Simulating the Sierra Nevada snowpack: The impact of model resolution, snow albedo and multi-layer snow physics

Waliser, D.[1], J. Kim[2], Y. Xue[2], Chao, Y[1]., A. Eldering[1], R. Fovell[2], A. Hall[2], Q. Li[2], K. Liou[2], J. McWilliams[2], S. Kapnick[2], R. Vasic[2,3], F. De Sale[2], and Y. Yu[2]

[1]Jet Propulsion Laboratory/Caltech/NASA, [2]University of California, Los Angeles , [3]National Centers for Environmental Prediction/NOAA

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1. Introduction

The snowpack in the Sierra Nevada region is important to the water resources in California. The high elevation snowpack serves as a natural reservoir which stores fresh water during the wet cold season and releases it gradually during the dry warm season. About 60% of the water supply for southern California comes from melting Sierra Nevada snowpack. Snowmelt also affects hydropower generation in California. Consequently, the impact of global warming on the snowpack in the Sierra Nevada region has become one of the leading topics in the regional climate change studies for the California region (Leung and Ghan 1999; Kim 2001; Kim et al. 2003). Snow budget in the Sierra Nevada is affected by a number of factors such as insolation, air temperature, and orography. Previous studies on the impact of climate change on the Sierra Nevada snowpack has focused solely on the impact of low tropospheric warming (e.g., Leung and Ghan 1999; Kim 2001; Kim et al. 2003; Cayan et al. 2008) in addition to precipitation, since low level temperatures affect two important factors, rainfall-snowfall partitioning and snow ablation, in determining snow budget. For a more comprehensive understanding and projection of the Sierra Nevada snowpack in future climate, it is necessary to investigate the role of other factors that also affect snow budget.

Representations of orography, snow albedo, and the physical processes within a snowpack are among the key players in simulating the spatiotemporal variations in snowpack.

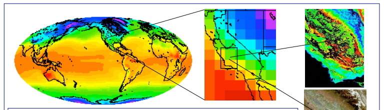

Figure 1. Global (left) and southwest US (middle) surface air temperature for Jan 1999 from the NCAR 20th century climate simulation contribution to the IPCC's 4th Assessment. (right) MODIS-derived surface skin temperature and false-color images at 1km resolution for a region in California for midday June 3, 2005. Blue->red in each image scales roughly as -35C->34C, -6C->18C, 13C->54C for left, middle, right panels, respectively.

A considerable part of the uncertainty in simulating high elevation snowpack is associated with the representation of orography in a climate model. To illustrate, **Figure 1** compares a global SAT map for Jan 1999 from one of the GCMs in **Figure 1** and the MODIS-derived SAT. As shown in false-color images for an embedded sub-domain in the region the variability in the key atmospheric (e.g. clouds, SAT) and land surface (e.g., vegetation types, snow cover) fields vary according to orography in the region. The regional structure in key variables is simply not represented in GCM simulations. This is a crucial problem in California where spatial distributions of precipitation and SAT are strongly correlated with the complex terrain in the region.

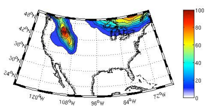

Figure 2. The cold season snow-water equivalent (SWE) for 1961-1980 in a CCSM-3 climate simulation.

The problem in simulating SWE in a GCM due to poor representation of regional-scale orography is clearly seen in Figure 1. The GCM terrain does not resolve significant orography in the Pacific coast region which is characterized by the Coastal Range, the Cascade/Sierra Nevada ranges; as a consequence, the significant SWE in the Cascade and the Sierra Nevada region is completely missed in the GCM simulation.

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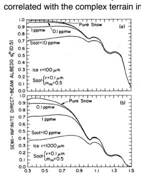

Figure 3. Effects of soot concentration on snow albedo (from Warren and Wiscombe 1980) for the ice grain size of (a) 100μm and (b) 1000μm.

