# ANALYSIS OF FUTURE SNOW CONDITIONS FOR THE NATIONAL CLIMATE ASSESSMENT

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## ABSTRACT

The Third National Climate Assessment Report is under development. To support this effort, regional analyses of climate conditions were conducted, focusing on both historical trends deduced from observations and future projections derived from climate model simulations. A recent project on snowfall trends generally found declining total snowfall in the western U.S. at cooperative observer sites. Since the 1990s, the area with extreme high seasonal snowfall has been well below the long-term mean. Climate model simulations show substantial future warming throughout the west. Precipitation is simulated to decrease in the Southwest and increase in the Northwest and Alaska. These results suggest future declining snowpack in the southwest. (Keywords: climate assessment, snowfall, projections)

## INTRODUCTION

The 1990 Global Change Research Act mandated that national assessments of climate change be prepared not less frequently than every four years. The second, most recent, national assessment was published in 2009 (Karl et al. 2009). To meet the requirements of the Act, a third National Climate Assessment (NCA3) report is now being prepared, and scheduled to be released in early 2014.

An analysis of historical conditions from observations and future conditions from climate model simulations was undertaken to provide a resource for the authors of the NCA3. The analysis of historical conditions was based primarily on data from the National Weather Service Cooperative Observer Network (COOP).

For the future conditions, it was decided to use the set of global climate model simulations performed for the Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Report (AR4), also referred to as the Climate Model Intercomparison Project Phase 3 (CMIP3) suite. These simulations have undergone extensive evaluation and analysis by many research groups. Simulations from 15 models were used in the analysis. Two emissions scenarios were considered, the A2 (a high emissions scenario) and the B1 (a low emissions scenario. These scenarios were selected because they incorporate much of the range of potential future human impacts on the climate system and because there is a large body of literature that uses climate and other scenarios based on them to evaluate potential impacts and adaptation options. These scenarios represent different narrative storylines about possible future social, economic, technological, and demographic developments (IPCC 2000).

A second source of future projections used in our analysis is a set of dynamically-downscaled simulations, driven by CMIP3 models, produced by the North American Regional Climate Change Assessment Program (NARCCAP). This multi-institutional program has produced regional climate model (RCM) simulations in a coordinated experimental approach. At the time that this analysis was begun, simulations were available for 9 different combinations of an RCM driven by a general circulation model (GCM). These 9 combinations involved four different GCMs and six different RCMs. Each GCM-RCM combination produced simulations for the periods of 1971-2000 and 2041-2070 for the high (A2) emissions scenario only. These simulations are at a resolution of approximately 50 km (~30 miles), covering much of North America and adjacent ocean areas.

## HISTORICAL SNOW TRENDS

Kunkel et al. (2009a,b) reported on an extensive analysis of snowfall trends in the U.S. This analysis used a set of stations that had been assessed as sufficiently temporally homogeneous for trend analysis. Preliminary results of this effort were reported at previous Western Snow Conferences (Kunkel et al. 2006, 2007). A brief summary of key results of this project is presented here.

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Figure 1 shows annual regional values of a metric of extreme high seasonal snowfall for the southwest and northwest regions of the U.S. This metric is an estimate, based on the individual station values, of the percent of area experiencing seasonal snowfall totals that exceed the 90th percentile threshold. The nominal long-term average value of this metric is 10% by virtue of the percentile-based definition. In the southwest, there has been a general decline in area since a peak in the 1970s. Values have been quite low since the late 1990s. In the Northwest, the areal values have been generally below the long-term average since the 1970s. As with the Southwest, these values have been particularly low since the late 1990s.

Figure 2 shows annual variations in a similar metric for extreme low seasonal snowfall. In the Southwest, there is little trend in this metric. However, in the northwest, the percent area with extreme low snowfall has been well above the long-term mean since the late 1990s.

