The Sensitivity of the Mid-21st Century Cold Season Hydroclimate in California to Global Warming: An RCM Projection Based on NCAR CCSM3 Projection with the SRES-A1B Emission Scenarios

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1. Introduction

- Recent studies strongly suggest that the increase in anthropogenic greenhouse gases will induce significant global climate changes in this century.
- Future changes in regional hydroclimate in response to the global climate change is an important concern for California:
  - California relies heavily on the cold season precipitation and snow accumulation for the water supply during dry warm seasons.
  - Observations revealed that global climate change appears to be affecting the snowpack and snowmelt-driven runoff in California's mountainous region.
  - California's water supply is already marginal for supporting its large population/industries.
  - Thus, reliable assessments of the impact of the climate change on the future water resources has been an important for the water managers in California.
- The amplitude and consequences of the global climate change are still far from certain, particularly on regional and local scales (Figure 1.1).
  - The IPCC GCMs project increases in the surface air temperature in California; however, the amount of warming vary widely among GCMS.
  - Projection of future precipitation is even more problematic; the models are not even in agreement whether California will become wetter or drier.
- A considerable part of the uncertainty lies in the fact that the global models poorly, or do not, resolve terrain variations that play a crucial role in shaping the hydroclimate in California and similarly mountainous regions.
  - Figure 1.2 shows that GCMs inability in resolving California's major terrain features, the Coastal Range and the Sierra Nevada, resulted in totally unrealistic snowpack.
  - Thus, the present-day GCM results are not suitable for assessing the impact of the global climate change on the hydroclimate and water resources in California.

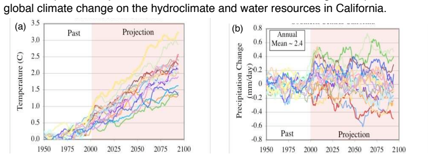

Figure 1.1 Projections of the changes in (a) annual mean surface air temperature and (b) precipitation for Southern/Central California relative to a climatology for the period 1900-1999 from 17 different GCMs for the IPCC's 4th Assessment Report on the basis of the SRES-A1B emissions storyline.

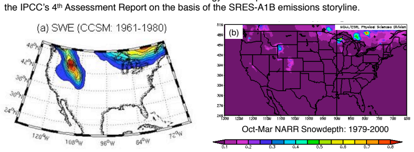

Figure 1.2 The snow-water equivalence (SWE) in (a) CCSM and (b) North American Regional Reanalysis

- To address this issue, the UCLA Joint Institute for Regional Earth System Science and Engineering (JIFRESSE), a collaboration between UCLA and JPL for improving the understanding and projections of the impact of global climate change on regional sectors, has developed a comprehensive Regional Earth System Model (RESM).
- The RESM is based on one-way and/or interactive nesting of the models for limited-area atmosphere (WRF), ocean (ROMS) and air quality (CMAQ) for advanced treatments of the physical and dynamical processes in the regional climate system (Figure 1.3).

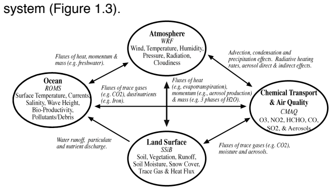

Figure 1.3 A schematic illustration of the nesting of the regional modeling components within the RESM.

This study investigates the impact of the climate change induced by the increase in the anthropogenic greenhouse gases on the surface hydroclimate in California by dynamically downscaling a global climate scenario generated from the NCAR CCSM3 on the basis the IPCC SRES-A1B emission profile.

2. Experimental Design

- The dynamical downscaling is performed using the RESM based on WRF 2.2.1 [http://wrf-model.org].
- The physics options selected in this experiment include the NOAH land-surface scheme, the RRTM longwave radiation scheme, Dudhia shortwave radiation, and the WSM 3-class with simple ice cloud microphysics scheme.
- The large-scale lateral boundary forcing including SST has been updated at 6-hour intervals.

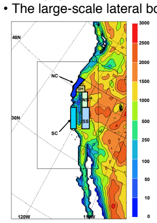

Figure 2.1 The model terrain.

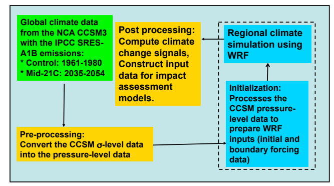

Figure 2.2 Data flow in the regional climate change simulations.

