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

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1. Introduction

- The Sierra Nevada snowpack plays a crucial role in the water resources and hydropower generation 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.
- Consequently, the impact of global warming on the Sierra Nevada snowpack has become one of the leading topics in the regional climate change studies for the California region.
- The calculation of the Sierra Nevada snowpack in climate models involves significant uncertainties.

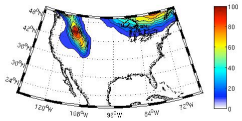


Figure 1. The cold season snow-water equivalent (SWE) for 1961-1980 in a CCSM-3 climate simulation.

- Representation of orography in a climate model according to spatial resolutions can cause significant uncertainties in simulating high elevation snowpack.
  - Precipitation and the low-level air temperature, thus the local SWE field, are strongly influenced by terrain.
  - Figure 1 shows that a coarse resolution GCM fails to capture snow field over the Sierra Nevada.

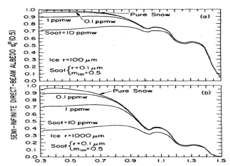


Figure 2. Effects of soot concentration on snow albedo (from Warren and Wiscombe 1980) for the ice grain size of (a) 100μm and (b) 1000μm.

- Snow albedo in the presence of aerosol deposition is another important factor in determining SWE.
  - Snow albedo determines the amount of input solar energy into snowpack; the leading energy source for the energy balance.
- Impurities in snow, especially black carbon, strongly affect snow albedo.
  - Impurities affect snow albedo in the spectral range $\lambda<1\mu m$ where most of solar energy resides.
  - Warren and Wiscombe (1980) showed that for ice grain radius of 100mm 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 2).
  - 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.

- Representation of snow processes in a climate model also influence the SWE calculation.
  - To initiate snowmelt in a single layer snow framework, the temperature of the entire snowpack needs to be above the freezing temperature.
  - In a multi-layer framework, only the snow temperature in the top layer must be elevated above 0°C to start snowmelt.

- **This study examines the impact of RCM resolution, variations in 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 the climate change sensitivity of SWE in the Sierra Nevada based on 36km and 12km resolution simulations,**
  - **the sensitivity study of SWE simulations in the Sierra Nevada according to the assumed variations in snow albedo, and**
  - **a comparison of the SWE simulated using a single- and multi-layer snow model within the WRF-SSiB model.**

2. Experimental Design

- The numerical experiments are performed using the Regional Earth System Model (RESM) being developed at the UCLA-JPL Joint Institute for Regional Earth System Science and Technology (JIFRESSE) on the basis of the WRF model, the regional ocean model (ROM), the Simplified SiB (SSiB) model, and the Community Multi-scale Air Quality (CMAQ) model.
- 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 (Figure 3a), is performed for the 10 winter seasons each for the late 20th century (1971-1080) and mid-21st century (2045-2054) periods.
- SWE simulations based on different snow layering is performed over a North American domain at an 80km horizontal resolution (Figure 3b).

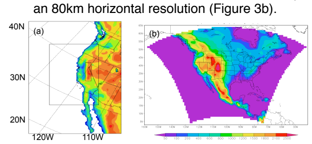


Figure 3. The model domains used in this study.

The effects of model resolution and snow albedo on SWE are analyzed in terms of terrain elevation range for the 12/36km horizontal resolutions:

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

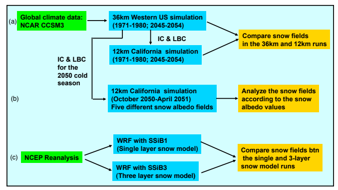


Figure 4. The data flow in the three RCM runs:

(a) The effects of RCM resolutions on SWE climate change sensitivity,

(b) The effects of snow albedo on SWE, and

(c) A comparison of the SWE simulated using a single- and three-layer snow model in the SSiB-1 and SSiB-3 LSM.

3.1 Snow simulations according to RCM resolutions

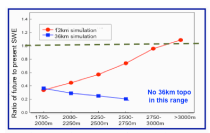


Figure 5. The SWE climate change sensitivity in the 12km and 36km runs.

The climate change sensitivity (the ratio between the future- and the 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.

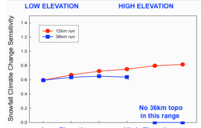


Figure 6. The snowfall climate change sensitivity.

- Both runs generate similar climate change signals in snowfall for all elevation ranges.
  - The differences in the climate change signals in snowfall are not likely the cause for the differences in the SWE climate change signals in Figure 5.

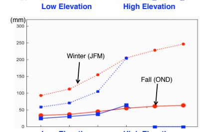


Figure 7. The seasonal snowfall (mm) in the present-day climate simulated with the 12km (red) and 36km (blue) resolutions.

