P2.16 IMPACT OF ENSO ON SNOWPACK OVER THE WESTERN UNITED STATES: A GCM STUDY

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1. Introduction

Many researchers (Cayan 1996; Clark et al. 2001; among others) have indicated that snowpack is a major water resource in the western United States (U.S.). In this region, 50% - 70% of the annual precipitation falls as snow in mountainous areas (Serreze el at. 1999) and 75% - 85% of the annual discharge is derived from the snowpack (Grant and Kahan 1974; Palmer 1988). Thus, an accurate forecast of snow amount is essential to managing the water supply in the western U.S. There has been some recent research reported to understand the mechanisms of snow variability in the western U.S. Cayan (1996) found that snowpack anomalies in this region has a teleconnection with the winter Southern Oscillation Index (SOI), a measure of the El Niño-Southern Oscillation (ENSO). Clark et al. (2001) indicated that ENSO cycles could be used as a factor to predict snowpack evolution in the Columbia and Colorado River basins. McCabe and Dettinger (2002) showed that April 1 snow water equivalent (SWE) over the western U.S is associated with the ENSO-induced anomalous atmospheric pattern in the middle latitudes, and Lau and Nath (2001) pointed out that the tropical Pacific SSTs strongly affect the middle latitude atmospheric circulations. These studies provide us with evidence that ENSO episodes play an important role in producing anomalous middle latitude atmospheric circulation patterns during winter and spring, changing the atmospheric moisture advection and affecting winter and spring snowfall, and thus, leading to snowpack variations in the western U.S. The objectives of our study are to clarify these processes through quality reanalysis and observed datasets and to evaluate a realistic GCM's predictability for these phenomena.. Little work on this aspect is in current literature and this information is crucial to climate and water resource forecast advancements .*

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2. Model and data

The GCM used in this study is the Community Climate Model version 3 (CCM3) developed by the National Center for Atmospheric Research (NCAR) (Kiehl et al. 1996) It has 18 vertical atmospheric levels extending from the surface boundary layer to the 2.9 mb level, and a horizontal grid of approximately 2.8^o X 2.8^o. The original land surface model (Bonan 1996) in the CCM3 has been replaced by a Snow-Atmosphere-Soil Transfer (SAST) model (Jin et al. 1999) in which the sophisticated physical processes of snow and soil are addressed through three snow layers and ten soil layers based on energy and mass balance equations. The vegetation mode of the land surface is taken from the Biosphere-Atmosphere Transfer Scheme version 1e (BATS 1e) (Dickinson et al. 1993).

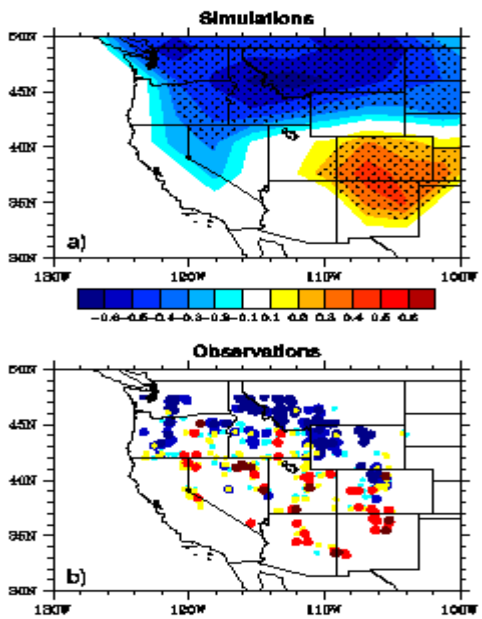
A 45.5-year simulation from December 1949 to May 1995 was generated from the CCM3 driven by observed global SST data with year-to-year variations. 500 mb wind field reanalysis data from the National Centers for Environmental Prediction (NCEP) were used to evaluate the corresponding model output. The observed SWE depths for the first days of January, February, March, and April were collected from more than 300 snowcourse locations in the western United States (Clark et al. 2001). Precipitation and surface air temperature observations with a gridded 5^o X 5^o horizontal resolution (Hulme et al. 1998; Jones 1994) were obtained from the Climate Research Unit (CRU), University of East Anglia, United Kingdom.