- The domain covers the western United States (WUS) region at a 36km resolution and 27 sigma layers.
  - At this resolution, the model terrain captures major orographic features within the WUS region; however, the high elevation regions in the Sierra Nevada and the narrow but steep coastal terrain is somewhat under-represented.
- Also shown in Figure 2.1 are the 5 sub-regions, Northern Coastal Range (NC), Southern Coastal Range (SC), Mt Shasta (SH), Northern Sierra Nevada (NS0, and Southern Sierra Nevada (SS), for more detailed investigation of the projected climate change signals within California.
  - The three sub-regions, SH, NS, and SS feeds most of the major reservoirs that supplies water in California
- Cold-season (October-March) climate simulations for the two 20-year periods are performed:
  - mid-21st Century (2035-2054) and the late 20th Century (1961-1980).
- Climate change signals are calculated as the differences between the two 20-year climatology.

3. Results

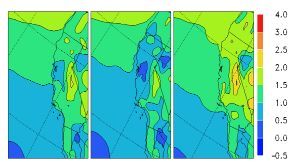

Figure 3.1 Low-level air temperature signals (K)

- Increases in the low-level temperature by 1-2.5K are projected (Fig. 3a).
  - Seasonally, the low-level warming is larger in winter (Fig. 3.1c) than in fall (Fig. 3.1b).
  - Geographically, the warming signals increase towards the north, away from the coastline, and in higher elevations.
  - **The largest warming occurs in the high elevation Sierra Nevada region during winter (JFM).**

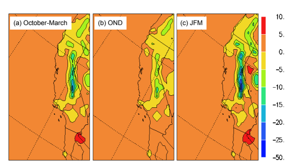

Figure 3.2 Surface albedo signals

- The large warming in the high elevation region is accompanied by a large decrease in the surface albedo.
  - The projected decrease in the surface albedo is more pronounced in winter than in fall.
- In conjunction with the snowpack changes (Fig. 3.6), the results show that the temperature changes in the high elevation regions are augmented by snow-albedo feedback.

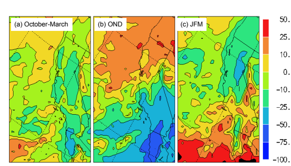

Figure 3.3 Precipitation changes (% of the late 20th century)

- Overall decreases in the cold season precipitation are projected for California (Fig. 3.3a).
  - The projected precipitation change signal also varies according to geography and season.
  - In fall, precipitation increases (decreases) in northern (southern) California.
  - This north-south pattern in fall is reversed in winter.
  - The statistical significance of the positive signals are generally below 50%.
  - The decrease in the cold season precipitation is most pronounced in the high elevation regions.

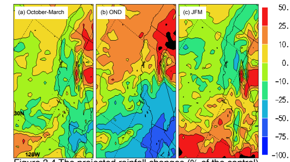

Figure 3.4 The projected rainfall changes (% of the control)

- The cold season rainfall decreases in California.
- The spatial pattern of the seasonal precipitation changes are associated chiefly with the rainfall changes.
- One exception is in the northern Sierra Nevada region where rainfall increases in both seasons.
  - The increase in rainfall in the region is one of the most important consequences of the low level warming; converting snowfall in colder climate into rainfall in warmer climate.

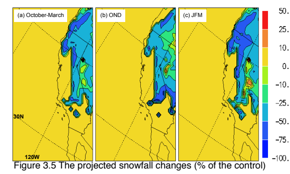

Figure 3.5 The projected snowfall changes (% of the control)

- Snowfall also decreases everywhere in California.
  - The decreases range between 25 and 50% of the control climate in most of the Sierra Nevada.
  - The projected snowfall decrease is larger in winter than in fall.
- The projected snowfall decreases in high elevation regions will be an important concern for the water supply in California as the warm season water supply in the region heavily relies on snowmelt driven runoff in high elevation regions.

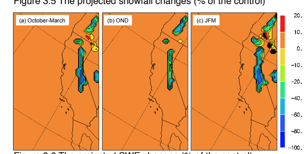

Figure 3.6 The projected SWE changes (% of the control)

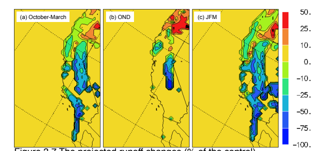

Figure 3.7 The projected runoff changes (% of the control)

In response to the precipitation and temperature changes, the seasonal mean SWE and runoff in high elevation regions decrease substantially, most notably in winter. The decrease in winter SWE will exert an adverse impact on the warm season water supply in the region