Both runs could capture the snowfall increase with increasing elevation; however, the 36km run underestimates winter snowfall. These differences in the snowfall amounts between the two runs are amplified via snow-albedo feedback, resulting in the large differences in the SWE climate change signals.

- The results suggest that the climate change signals in SWE could vary notably according to model resolutions.
- The sensitivity of snowfall that is more directly determined by the changes in large-scale circulation is not affected much by the model resolution
- The amount of snowfall varies according to the model resolutions.
- The differences in the snowfall amount is amplified via snow albedo feedback to result in significant differences in the SWE change signals.

3.2 The effects of snow albedo

- Snow albedo can change due to the presence of anthropogenic aerosols, especially black carbon (BC).
- The deposition of BC on the Sierra Nevada snowpack can be influenced by local emissions.
- This case study assumes two emission scenarios:
  - Control run: The cold season October 2050 – April 2051 with the Noah LSM default snow albedo values.
  - Increased emissions: Two runs in which the snow albedo values are of 75% and 90% of the control run.
  - Reduced emission: Two runs in which the snow albedo values are 110% and 125% of the control run.
- The impact of the snow albedo alterations on the SWE in the Sierra Nevada region is investigated.

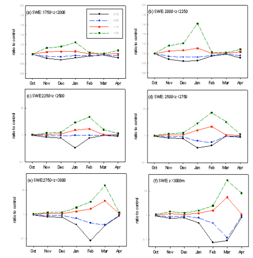
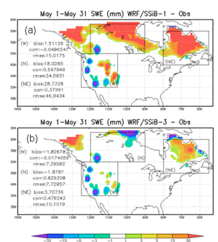


Figure 8. The ratio of the monthly SWE in the sensitivity runs to that in the control run within the 6 elevation ranges .

- Snow albedo changes can significantly alter the simulated SWE (Figure 8):
  - Decreased (increased) snow albedo reduces (increases) SWE in early (late) cold season.
- The sensitivity of SWE to the albedo changes increases with increasing elevations.
  - The peak SWE sensitivity to the prescribed snow albedo changes occurs later in the cold season as terrain elevation increases.
  - The magnitude of the SWE sensitivity increases with increasing terrain elevation.
- *Examinations of the simulated surface albedo (not shown) reveal that the discrepancy in the timing of the SWE sensitivity between the increase and decrease of snow albedo results from local snow albedo feedback*.
  - The local snow albedo feedback amplifies the differences in SWE due to the changes in snow albedo.
- The simulated snowmelt also varies according to snow.
  - Decreased snow albedo increases (decreases) runoff in early (late) cold season.
  - Increased snow albedo decreases (increases) runoff in early (late) cold season.
- The results suggest that alterations in local BC emissions can affect the hydroclimate in the Sierra Nevada region via alterations in snow albedo.

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



- A model framework in which snow physics are represented can also be an important source of uncertainties in simulating snowpack.
  - In many snow models, for example, the amount of energy input to initiate snowmelt varies according to the thickness of a model snow layer via snow temperature.
- In order to examine this concern, SWE in North America during May 1998 has been simulated using two different snow models:
  - A single layer representation in lieu of SSiB-1 and
  - A three layer snow representation with the SSiB-3 model (Xue et al. 2003).
- The single layer model overestimates the observed SWE (Mote et al. 2005), most notably in Canada and the Rocky Mountains (Figure 9a).
- Much of the positive biases in the single layer snow model simulation could be alleviated by using the three-layer snow model (Figure 9b).
- Underestimation of SWE in the single layer model persists in the three layer simulation; perhaps due to the lack of terrain representation (80km).

Figure 9. The SWE biases in: (a) single-layer and (b) three-layer snow model simulations.

Summary and conclusions

Projection of the Sierra Nevada SWE climate change signals can be significantly influenced by the spatial resolution.

(1.1) The differences in the projected SWE climate change sensitivity is more directly related with the amount of snowfall than the climate change sensitivity of snowfall in the two simulations.

(1.2) The snowfall differences between the two simulations are amplified via snow-albedo feedback to result in the large differences in the SWE sensitivity despite the similar snowfall sensitivity.

(1)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) A decrease (increase) in snow albedo decreases (increases) SWE in early (late) cold season.

(2.2) The changes in snow albedo also affect snowmelt and runoff.

(2.3) The results suggest that increased future emissions will further worsen not only future air quality but also the adverse impact of the anthropogenic global climate change on California's water resources via even earlier snowmelt. Reduced emissions can partially counteract the adverse impact.

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

Acknowledgements

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