Importance of aerosol deposition on snow albedo in the Sierra Nevada region can be inferred from previous studies. Warren and Wiscombe (1980) showed that impurities in snowpack such as dusts and BC can reduce snow albedo in the spectral range shorter than 1 μm where most of solar energy resides. For ice grain radius of 100mm, for example, their calculations show that the average snow albedo for the wavelengths between 0.4 and 1 μm varies from near unity for pure snow to below 0.4 with a presence of a small amount of soot within the snow layer (Figure 3). Significant anthropogenic emissions in California, in conjunction with prevailing westerly winds that transport fine particulates into the Sierra Nevada region, can alter the snow albedo in the Sierra Nevada region. Thus, the sensitivity of the Sierra snowpack to the deposition of particulates needs investigation.

Another challenge in simulating long-term variations in snowpack is the complexity in the physical processes interior of the snowpack. Snow models that have been used in climate simulation ranges from a relatively simple single snow layer model that considers only a limited physical processes within snowpack to state-of-the-art multi-layer models that can resolve a number of important physical processes within snowpack over extended periods (e.g., Yang et al. 1997; Slater et al. 2001; Ek et al. 2003; Xue et al. 2003). Most regional climate models use single layer representations of snow cover. *A problem with single layer representations is that for the melting process to occur, the temperature of the entire snow layer must rise above the freezing point before the layer starts to melt. In reality, the near surface layer can readily warm up relative to deeper levels and begin the melting process.* Incorporating this realism into a model would alter snowpack loss rate significantly, not only for the spring snow ablation period but also for the winter snow accumulation period. Xue et al. (2003) have recently constructed a multi-layer snow model to improve the snow ablation process on the basis of considerably complex snow schemes (Anderson 1976; Jordan 1991) with substantial simplification and improvements in physics. The snow model has been subsequently incorporated into the recent SSiB-3. Tests of the new snow model against in-situ data (Xue et al. 2003) and in the Project for Intercomparison of Land Surface Parameterization Schemes (Bowling et al. 2002; Nijssen et al. 2002; Rutter et al. 2008) showed that the new model performs better than more traditional simplified schemes. These tests showed that the multi-layer treatment of snowpack results in faster snowmelt in high elevation regions. Considering the importance of long-term snow budget in water resources for California, the difference in snowpack simulation due to more physically-based snow model needs close examination in order to improve the projection of the impact of anthropogenic global climate change on the Sierra Nevada snowpack and in turn on the water resources in California.

This study examines the impact of RCM resolution, snow albedo, and the multi-layer treatment of snow physics on simulating the snowpack in the Sierra Nevada region. Experimental designs for examining the impact of RCM resolution, snow albedo and the multi-layer snow physics are presented in Section 2. Sections 3 presents the results obtained in; a comparison of snow fields in 36km and 12km resolution simulations, the sensitivity study of SWE simulations in the Sierra Nevada according to the snow albedo, and a comparison of the SWE fields simulated using a single- and multi-layer snow model.

2. Experimental Design

The numerical experiments presented in this study are performed using the Weather Research and Forecast (WRF) model, version 2.2.1 (Skamarock et al. 2005). Details of the WRF model can be found on the WRF model website http://wrf-model.org, and will not be elaborated here . For the investigation of the impact of RCM resolutions on simulating the Sierra Nevada snowpack, one-way, self-nested simulations in which a 12km resolution run is driven by the data from a 36km resolution run, is performed for the 10 winter seasons each for the late 20th century (1971-1080) and mid-21st century (2045-2054) periods. The physics options selected in the 36km resolution runs include the NOAH land-surface scheme, the simplified Arakawa Schubert (SAS) convection scheme, the RRTM longwave radiation scheme, Dudhia shortwave radiation, and the WSM 3-class with simple ice cloud microphysics scheme. The physics schemes used in the 12km simulations are the same as in the 36km simulations except that convection is deactivated. The physics schemes employed in the 80km simulations are the same as in the 36km model simulations except that the Kain-Frish convection scheme and SSiB LSM are used instead of the SAS and Noah LSM, respectively, for calculating convection and land-surface processes.

