Volume 18, Number 6 15 April 2004

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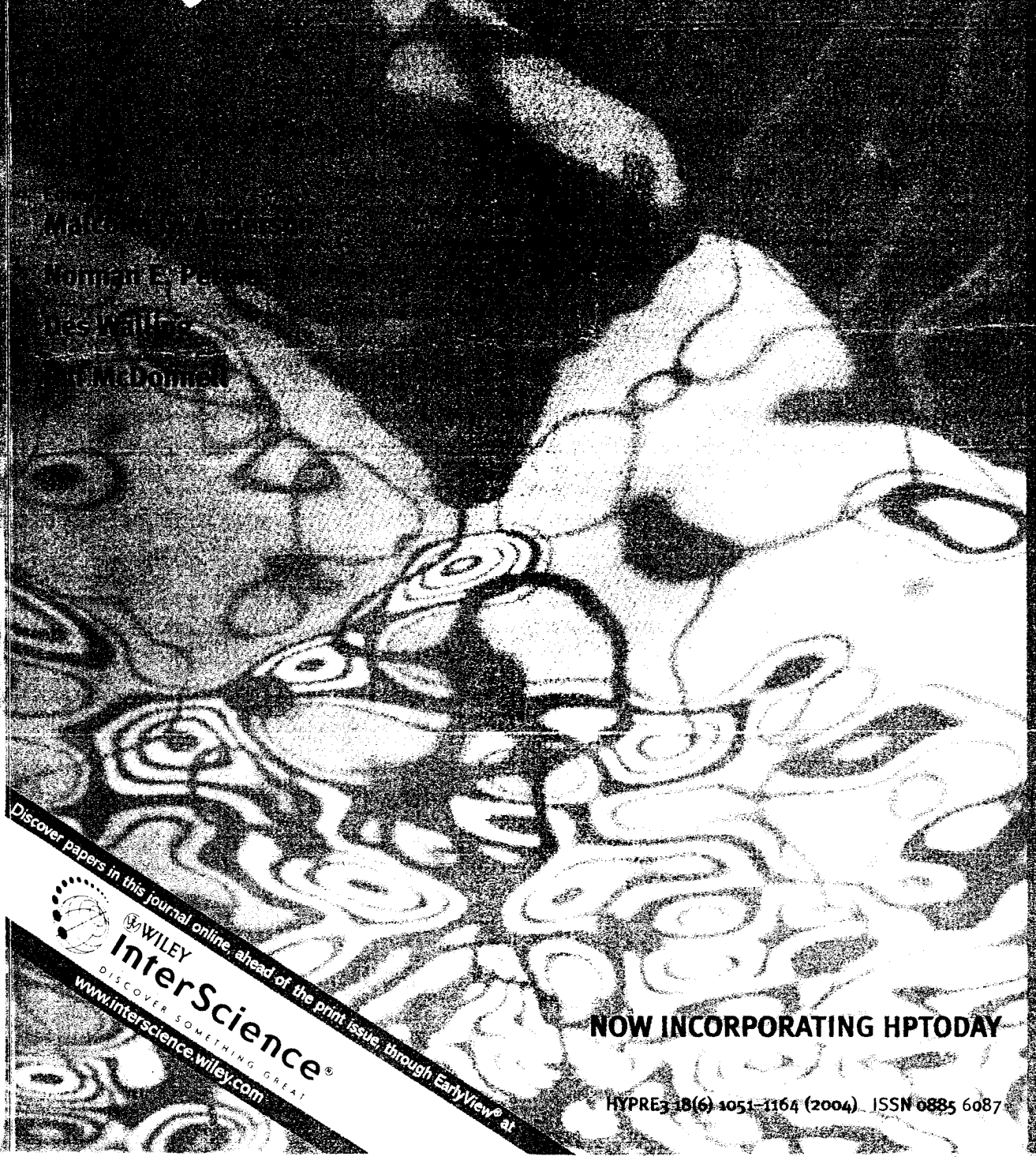

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HUPRE3 18(6) 1051–1164 (2004)
ISSN 0885-6087

HYDROLOGICAL PROCESSES

Subscriptions

Hydrological Processes (Print ISSN 0885-6087; Online ISSN 1099-1085 at Wiley InterScience, www.interscience.wiley.com) is published monthly except semi-monthly in February, April, June, August, October and December, total 18 issues, by John Wiley & Sons, Ltd., The Atrium, Southern Gate, Chichester, West Sussex PO19 8SQ, UK.

Subscription Rates

Volume 18 2004 18 issues

Online only US$2830.00
Print only US$2830.00
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Hydrological Processes is covered by the following abstracting and indexing services: BHRA Fluid Engineering Centre (Elsevier), Bibliography & Index of Geology (GeoRef), CAB Abstracts, Cambridge Scientific Abstracts, CompuMath Citation Index (ISI), Current Contents®/Agriculture, Biology & Environmental Sciences (ISI), EAUDOC, Ei COMPENDEX PLUS, Ei Page One, Energy Abstracts (EIC), Environment Abstracts (CIS), Fluidex (Elsevier), GeoArchive (Geosystems), Geobase (Elsevier), Geographical Abstracts: Physical Geography (Elsevier), GeoRef, GeoSEARCH (Geosystems), Geotitles: Geoarchaeology (Geosystems), Groundwater & Soil Contamination Database, Hydrotitles (Geosystems), INSPEC, International Civil Engineering Abstracts (Anbar), ISI Alerting Services, Science Citation Index® (ISI), Science Citation Index Expanded (also known as SciSearch®) (ISI), Science Citation Index® (ISI), Soil and Fertilizer Abstracts (CAB).

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Production Details

Printed on acid-free paper.
Typeset by Laser Words, Madras, India.
Printed and bound in Great Britain by Bell & Bain Ltd., Glasgow, UK.

Identification Statement

Hydrological Processes (ISSN 08856087) is published monthly, except semi monthly during February, April, June, August, October and December, total 18 issues by John Wiley & Sons, Ltd., The Atrium, Southern Gate, Chichester, West Sussex PO19 8SQ, UK. Periodicals postage paid at Jamaica NY. Air freight and mailing in the USA by Publications Expediting Inc., 200 Meacham Ave., Elmont, NY 11003, USA. USA POSTMASTER please send address changes to: *Hydrological Processes*, c/o Publications Expediting Inc., 200 Meacham Ave., Elmont, NY 11003, USA.

HYDROLOGICAL PROCESSES
Hydrol. Process. **18**, 1053–1071 (2004)
Published online in Wiley InterScience (www.interscience.wiley.com). DOI: 10.1002/hyp.5511

Effects of the El Niño–southern oscillation on temperature, precipitation, snow water equivalent and resulting streamflow in the Upper Rio Grande river basin

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Abstract:

Snowmelt runoff dominates streamflow in the Upper Rio Grande (URG) basin of New Mexico and Colorado. Annual variations in streamflow timing and volume at most stations in the region are strongly influenced by the El Niño–southern oscillation (ENSO) through its modulation of the seasonal cycles of temperature and precipitation, and hence on snow accumulation and melting. After removing long-term trends over the study period (water years 1952–99), the dependence of monthly temperature, precipitation, snow water equivalent (SWE) at snowcourse stations, and streamflow throughout the URG on ENSO was investigated using composite analyses of the detrended residuals and through dependence of the residuals on the Climate Prediction Center southern oscillation index during the preceding summer and fall. The climate of La Niña years was found to differ significantly from either El Niño or neutral years. Moreover, significant climatological ENSO-related effects are confined to certain months, predominantly at the beginning and end of the winter season. In particular, March of La Niña years is significantly warmer and drier than during either El Niño or neutral years, and November of El Niño years is significantly colder and wetter. Differences in temperature and precipitation lead to significant differences in SWE and streamflow in the URG between the three ENSO phases. Copyright © 2004 John Wiley & Sons, Ltd.

KEY WORDS ENSO; Upper Rio Grande; snowmelt; temperature; precipitation; snow water equivalent; streamflow.

INTRODUCTION

Water resource allocation and management is a growing concern for the southwestern USA. 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 include more efficient management of existing water resources based on forecasts of water supply. From this perspective, the recognition of the effects of the El Niño–southern oscillation (ENSO) phenomenon on western US climate and hydrology, especially precipitation, temperature, and resulting snowpack, is particularly beneficial for water resource management, because it offers the possibility of predicting the spring snowpack, and thus increasing the lead time of the streamflow forecasts used by water managers (Ropelewski and Halpert, 1986; Redmond and Koch, 1991; Cayan and Webb, 1992; Kahya and Dracup, 1993; Woolhiser *et al.*, 1993; Dracup and Kahya, 1994; Groisman and Easterling, 1994; Cayan, 1996; Brown, 1998; Cayan *et al.*, 1999; Clark *et al.*, 2001).