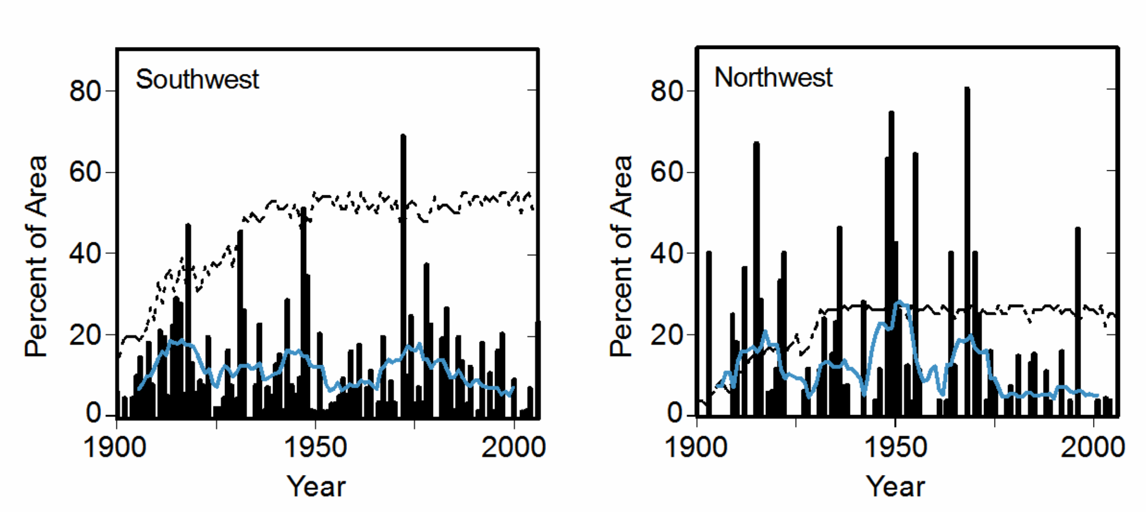

Figure 1. Regional average annual percentages of homogeneous snowfall stations exceeding the 90th percentile, 1900–01 to 2006–07 for the Southwest (left) and Northwest (right) U.S. The snowfall percentile threshold for each station was calculated using the base period of 1937–38 to 2006–07. The percentage of stations exceeding the threshold for each region is calculated by dividing the number of stations in the region exceeding the threshold by the number of active stations each year. The thick blue line is an 11-yr running mean of the percentages, and the dashed line indicates the number of active stations each year. From Kunkel et al. (2009a).

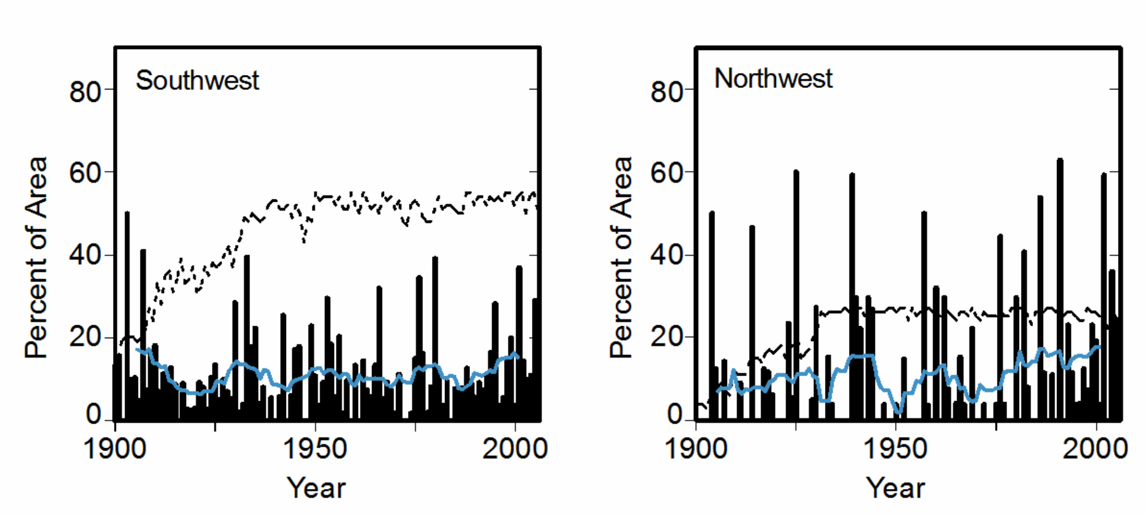

Figure 2. Same as Fig. 1 except this is the percentage of area with snowfall below the 10th percentile.

Figure 3 shows trends in total annual snowfall at individual stations for the period of 1930-2007. Snowfall declined over much of the nation during this period, with the largest rates of reduction in the Pacific Northwest, the Southwest, a region centered on eastern Kansas and Missouri, and across the mid-Atlantic. Upward trends are observed along the lee of the Rocky Mountains, in the north-central U.S. and around the Great Lakes.