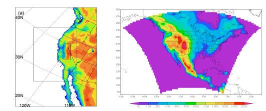

Figure 4. The model terrain used in the three experiments in this study. The outer-most and middle areas in Figure 4a are used in the 36km and 12km resolution runs, respectively. The inner-most box in Figure 4a is the Sierra Nevada region. Figure 4b presents the 80km resolution WRF model domain used in the experiment in which the SWE fields simulated using a single- and multi-layer snow model simulations are compared.

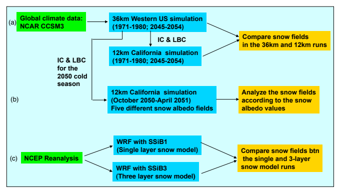

Figure 5. The data flow in the three regional simulations:

(a) The effects of RCM resolutions on snow simulation,

(b) The effects of snow albedo, and

(c) The comparison of the snow fields simulated using a single- and three-layer snow model in the SSiB-1 and SSiB-2 LSM.

The effects of model resolution and snow albedo sensitivity runs are analyzed in terms of terrain elevation range:

Elevation Category		Mean Elev [12/36]	# grid points [12/36]
1:	1750-2000	1869/1901	74/ 7
2:	2000-2250	2125/2115	72/ 6
3:	2250-2500	2366/2396	48/10
4:	2500-2750	2617/2538	27/ 5
5:	2750-3000	2868/ NA	25/ 0
6:	>3000	3103/ NA	16/ 0

3. Results

3.1 Snow simulations according to RCM resolutions

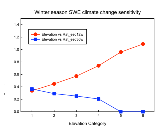

Figure 6. The ratio of the seasonal SWE between the future and present-day model climatology.

The climate change signals (the difference between the future and present-day model climatology) in SWE are similar in the lowest elevation range; however, the differences between the two projections increase as the terrain elevation increases. In the 12km simulation, the climate change signal decreases as the terrain elevation increases; the results in the 36km simulation show opposite variations.

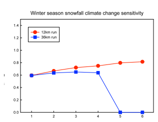

Figure 7. The ratio of the seasonal snowfall between the future and present-day climatology.

The climate change signals in the seasonal mean snowfall calculated in the 12km and 36km runs are similar in all elevation ranges. The 36km run generates slightly larger decrease in snowfall in higher elevation ranges; however, the difference between the 12km and 36km projections are small. The only notable differences occur in the highest two elevation ranges. This is caused by the fact that the highest terrain in the 36km simulation is below the 2750m level (not shown). Thus, the seasonal snowfall signals cannot explain the differences in the SWE signals generated with different spatial resolutions. This result suggests that the climate change signals in the seasonal snowfall is directly related to the differences in the large-scale atmospheric conditions between the present-day and the future climate.

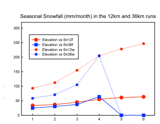

Figure 8. The seasonal mean snowfall in the present-day climate simulated with the 12km and 36km simulations.

Even though the climate projections with different resolutions generated similar amounts of climate change signals in snowfall (Figure 7), the amount of snowfall differ significantly according to the resolution, especially in winter (Figure 8). Both projections capture the increase in the seasonal snowfall with increasing elevation; however, the 36km run significantly underestimates winter snowfall in the lowest three elevation ranges. The differences in the seasonal snowfall amounts between the two simulations are mainly related with the internal processes within the model.

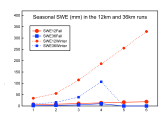

Figure 9. The seasonal mean SWE in the present-day climate simulated with the 12km and 36km simulations.

