Variation of Snow Water Equivalent and Streamflow in relation to the El Niño/Southern Oscillation

by

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INTRODUCTION

Water supply forecasts are issued on a monthly basis through the cooperative efforts of the National Weather Service and the Soil Conservation Service beginning in January each year. They ar used in the operation of many reservoirs but are only produced for those areas of the western United States where snowmelt represents a significant fraction of the runoff. In fact, it is the accumulation of moisture in the snowpack which makes these forecasts possible. Water supply forecasts are currently based on regression models relating seasonal streamflow volume (often April through September) to snow water equivalent, precipitation and antecedent moisture conditions. The accuracy of water supply forecasts produced using the regression procedures depends on the fraction of seasonal streamflow volume that is due to snowmelt, on the natural variability in the local climate and on the date of the forecast. An evaluation of forecast errors by Shafer and Huddleston (1984) shows average errors of slightly more than 20% for March forecasts in the Pacific Northwest, decreasing to between 10% and 15% for the May forecast. The largest errors tend to occur for those streams in which the contribution from snowmelt is a smaller part of the total streamflow volume. These average errors are for months when much of the snowpack has already developed so that relatively small errors would be expected. Although forecasts are made as early as January 1, they did no analysis for errors of these early season forecasts. In another analysis of water supply forecast accuracy, Shaake and Peck (1985) identified three primary sources of error: climate error, model error and data error. Of these three sources, climate error was the dominant component, particularly early in the forecast season. Thus, improvements in the understanding of climate variability which result in better long-range climate forecasts could be used to decrease the error of water supply forecasts.

This paper describes a study of the relationship between a well-known, large-scale climate phenomenon, the El Niño-Southern Oscillation (ENSO), and seasonal precipitation, snow water equivalent (SWE) and streamflow volume in the western United States. Of particular interest in this investigation is the nature and the strength of any relationship and the likelihood that this line of investigation may lead to useful information which could be incorporated into water supply forecasting procedures. First, a brief review of the ENSO phenomenon is presented, followed by a discussion concerning the current level of understanding of the relationship of this phenomenon to climate of the western United States. Then, seasonal precipitation, snow water equivalent and streamflow volume data at selected sites are analyzed in relation to an index of ENSO to determine the nature of that association.

THE EL NIÑO/SOUTHERN OSCILLATION AND WESTERN CLIMATE

The dependence of streamflow on surface climate, in particular precipitation, is well understood by hydrologists. The processes producing streamflow have long been conceptualized in the hydrologic cycle and have been quantified, particularly over short time intervals, for the purposes of flood prediction and forecasting. However, climate inputs to hydrologic models have been considered largely random from the point of view of predicting future streamflow. As a result, predictions or forecasts of future climate on time scales of months, seasons and years have been based principally on climatology, considering only the observed random variation. Using this approach, predictability results from whatever persistence is observed in the historic record.

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The El Niño/Southern Oscillation Phenomenon

Over the past two decades great strides have been made in both the description and the understanding of the nature of climate variability on large spatial and temporal scales. On a global scale, the largest and most significant climate pattern is the combined ocean-atmosphere phenomenon called the El Niño-Southern Oscillation (ENSO). The Southern Oscillation is a circulation feature in the equatorial Pacific Ocean characterized by high surface pressure centered in the South Pacific near Tahiti and low surface pressure centered over Indonesia and northern Australia (Rasmusson, 1984). This pressure gradient induces a circulation system known as the Walker Cell in the plane of the equator and is responsible for much of the seasonal precipitation in the western Pacific. As relatively cool, dry air moves westward it is warmed and moistened by the waters of the western Pacific and precipitation is produced by condensation of the rising air. The circulation cell is closed as the drier air returns eastward in the upper atmosphere. This pressure pattern is illustrated in Fig. 1, a map depicting the correlation of annual mean sea level pressures with sea level pressure at Darwin, Australia. Contour lines show the distribution of the correlation coefficient in tenths; stippled areas are those in which the value of the correlation coefficient exceeds +/- 0.4. Tahiti and Darwin are at the opposite ends of the Walker Cell and the standardized difference in sea level pressure between these two locations is commonly used in the Southern Oscillation Index (SOI). A positive SOI is associated with a strong gradient and thus strong equatorial winds from the east, while a negative SOI occurs when the gradient is weaker than normal and the easterlies decline in strength.