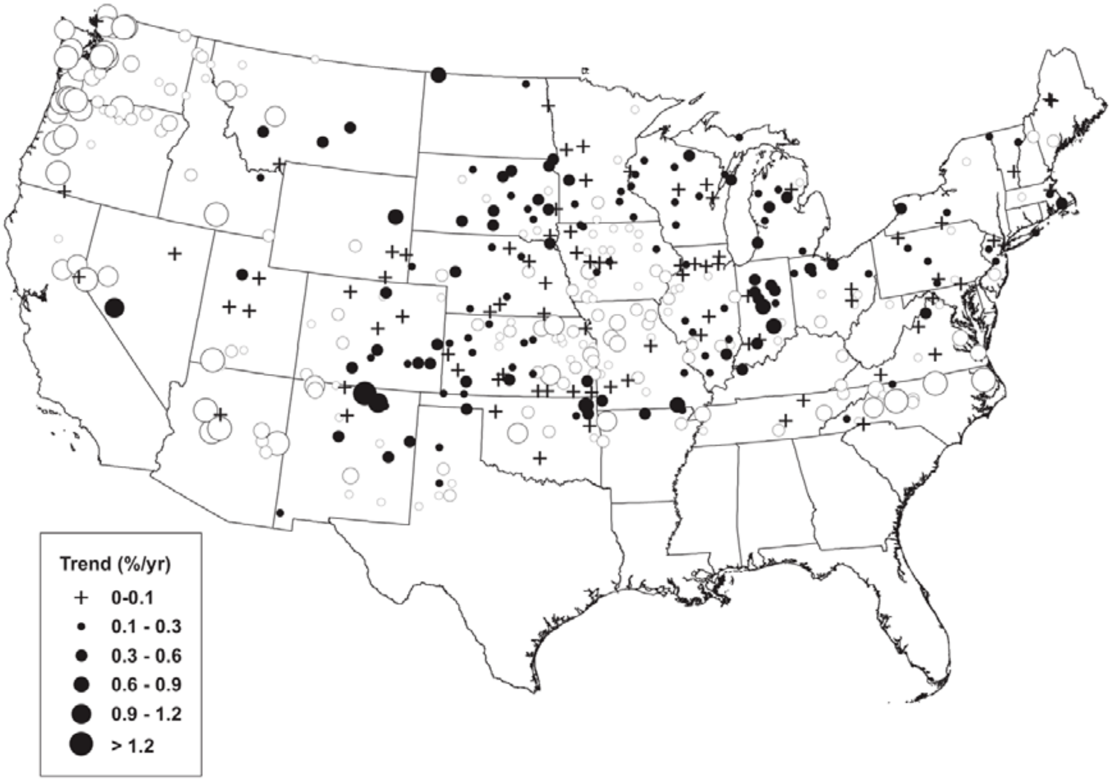

Figure 3. Trends in annual snowfall for 1930–31 to 2006–07 for individual stations. Trends are given as a percentage of the 1937–38 to 2006–07 snowfall mean per year. Closed circles: positive trends; open circles: negative trends; plus signs: no trends. From Kunkel et al. (2009b).

## FUTURE PROJECTIONS

Figure 4 shows the simulated change in annual mean temperature for three future time period with respect to a reference period of 1971-1999, for both emissions scenarios, averaged over the entire Southwest region for 14 (B1) or 15 (A2) CMIP3 models. In addition, values for 9 NARCCAP simulations and the 4 GCMs used to drive the NARCCAP experiment are shown for 2041-2070 (A2 scenario only) with respect to 1971-2000. Both the multi-model mean and individual model values are shown. For the high (A2) emissions scenario, the CMIP3 models simulate average temperature increases of 2.9°F by 2035, 4.7°F by 2055, and nearly 8°F by 2085. The increases for the low (B1) emissions scenario are nearly as large in 2035 at around 2.5°F, but by 2085 the increase of 4.6°F is over 3°F smaller than in the A2 scenario. For 2055, the average temperature change simulated by the NARCCAP models (4.4°F) is comparable to the mean of the CMIP3 GCMs for the A2 scenario.

A key overall feature is that the simulated temperature changes are similar in value for the high and low emissions scenarios for 2035, but largely different for 2085. This indicates that early in the 21st century, the multi-model mean temperature changes are relatively insensitive to the emissions pathway, whereas late 21st century changes are quite sensitive to the emissions pathway. This arises because atmospheric $CO_2$ concentrations resulting from the two different emissions scenarios do not considerably diverge from one another until around 2050. It can also be seen from Fig. 4 that the range of individual model changes is quite large, with considerable overlap between the A2 and B1 results, even for 2085. The range of temperature changes for the GCMs used to drive the NARCCAP simulations is small relative to the range for all CMIP3 models. This may be largely responsible for the relatively small range of the NARCCAP models. The results for the northwest U.S. and Alaska (not shown) are similar to these results.