	Season	NC	SC	SH	NS	SS
Precipitation (mm/mo)	Fall (OND)	22.5 (11.5)	-6.6 (-11.7)	23.5 (15.2)	16.1 (9.85)	-16.0 (-15.4)
	Winter (JFM)	-64.4 (-21.5)	-15.1 (-14.6)	-44.8 (-17.2)	-82.6 (-26.6)	-39.8 (-20.9)
	Oct-Mar	-21.0 (-8.46)	-10.9 (-13.6)	-10.7 (-5.2)	-33.2 (-14.0)	-27.9 (-19.0)
Rainfall (mm/mo)	Fall (OND)	25.4 (13.5)	-6.7 (-12.2)	34.8 (28.0)	29.6 (22.7)	-3.6 (-5.1)
	Winter (JFM)	-54.7 (-19.4)	-15.5 (-15.0)	-14.0 (-6.93)	-45.8 (-19.1)	-12.2 (-10.7)
	Oct-Mar	-14.6 (-6.23)	-11.2 (-14.0)	-10.4 (6.4)	-8.1 (-4.4)	-7.9 (-8.6)
Snowfall (mm/mo)	Fall (OND)	-2.9 (-41.7)	0.2 (n/a)	-11.3 (-40.5)	-13.5 (-40.5)	-12.5 (-36.5)
	Winter (JFM)	-9.7 (-53.1)	0.4 (n/a)	-30.8 (-51.3)	-36.8 (-52.6)	-27.6 (-36.5)
	Oct-Mar	-6.3 (-50.0)	0.3 (n/a)	-21.1 (-46.9)	-25.1 (-48.7)	-20.0 (36.5)
Runoff (mm/mo)	Fall (OND)	-0.1 (-0.4)	-0.2 (-11.2)	-0.7 (5.6)	-1.9 (-10.7)	-6.5 (-63.1)
	Winter (JFM)	-12.9 (-10.4)	-3.4 (-28.2)	-3.6 (-3.8)	-24.9 (-22.6)	-16.5 (-29.4)
	Oct-Mar	-6.5 (-50.0)	-1.78 (-26.7)	-1.4 (-2.7)	-13.4 (-21.0)	-11.5 (-34.6)
Snowmelt (mm/mo)	Fall (OND)	-2.89 (-42.0)	0.2 (n/a)	-10.1 (-36.4)	-11.3 (-37.7)	-8.5 (-29.9)
	Winter (JFM)	-9.75 (-52.8)	0.4 (n/a)	-32.3 (-51.9)	-39.4 (-54.0)	-30.7 (-38.6)
	Oct-Mar	-6.32 (-50.0)	0.3 (n/a)	-21.2 (-47.2)	-25.4 (-49.2)	-19.6 (-36.3)
SWE (mm)	Fall (OND)	0.1 (42.3)	0.0 (0.0)	-1.1 (-32.9)	-1.4 (29.9)	-3.1 (-42.7)
	Winter (JFM)	-1.3 (-78.5)	0.0(0.0)	-2.9 (-58.1)	-5.0 (-65.5)	-13.2 (-67.9)
	Oct-Mar	-0.6 (-60.8)	0.0 (0.0)	-3.2 (-52.0)	-3.21 (-52.0)	-8.2 (-61.1)
2m Air Temperature (C)	Fall (OND)	0.87	0.59	0.95	0.98	1.38
	Winter (JFM)	1.73	1.42	1.77	1.94	2.09
	Oct-Mar	1.30	1.36	1.36	1.46	1.74

Table 1. A summary of the climate change signals in key surface hydrologic variables. The numbers in the parenthesis are the climate change signals in terms of the percent of the control climatology.

Conclusions

(1) **Low tropospheric warming of 1-2.5K** in California is projected with larger increases in high elevation regions during winter. The geographical variations in the projected warming signals are associated with the significant depletion of snowpack in the warmer climate and the prevailing westerlies.

(2) The **surface albedo decreases notably in high elevation regions**. The decrease in the surface albedo is more pronounced in winter than in fall because the depletion of snowpack is larger in winter than in fall.

(3) The cold season precipitation decreases in California. The precipitation changes show strong interseasonal and geographical variations.

(4) Snowfall decreases throughout the cold season by 25-50% of the amount in the present-day climate. The largest percent-decrease in snowfall occurs in winter.

(5) The snowpack in the high elevation Mt. Shasta and the Sierra Nevada regions decrease by over 40% in fall and nearly 70% in winter due to reduced snowfall and the higher low-level air temperature.

(6) The cold season runoff decreases in California due to reduced precipitation.

The climate change signals obtained in this study, especially the reduction in high elevation snowpack, suggests that the climate change will adversely affect the water resources in California.

It must be noted that the results in this study represent only one of many equally plausible climate change projections. The changes in the key surface hydroclimate fields projected in this study compare qualitatively with the results in previous studies; however, details in the climate change signals vary primarily due to the differences in the GCM climate projections used to drive an RCM.

Acknowledgement

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