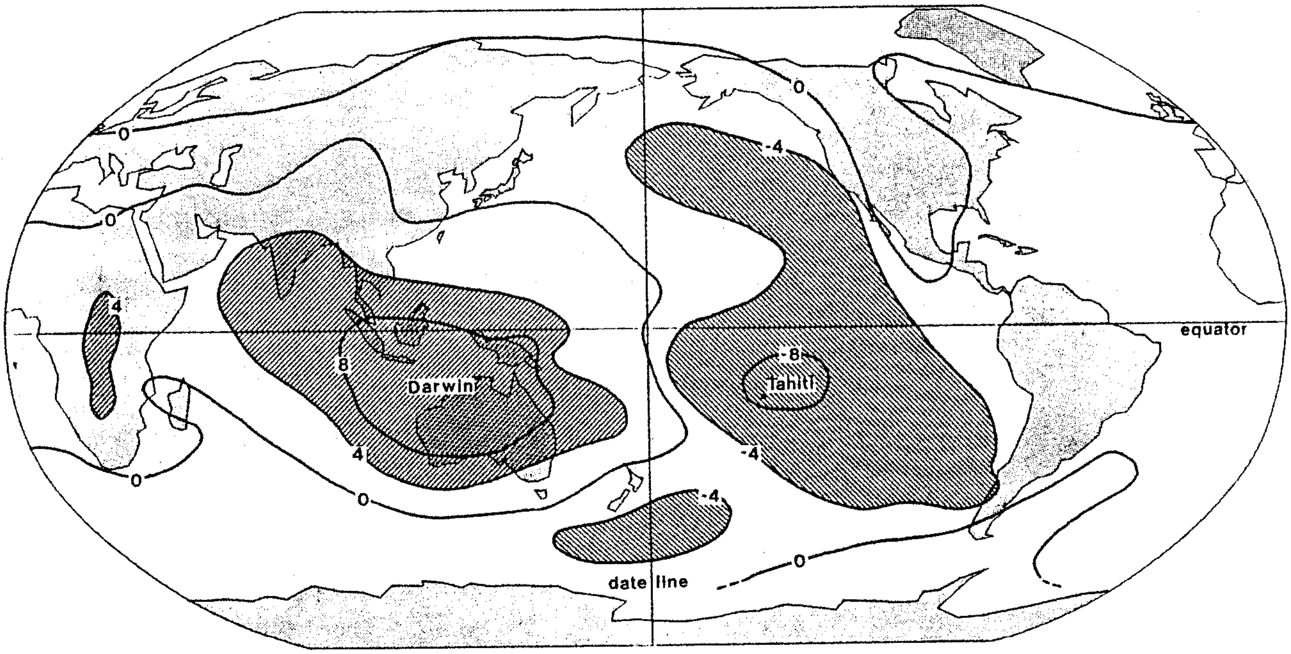

Figure 1. Southern Oscillation shown by Correlation of Annual Mean Sea Level Pressures with Darwin, Australia (after Rasmusson, 1984).

This simplified model of the Walker Cell is linked to sea surface temperatures (SST) in the equatorial ocean. The cell is at its strongest when SST in the eastern Pacific are anomalously cool while those in the western Pacific are anomalously warm. The strength of the Southern Oscillation varies seasonally with the cycle of SST, typified by a warming in the eastern and central Pacific beginning in the summer and reaching its maximum in the Northern Hemisphere winter. The warming results in a decrease in the east-to-west pressure gradient and a corresponding decrease in surface winds. This phenomenon of high SST in the eastern Pacific is called El Niño. Occasionally, the increase in SST is well above average, as was the case in 1982, and the circulation is strongly affected, resulting in dramatic climate anomalies on either end of the Southern Oscillation. The term ENSO is commonly used to describe this combination of events, anomalously high SST in the eastern Pacific and a low pressure gradient in the Southern Oscillation (negative SOI). Conversely, the term anti-ENSO, or La Niña, is used to indicate the opposite phase of the oscillation (positive SOI). Strong to moderate ENSO events (as classified by Quinn et al, 1978, and Rasmusson, 1984) have been observed to occur on an average of once every five to seven years. These events are highlighted in Fig. 2, a time series of the SOI (solid line) and standardized anomalies of SST off the South American coast near Chicama, Peru (dashed line). Shading indicates major occurrences of ENSO since 1935, the 1982-83 occurrence being the most intense.

