Effects of the El Nino/Southern Oscillation (ENSO) on Precipitation, Temperature, and Snow Distribution in the Upper Rio Grande River Basin

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ABSTRACT

Snowmelt dominates streamflow in the Upper Rio Grande Basin in New Mexico and Colorado. The basin is strongly influenced by El Nino/Southern Oscillation (ENSO) through its effects on the both accumulation and melting of snow. While much work has related variations in streamflow to ENSO, relatively little work has been done relating the observed ENSO induced variations in precipitation and temperature to changing snowpack conditions. These relationships between differences in precipitation, temperature for different ENSO phases, El Nino, Neutral, and La Nina years and snow cover extent are investigated, using snowpack telemetry (SNOTEL), meteorological data, and snow covered area (SCA).

Key words: ENSO, SNOTEL, Rio Grande, Snowmelt, SCA.

INTRODUCTION

Water resource allocation and management is a growing concern for the southwestern United States. As the region's population continues to expand, water resources will remain a major concern into the foreseeable future and may be a limiting factor in the region's future growth. Possible responses to this situation include reducing demand and increasing supply, but also more efficient water resource management, based on the forecasts of water supply. In the Upper Rio Grande River in Colorado and New Mexico (Figure 1), snowmelt runoff is the primary source of surface water, which allows the prediction of the annual supply by estimation of spring snowpack. From this perspective, the recognition of the effects of the El Nino/Southern Oscillation (ENSO) phenomenon on western US climate and hydrology, especially precipitation, temperature, snowpack, and finally resulting streamflow (Brown, 1998; Cayan, 1996; Cayan and Webb, 1992; Groisman and Easterling, 1994; Kahya and Dracup, 1993;Dracup and Kahya, 1994; Cayan et al., 1999; Woolhiser et al., 1993; Clark et al., 2001; Redmond and Koch, 1991; Ropelewski and Halpert, 1986, 1989) is particularly beneficial for water resource management, because it offers the possibility of predicting the spring snowpack, and thus increasing the lead time of forecasts of streamflow that water managers can use. During the El Nino phase, there is more precipitation, more streamflow, and lower temperature in the Southwest. During La Nina phase, precipitation is lower, temperatures are higher and streamflow is reduced. Redmond and Koch (1991) used the correlation to characterize the climate and streamflow response to ENSO and Pacific North

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America (PNA) pattern in the western United States, and Ropelewski and Halpert (1986, 1989), Kahya and Dracup (1993) and Dracup and Kahya (1994) detected consistent response regions in the United States in terms of precipitation, temperature, and streamflow for El Nino and La Nina periods through harmonic and composite analysis. More recent papers investigated how the daily precipitation and streamflow frequency and amount is affected by ENSO phases (Woolhiser et al., 1993; Gershunov, 1998; Gershunov and Barnett, 1998; Cayan et al., 1999). Cayan et al. (1999) investigated the differences of the amount and frequency in streamflow along with precipitation in the western United States between the two ENSO phases and found a higher than average frequency of occurrence in high precipitation and streamflow in the Southwest during El Nino years, and the opposite during La Nina years. Cayan (1996) described the relationship between precipitation, temperature and April 1 snow water equivalent (SWE) in the five regions encompassing the western United States. He also mentioned the anomalous relationship of SWE with three large atmospheric circulations, the Central North Pacific (CNP) sea level pressure index, PNA, and ENSO. Brown (1998) demonstrated differences in snow conditions during El Nino and La Nina periods using satellite and climate station data throughout the United States. Clark et al. (2001) compared SWE between two representative basins, the Columbia River system, which represents the Pacific Northwest, and the Colorado River system, which represents the Southwest. Serreze et al. (1999) examined regional differences between temperature, precipitation, and SWE in snow pack telemetry (SNOTEL) station in the seven different regions of western United States. Serreze et al. (2001) also attributed large positive annual snowfall anomalies in the western United States not only to an increased number of snowy days, but also larger snow events.