For the southwestern USA, it is generally observed that, during the negative phase of ENSO (El Niño), there is higher precipitation, higher streamflow, and lower temperatures, whereas during the positive ENSO phase

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Received 4 June 2003
Accepted 13 November 2003

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(La Niña) the precipitation is lower, streamflow is reduced, and temperatures are higher. Considerable research has examined the relationship between climate, snow conditions, and resulting streamflow with ENSO on a regional scale in the western USA. Redmond and Koch (1991) found negative correlations between average October–March monthly precipitation and June–November averaged southern oscillation index (SOI) and positive correlations over the same period between temperature and SOI in the desert southwest. Ropelewski and Halpert (1986, 1989), Kahya and Dracup (1993) and Dracup and Kahya (1994) detected consistent response regions in the USA in terms of precipitation, temperature, and streamflow for El Niño and La Niña periods through harmonic and composite analysis. More recent papers have investigated how daily precipitation, temperature, and streamflow frequency and volume are affected by ENSO phase (Woolhiser *et al.*, 1993; Gershunov, 1998; Gershunov and Barnett, 1998; Cayan *et al.*, 1999). For example, Cayan *et al.* (1999) found a higher than average frequency of occurrence of high precipitation and streamflow in the desert southwest during El Niño years, and the opposite during La Niña years. Cayan (1996) noted that there are more significant differences in 1 April snow water equivalent (SWE) between La Niña and neutral years than between El Niño and neutral years in five regions encompassing the western USA, especially in the Rocky Mountains. Brown (1998) also demonstrated the differences in snow conditions during El Niño and La Niña periods using satellite and climate station data throughout the USA. Clark *et al.* (2001) showed that differences in the seasonal changes and intensities of SWE response to each ENSO phase exist in several smaller regions of the desert southwest.

This previous research has demonstrated precipitation, temperature, snow and subsequent streamflow responses to climatic variability over relatively large spatial scales, such as the western USA. 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, or the response may even differ within the basin of interest. Accordingly, this paper investigates how the seasonal cycles of precipitation and temperature, and the resultant snowpack and streamflow in the Upper Rio Grande (URG) river basin, are modulated by variable sea-surface temperatures in the tropical Pacific Ocean (i.e. ENSO).

The URG (Figure 1) of southern Colorado and northern New Mexico, defined here as the area draining the Rio Grande at Espanola, NM (at the downstream end of HUC 130201), has an area of approximately 43 000 km^2, including a non-contributing area in the northeast, and elevations ranging from approximately 1600 to 4200 m, with highest elevations found in the northwest corner of the basin along the continental divide. Snow formation usually begins in late October, with the snowpack approaching its maximum near 1 April as measured by SWE values from snowcourse sites scattered across the basin and in more recent years also at snowpack telemetry (SNOTEL) sites.

Several factors led to the selection of this basin as the study area. The primary reason is that all reaches of the Rio Grande are heavily utilized as a water resource. The ground water resources in the Middle Rio Grande basin, which is just downstream and supplies water to the Albuquerque metropolitan area, have recently been determined to be significantly less than previously believed (Thorn *et al.*, 1993; Bartolino and Cole, 2002), putting further pressure on the surface water supply from the URG. In addition, as mentioned above, it is not clear that the results of the rather large-scale studies of the influence of ENSO on climate and streamflow can be successfully scaled down to this basin, especially because the URG lies near the northern limit of the southwestern USA region as defined in previous studies.

This study combines meteorological data from National Weather Service (NWS) stations, which are located at lower elevations (Table I), with SWE data from snowcourse sites, which are located at higher elevations (Table II). Meteorological observations are combined with streamflow data from US Geological Survey (USGS) streamgauging stations (Table III) having long records. Both stations on the Rio Grande River itself and in tributary basins with limited direct human influence are investigated. The locations of all observation sites are shown in Figure 1. Analysis begins in 1952, because prior to this date the temperature and precipitation time series at NWS stations are very incomplete.

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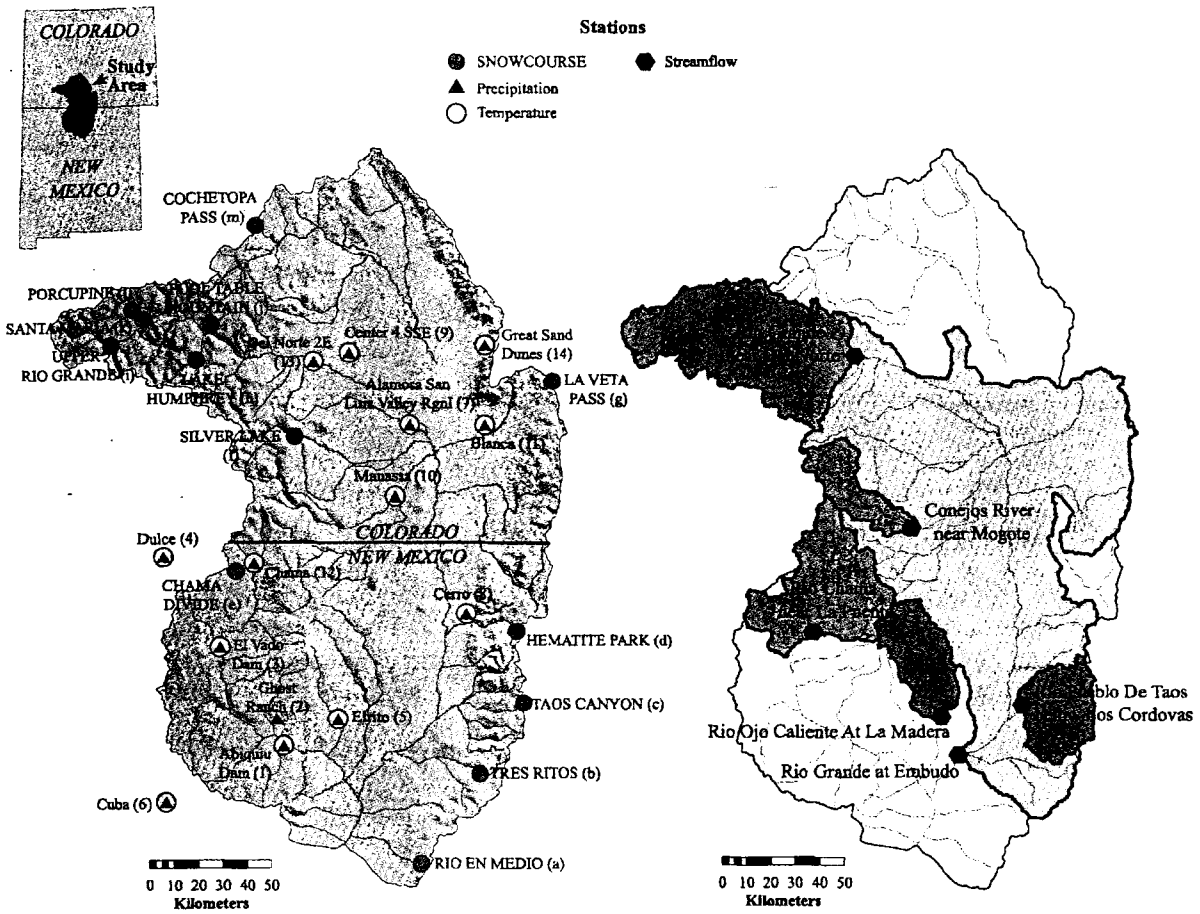

Figure 1. Maps of the Upper Rio Grande river basin showing the gauging sites used in this study: (a) NWS temperature and precipitation stations and snowcourse sites (left); (b) USGS streamflow gauging stations and their drainage basins (right)

Combining temperature and precipitation observations with long-term snowcourse measurements and streamflow enables investigation of how variations in ENSO are associated with differences in monthly precipitation and temperature, which in turn affect SWE and streamflow. It is hoped that, by understanding these relationships better, streamflow prediction in the URG can be improved. It is also hoped that a better understanding of these relationships can improve modelling of how the magnitude and timing of streamflow in the URG river basin may be altered by anthropogenic climate changes, such as global warming.

METHODS

ENSO designation criteria

Determination of ENSO phase has historically been accomplished using the SOI, which is based on deviations in the sea-level pressure differences between the island of Tahiti and Darwin, Australia. In this study, a water year (WY; October–September) in the period 1952–99 was assigned to one of three ENSO phases (El Niño, neutral and La Niña) by three different methods, which employ two different indices: the Climate Prediction Center (CPC) SOI and the Troup SOI for the period 1952–99 (WY). If at least one of the three methods designated a year as either El Niño or La Niña it was considered as such, otherwise it was

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Table I. Temperature and precipitation stations

Station		Elevation (m)	Mean Annual Temperature (°C)	Mean Annual Precipitation (mm)
Number	Name			
1	Abiquiu Dam	1945	10·28	251
2	Ghost Ranch	1969	—[a]	288
3	El Vado Dam	2054	7·05	372
4	Dulce	2071	6·88	450
5	El Rito	2094	9·34	314
6	Cuba	2147	7·79	336
7	Alamosa San Luis Valley Rgnl	2296	5·14	185
8	Cerro	2332	6·85	329
9	Center 4 SSW	2339	5·04	183
10	Manassa	2344	5·74	200
11	Blanca	2362	5·66	222
12	Chama	2393	5·57	545
13	Del Norte 2E	2399	6·22	262
14	Great Sand Dunes National Monument	2475	6·43	287

[a] Data not available.