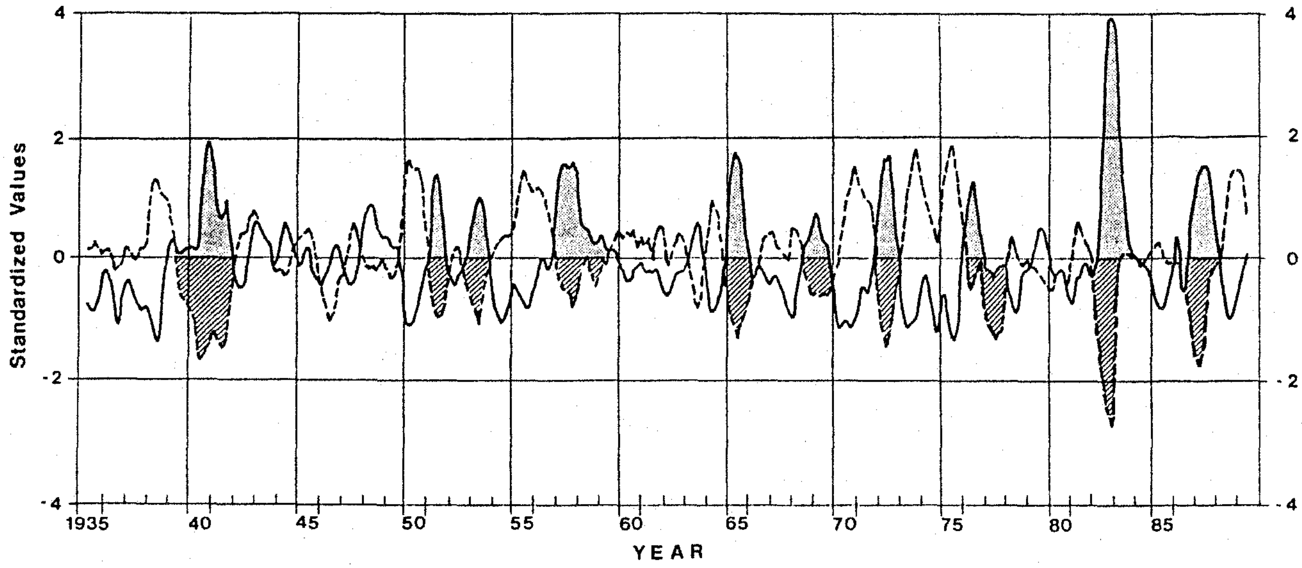

Figure 2. Time series of SST and SOI showing major El Niño events (after Rasmusson, 1984, and Mo, 1989).

ENSO and Climate of the Western United States

Although the processes which comprise the ENSO phenomenon are located principally in the equatorial ocean, it is now clear that it is the dominant signal in the interannual variability of global climate. Connections with the midlatitudes have been established both through observational studies using circulation data (e.g., Horel and Wallace, 1981, and Yarnal, 1985) and theoretical computer models (e.g., Hoskins and Karoly, 1981). In particular, the most persistent and recurring pattern of atmospheric circulation in the Northern Hemisphere, the Pacific North American pattern (PNA), has been shown to be closely associated with ENSO. This pattern, first described by Wallace and Gutzler (1981), occurs commonly over the northeastern Pacific Ocean and North America. It is characterized by two phases, either of which forms a series of alternating highs and lows in the pressure field of the upper atmosphere. The positive phase is an amplification of the normal circulation over North America, characterized by (1) a deep Aleutian low pressure area extending from the surface to the upper atmosphere over the northeastern Pacific Ocean, (2) an anomalously strong area of high pressure centered over western Canada and (3) an area of lower than normal pressure over the southeastern United States. In this phase of the PNA pattern above normal temperatures and dry conditions are experienced in the western United States, while the eastern United States experiences conditions cooler and wetter than normal due to the influence of the deep trough of low pressure. Conversely, a reverse-PNA pattern is associated with cooler and wetter conditions in the West due to a reversal of the west-to-east sequence of high and low pressure areas.