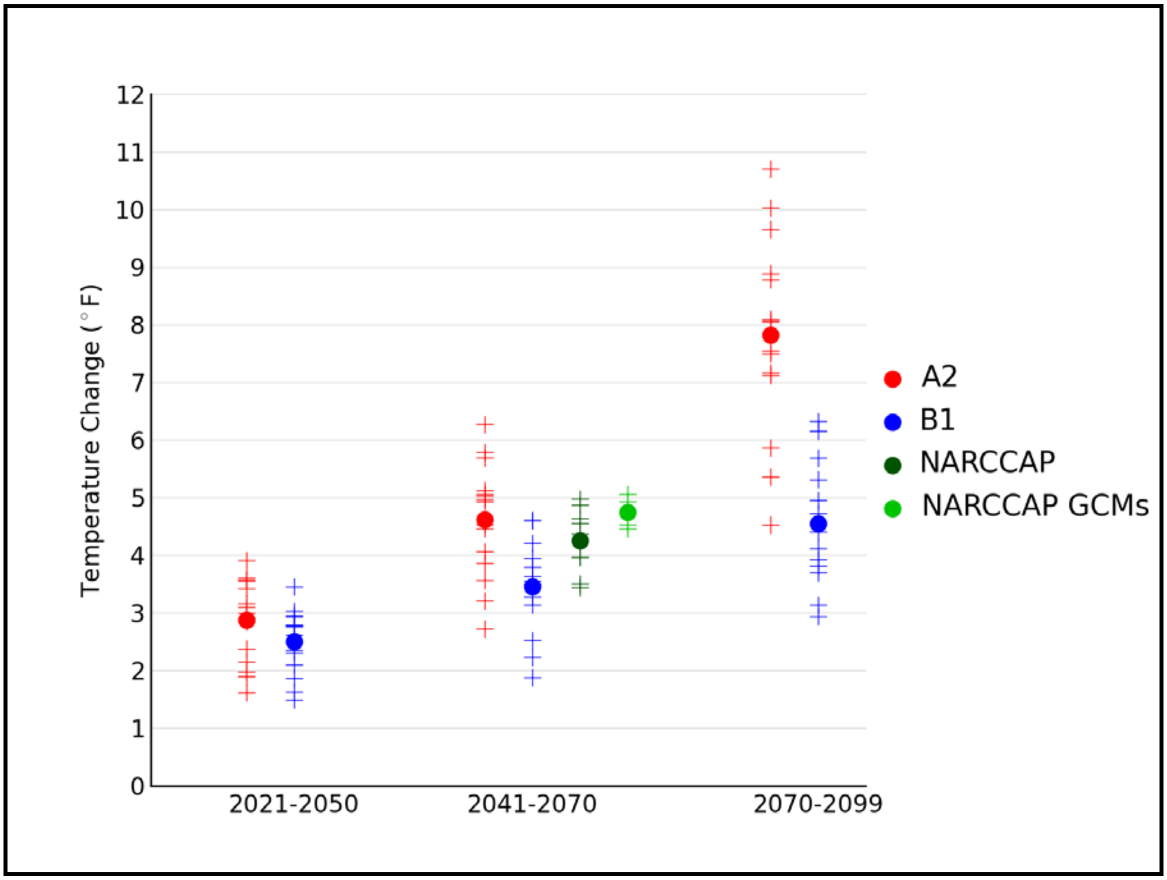

Figure 4. Simulated annual mean temperature change (°F) for the Southwest U.S. (CA, NV, UT, CO, AZ, and NM), for three future time periods (2021-2050, 2041-2070, and 2070-2099) with respect to the reference period of 1971-1999 for the CMIP3 models and 1971-2000 for the NARCCAP models. Values are given for the high (A2) and low (B1) emissions scenarios for 14 (B1) or 15 (A2) CMIP3 models. Also shown for 2041-2070 (high emissions scenario only) are values for 9 NARCCAP models, as well as for the 4 GCMs used to drive the NARCCAP simulations. The small plus signs indicate each individual model and the circles depict the multi-model means. The range of model-simulated changes is large compared to the mean differences between A2 and B1 in the early and middle 21st century. By the end of the 21st century, the difference between A2 and B1 is comparable to the range of B1 simulations. From Kunkel et al. (2013a).

Figure 5 shows the simulated change in seasonal mean precipitation for each future time period with respect to 1971-1999, for the high (A2) emissions scenario, averaged over the entire Southwest region for the individual 15 CMIP3 models, as well as the NARCCAP models for 2041-2070, relative to 1971-2000. Both the multi-model mean and individual model values are shown. The simulated multi-model mean decreases are largest in the spring, ranging from -6% in 2035 to -17% in 2085. The NARCCAP models, which are displayed for 2055, indicate changes close to the same as the CMIP3 models. The model ranges in Fig. 5 are large compared to the multi-model mean differences. This illustrates the large uncertainty in the precipitation estimates using these simulations.