Table II. Snowcourse sites

Site		Elevation (m)
Identify	Name	
a	Rio En Medio	3139
b	Tres Ritos	2621
c	Taos Canyon	2774
d	Hematite Park	2896
e	Chama Divide	2384
f	Silver Lakes	2896
g	La Veta Pass	2877
h	Lake Humprey	2743
i	Upper Rio Grande	2865
j	Pool Table Mountain	2999
k	Santa Maria	2926
l	Porcupine	3133
m	Cochetopa Pass	3048

considered as neutral. The designation of ENSO phase based on these three criteria is shown in Figure 2. The three methods occasionally differ in their assignment of ENSO phase to each WY. However, conflict never occurs between El Niño and La Niña, only between El Niño or La Niña and neutral.

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 Niño (La Niña) year (Ropelewski and Jones, 1987; Dracup and Kahya, 1994). This method suffers from the problem that ENSO designation may change through time as additional years are added.

The second method uses the Troup SOI. When average Troup SOI values for the period running from April of the previous WY to March of the current WY fall below −5, the current year is designated as an El Niño year. When average SOI values for the April–March period are above +5, the year is designated as a La Niña year (Chiew *et al.*, 1998).

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Table III. Characteristics of streamgauging stations

Station	USGS number	Period of record (WY)	Station elevation (m)	Drainage area (km^2)	Annual average streamflow ($m^3\ s^{-1}$)	Linear trend in standardized annual average streamflow[a] ($year^{-1}$)	Station summary
Rio Chama, near La Puente	08284100	1956–99	2159	1229	10·25	**0·0097**	Diversions for irrigation of about 41·6 km^2
Rio Ojo Caliente, at La Madera	08289000	1952–99	1938	1073	1·94	0·0088	Diversions for irrigation of about 14 km^2
Rio Grande, at Embudo	08279500	1952–99	1765	19 098	22·87	**0·0122**	Irrigation of about 2504·8 km^2 in Colorado and 161 km^2 in New Mexico
Rio Pueblo De Taos, below Los Cordovas	08276300	1958–99	2028	973	1·89	**0·0180**	Diversions for irrigation of about 48·5 km^2
Rio Grande, near Del Norte	08220000	1952–99	2432	3379	24·00	**0·0067**	Small diversions for irrigation, storage in four reservoirs (0·156 km^3 total capacity), and some incoming interbasin transfers
Conejos River, near Mogote	08246500	1952–99	2521	722	8·81	0·0031	Small diversions for irrigation

[a] Streamflows are standardized by dividing by mean annual streamflow. Slopes in bold typeface are significant at the 90% level.

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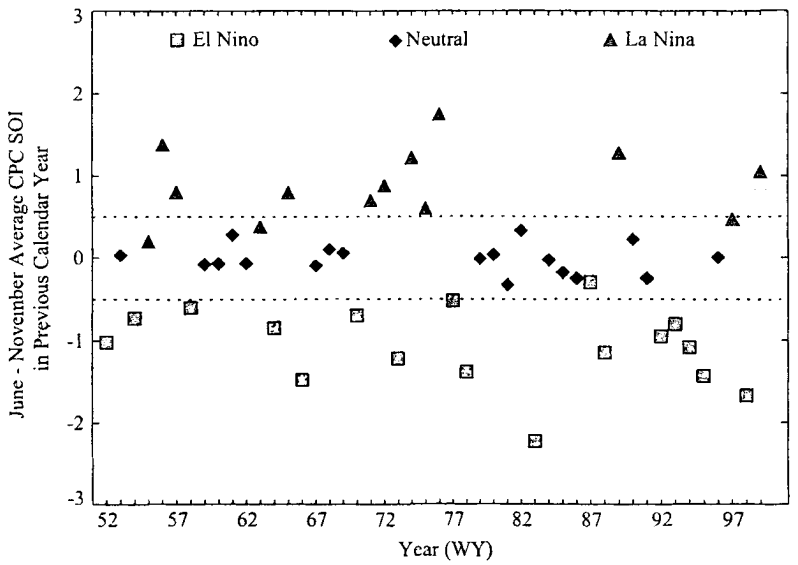

Figure 2. Designation of ENSO phases in each year. Symbols show designation of the ENSO phase of each year following the criteria described in the text. Location of symbols gives the June–November average CPC SOI. The dashed lines, at ±0·5, separate the years into La Niña (top), neutral (middle), and El Niño (bottom), according to the CPC SOI criterion

The third method follows the criteria used by Redmond and Koch (1991) and Cayan *et al.* (1999). When the average CPC SOI of June to November of the previous CY is −0·5 or less, then the present WY is designated as El Niño. If it is greater than or equal to +0·5, then the present WY is designated as La Niña. June to November SOI values are selected because SOI values for these months exhibit the strongest correlation with winter climate over the western USA among the averages of leading 6-month SOI values prior to the winter in question.

To check the randomness of assigned ENSO phase through time, two runs tests were performed (Davis, 1986). In each, the years of one ENSO phase (El Niño or La Niña) were assigned a value of one and the other two assigned a value of zero. The randomness of this binomial distribution was then tested using a runs test. The Z statistic and associated probability were 0·33 and 0·37 respectively for El Niño years, indicating they occur randomly throughout the study period. For La Niña years the Z statistic and its probability were −1·47 and 0·07 respectively, indicating La Niña years are not randomly distributed over the study period, but are rather clumped in a few periods. That is, there is a possibility that these clumped La Niña years could result in periods of higher or lower values of the interest variables in terms of long-term trends. Therefore, it was necessary to remove any long-term trends in the climate variables to isolate ENSO effects from background climate variability.

Data

Figure 1 shows the locations of the NWS, snowcourse, and streamgauging stations that provide the temperature, precipitation, SWE, and streamflow records used in this study, and Tables I–III provide basic information about them. All NWS stations are located at relatively low elevations in the basin between 1945 and 2475 m a.s.l., whereas snowcourse sites are located relatively higher in the basin at elevations between 2384 and 3139 m a.s.l. Only those NWS and snowcourse stations with records covering the period from 1952 to 1999 and with a small percentage of missing days were used in the analysis.

To create uniform time series of temperature and precipitation, small gaps in missing data were replaced. Gaps in NWS daily average temperatures were filled at the daily time scale using regressions against another

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station with a complete or nearly complete record. Daily average temperatures were then averaged up to monthly values. NWS daily precipitation depths were summed to monthly totals with months having 10 or more missing days considered to be missing months. These months were then filled at the monthly time scale by the normal-ratio method (e.g. McCuen, 1998) using the average of monthly to annual total precipitation. Snowcourse SWE exists as individual measurements taken once per month, near the end of the months of January through to March or April. No attempt was made to replace missing snowcourse measurements. Monthly streamflow data were taken as published by the USGS, so no replacement of missing periods was performed.

Removal of long-term trends

Following the creation of monthly data sets as described above, long-term trends in each variable of interest were removed. This was done to isolate the effect of short-term and potentially ENSO-related fluctuations from longer term factors such as the Pacific decadal oscillation, as stated above. Long-term temporal trends were estimated by fitting first- and second-order polynomials to the monthly temperature, precipitation, and SWE data, and to annual streamflow time series. Except in the case of streamflow, for each station, a long-term trend was computed separately for each month. In the first-order analysis of temperature and precipitation, a significant fraction of station-months (25% for both temperature and precipitation) had slopes significant at the 90% level. Linear temperature trends for individual station-months had ranged from −0·052 to 0·078 °C year^{-1}, and monthly averages of slopes over all stations ranged from −0·016 (October and June) to 0·044 °C year^{-1} (March). As an example, Figure 3 shows the slopes of the linear trends in average temperature for each station during October and March. The average linear temperature increase over all stations and months was just 0·002 °C year^{-1}.