The differences in the snowfall in the two projections result in notable differences in the simulated SWE. This may explain the differences in the SWE climate change signals shown in Figure 6. The larger snowfall in the 12km run will result in larger snow cover fraction/period and, subsequently, larger surface albedo. The larger snow albedo will generate smaller snow ablation during the cold season. Thus, *the differences in the SWE sensitivity between the 12km and 36km simulations are likely to be caused by the snow-albedo feedback within the RCM, initiated by the differences in the snowfall amounts.*

3.2 The effects of snow albedo

To examine the impact of snow albedo changes that can occur due to anthropogenic aerosols, especially black carbon (BC) on the Sierra Nevada snowpack, a set of simulations have been performed with the snow albedo values 75%, 90%, 100%, 110%, and 125% of the default value used in the Noah LSM for the cold season from October 2050 to April 2051. The two smaller (larger) snow albedo represent cases in which anthropogenic emissions are larger (smaller) than in the control run.

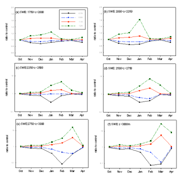

Figure 10. The ratio of the SWE in the 4 sensitivity runs to that in the control run within the 6 elevation ranges .

The most notable features in the sensitivity of the simulated snowpack to snow albedo are that *the magnitude of the sensitivity is larger in higher elevation regions than in lower elevation regions*. In the lowest two elevation ranges, 1750-2000m and 2000-2250m, reduction of snow albedo by 25% resulted in the reduction in SWE by as much as 20% of the values in the control run. Increases in snow albedo result in similar sensitivity in SWE but with an opposite sign and larger magnitudes.

The timing of peak sensitivity varies according to the sign of the snow albedo changes and terrain elevations. In all elevation ranges, the peak percentage reduction of SWE due to the decrease in snow albedo appears about one month earlier than the peak percentage increase of SWE due to increased snow albedo. In the lowest two elevation ranges, the largest reduction in the SWE corresponding to decreased snow albedo occurs in December; the largest impact of the increased snow albedo in the same elevation range occurs in January. Similar differences in the timing of the occurrence of maximum sensitivity according to the decrease and increase in snow albedo occurs in all elevation ranges.

The timing of the peak SWE sensitivity to the snow albedo changes also vary according to terrain elevation. In the lowest two elevation ranges, the peak reduction in SWE due to decreased snow albedo occurs in December; it appears in February in the two highest elevation ranges. The peak response timing of SWE to the increased snow albedo also show similar elevation dependences; January in the lowest two ranges and March in the highest two elevation regions. *The discrepancy between the timing of the peak response to the increase or decrease of snow albedo reveals that the alterations in snow albedo due to BC deposits are further amplified through local snow-albedo feedback*.

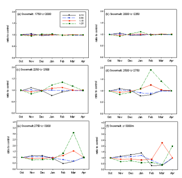

Figure 11. The ratio of the simulated snowmelt in the 4 sensitivity runs to that in the control run within the 6 elevation ranges .

The decrease (increase) in snow albedo results in the increase (decrease) in snowmelt in earlier months of the cold season. This in turn decreases (increases) snowmelt during the later part of the cold season for the decreased (increased) snow albedo.

The timing of the response of the snowmelt to the albedo changes appears in later months as terrain elevation increases as well.

The response of the snowmelt to the alterations in snow albedo is most noticeable in high elevation regions.

The most notable impact of the decrease in snow albedo is enhanced (reduced) snowmelt in earlier (later) part of the cold season, resulting in adverse impacts on warm season water resources in California. The two experiments with larger snow albedo values (lines red and green) shows that increase in snow albedo will suppress snowmelt in the early part of the cold season and will enhance in the later part of the season. This can partially alleviate the adverse impact of global warming on California water resources which will promote earlier snow depletion. The timing of peak impact of altered snow albedo on the simulated snowmelt also varies with elevation in a similar way as for SWE, i.e., the peak response appears later in higher elevation ranges than in lower regions, especially in the cases of increased snow albedo.

The simulated snowmelt also responds to the snow albedo changes according to the snowmelt changes (not shown). The decrease (increase) in snow albedo results in the increase (decrease) of runoff during the early part of the cold season and decreased (increased) runoff in the later part of the cold season.