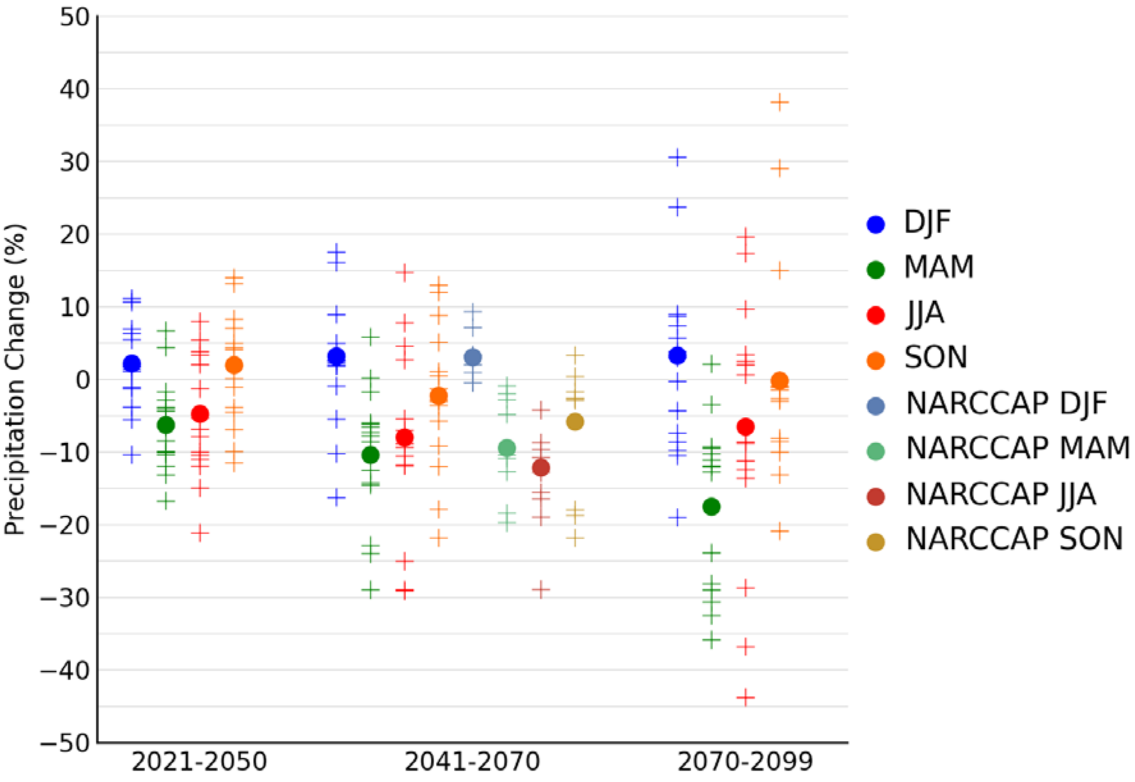

Figure 5. Simulated seasonal mean precipitation change (%) for the Southwest U.S. (CA, NV, UT, CO, AZ, and NM), for each future time period (2021-2050, 2041-2070, and 2070-2099) with respect to the reference period of 1971-1999. Values are given for all 15 CMIP3 models for the high (A2) emissions scenario. Also shown are values (relative to 1971-2000) for 9 NARCCAP models for 2041-2070. The small plus signs indicate each individual model and the circles depict the multi-model means. Seasons are indicated as follows: winter (DJF, December-January-February), spring (MAM, March-April-May), summer (JJA, June-July-August), and fall (SON, September-October-November). The range of model-simulated changes is large compared to the mean changes and to differences between the seasons. From Kunkel et al. (2013a).

Figure 6 shows the simulated change in seasonal mean precipitation for three future time period with respect to 1971-1999, for the high (A2) emissions scenario, averaged over the entire Northwest region for the 15 CMIP3 models, as well as the NARCCAP models for 2055, relative to 1971-2000. Again, both the multi-model mean and individual model values are shown. The CMIP3 models simulate increases for winter, spring, and fall, but decreases for summer, for all three time periods. The changes is summer precipitation are large compared to those for the other seasons, ranging from around -12% in 2035 to -24% in 2085. The magnitudes of the NARCCAP multi-model mean values are similar to those of the CMIP3 models for three of the four seasons; for summer the NARCCAP mean is somewhat less negative than the CMIP3 mean. As was the case for the Southwest region, the model ranges in Fig. 6 are large compared to the multi-model mean differences.