Linear trends for individual precipitation station-months ranged from −0·280 to 0·644 mm year^{-1}, and monthly averages ranged from −0·064 (December) to 0·327 mm year^{-1} (September), with an average over all stations and months of 0·137 mm year^{-1}. Owing to a larger variance relative to precipitation, only 3 of 39 (7·7%) station-months of SWE values had significant linear trends, with slope values ranging from −2·1 to 2·1 mm year^{-1}. As given in Table III, standardized linear trends in streamflow had slopes ranging from

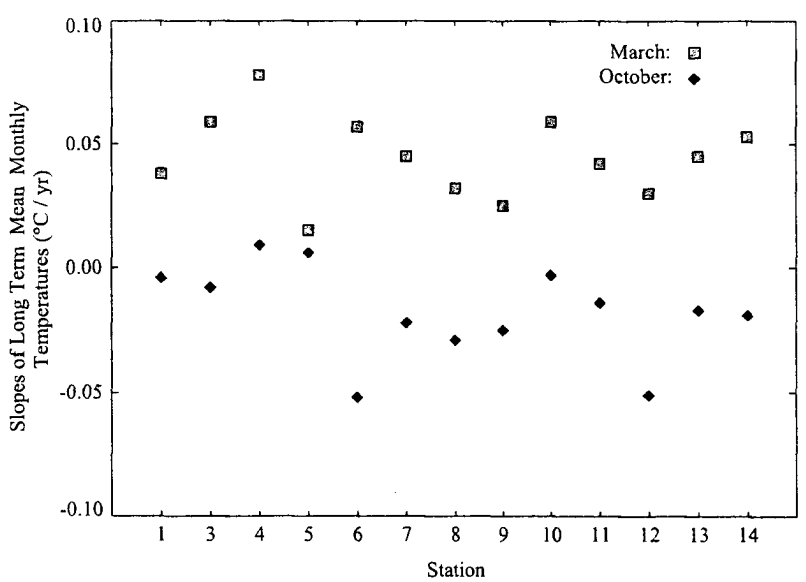

Figure 3. Slopes of October and March monthly average temperature versus time, obtained by linear regression. October is the month having the smallest slope averaged over the stations, and March is the month with the largest averaged slope

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0·0031 year^{-1} at the Conejos River station to 0·018 year^{-1} at the Rio Pueblo station. In all but the Conejos River and Rio Ojo stations, trends were significant at the 90% level.

Similar levels of significance were found for both coefficients in the second-order analysis. However, the removal of linear trends in temperature and streamflow were deemed to be sufficient, as subsequent composite analysis (described below) was found to be relatively insensitive to the use of first- versus second-order residuals.

Streamflow exhibits both a strong annual cycle and a large non-Gaussian variation at the monthly time scale; therefore, long-term trends in streamflow were obtained and subtracted only at the annual (WY) time scale. Monthly residuals were then computed using a downscaling technique, in which the annual residual for a given year was divided into monthly residuals by multiplying the year's residual by the monthly fraction of that year's annual streamflow in the original data. Analytically, if the annual residual for year T is denoted as $\varepsilon_Q(T)$ and defined in the usual way through $Q(T) = a_Q + b_Q T + \varepsilon_Q(T)$, where $Q(T)$ is the annual average streamflow in year T and a_Q and b_Q are the constants defining the estimated linear trend, then the monthly residual for month t in year T, $\delta(t, T)$, is computed as

$$\delta(t, T) = \frac{q(t, T)}{12Q(T)}\varepsilon_Q(T) \tag{1}$$

where $q(t, T)$ is the average streamflow in month t in year T. Where appropriate, results using the streamflow residuals given below have been standardized by dividing by the root-mean-square-residual (RMSR), defined as

$$\mathrm{RMSR} = \sqrt{\frac{1}{N}\sum_{T=1}^{N}\varepsilon_Q^2(T)} \tag{2}$$

where N is the number of years of record, and other symbols are defined as before.

Tests for dependence on ENSO

After residuals were obtained by subtracting the linear trend, two types of analysis were performed to test dependence of the variables on ENSO. First, continuous dependence on ENSO was tested by plotting the residuals versus June to November average CPC SOI. Second, a composite analysis was performed, in which separate averages of the residuals for El Niño, neutral, and La Niña years were obtained for each variable, month, and station, according to the ENSO phase designations shown in Figure 2.

RESULTS

Continuous dependence on CPC SOI

Among the meteorological variables (maximum and average monthly temperatures and total monthly precipitation) the number of station-months exhibiting linear dependence (i.e. correlation) on CPC SOI at various significance levels is similar for both the original variables and detrended residuals. For example, for average monthly temperature, the fraction of station-months having significant correlation at the 90% level is 12·8% for the original variables and 15·4% for the residuals; for monthly total precipitation, these fractions are 17·3% and 12·2% respectively. Using maximum monthly temperatures as opposed to average monthly temperatures greatly increases the number of station-months having significant correlation; for this variable, the fractions are 23·7% for the original variables and 24·4% for the residuals.

Temperature and precipitation. As in the analysis of temporal trends above (and in the composite analysis below), certain months stand out as having the most significant linear dependence on CPC SOI. For average monthly temperature, these months are March and November. The correlations of March average temperature

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residuals versus CPC SOI are positive at all stations with an average slope of 0·526 °C per SOI unit (note from Figure 2 that the total range of CPC SOI is about four units), and are significantly positive at the 90% level at 10 of the 13 stations. This indicates colder temperatures in El Niño years and warmer temperatures in La Niña years, as expected. Similarly, for the residuals in November, all correlations are again positive, with an average slope of 0·401 °C per SOI unit, but the significance is not as high: only two are significant at the 90% level, but 11 of 13 are significant at the 70% level. The results are similar in the original variables for November, but not as strong for March. Combining November and March, four stations have the weakest relationship to the CPC SOI: Dulce, El Vado Dam, Blanca, and Chama (stations 3, 4, 11 and 12). As can be seen in Figure 1(a), the first three of these stations are clustered in the upper reaches of the Rio Chama drainage basin in the west-central portion of our study area.

For precipitation, the months with the strongest linear dependence on CPC SOI were November, December, and March. The correlations of total monthly precipitation residuals versus CPC SOI are negative for all stations during these months, with average slopes of −3·53, −3·11, and −4·08 mm per SOI unit respectively. This indicates these months are wetter in El Niño years than in La Niña years. These correlations are significant at the 90% level at 3 of 14 stations in November and December, and at 8 of 14 stations in March. The number of significant slopes jumps to 12, 10, and 12 in November, December, and March respectively, if the 70% significance level is considered. The results are somewhat stronger in the case of precipitation residuals than in the original variable. Unlike temperature, there is not a clear geographical clustering of the stations that fail to have significant slopes.

Snow water equivalent. Whether residuals or original values are considered, no snowcourse stations have significant correlations (at the 90% level) of SWE with SOI for January and February, but several do have significant negative correlations during (late) March. The latter are the snowcourse stations in the eastern portion of the study area (stations a–d and g). This implies larger snow storage in El Niño years than in La Niña years. As will be discussed in the composite analysis below, this is the result of a decrease in SWE from February to March in La Niña years, apparently caused by warmer March temperatures and lower March precipitation.

Streamflow. Annual streamflow and its residuals at all the stations exhibit negative correlation with June to November CPC SOI, implying more runoff in El Niño years, as would be expected (see Figure 4 for the results in the residuals). This dependence is significant at the 90% level at the Rio Chama station, Rio Grande at Embudo, and the Rio Pueblo station for the original variables, but only at the Rio Pueblo and Rio Ojo stations in the residuals. The four southernmost stations (all stations except Rio Grande near Del Norte and the Conejos River station) have slopes that are significant at the 70% level, whether original variables or residuals are considered.

The lack of significance of the Rio Grande near Del Norte can be understood in terms of the SWE results discussed above, since the cluster of snowcourse stations in its drainage basin did not show a significant correlation between SWE and the June to November CPC SOI. Because no meteorological stations are situated in this watershed (the Del Norte NWS station is near the streamgauge and thus is unlikely to characterize the entire drainage basin), it is difficult to characterize streamflow in this basin in terms of temperature and precipitation. Human regulation of streamflow may also be an influence on the dependence of streamflow on ENSO in this watershed.