A small number of empirical studies support this relationship between the PNA pattern and surface climate in the western United States. Redmond and Koch (1991), for example, have shown a significant correlation between an index of the PNA pattern with temperature and to a lesser extent precipitation when the data are aggregated over the six-month winter season (October through March). Yarnal and Diaz (1986) have also shown a connection between the PNA pattern and climate along the coastal margin of North America. A strong PNA pattern raises winter (Dec-Feb) temperatures along the entire coastal margin and suppresses precipitation below normal. This relationship is reversed during winters that experience the reverse-PNA pattern. Of direct relevance to this study is their observation that a strong PNA circulation pattern occurs more frequently during years when strong to moderate ENSO events occur and a reverse-PNA pattern during years when La Niña occurs, thus providing a direct link to the climate of the western United States.

A number of other analyses have documented the mid-latitude response directly as related to the ENSO phenomenon. Ropelewski and Halpert (1986), for example, identified consistent responses in both temperature and precipitation in several regions of North America during ENSO years. In particular, increased precipitation was noted in the states bordering the Gulf of Mexico, in the High Plains and the Great Basin; whereas decreased precipitation was noted in the Pacific Northwest. It is interesting to note that the response in the Pacific Northwest is most apparent in the December to March season, several months after the onset of the ENSO event which was assumed to begin in the summer months. Namias and Cayan (1984) presented maps of winter season temperature and precipitation anomalies in the United States for nine ENSO years since World War II. These show a disposition towards above normal temperatures in the Northwest and below normal in the Southeast. For precipitation the signal is more ambiguous throughout the country.

For the western United States, Redmond and Koch (1991) used correlation analysis to produce results consistent with the aforementioned study of Ropelewski and Halpert (1986). For divisional precipitation data totalled over the six-month winter season, correlation coefficients with the SOI were as large as +0.5 in the Pacific Northwest indicating that above normal precipitation is strongly associated with a positive SOI, or La Niña event. Conversely, below average precipitation is associated with ENSO events. The opposite response was noted in the Southwest where above normal winter precipitation was found to occur during ENSO events. These correlations were for an SOI averaged over a six-month period from June through November, again indicating that ENSO may be a precursor to climate events in the western United States.

In sum, it is clear that interannual climate variability in the western United States is significantly associated with the ENSO phenomenon, although the timing and the regional pattern of the response is quite variable. In the remaining sections of this paper the nature and statistical significance of the relationship between the Southern Oscillation Index and seasonal precipitation, snow water equivalent and streamflow volume is investigated. If the state of the tropical atmosphere in the Pacific Ocean can be identified as a precursor to upcoming precipitation and streamflow, it may be an important factor in seasonal water supply forecasting.

SELECTION OF STUDY SITES AND DATA COMPILATION

The western United States, essentially that area between the Rocky Mountains and the Pacific Ocean, exhibits a broad range of climates and climate behavior, varying with distance from oceanic moisture sources and topographic influences. Precipitation in particular is extremely complex, both as regards mean annual amounts and seasonal distributions. More than in other parts of the country, terrain features, expressed both in altitude and in directional alignment, strongly influence both spatial and temporal distributions. However, a common characteristic throughout the West is the seasonal snowpack which accumulates in the mountains during the winter months and melts during the late spring and summer months producing the streamflow which is a primary water supply in many areas.

The objective of this study, as noted, is to evaluate the variability of seasonal precipitation, snow water equivalent and streamflow volume in relation to ENSO throughout the western United States. To do so, eleven sites were selected for analysis, one in each of the western states where water supply forecasts are produced (Fig.3). The principal criterion in site selection was the availability of data on the three principal variables of interest over a sufficient period of time to establish whether there was an association of the variable with ENSO and, if so, the magnitude of the association. The search for sites was further restricted to data contained in the Centralized Forecast System (CFS) database developed and maintained by the Water Supply Forecasting Staff (WSFS) of the Soil Conservation Service. Most of these data are used in the development and application of water supply forecasting models and are from sites in the major river basins of the western United States. In addition to the hydroclimate data, a quantitative description of the ENSO phenomenon was also required. For this purpose the Southern Oscillation Index (SOI) was used, as defined earlier in this paper.