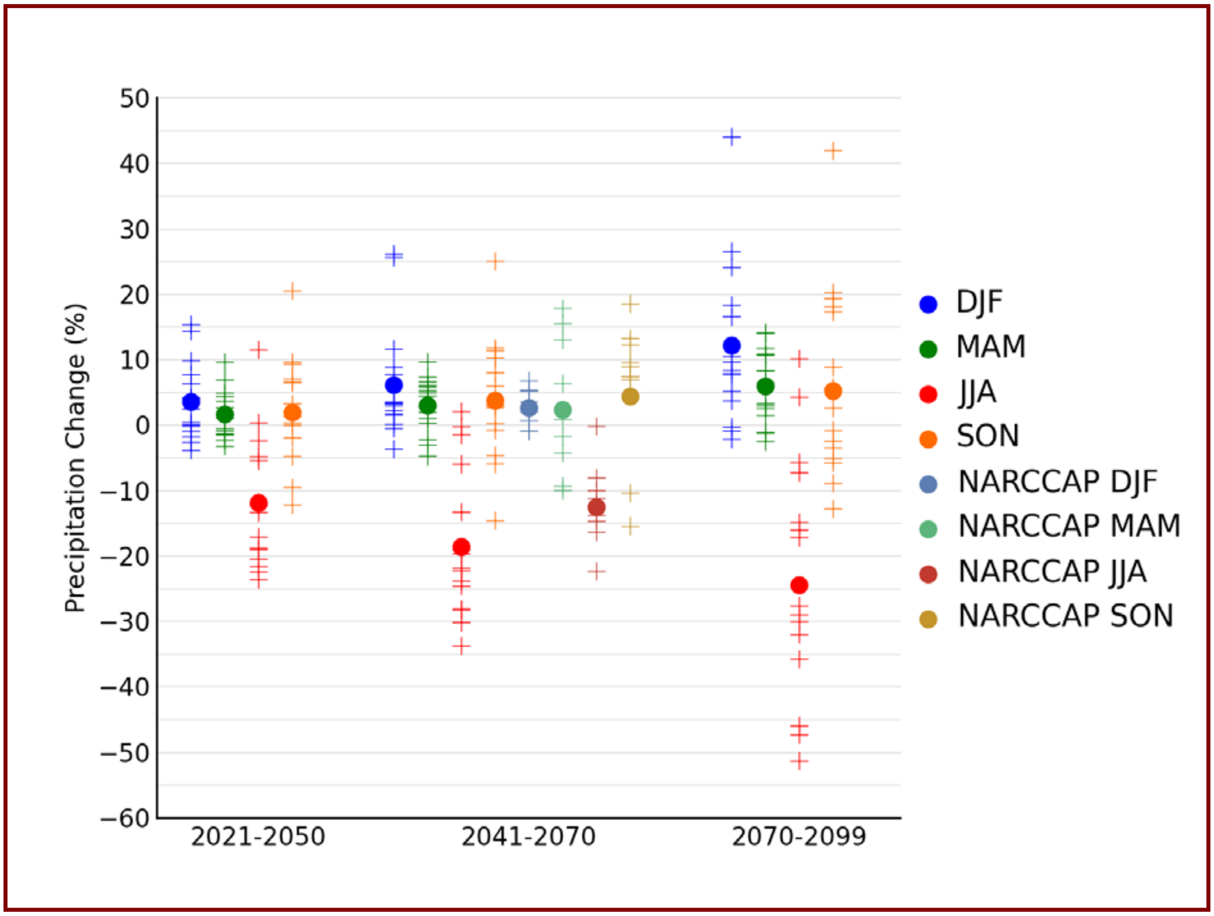

Figure 6. The same as Fig. 5 except for the Northwest region (WA, OR, ID). The ranges of model-simulated changes are large compared to the mean changes and to differences between the seasons. From Kunkel et al. (2013b).

Figure 7 shows the change in seasonal mean precipitation for three future time period with respect to 1971-1999, for the high (A2) emissions scenario, averaged over Alaska for the 15 CMIP3 models. Again, both the multi-model mean and individual model values are shown. The simulated multi-model mean precipitation changes are largest in winter, ranging from +10 to +28%. For the other three seasons, the mean simulated changes are also positive and increase over time. The model ranges in Fig. 7 are large compared to the multi-model mean differences.