Composite analysis

Composite analysis is the analysis of composites created by separating instances of a climatic phenomenon into classes based on some criterion, and then combining, usually by averaging, the instances falling into each class (Kahya and Dracup, 1993; Dracup and Kahya, 1994; Brown, 1998; Clark *et al.*, 2001). Here, we apply composite analysis to the weather and hydrology in the URG by first separating the years into El Niño,

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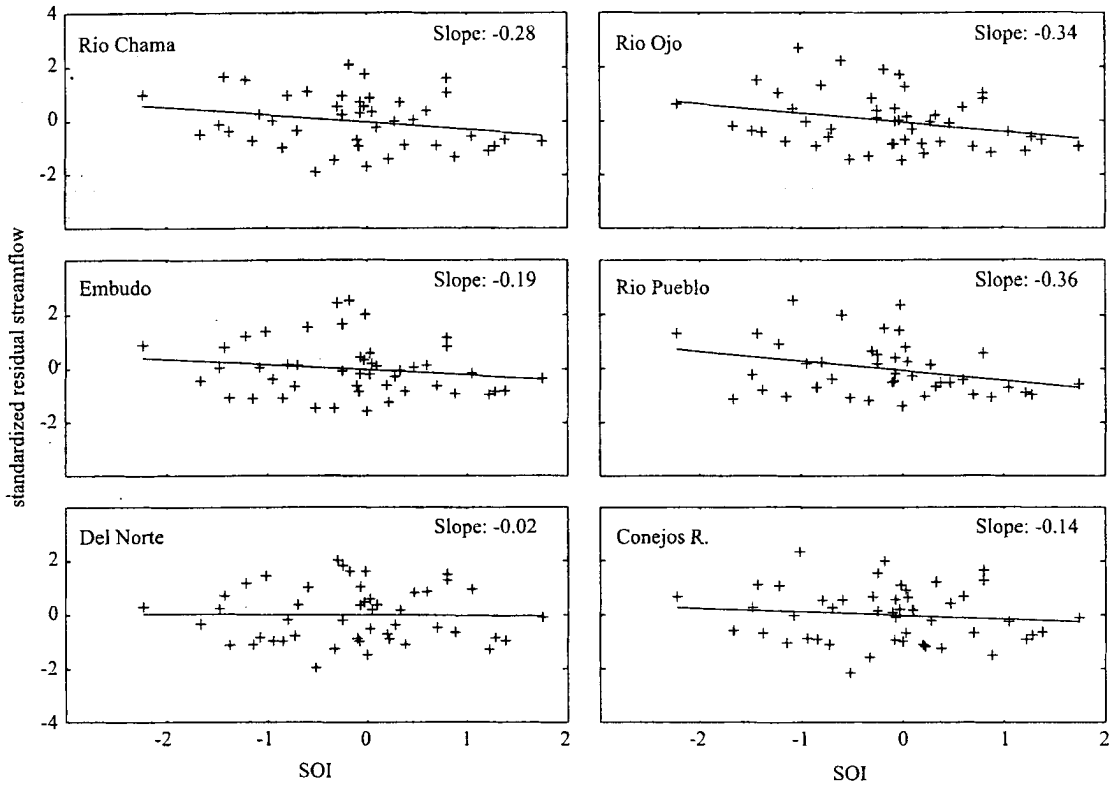

Figure 4. Regression of standardized annual streamflow residuals versus June–November average CPC SOI. Standardization here is by division by the station's RMSR (see Equation (2) for definition)

neutral, and La Niña years, according to the criterion described in the ENSO designation section above, and then by combining the years by averaging the temperature, precipitation, SWE, and streamflow data separately for each ENSO phase, primarily to test whether statistically significant differences exist between the ENSO phases.

Temperature and precipitation. Overviews of the composite analysis results for temperature and precipitation residuals are shown in Figures 5 and 6. The statistically significant months are the same as observed above in the linear dependence of these variables versus CPC SOI. In Figure 5, it may be seen that El Niño years are colder vis-à-vis neutral years in November and March, whereas La Niña years are warmer vis-à-vis neutral years in March, but without much difference in November. Figure 6 shows that El Niño years are unusually wet (wetter than neutral years) in November, whereas in December and March it is La Niña years that are unusually dry (drier than neutral years).

Spatial patterns in temperature and in precipitation residuals between ENSO phases across the basin are illustrated in Figures 7 and 8 respectively. Figure 7 suggests the presence of two inter-basin geographical patterns in the residual temperatures. The first is a spatial variability in the colder El Niño November temperatures. During El Niño years, stations in the northern and eastern sections of the basins appear to have colder temperatures than other stations. This is consistent with t-test statistic results (Figure 5). November El Niño temperature residuals are smallest for stations in the southwestern portion of the basin, which is consistent with the CPC SOI dependences for these stations.

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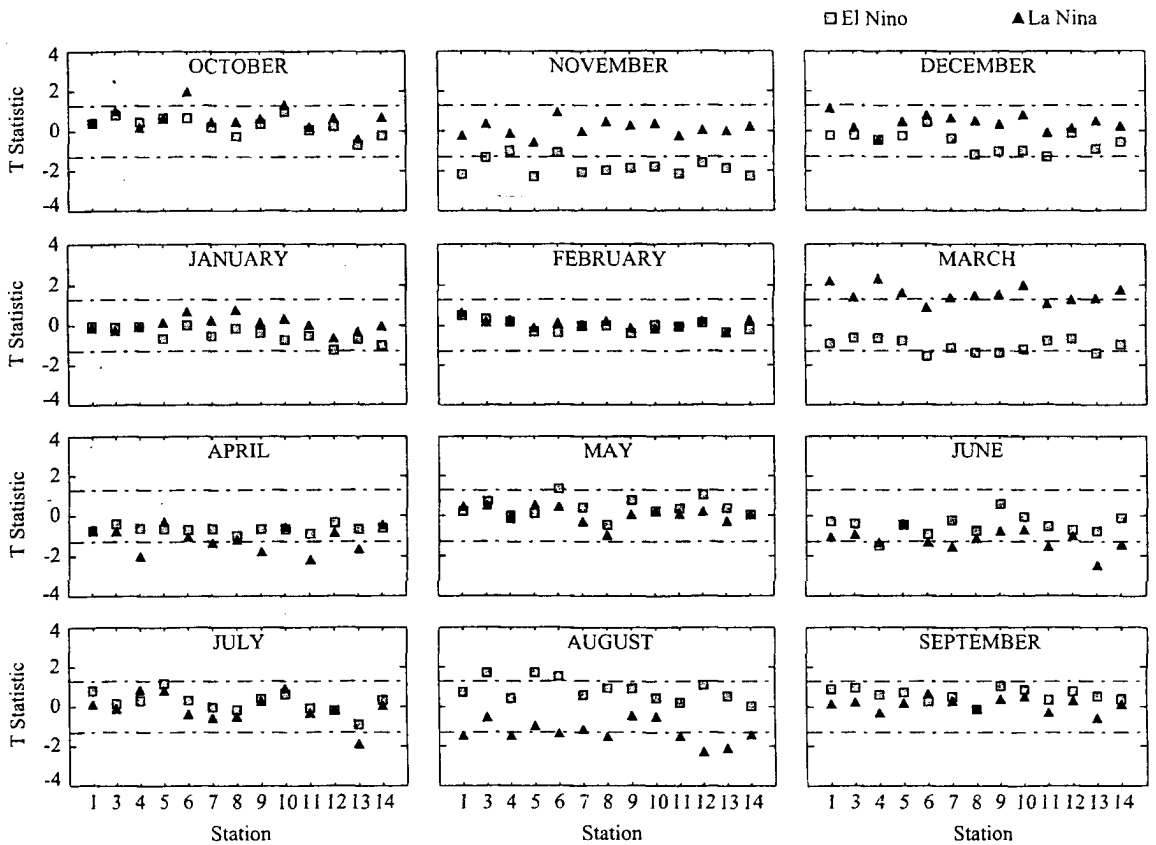

Figure 5. The t-statistics of differences of composite average monthly temperature residuals between El Niño and neutral years and between La Niña and neutral years

Stations across the entire basin show the March temperature of La Niña years to be warmer than neutral or El Niño years. Thus, warmer temperatures during March in La Niña years appear to be more spatially uniform than the colder El Niño November temperatures. However, warmer temperatures in the southwestern portion of the basin appear slightly less than those in the northeast.

A map of composite average precipitation residuals from October to September is illustrated in Figure 8. Overall, spatial patterns in the monthly precipitation residuals are less obvious than those for the temperature residuals. However, during the snow season, March precipitation during La Nina years is most notably lower in the southwestern stations, but a more mixed response is seen at the other stations. Stations in the southern half of the basin also tend to experience a greater increase in precipitation during November of El Niño years, but the response is not seen at all stations.

Snow water equivalent. Composite averages of SWE residuals at the snowcourse stations are shown in Figure 9, and exhibit consistent spatial patterns. With a single exception (Silver Lake), all stations with small SWE residuals for the January through to March period occur along the URG's western side. The stations with the largest decrease in March SWE during La Niña years occur on the basin's eastern side. A one-tailed t-test (not shown) indicates that either, or both, of the differences between El Niño or La Niña and neutral years are significant at about the 90% level for March at these eastern stations. This is consistent with the analysis of the linear dependence of SWE on CPC SOI.