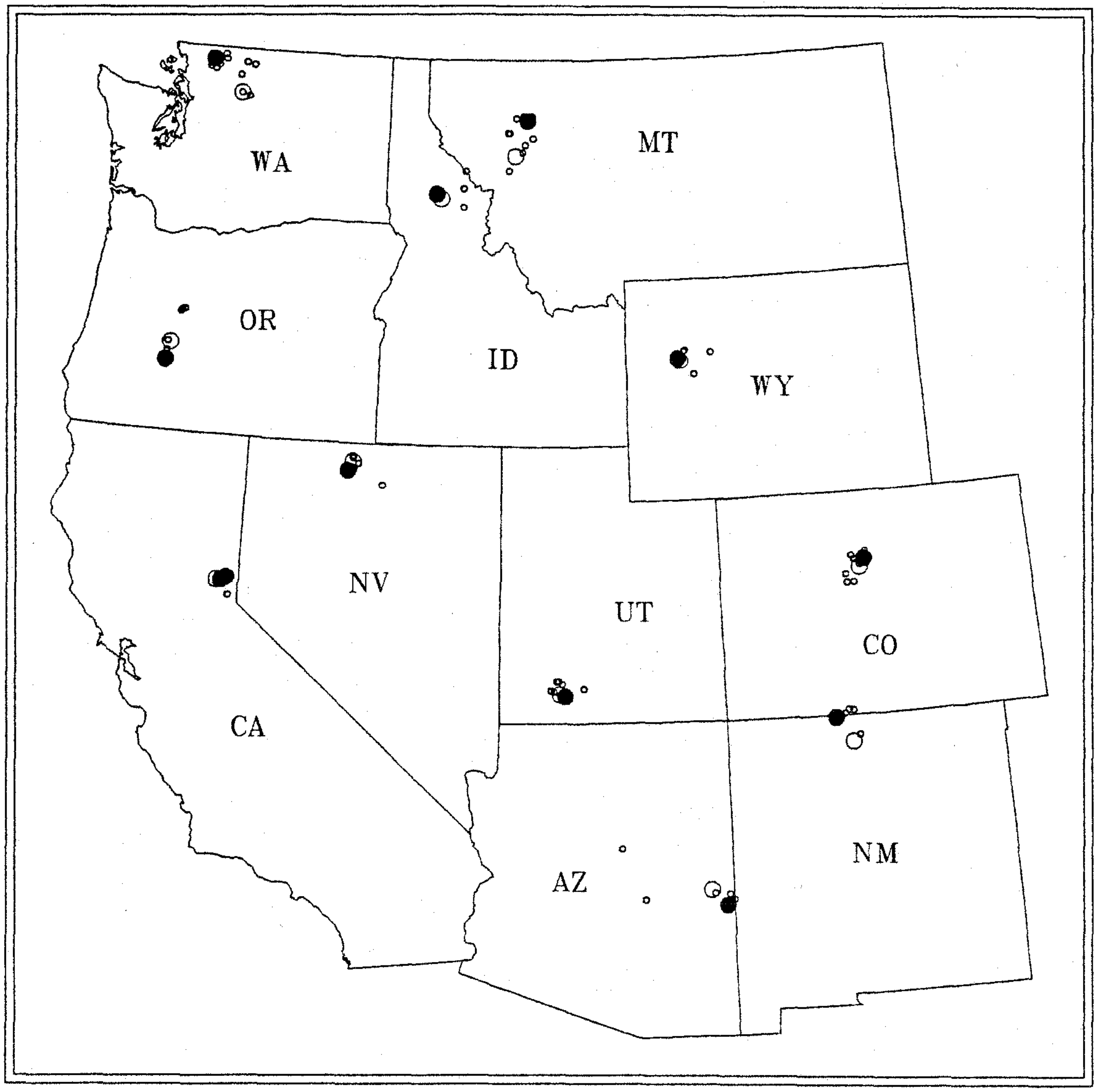

Figure 3. Location of study sites throughout the western United States.