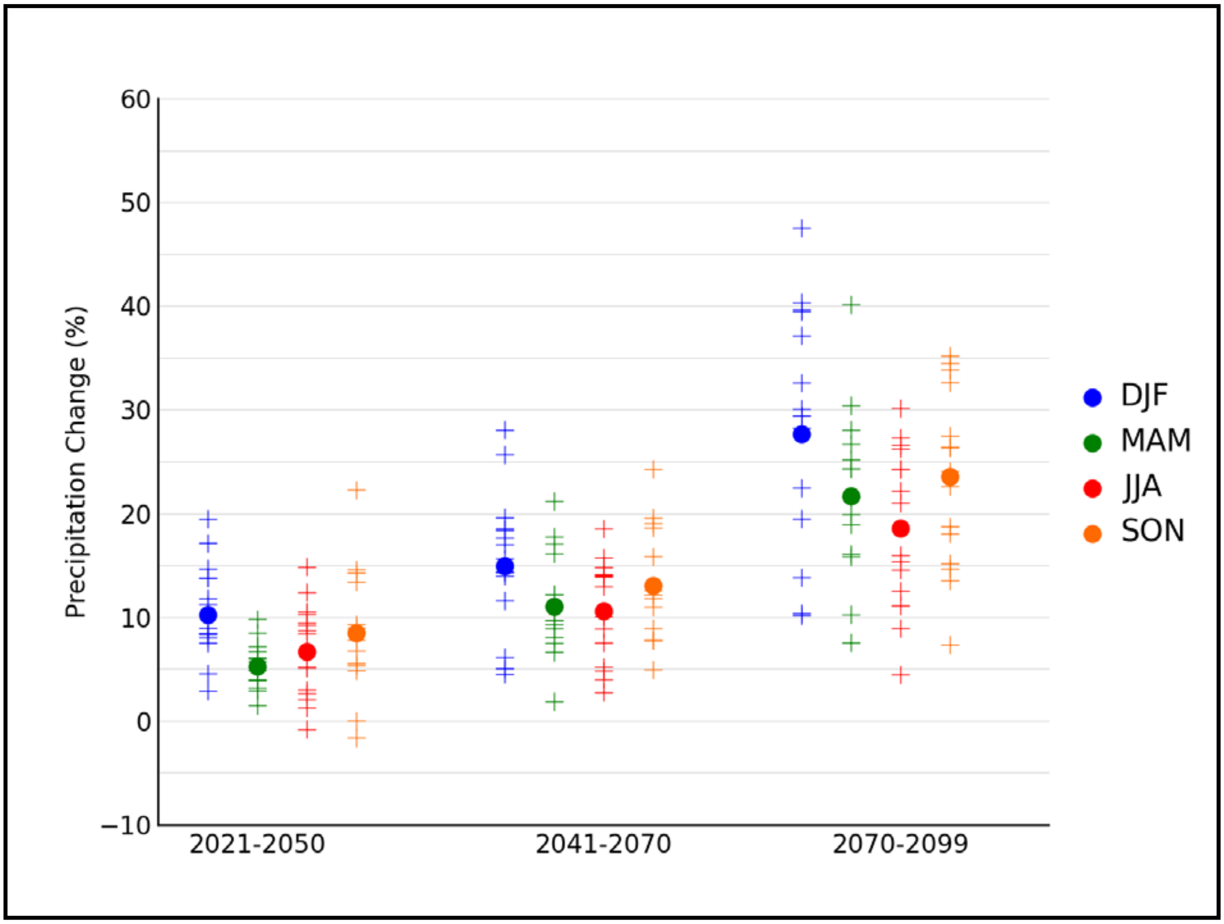

Figure 7. Same as Fig. 5 except for Alaska. From Stewart et al. (2013).

Figure 8 shows the spatial distribution of multi-model mean simulated differences in average annual precipitation for the three future time periods (2035, 2055, 2085) with respect to 1971-1999, for both emissions scenarios, for the 14 (B1) or 15 (A2) CMIP3 models. Spatially, there is a north-south gradient in precipitation changes with generally drier conditions in the south and wetter conditions in the north. In the west by the end of the 21st Century, the models generally simulate statistically precipitation decreases in southern California, all of Arizona and New Mexico, and southern Colorado under the A2 scenario. Statistically significant increases are simulated in Washington, Idaho, Montana, and most of Wyoming under the A2 scenario.

## DISCUSSION

The model-simulated future climate changes in the southwest U.S. include a large increase in temperature and a decrease in precipitation. Together these changes suggest a future reduction in snowfall, which would be an extension of historic trends. By contrast, the models simulate increases in precipitation in the Northwest. While the projected increases in temperature would suggest an increase in snow levels and probable decreases in snowfall at lower elevations, there could be compensating increases at higher elevations where temperatures remain cold enough for snow. Thus, the impact on overall snowpack is not clear. In Alaska, all models simulate future increases in precipitation, with the largest increases in the winter. Since temperatures will remain cold enough for snow there, it seems highly likely that snowfall will increase.