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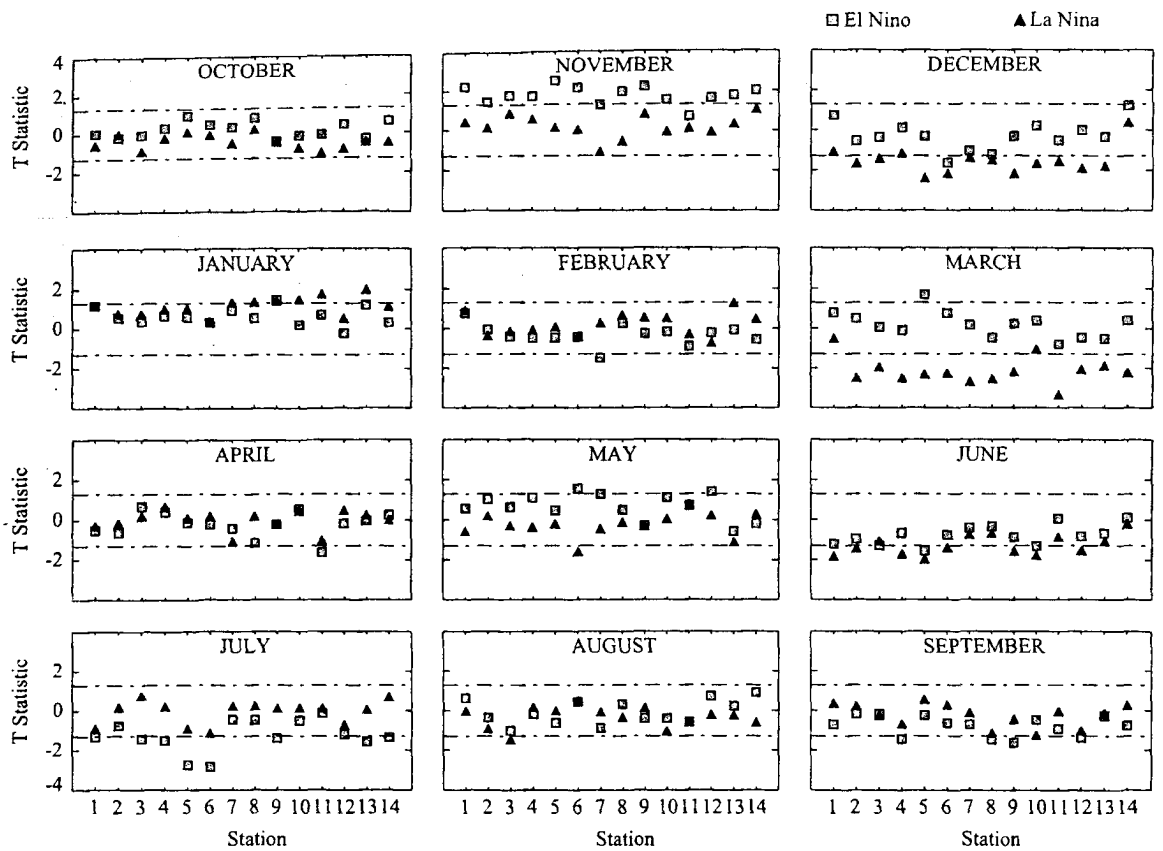

Figure 6. The t-statistics of differences of composite average monthly precipitation residuals between El Niño and neutral years and between La Niña and neutral years

Streamflow. Composite average analyses of annual residual streamflow are shown in Figure 10a. As expected, El Niño years have higher residual streamflow than La Niña years, except at Rio Grande at Del Norte. Standardizing the residuals by dividing by the station's RMSR, as in Figure 10b, gives a more realistic picture of the significance of the differences, where, according to a t-test (not shown), the streamflow in La Niña years is significantly less at about the 90% level than that in the neutral years at all stations except Rio Grande at Del Norte. The difference between La Niña and neutral years at Conejos River near Mogote is a bit deceiving, however, since at this station the composite average streamflow residual in neutral years is larger than that during El Niño years.

Figure 11 shows the composite average of the standardized monthly streamflow residuals in the map. In interpreting these plots, it is important to remember the definition of the monthly residual, given by Equation (1). Based on this definition, it can be seen that the monthly residual for a certain ENSO phase is the combined effect of the size of the annual residuals for that phase and the proportion of the annual flow volume in that month. Thus, for example, the large negative La Niña residual in April at the Rio Chama station implies that this station has relatively large average annual residuals in La Niña years and that a large proportion (in fact, the largest of any month) of annual flow volume occurs during April. More subtly, the positive monthly average La Niña residual in June at this station is due to a few La Niña years having positive residuals and relatively significant streamflow during June, whereas most La Niña years have negative residuals and relatively little streamflow during June. This same situation occurs in July at

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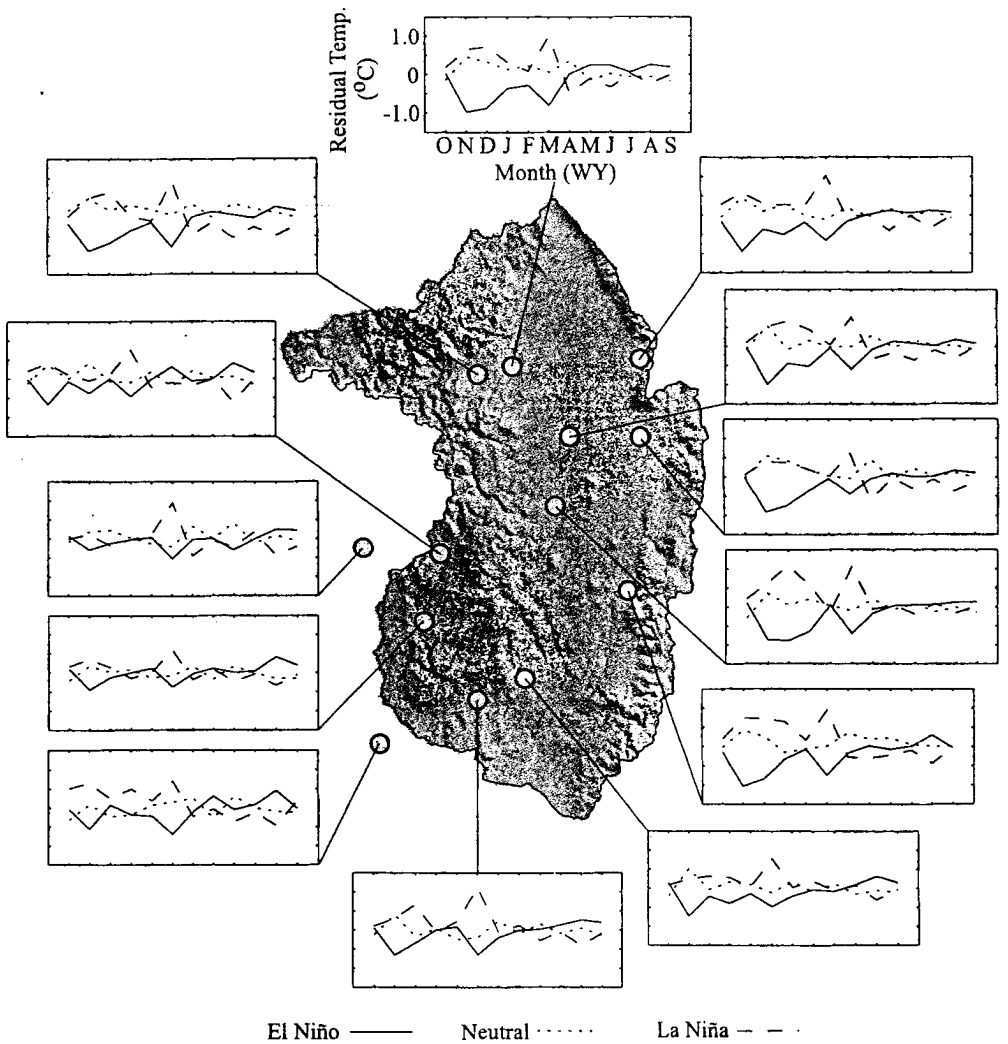

Figure 7. Map of composite average monthly temperature residuals at each station from October through to September for El Niño (solid), neutral (dotted), La Niña (dashed) years

the Rio Grande near Del Norte and the Conejos River near Mogote. An analogous situation is obtained for the negative composite average residual streamflow in April during El Niño years at the Rio Chama station.

These monthly composite average residual plots, therefore, show certain subtle features at each basin that make generalization difficult. The Rio Chama and Rio Ojo stations, which are the two smaller basins in the southwestern portion of the study area, show strong evidence of a lag in the maximum streamflow month between La Niña and El Niño years, with the La Niña maximum streamflow month occurring earlier in the year, as generally warmer March temperatures and lower March SWE values at the snowcourse stations on the east side of the URG would suggest. However, the snowcourse station actually within the Rio Chama basin (Chama Divide) does not show lower March SWE values, and the stations with the strongest tendency to have reduced March SWE are in the region of the Rio Pueblo in the southeast, which does not exhibit a lag in the maximum month between La Niña and El Niño.