Selection of River Basins

One river basin was selected from each of the eleven western states. Each has a USGS streamgaging station with a period of record sufficiently long to permit evaluation of the association of streamflow with ENSO. The basins are all located in headwater areas and are significant sources of water supply to downstream users. For the most part, storage and diversions above the gaging points are limited; where necessary, the data have been corrected for these impacts. Monthly streamflow data for the period of record were retrieved from the CFS system and aggregated into seasonal runoff volumes based on the forecast season used by the WSFS at each location. This varies from April through September for much of the Pacific Northwest and Rocky Mountains to February through May in parts of the southwest.

Precipitation Data

Winter precipitation is the source of moisture for mountain snowpacks, although the accumulation season varies somewhat throughout the western United States depending on latitude and elevation. Annual precipitation in the Pacific Northwest is concentrated in the period October through March, whereas in the desert Southwest only about half of the annual precipitation falls during this same six-month period. However, in the mountains of both these regions, the snowpack derives from precipitation during this time period. Therefore, in this analysis our attention centers on precipitation for the six-month period of October through March as an indication of the moisture producing the snowpack. A single National Weather Service (NWS) station in each river basin was selected for analysis and monthly precipitation was aggregated into six-month totals.

Selection of a Representative Snow Course

Most precipitation gages are located at low elevations and it is uncertain whether these data are representative of precipitation at higher elevations. A better indicator of moisture accumulation in mountainous areas is the snow water equivalent (SWE) observed by the Soil Conservation Service at numerous sites throughout the western United States. Historically, SWE has been monitored on the first of each month beginning in January. The change in SWE through the year is dependent not only on the amount of snowfall but also on the amount of snowmelt which may have occurred during each month. Nevertheless, SWE is the single most important predictor of seasonal streamflow and must therefore be considered a good indicator of accumulated mountain precipitation.

In each river basin selected for evaluation there are a number of snow courses which tend to be clustered at higher elevations near the head-waters. Since these sites are usually within homogeneous climatic regions the variation in SWE is normally highly correlated among sites. Although the month of maximum accumulation may vary from one basin to another across the western United States, the March SWE was used uniformly in this analysis for comparison. One cluster of sites in each of the eleven river basins was selected from the data base.

In an attempt to determine the most representative site and separate out factors that influence the correlation between sites, principle component analysis (PCA) was conducted on the clusters in each basin. Briefly, PCA is a procedure which forms linear combinations of the variables in a multivariate data set with the objective of explaining the maximum amount of the variability in the entire data set with the first PC, and the maximum amount of the remaining variance with each succeeding PC. Between 75 to 95 percent of the variance in the clusters of snow courses was explained by the first principle component, indicating that the snow courses tend to vary over time in a similar manner. The clusters which exhibited the highest values for variance explained by the first PC were homogenous in their temporal variation while those with the lower values often had one or more sites which behaved differently from the majority.

The most representative site was identified based on the correlation coefficient, often called the loading, between the first PC and the individual snow course. The site with the highest loading was selected as the most representative site in a cluster. Three factors seem to have a significant effect on the loading of an individual snow course on the first PC. First, low elevation sites in several clusters were identified by PCA because at these locations snow had often completely melted by March while at higher elevation sites snow was still accumulating. This resulted in these sites showing much less variation than higher elevation sites. The second factor that seemed to be identified by PCA was orographic location. Sites located on different sides of mountain ranges are often effected by considerably different weather patterns and thus exhibit diverse accumulation patterns. Finally, irregularities in the data set were also screened by this technique.

The results of a PCA for the cluster of snow courses in the Wind River basin in Wyoming is shown in Table 1 to illustrate the technique. Loadings of the March SWE for each location on the first PC is shown along with the variance explained by each PC. An inventory of the eleven sites used in this study is presented in Table 2, identifying the National Weather Service climate stations, the snow courses and the U.S. Geological Survey streamgaging sites.

The Southern Oscillation Index

The monthly Southern Oscillation Index (SOI), as published by the Climate Analysis Center, is used as an indicator of the state of the climate in the tropical Pacific Ocean. When the SOI has a negative value, the pressure gradient is weaker than average which is typical of El Niño. Conversely, a positive value indicates a strong pressure difference representative of La Niña. When the historic values of the SOI are compared with lists of El Niño occurrences, (e.g. Rasmusson, 1984), it appears to be a very good indicator. This behavior can also be seen in the time series of SOI presented in Fig. 2. The SOI represents a continuous and quantifiable measure which can then be related to hydroclimatic variables. It is used in the subsequent analyses in this paper to assess the association between atmospheric and oceanic phenomena in the tropical Pacific Ocean and hydroclimatic response in the western United States.