3 Results

3.1 Relationship between SWEs in the western U.S. and tropical Pacific SSTs

Figure 1 illustrates the correlations between observed Nino-3.4 SSTs averaged over 120°W-170°W and 5°S-5°N (Trenberth 1997), and SWEs from model output and observations during winter and early spring (averaged over January, February, and March) for a period of 45 years (1950-1994). The results indicate that the simulations have negative values in the northwestern U.S. (Figure 1a), which are consistent with the observations

(Figure 1b). In contrast, in the southwestern U.S., most snow course stations give positive values except that the correlations in Colorado vary from negative to positive values southwardly, which was also described by Clark et al. 2001. For the model output, the positive correlations cover all of Colorado and most of New Mexico mountainous regions, while the correlations were not calculated in west Utah and Arizona because no snow was present at the surface due to warm biases in the model. Generally, the patterns for both simulations and observations are quite similar in the western U.S. In order to understand the mechanisms of SWE variability in the western U.S., the observed and simulated SWE anomalies in the area (44^{o}N-50^{o}N and 102^{o}W-122^{o}W) over the northwest where both observations and simulations have negative



correlations were averaged to generate two 45-year

Figure 1 Correlation coefficients between Niño-3.4 SST and (a) SWEs from CCM3 output and (b) observed snowcourse data in western U.S. Values in stippled areas pass the 95% significance Student's *t* test.

time series. In terms of these two time series, the Niño 3.4 SST anomalies were averaged over the years when both observed and simulated SWEs had positive anomalies with above 95% confidence, and also over the years when SWEs had negative anomalies that passed the same confidence level. This method was also applied to the area (33^{o}N-39^{o}N and 102^{o}W-110^{o}W) in the southwest. The results are presented in Table 1, showing that the high and low northwest and high southwest SWEs were significantly connected with the variations of the tropical Pacific SSTs , but the corresponding

Table 1. Snow variations in the western U.S. and the corresponding tropical Pacific SST anomalies.

Region	Snow Anomalies	Sample Number (Years)	Niño-3.4 SST Anomalies (^{o} C)
Northwest	Above Normal	11	-0.38 (La Niña)
	Below Normal	15	0.45 (El Niño)
Southwest	Above Normal	12	0.61 (El Niño)
	Below Normal	15	*-0.21*

SST anomaly for the low southwest SWEs did not pass the 90% significance test.

3.2 The impact of tropical Pacific SSTs on the SWEs in the western U.S.

Figure 2a gives the observed SST anomalous pattern averaged over the period when the above normal SWEs occurred in the northwestern U.S., which is similar to the SST geographic distribution of La Niña events. This pattern drove the atmosphere and produced an anomalous 500 mb wind field from the NCEP reanalysis data, indicating that an anticyclone and a cyclone of the anomalies were located in the North Pacific south of the Aleutian Islands and in the middle of Canada, respectively. This pattern brought the moist air from the North Pacific to the northwestern U.S. (Figure 2b), increased observed precipitation during the winter and early spring (Figure 2d), and therefore, led to the positive SWE anomalies in the region. For the equivalent periods, the observed La Niña-like SST pattern forced the CCM3 to produce an anomalous 500 mb wind field, which drifted from the corresponding positions in the NCEP reanalysis data (Figure 2b). The biased wind field produced strong cold northerlies in the northwest (Figure 2c) and decreased the surface air temperature (Figure 2e). The colder temperature amplified the fraction of snowfall in the precipitation, slowed snowmelt processes, and thus, deepened the snowpack in the northwestern U.S. during snow seasons. Although the simulated above-normal SWEs based on the La Niña-like SST pattern were consistent with the observations in the northwest, the reasons were different due to the climate drift in the model, which possibly was caused by unrealistic heat flux exchanges between the surface and the atmosphere. The processes for lower

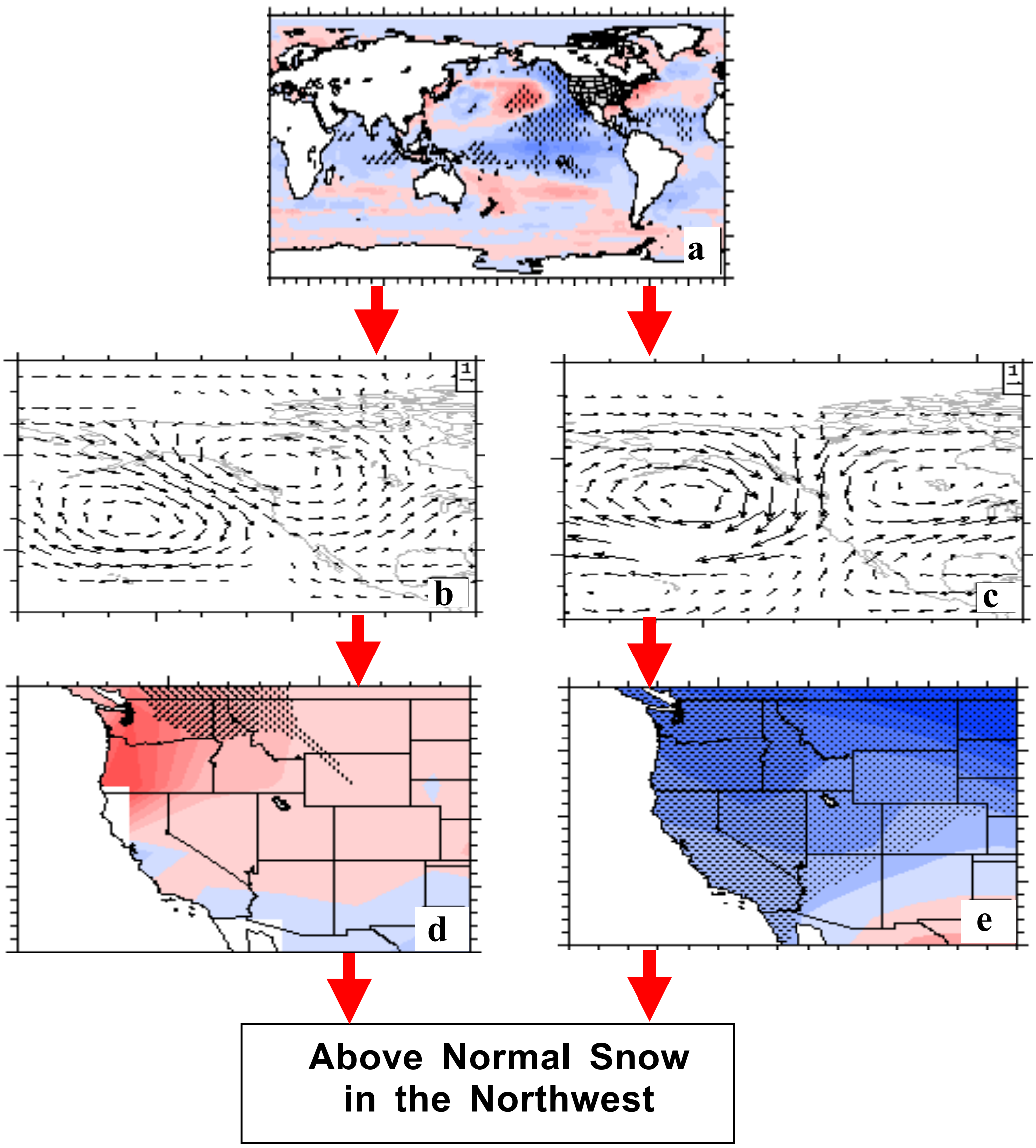


Figure 2 Anomalous fields during thicker snow period in the northwestern U.S.: a) Observed SST, b) NCEP reanalysis and c) CCM3 simulated 500 mb wind fields, d) observed precipitation, and e) simulated surface air temperature. Stippled areas pass the 90% significance Student's *t* test.

SWEs in the northwest are analogous, but opposite to the above case (Figure not shown).

Figure 3a illustrates the observed SST anomalous pattern that connected with the thicker snowpack in the southwestern U.S., which resembles El Niño SST anomalies. The El Niño-like SST pattern drove the atmosphere to generate an anomalous 500 mb wind field with a northwest-to-southwest structure of an anomalous cyclone in the North Pacific (Figure 3b). This cyclone protruded into the southwestern U.S., attracted moist air from the Mexican Gulf to the region. Thus, the precipitation was exaggerated (Figure 3d), which intensified snow accumulations in winter and early spring. The model accurately simulated these processes (Figure 3c and 3d).

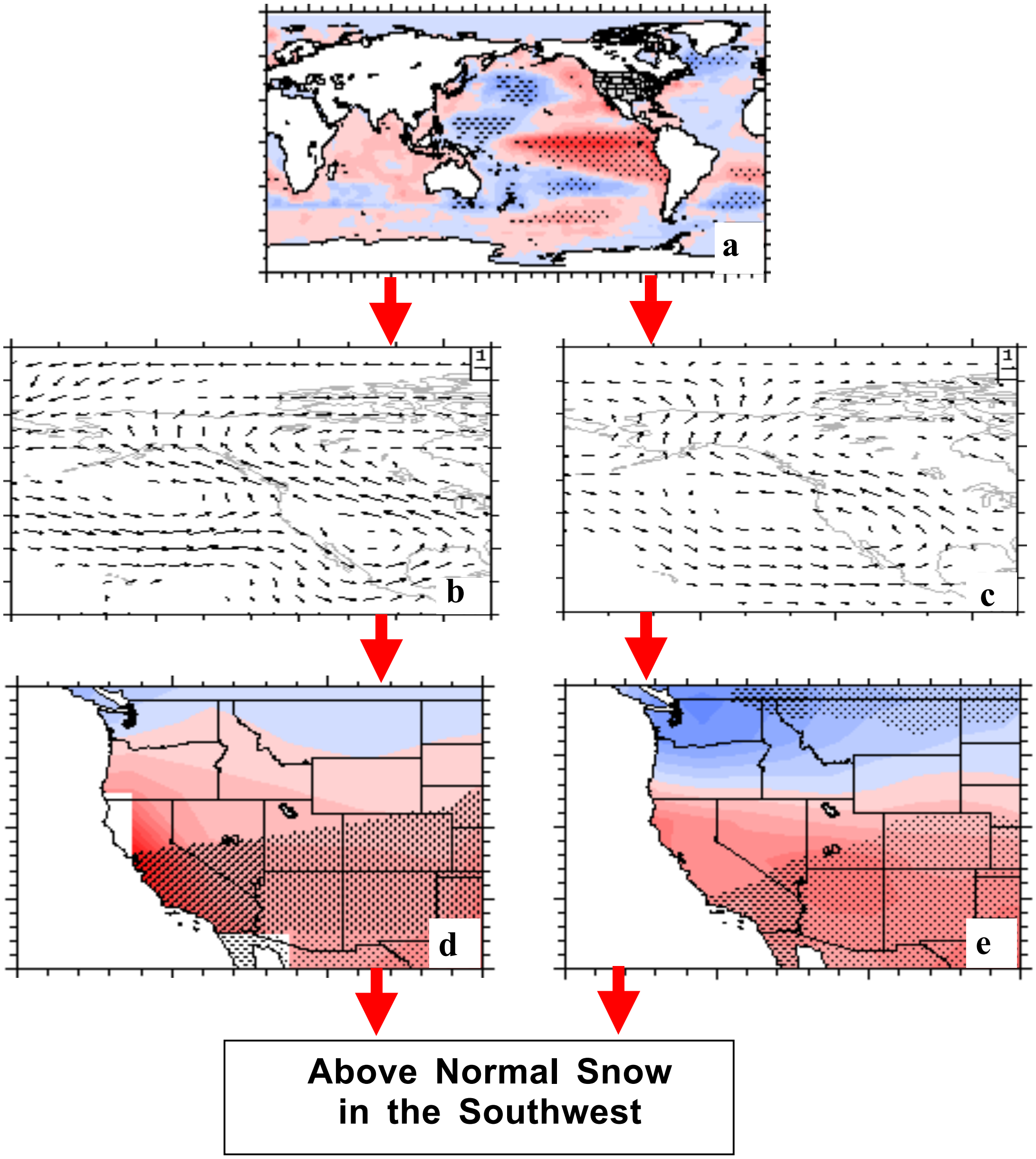


Figure 3 Anomalous fields during thicker snow period in the southwestern U.S.: a) Observed SST, b) NCEP reanalysis and c) CCM3 simulated 500 mb wind fields, d) observed precipitation, and e) simulated surface air temperature. Stippled areas pass the 90% significance Student's *t* test.

As aforementioned, the tropical Pacific SST stayed close to a normal condition during the thinner snowpack periods in the southwest. On average in these periods, the 500 mb wind field had an anomalous anticyclone located in the southwest according to both reanalysis data and simulations (Figure 4b and 4c), which led to a decrease in precipitation (Figure 4d and 4e) and thus, shallow snowpack in the southwest. The reasons for the anticyclone formation were investigated through analyses of the precipitation anomaly time series. Figure 5 shows the comparison of areally averaged precipitation anomalies over the southwest from CCM3 output, CRU observations, and NCEP reanalysis data during the lower snowpack periods. The three datasets commonly produced the peak values of the precipitation anomalies in September before snow seasons began. The exaggerated

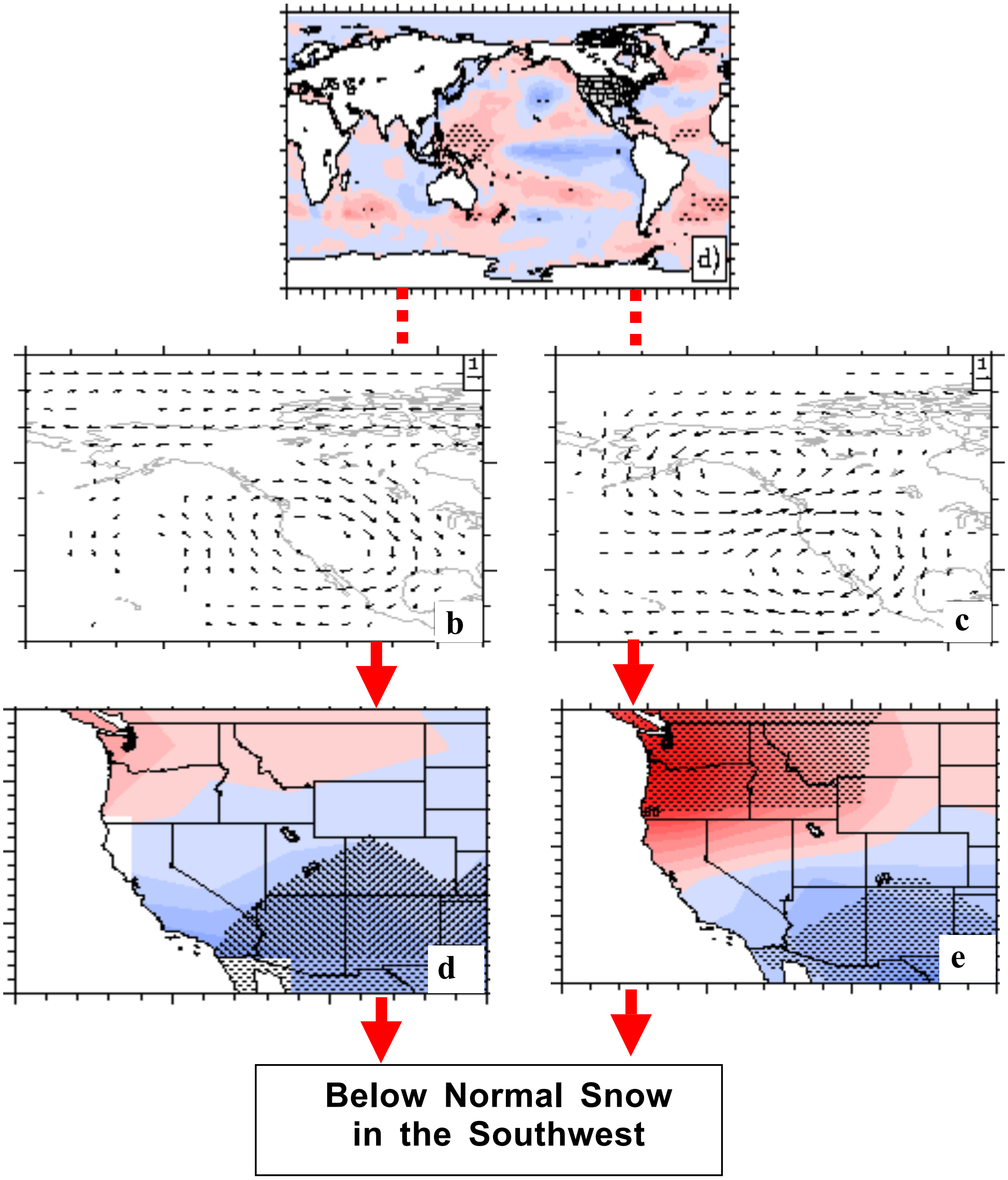


Figure 4 Anomalous fields during thinner snow period in the southwestern U.S.: a) Observed SST, b) NCEP reanalysis and c) CCM3 simulated 500 mb wind fields, d) observed precipitation, and e) simulated surface air temperature. Stippled areas pass the 90% significance Student's *t* test.

precipitation released extra latent energy heating up the atmosphere to help forming an anticyclone. This anticyclone was maintained throughout the winter, and weakened the precipitation in the southwestern U.S. without further disturbances from other sources.

4.Conclusions

Although the resulting snow cover patterns are similar for both simulations and observations over the northwestern U.S., the reasons are different. The observed anomalous snow patterns were caused by the winter precipitation variability that is associated with the ENSO, whereas the simulated snow patterns resulted from the temperature variations due to the climate drift in the model. The simulated positive snowpack anomalies over the southwestern U.S. that resulted from the stronger precipitation were associated with the warm phase of the ENSO, which was consistent with the observed processes. However, the

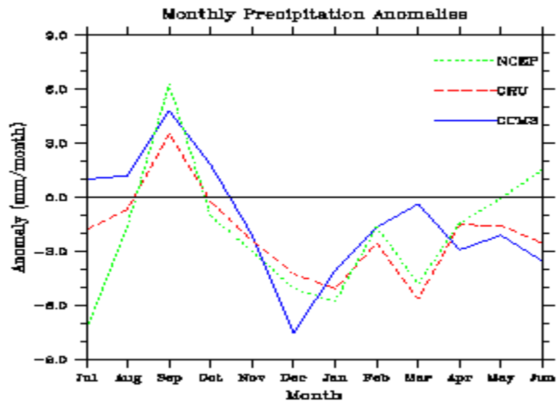


Figure 5. Comparison of precipitation anomalies from CCM3 output, observations from Climate Research Unit (CRU), United Kingdom, and NCEP reanalysis data.

negative snowpack anomalies in the southwest for both simulations and observations were attributed to a local anomalous anticyclone caused by latent heat released by the exaggerated local precipitation in fall, and appear to have no connections with tropical Pacific SSTs. The above discussions for the connections between the ENSO cycles and the snow anomalies in the western U.S. will greatly benefit the future climate model development and forecast.

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