3.2 SWE in a multi-layer snow model simulation: A comparison against a single layer simulation

An additional uncertainty in snowpack and snowmelt simulation derives from the model physical formulation of important snow processes within the snow pack including snow compaction, heat conduction, snow grain growth, and snow melting. In order to improve, a three-layer representation of snow physics have been implemented in a new snow model (Xue et al. 2003). The model includes an efficient snow cover layering system for realistically simulating important snow process, and has been included in SSiB-3 (Xue et al., 2003) LSM. There are three prognostic variables in the snow model: specific enthalpy, SWE, and snow depth. The SSiB-3 model with the multi-layer snow physics has been utilized in a seasonal simulation to examine the impact of more comprehensive representation of snow physics in simulating snowpack during the spring ablation period.

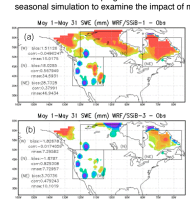

Figure 12. The monthly mean SWE (mm) simulation errors against observation: (a) a single layer snow model (SSiB-1) and (b) 3-layer snow model (SSiB-3).

Figure 12 shows the biases in the seasonal SWE simulated using the single-layer (Figure 12a) and multi-layer (Figure 12b) snow model. In order to clearly show the improvement in simulating SWE by the use of the multi-layer snow model, we divide snow areas into three regions: western U.S. (W), northern Canada (N), northeastern Canada (NE). In W, the use of a three-layer snow model reduces the root-mean-square error (RMSE) in the single-layer snow model simulation by 50%. For the western part of W that includes the Sierra Nevada region, the RMSE is reduced by as much as 80% due to the use of the multi-layer snow model. In N and NE, the improvement in SWE simulation by the use of the multi-layer snow model is more substantial. The absolute bias in the single-layer snow model simulation is reduced by almost 90%, and the spatial correlation between the simulated and observed SWE is increased by 50% and 25% for N and NE, respectively, by the use of a multi-layer snow model.

Summary and conclusions

The impact of model resolution, snow albedo, and the use of physically more detailed snow model on simulating the cold season snow field has been investigated in a series of numerical experiments. The most important findings in these studies are:

(1) Projection of climate change signals in the SWE in the Sierra Nevada region can be significantly influenced by the spatial resolution of an RCM

(1.1) The sensitivity of the snowfall signals to RCM resolution is not very significant; however,

(1.2) RCM resolution can cause significant uncertainties in projecting the climate change signals in SWE.

(1.3) The differences in the SWE climate change signals between the simulations with different spatial resolution appears to be related with the differences in the amount of snowfall between the two simulations. The snowfall differences are amplified via snow-albedo feedback within the RCM.

***(2) Alterations in snow albedo possibly via the deposition of anthropogenic BC can exert large influences on high elevation snowpack and the associated surface hydrology*.**

(2.1) The decrease in snow albedo (enhanced emissions/BC depositions) causes the increase in snowmelt and runoff and the decrease in SWE during the early part of the cold season. This in turn result in the reduction in SWE, snowmelt, and runoff during the late part of the cold season and spring.

(2.2) The increase in snow albedo (reduced emissions/BC depositions) causes the decrease in snowmelt and runoff and the increase in SWE during the early part of the cold season. This in turn result in the enhancement in SWE, snowmelt, and runoff during the late part of the cold season and spring.

(2.3) Increased emissions will further worsen the adverse impact of the increase of low-level air temperature associated with anthropogenic global climate change on California's water resources by reducing snowmelt driven runoff during the late winter and spring. Reductions in local emissions can alleviate the adverse impact as it tends to suppress early snowmelt to result in an increase in snowmelt-driven runoff during the late winter and spring.

(3) ***More realistic treatment of snow physics within a multi-layer snow model framework can improve SWE simulations during the spring snowmelt season***.

(3.1) Compared to a multi-layer snow model, the multi-layer treatment of the physical processes within snowpack can improve the simulation of gradual snowmelt starting from the top of the snowpack.

(3.2) The use of a multi-layer snow model could significantly reduce the SWE biases in the single-layer simulation.

(3.3) The use of multi-layer snow model in a climate model may be an important for reducing the errors in simulating surface snowpack and the associated feedback.

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