This previous research has demonstrated the response of snow and subsequent streamflow response to climatic variability over relatively large spatial scales, such as the western United States, continental United States, or globally. While helpful in understanding the general climatic responses in large areas, it is of limited practicality in water resource management because the characteristic response of specific hydrologically important areas within the regions may differ from the regional response to ENSO events. This study investigates how large scale atmospheric circulation affects the monthly precipitation, temperature and finally snow distribution in the Upper Rio Grande Valley. Because snow accumulation is largely controlled by temperature and precipitation, both of which depend on elevation, combining National Climatic Data Center (NCDC) stations, which are located in lower altitudes with SNOTEL sites, located at higher altitudes, gives the bulk of the important information regarding the variation of temperature and precipitation throughout the basin during El Nino, Neutral, and La Nina episodes. This paper also investigates how differences in monthly precipitation and temperature affect the snow distributions, which is directly related to the amount of streamflow during El Nino, Neutral and La Nina years. It is hoped that by better understanding these relationships, streamflow prediction in the Upper Rio Grande can be improved.

METHODS

ENSO designation criteria

The ENSO status (El Nino, La Nina and Neutral) of the water years (WY) 1952-1999 were first designated by three methods using the Climate Prediction Center (CPC) Southern Oscillation Index (SOI) and the Troup SOI. In the first method, when the 5-month running mean of the CPC SOI is in the lower (upper) 25% of its distribution for five consecutive months in a calendar year (CY), then the following WY is designated as an El Nino (La Nina) year (Ropelewski and Jones, 1987; Dracup and Kahya, 1994). One problem with this method is that the designation may change through time as additional years are added. The second method uses Troup SOI. When average SOI values of April of previous WY to March of present WY are below –5, the year is an El Nino year and when those average SOI values are above 5, the year is a La Nina year (Chiew et al., 1998). The final method follows the criteria used in Redmond and Koch (1991), Cayan et al. (1999): when the average CPC SOI of June to November of the previous CY is -0.5 or less, the present WY is designated as El Nino, while if its averages are above +0.5, then the WY is designated as La Nina. The reason that June to November SOI values are selected is that it is generally believed SOI values for these months have the strongest correlation with October to March climate data in the western United States among leading 6-month average SOI values. For all three methods, years not designated as El Nino or La Nina are designated as Neutral. Finally, if at least one of the three criteria designated a year as either El Nino or La Nina it was considered as such in this paper. Using this approach, the selected El Nino, Neutral, and La Nina water years from 1981 to 1999 are shown in Table 1.

Table 1. Designated ENSO states (WY 1981-1999)

Year	1981	1982	1983	1984	1985	1986	1987
ENSO status	Neutral	Neutral	El Nino	Neutral	Neutral	Neutral	El Nino
Year	1988	1989	1990	1991	1992	1993	1994
ENSO status	El Nino	La Nina	Neutral	Neutral	El Nino	El Nino	El Nino
Year	1995	1996	1997	1998	1999		
ENSO status	El Nino	Neutral	La Nina	El Nino	La Nina		

One particularly interesting phenomenon during this period is that El Nino episodes happened for 4 consecutive years, 1992-1995. These anomalous consecutive El Nino years have been investigated using statistical methods (Trenberth and Hoar, 1996; Rajagopalan et al., 1997).

Climate Data

Figure 1 shows the locations of all the NCDC and SNOTEL stations providing temperature and precipitation information used in this paper. All NCDC stations are located at altitudes between 1730 and 2475m, while SNOTEL sites are located at higher elevation in the basin, between 2550 and 3550m. Therefore, data from the two types of station show different portions of the climatic variables which affect snowfall and streamflow (Changnon et al., 1991).