RELATIONSHIP OF SOI TO PRECIPITATION, SWE AND STREAMFLOW

Correlation analysis is used to explore the nature of the association between the SOI, an indicator of El Niño and La Niña events, and climatic and hydrologic events in the western United States. The analyses are designed to answer several questions related to the nature and magnitude of the association of western climate and streamflow. First, the temporal association of SOI with winter precipitation, March SWE and streamflow during the principal runoff period is investigated to determine the time period for which a maximum correlation exists. The correlation of precipitation, SWE and streamflow with SOI is then determined at all sites to evaluate the magnitude and sign of the correlation as well as the spatial variation across the region.

Temporal correlations

Previous studies have suggested that the occurrence of El Niño (or La Niña) is a precursor to certain climatic and hydrologic behavior in the western United States. To assess this behavior, SOI was averaged over successive two, three, four, five and six-month periods and correlated with seasonal streamflow volume as a measure of the aggregate climatic response. The correlation coefficients were calculated for SOI averaging periods beginning in April of the previous year through April of the year in which the streamflow was observed. The largest correlation coefficients were observed when SOI was averaged over a three-month period. Results of this analysis for two sites, the Lochsa River in Idaho and the Salt River in Arizona, are shown in Fig. 4. These sites exhibited among the highest correlations observed and are indicative of the behavior in the Pacific Northwest and Southwest, respectively. Fig. 4 shows the correlation of the three-month averaged SOI with April through September runoff volume for the Lochsa River and February through May runoff for the Salt River. It is obvious from the graphs that strong correlations exist for SOI averaged over a three-month period beginning as early as June of the previous year. For the Lochsa River, the maximum correlation occurred for SOI averaged over the period beginning in July of the previous year while for the Salt river the maximum value is for October-December averaged SOI. In both cases, statistically significant correlations occur at least over the period from June through February. For comparison the null hypothesis of no correlation can be rejected for correlation coefficients greater than 0.274 for the Lochsa River and 0.223 for the Salt River. The magnitude of these correlations is considerably stronger than those observed by Redmond and Koch (1991) for annual streamflow and SOI averaged over a six-month period.

Table 1. Results of a principle components analysis for the Wind River Basin in Wyoming.

	COMPONENT LOADINGS						
SNOW COURSES	1	2	3	4	5	6	7
F10	.940	-.181	.212	-.123	-.040	-.125	-.078
F08	.958	.107	.152	.047	.208	-.003	.054
F07	.967	.123	.046	.132	-.036	.111	-.126
F06	.968	.066	.121	.067	-.147	.008	.131
F04	.952	.078	-.165	-.220	.006	.104	.020
F03	.915	.120	-.359	.080	.005	-.113	-.007
F01	.319	-.944	-.068	.043	.017	.033	.015
	PERCENT OF TOTAL VARIANCE EXPLAINED						
	1	2	3	4	5	6	7
	78.868	13.922	3.508	1.368	.970	.752	.613

Table 2. Climate station, snow course, and stream gage for selected basins in the Western US.

STATE NAME	CLIMATE STATION	SNOW COURSE	STREAM GAGE
WA	NEWHALEM	MARTEN LAKE	SKAGIT R AT NEWHALEM
OR	OAKRIDGE FH	NORTH UMPQUA	MF WILLAMETTE R NR OAKRIDGE
ID	FENN R.S.	SHANGHAI SUMMIT	LOCHSA R NR LOWELL
MT	SEELEY LAKE R.S.	SPOTTED BEAR MTN	SWAN R NR BIGFORK
WY	DUBOIS	DUNOIR	WIND R NR DUBOIS
CA	TRUCKEE R.S.	INDEPENDENCE CAMP	L. TRUCKEE R NR BOCA RES
NV	PARADISE VALLEY	LAMANCE CREEK	L HUMBOLDT R NR PARADISE
UT	ALTON	HARRIS FLAT	SEVIER R AT HATCH
CO	DILLON 1 E	BERTHOUD FALLS	BLUE R NR DILLON RES
AZ	WHITERIVER	BEAVER HEAD	SALT R NR ROOSEVELT
NM	CHAMA	CHAMITA	RIO CHAMA NR EL VADO RES

The other interesting result of this analysis is the sign of the correlation coefficient. A strong positive correlation was noted for the Lochsa River while a similarly strong negative correlation was observed for the Salt River. This is consistent with previously observed results which indicate the propensity for below (above) average flow in the Pacific Northwest (Southwest) during El Niño events, when the SOI is negative.