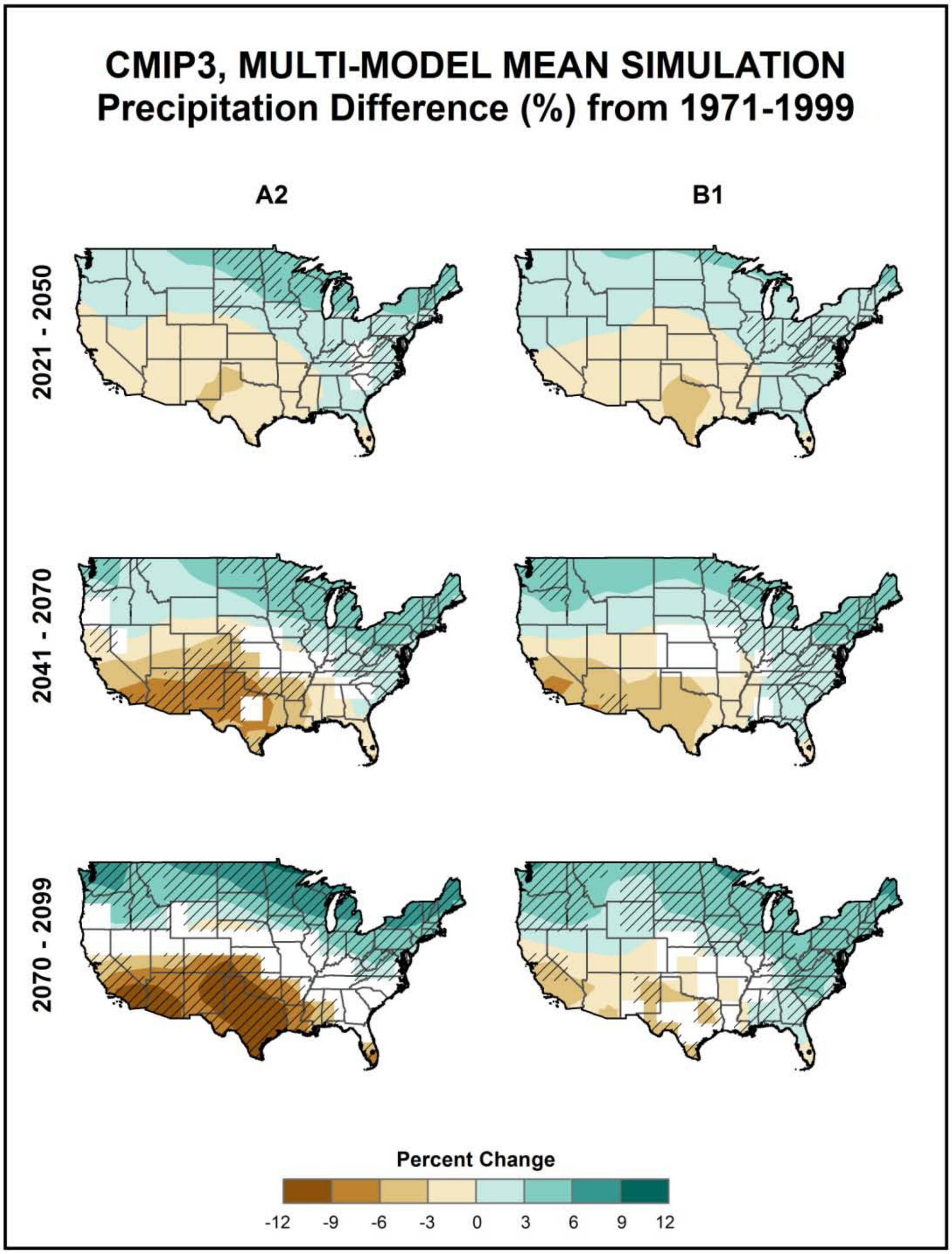

Figure 8. Simulated difference in annual mean precipitation (%) for the contiguous United States, for three future time periods (2021-2050, 2041-2070, and 2070-2099) with respect to a reference period of 1971-1999. These are multi-model means for the high (A2) and low (B1) emissions scenarios from 14 (B1) or 15 (A2) CMIP3 global climate simulations. Color only (category 1) indicates that less than 50% of the models show a statistically significant change in precipitation. Color with hatching (category 3) indicates that more than 50% of the models show a statistically significant change in precipitation, and more than 67% agree on the sign of the change. Whited out areas (category 2) indicate that more than 50% of the models show a statistically significant change in precipitation, but less than 67% agree on the sign of the change. Generally, the models simulate increases in the north and decreases in the south of the U.S.

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