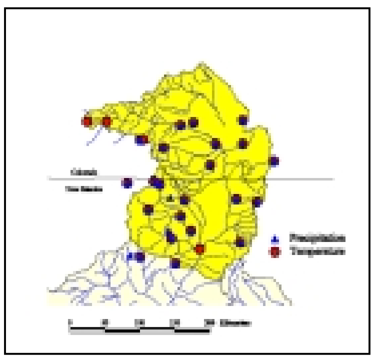

Figure 1. Locations of all the NCDC and SNOTEL stations.

The average daily temperature at the SNOTEL sites (ftp://ftp.wcc.nrcs.usda.gov/data/snow/) and the monthly NCDC temperature (http://www.ncdc.noaa.gov) were used to calculate monthly temperature. In the case of SNOTEL stations, monthly average values were calculated from daily averages for the period 1990 to 1999, and for NCDC stations, the monthly values for the period 1981 to 1999 were used. There are many missing data in the SNOTEL daily temperature data for the period 1990 to 1999. In order replace missing data values and extend the SNOTEL daily data back to 1981, a linear regression method was used. The daily data of a station having the most complete data set in each year were considered as the independent variable and the daily data of stations having missing data set were considered as the dependent variable. Then the linear regression equations between these two data sets were calculated and used to replace the missing data values. Figure 2 shows one typical example of linear regression between two SNOTEL stations. These linear regression equations were used because temperature linearly decreases with elevation in mountainous regions. This same technique was used for extending the shorter period of temperature data in the SNOTEL stations. We again calculated the linear regression equations between NCDC and SNOTEL stations from 1990 to 1999. These equations were then used to extend monthly temperature data of SNOTEL stations from 1981 to 1989, using original monthly temperature data of NCDC stations as the independent variable. Figure 3 shows one typical example of linear regression for monthly temperature between one NCDC station and one SNOTEL station from 1990 to 1999. Temperatures were obtained in these ways for 13 NCDC stations and 14 SNOTEL sites.

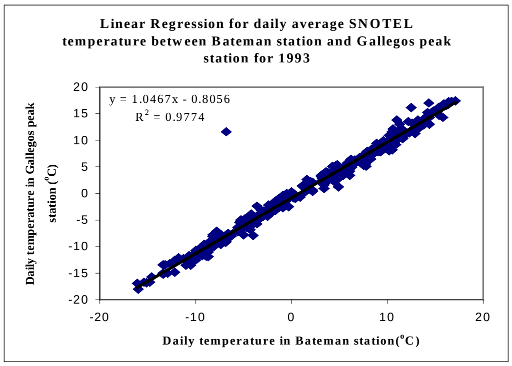

Figure 2. Typical example of linear regression between two SNOTEL stations. There were 16 missing data at Gallegos Peak station and no missing data at Bateman station

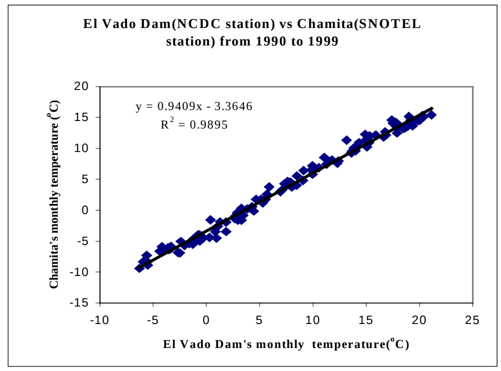

Figure 3. Typical example of linear regression from 1990-1999 between one from NCDC stations (x-axis) and one from SNOTEL stations (y-axis)

To calculate the positive degree-days in the NCDC and SNOTEL stations, the maximum, minimum, and average temperatures of NCDC and SNOTEL stations were used. SNOTEL stations offered maximum, minimum and average daily temperatures. However, NCDC stations just offered the maximum and minimum daily temperatures. So, the average daily temperatures of NCDC stations were calculated as the average of maximum and minimum temperatures. In computing degree-days, it was assumed that maximum and minimum temperatures last for 6 hours in a day and the average temperature lasts for 12 hours in a day (Pick, 1994).

Monthly precipitation totals were also calculated. For the SNOTEL sites, total monthly precipitation was determined by subtracting the last value of the previous month from the last of each month because they accumulative precipitation data. NCDC monthly totals were calculated from the daily values. If 10 or more days were lacking data in a month, monthly precipitation data were not calculated. Precipitation totals were obtained from 15 NCDC and 11 SNOTEL sites. The stations used for temperature and precipitation are different because some stations have good quality and length of temperature data, but not precipitation data or vice versa. In the case of the missing monthly precipitation data, which cannot be constructed using linear regression equation, the normal ratio method was used in which the missing data are calculated using the neighboring station values (Gupta, 1995).

Initial estimates of snow-covered area (SCA) in the region were made from the Northern Hemisphere EASE-Grid Snow-cover available from the National Snow and Ice Data Center. These weekly products were constructed from NOAA-NESDIS Weekly Northern Hemisphere Snow Charts from which the period of October 1971 through September 1995 was used. Snow-cover values are provided on an equal area grid with 25 km resolution. To calculate the monthly average SCA, we first determined which pixels cover our area of interest. Based on the grid values of those pixels, we calculated the area in which was covered in snow each week. Then, the monthly mean SCA in our area of interest was calculated using these weekly values.

RESULTS

Student t-test and cumulative positive degree-days for temperature

To test whether average monthly temperatures between El Nino vs. Neutral and La Nina vs. Neutral are significantly different or not, a Student t-test was used (Harnett, 1975) under the assumption that the two populations have different variances. Figure 4 shows the monthly temperatures during El Nino, Neutral, and La Nina years from November to April, and Table 2 shows the results of Student t-test using the yearly and monthly mean values during El Nino, Neutral, and La Nina in the period 1981-1999. Two-hundred and sixteen data points for El Nino and Neutral years, and eighty one data points for La Nina years were used. Four significantly higher temperature differences during La Nina periods and two significantly lower temperature differences during El Nino periods from October to April were detected. One interesting observation is that there are almost no temperature differences from April to August between El Nino, Neutral, and La Nina years. This phenomenon is also interesting in another aspect because when we think of the differences of temperatures during El Nino, Neutral, and La Nina years, the temperatures during El Nino years are generally believed to be lower compared with those of Neutral years and those of La Nina years higher than those of Neutral years. But, these patterns are only applicable to first half of the water years, not the entire year, at least in our area of interest. Finally, there were no differences in the slopes of linear regressions of temperature with elevation (not shown) in El Nino, Neutral, and La Nina years, which indicates that there was no difference in the environmental lapse rates between El Nino, Neutral, and La Nina years.

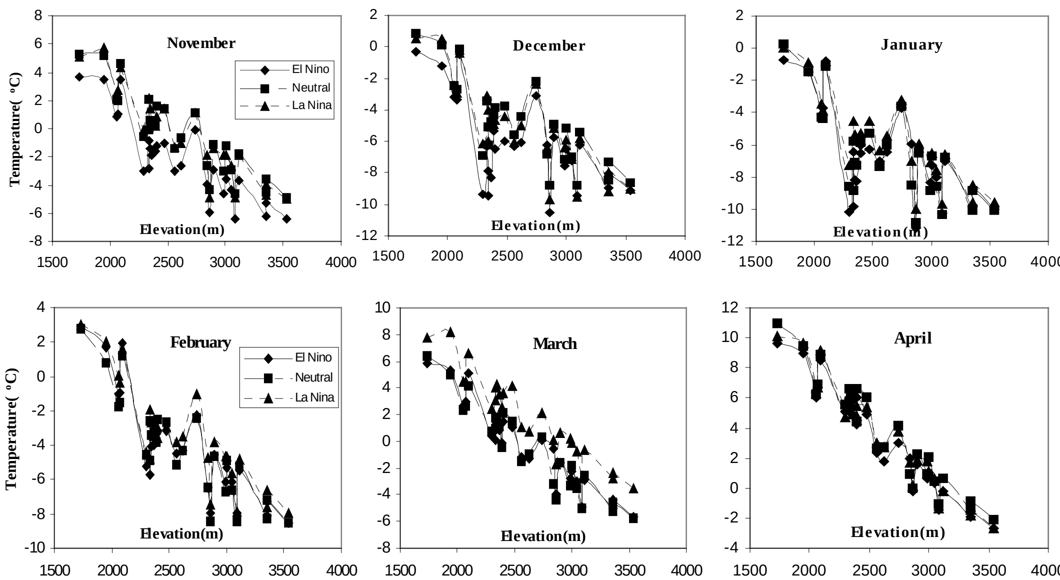

Figure 4. Comparions of composite monthly temperatures during El Nino, Neutral, and la Nina years using NCDC and SNOTEL stations from November to April for the period WY 1981-1999.

Table 2. Statistics of Student t-test to check whether monthly average temperature, when El Nino and Neutral or La Nina and Neutral, have significantly different means, compared with Neutral at 90% confidence level.

	t-statistics				Average Temperature (°C)		
	El Nino		**La Nina**		**El Nino**	**Neutral**	**La Nina**
October	0.2349	-	0.0351	High	5.25	4.83	5.76
November	1.75E-09	Low	0.9091	-	-2.24	-0.40	-0.35
December	2.75E-05	Low	0.5828	-	-6.25	-4.93	-5.15
January	0.5091	-	0.0965	High	-6.77	-6.62	-5.84
February	0.7143	-	0.0974	High	-4.13	-4.21	-3.48
March	0.9855	-	1.94E-07	High	-0.41	-0.49	1.82
April	0.1045	-	0.6468	-	3.20	3.73	3.49
May	0.0898	Low	0.8361	-	7.83	8.36	8.46
June	0.4816	-	0.5762	-	12.80	12.91	12.64
July	0.8194	-	0.4779	-	15.29	15.13	15.49
August	0.3647	-	0.8572	-	14.78	14.37	14.28
September	0.0734	High	0.0456	High	11.13	10.44	11.42

Figure 5 shows the cumulative positive degree-days for a NCDC and a SNOTEL station during El Nino, Neutral, and La Nina years. Comparing El Nino, La Nina with Neutral years, the effects of March's temperature during La Nina periods can be easily predicted. That is, there should be more snowmelt in the Upper Rio Grande during March of La Nina years. In the case of El Nino, the differences usually last from mid-November to late-December. However, when the fact that all the stations have below freezing temperatures and that during such periods, snow accumulation is a more significant phenomenon than snowmelt is considered, the relative effects of lower temperature during El Nino years on snow formation do not seem to be significant.

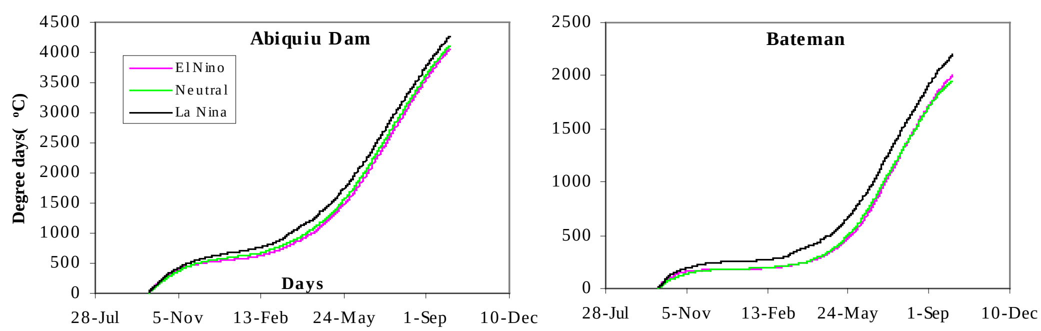

Figure 5. Cumulative positive degree-days for 1 NCDC station and 1 SNOTEL station using Maximum, Minimum, and average temperatures during El Nino, Neutral, and La Nina years