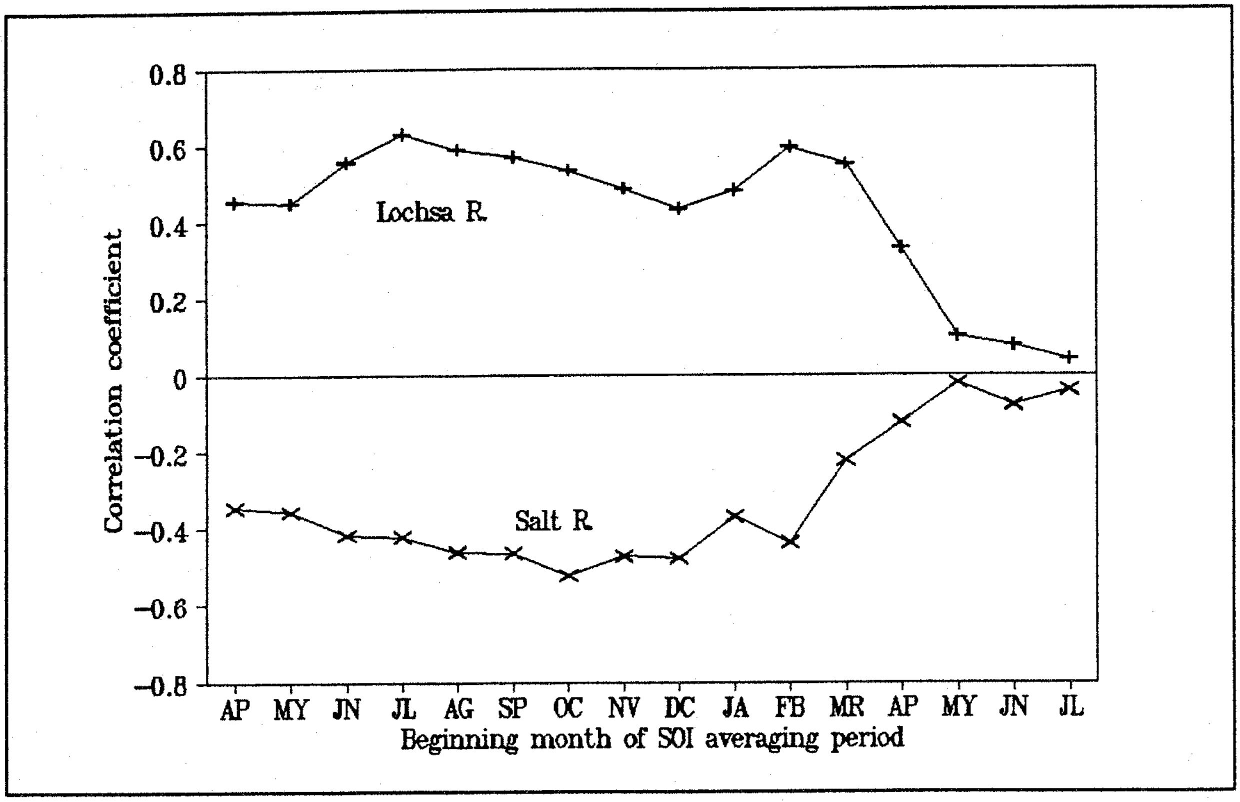

Figure 4. Correlation coefficients between three-month averaged SOI and seasonal streamflow volume for the Lochsa R., ID, and the Salt R., AZ.

Spatial relationships with SOI

Winter season precipitation, March SWE and seasonal streamflow volume for each of the eleven sites were correlated with SOI to examine the nature and magnitude of the relationship. In this analysis, SOI was averaged over the period from July through September. Observed correlation coefficients at many sites, including those in the Pacific Northwest, are the highest for this period. In addition, this period precedes the water year and may be useful for extension of the existing water supply forecasting procedures. