. In response to the Reviewer's comment, we have added these discussions in the revised text.

(7) Figure 4 labels are not clear. I was also wondering what is the size of the mountain relative to the 30km grid-boxes. It would be better to overlay a few contours of elevation height (1.5, 2, 2.5, 3 km) on the map.

Response: Following this constructive suggestions, we have incorporated contours of elevation height in Figure 4. See also item (1) in our response to Reviewer 1.

(8) It would be better to compare the WRF-3D surface fluxes with in-situ measurements to validate the results, although I am not sure about the data sources.

Response: Certainly, appropriate observed data over the mountain and snow areas that are compatible with the 30 km model resolution would be useful to calibrate 3D radiation parameterization in terms of surface fluxes. However, we are surprised by the Reviewer's nebulous comment here that he is "not sure about the data sources." We respectfully submit that this comment appears to be not in line with the constructive spirit that is so essential in the review process.

(9) Page 19401, Line 9, I think it should be "reduce" instead of "enhance" "the SWE in higher elevation regions".

Response: Thank you for catching the typo. The correction has been made.

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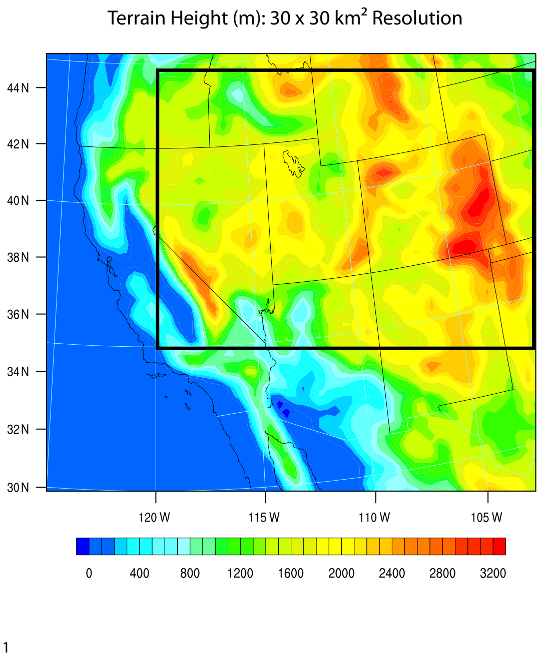

Fig. 1.

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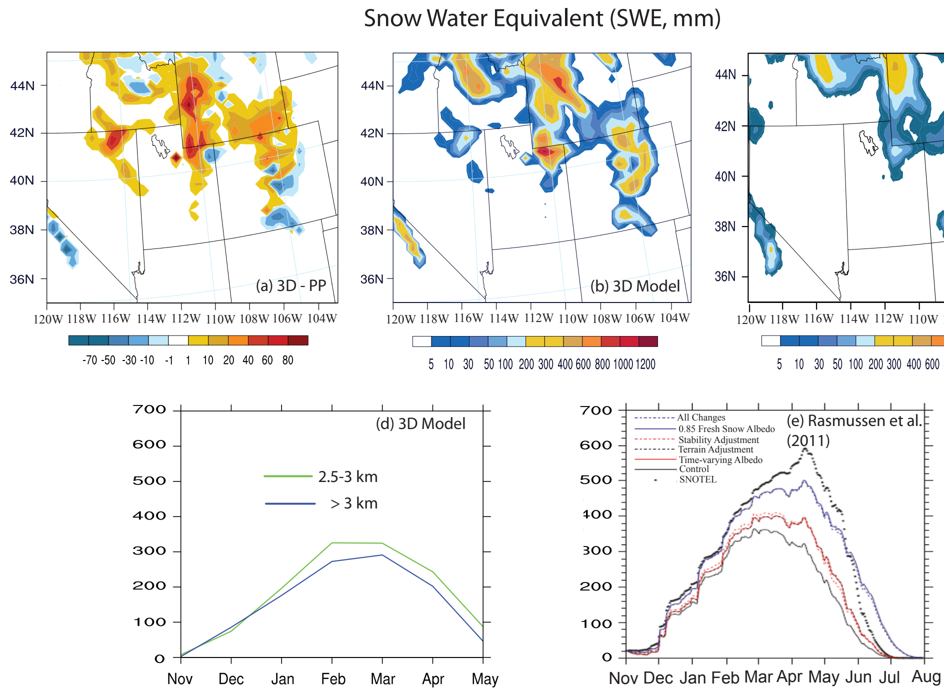

Fig. 2

Fig. 2.

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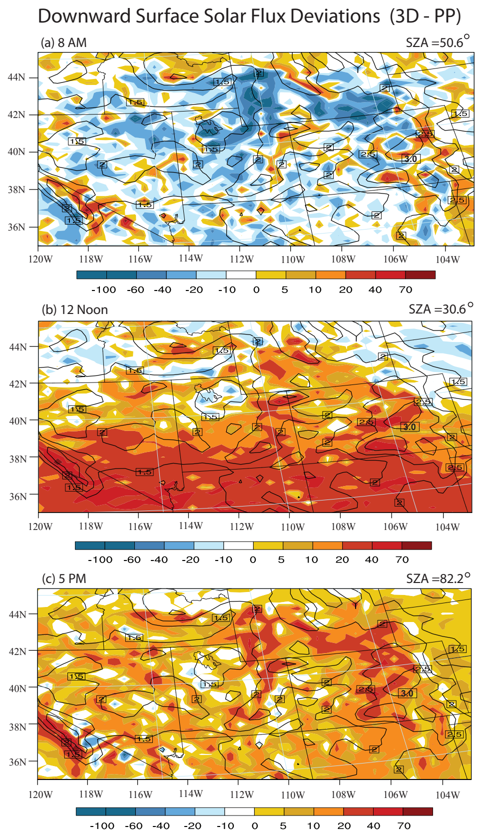

Fig. 4

Fig. 3.