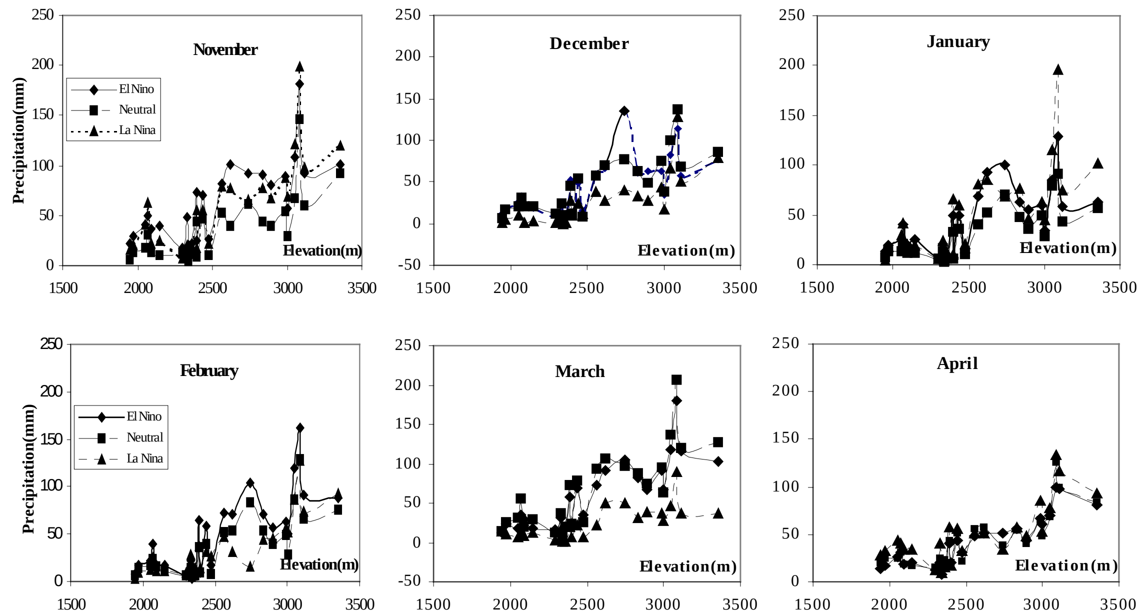

Figure 6. Comparisons of composite monthly precipitation during El Nino, Neutral, and La Nina years using NCDC and SNOTEL stations from November to April for the period 1981-1999.

Student t-test for precipitation

Figure 6 illustrates the precipitation differences during El Nino, Neutral, and La Nina years from November to April. The Student t-test using monthly precipitation data and monthly mean values using 1981-1999 is shown in Table 3. During El Nino periods, there seems to be generally more precipitation from October to April, while either higher or lower precipitation can occur during La Nina years, compared with Neutral years. So, some opposing effects appear in this region during La Nina periods. Precipitation is much at SNOTEL sites compared to NCDC sites. These differences are caused by the differences in the precipitation measuring instruments between two stations in addition to elevation effects. Doeskin and Schaefer (1987) and Serreze et al. (1999) explain how these instruments differ.

Table 3. Statistics of Student t-test to test whether monthly average precipitation for El Nino and La Nina years have significantly different means compared with Neutral Years at 90% confidence level.

	t-statistics				Average Precipitation (mm)		
	El Nino		La Nina		El Nino	Neutral	La Nina
October	0.0126	low	0.1232	-	37.45	47.00	56.88
November	2.03E-08	high	0.0012	high	62.16	36.20	56.59
December	0.8928	-	0.0016	low	43.77	43.14	26.14
January	0.0022	high	0.0043	high	42.96	30.40	49.91
February	0.0046	high	0.9085	-	48.66	36.05	35.40
March	0.2621	-	1.64E-15	low	58.07	64.34	23.34
April	0.6036	-	0.3229	-	40.42	42.41	48.78
May	2.02E-06	high	0.0294	high	45.80	31.41	42.46
June	7.13E-05	low	0.0054	low	24.66	33.50	26.50
July	5.69E-10	low	0.8506	-	42.38	64.81	63.93
August	0.0020	high	0.1089	-	82.49	69.61	78.19
September	3.86E-11	low	0.0337	low	36.54	58.41	48.78

Discussion of Monthly Characteristics

Figure 7 shows differences of monthly snow covered area (SCA) using weekly data during El Nino, Neutral, and La Nina years from 1972 to 1995. This study period differs from the NCDC and SNOTEL climatologies. This is especially important in the case of La Nina, since only the La Nina 1989 is in common and two La Nina years, 1975 and 1976 are added and two La Nina years, 1997 and 1999 are lost. So, the assumption that ENSO phenomena have the same characteristics over these slightly different periods is regarded. The relationship among temperature, precipitation, and SCA will be investigated from November to April because usually snow formation begins in November and snow disappearance is complete by the end of April.

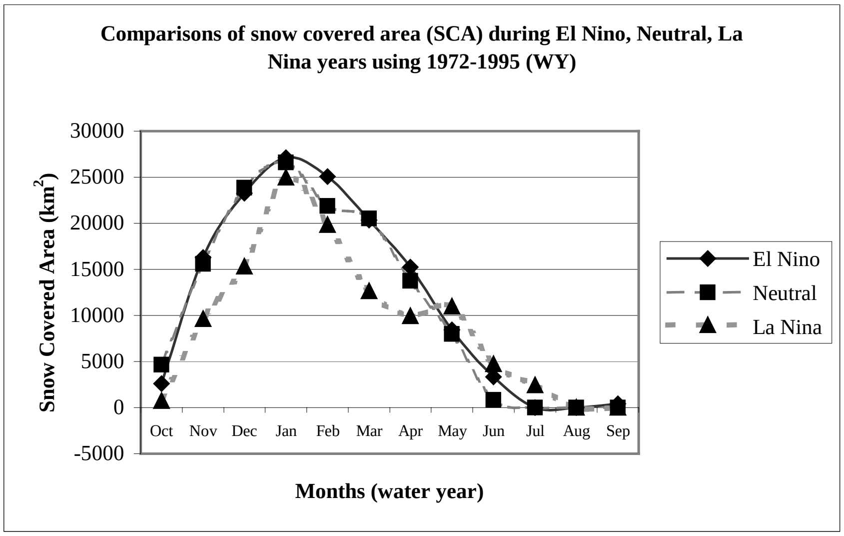

Figure 7. Comparisons of SCA during El Nino, Neutral, and La Nina year for the period 1972-1995.

November: The temperatures are significantly lower during El Nino years and precipitation is significantly higher during El Nino and La Nina years. So, comparing El Nino with La Nina years, the SCA seems to give consistent results. However, Neutral years are a little hard to explain. Maybe there is a different pattern between 1972-1995 and 1981-1999 in precipitation and temperature during November of Neutral years.

December: El Nino, Neutral, and La Nina years have all the average temperatures below freezing except at the lowest elevation stations. So, nearly all precipitation should fall as snow and little snow would melt. Therefore, effects of temperature on SCA would be small compared with the effects of precipitation. El Nino years have about the same amount of precipitation, and La Nina years have significantly lower precipitation compared to Neutral years. That apparently is the reason why La Nina phases have smaller SCA values compared with Neutral years and El Nino years almost the same snow covered area as Neutral years.

January: This month also has below freezing temperatures at almost all stations during El Nino, Neutral, and La Nina years. So, the effects of temperature on SCA would seem to be insignificant as in December. In the case of precipitation, El Nino, La Nina both have significantly more precipitation compared to Neutral years. Because La Nina years have much smaller snow covered area during the previous month, the effects in change of SCA are larger than during El Nino years. Also, the El Nino years have only a very minor increase compared to Neutral years.

February: During this month, some stations start to experience above freezing monthly temperature averages. So, temperature may have a greater effect compared with previous months, although the effects are probably not as significant as precipitation. So, El Nino years have higher SCA values compared with Neutral years, following precipitation, while La Nina years are a little lower than Neutral years, a result that would seem to be partially affected by temperature.

March: This is the month with the key differences in snow cover extent, since spring snowpack is traditionally measured as of April 1. Almost half of the stations have above freezing temperatures, and there are much higher temperatures during La Nina years. In the case of precipitation, La Nina years have much lower precipitation compared to Neutral years, while Neutral and El Nino years have similar temperature and precipitation. These factors appear to directly affect the SCA values. That is, SCA shows rapid decrease during La Nina years compared to Neutral years. This fact seems to imply important information for water resource managers regarding April 1 snowpack. They are relatively uninterested in how snowpack proceeds during winter period, but more interested in the snowpack in late March or early April (Cayan, et al., 1999). Moreover, Cayan (1996) showed that April 1 snowpack situation is largely controlled by March precipitation and temperature using multiple regression. In essence, during La Nina years the peak snow accumulation occurs earlier in the year, which should strongly affect the timing and amplitude of the annual hydrograh.

April: The precipitation and temperature of El Nino and La Nina periods in April do not show significant differences. Snow occupies almost the same area during El Nino and Neutral years, and a slight smaller area is occupied by snow during La Nina years. However, a smaller decrease in SCA is seen during La Nina years. This phenomenon is due to the fact that a large part of the snow already disappeared during March of La Nina periods. So, the extent of decrease is smaller than in El Nino and Neutral years.

CONCLUSION

Several interesting climatic responses to ENSO phases in our area of interest were found, although just seven El Nino and three La Nina episodes have been included in this paper. Data from NCDC stations and SNOTEL sites were examined in order to investigate the variations of temperature and precipitation over range of elevations in the Upper Rio Grande Basin during El Nino, Neutral, and La Nina years. When the rate of change in temperature and precipitation with respect to elevation are examined, there are no significant differences in relationship among El Nino, Neutral, and La Nina years. There were several exceptions regarding this phenomenon especially in precipitation. However, these exceptions seem to come from geographic characteristics such as aspect, vegetation cover or small scale climate control (Changnon et al., 1991), not large scale atmospheric circulation. When monthly temperature variations during ENSO episodes and Neutral years are compared, one interesting phenomenon is that the variation of temperature is only evident from September to March while other monthly values are almost the same during El Nino, Neutral, and La Nina years. Moreover, because major snow accumulation happens during those months, the effects of temperature on the variation of snow accumulation are quite important. There seemed to be more variations in precipitation during El Nino, Neutral, and La Nina periods compared with the variation of temperature among the stations. The temperature and precipitation during March of La Nina episodes is very interesting results. There were much higher temperature and much lower precipitation during March in La Nina episodes and this phenomenon strongly affected the SCA. When the degree-days are considered, the effects of March's temperature during La Nina episodes were easily seen in the several NCDC and SNOTEL stations, these effects were confirmed in the analysis of composite SCA data. Finally, it is generally believed that the relationship between precipitation and streamflow is nonlinear due to geographic characteristics in a specified area. And when we consider that the streamflow of our area of interest is largely controlled by snow accumulation, the investigation of snow distribution is crucial in order to predict with longer lead times the amount of streamflow in runoff periods following the snow accumulation season (Changnon et al., 1991). Moreover, monthly snow accumulation in a year depends on the monthly temperature and precipitation. So, this research will be helpful in those respects: to understand how different phases of ENSO affect the temperature and precipitation climatology, and thereby the snowpack accumulation and snowmelt and thus the streamflow.

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