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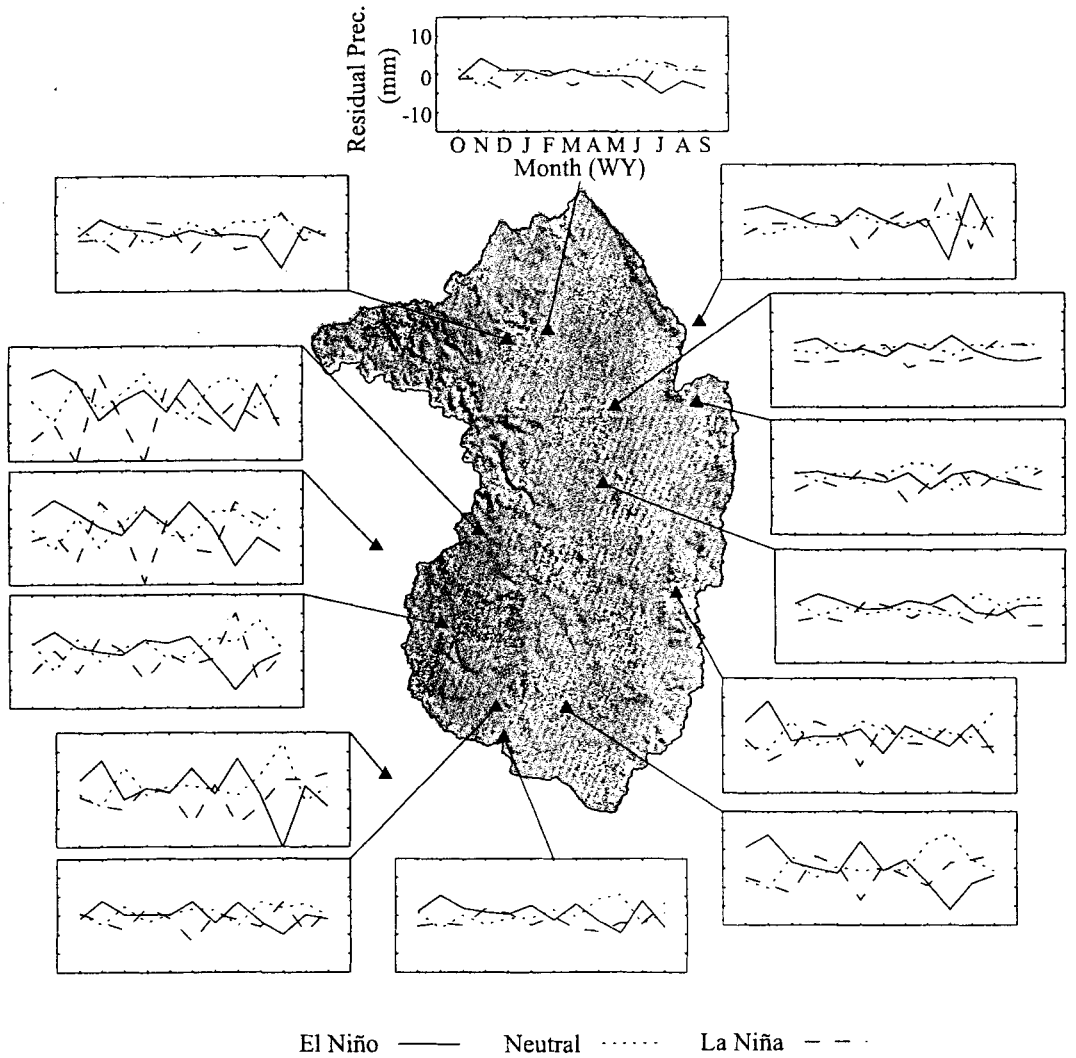

Figure 8. Map of composite average monthly total precipitation residuals at each station from October through to September for El Niño (solid), neutral (dotted), La Niña (dashed) years

However, the Rio Pueblo station shows significant winter streamflow during La Niña years (and very little during winter in other ENSO phases), as does Rio Grande at Embudo, to which the Rio Pueblo is a nearby tributary.

The most northern Conejos River and Rio Grande near Del Norte stations show rather similar behaviour: rather weaker separation of composite average annual residuals (especially at Rio Grande near Del Norte), an earlier maximum month during La Niña years (May) compared with El Niño and neutral years (June or July), and a higher or equally high maximum during neutral compared with El Niño years. These behaviours correspond to the warmer March during La Niña years, combined with little difference in SWE values; apparently, the average total snowpack affecting flow at these stations is rather independent of ENSO phase (again especially at Rio Grande near Del Norte), but it melts somewhat earlier during La Niña years.

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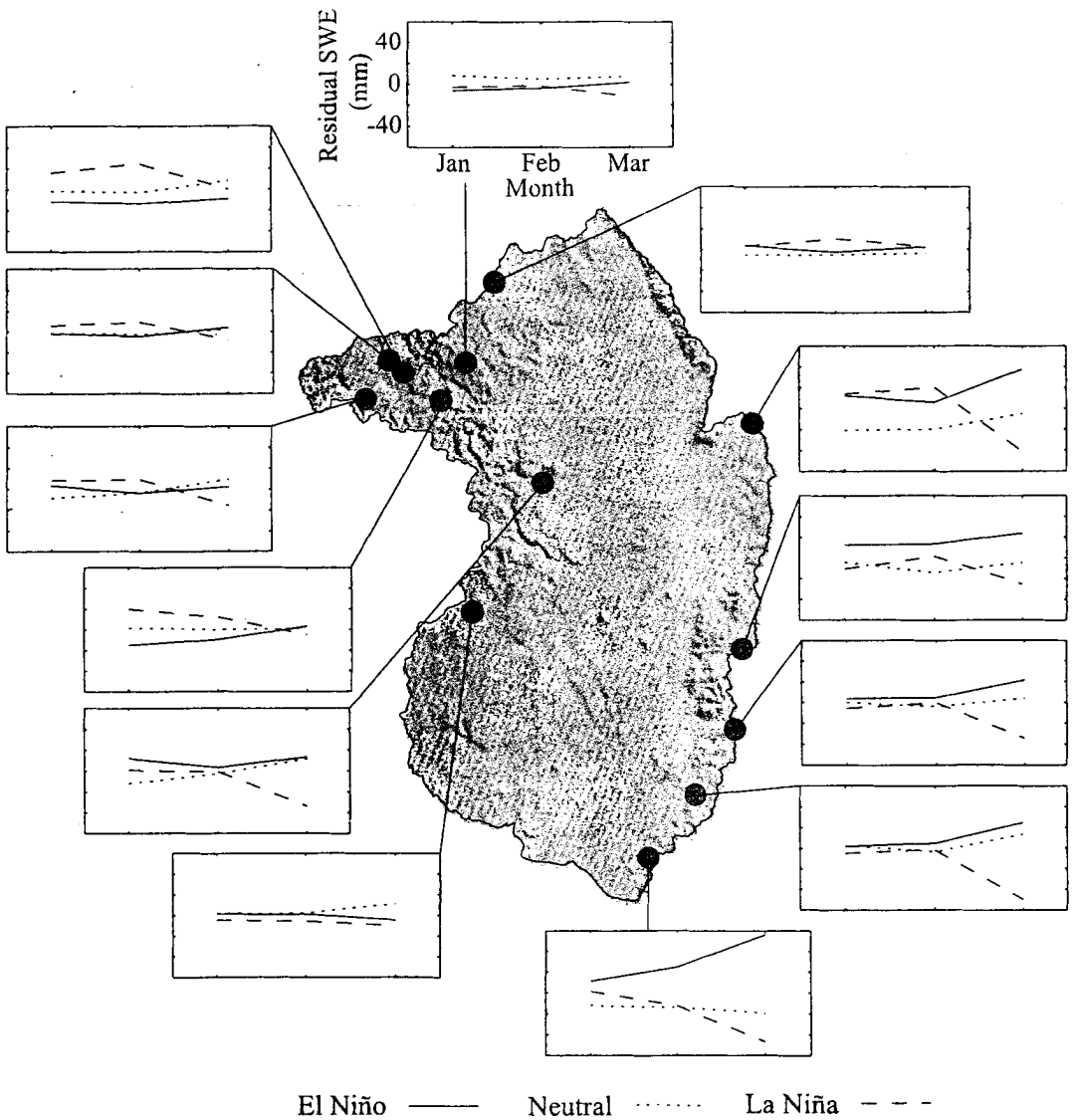

Figure 9. Map of composite average SWE residuals at each snowcourse station for January, February and March

CONCLUSIONS

Examination of two important climatic factors, temperature and precipitation, along with streamflow volumes and estimates of SWE at snowcourse stations, over the years 1952–99, demonstrates that ENSO appears to modulate temperature and precipitation across the basin, affecting snow accumulation and melt and the resulting streamflow in the URG river basin. Through these sequential observations of ENSO impacts, it is possible to demonstrate how the important climatological factors of temperature and precipitation are modulated by ENSO and how these climatological differences are embodied in the form of SWE and resultant streamflow differences among ENSO phases.

Comparing this research with previous work highlights some important characteristics concerning temperature and precipitation responses to ENSO episodes specific to the URG. First, temperature differences between

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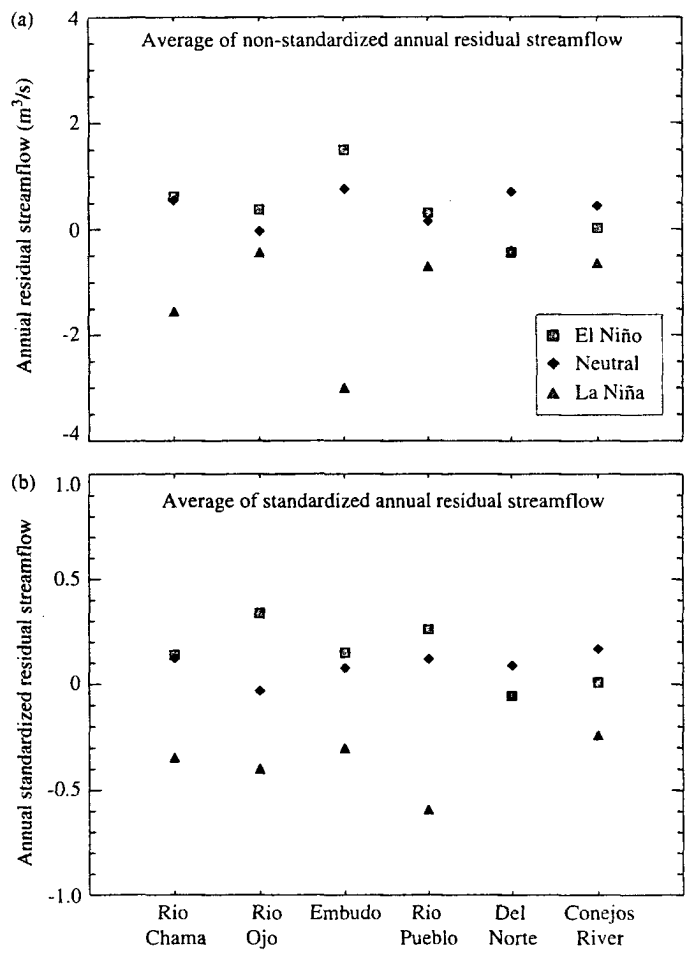

Figure 10. Composite average of annual streamflow residuals: (a) not standardized; (b) standardized by dividing by RMSR

the three ENSO phases are not uniform throughout the entire winter, but are concentrated at its beginning and end—only in November and March. Second, in El Niño years, compared with neutral years, the URG experiences lower temperatures, especially in the basin's northern and eastern sections. Third, during La Niña years, March temperatures are warmer across the entire basin. With respect to temperature at least, it can be said that ENSO in the URG affects the length of winter rather than its severity.

Statistically significant increases in monthly precipitation totals were found to occur only during November. Significantly lower precipitation occurred in La Niña years during December and March. So, as with temperature mentioned above, climatological precipitation differences during El Niño, neutral and La Niña years are confined to certain months, predominantly at the beginning and end of the winter season.

Differences in SWE among ENSO phases were found to exist only during March. Whereas meteorological variations in observed ENSO response were primarily temporal with relatively weak geographical variability, SWE dependence on ENSO was seen to vary geographically very strongly, with snowcourse stations on the eastern side of the URG showing a strong ENSO signal and those on the western side not.

These findings are also important in another respect. The URG has been the site of several studies investigating the effect of increased temperatures caused by anthropogenic climatic change (Rango, 1992; van Katwijk *et al.*, 1993; Rango and Martinec, 1997). Many of these studies have employed the Snowmelt

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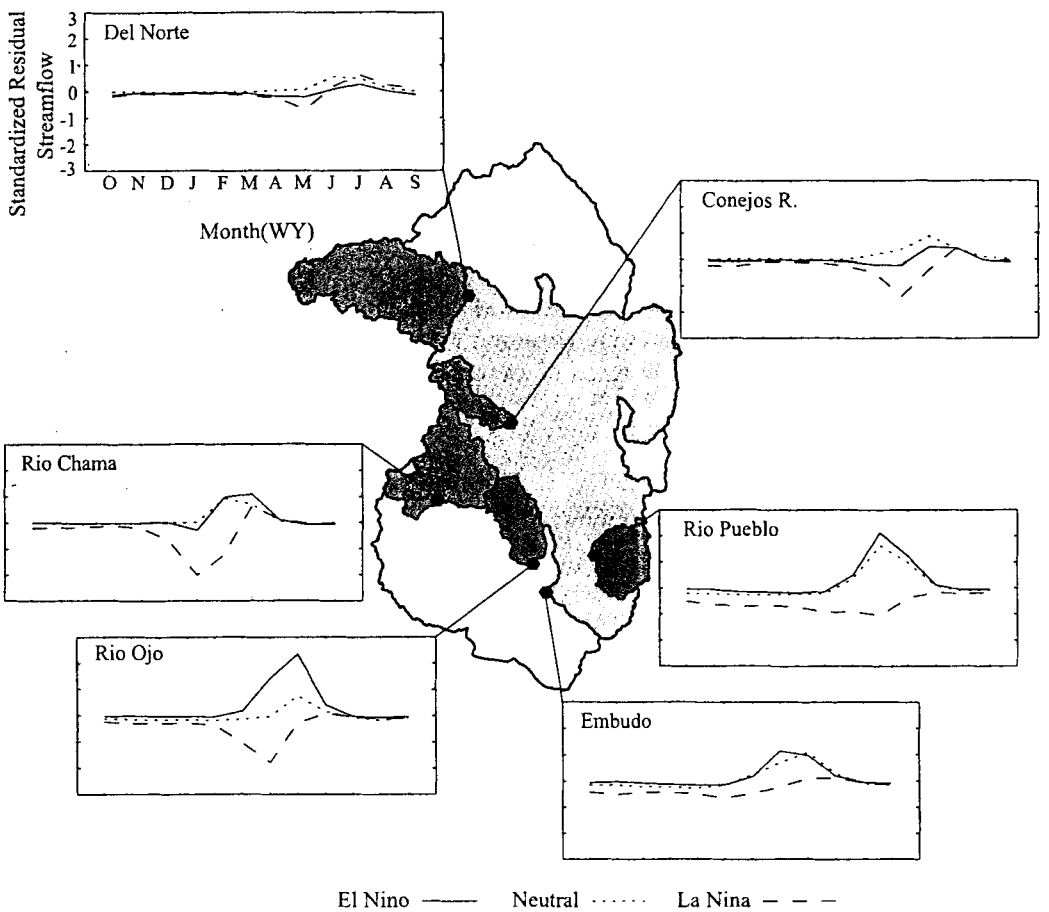

Figure 11. Map of composite average of monthly streamflow residuals standardized by dividing by RMSR for each of the gauging stations studied

Runoff Model (SRM), which is one of most popular models to simulate and predict snowmelt in mountainous areas. SRM has been used to model predicted changes in the streamflow regime caused by temperature changes (e.g. global warming). In these studies, temperature changes have usually been considered uniform. However, our work suggests that assuming a uniform warming may be overly simplistic, and future modelling efforts may be able to predict climatically induced streamflow variations more accurately if existing variations caused by ENSO are considered.

March during La Niña years is the critical month in determining differences in annual hydrograph in the URG. Higher temperatures and lower precipitation result in lower, and usually earlier, streamflow, compared with that of neutral and El Niño years. March, therefore, needs to be given special attention when modelling scenarios of streamflow under altered climatic conditions.

There are variable time lags between ENSO-modulated differences in temperature and precipitation and the resultant streamflow. Colder temperatures and greater precipitation in November of El Niño may result in more snow storage over the winter and higher streamflow during the following snowmelt season—a time lag of several months. However, the impact of warmer and drier conditions during March of La Niña years on streamflow is more immediate, with almost no lag time occurring between ENSO-modulated meteorological differences and the resultant streamflow.

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Finally, La Niña years experience decreased annual streamflow compared with both El Niño and neutral WY. However, examination of the reduction of runoff during the La Niña phase on a monthly basis reveals different responses at different stations. At most stations, with the exception of the Rio Grande at Embudo and Rio Pueblo, the peak streamflow month during La Niña years is earlier, though the size of the differences varies. At the Rio Grande near Del Norte, the effect of ENSO is rather slight, matching small differences in SWE between El Niño and La Niña years in this drainage basin. At the Rio Grande at Embudo and at Rio Pueblo, winter streamflow during La Niña years is greatly increased and the spring peak is attenuated.

The above observations demonstrate that improved streamflow forecasting using ENSO phase information, which has, in the past, been observed for the western USA in general, should indeed be possible specifically for the URG. Particular features of the differences between El Niño, neutral and La Niña WY in terms of temperature and precipitation and resulting SWE and streamflow that can contribute to the improved forecasting have been provided by this research. However, the responses vary in strength and in timing, and they cannot be completely characterized in terms of meteorological and SWE data, given the sparseness of the long-term data network.

ACKNOWLEDGEMENTS

This research was partially supported by Texas A&M Interdisciplinary Investigation grant IRI 99-35.

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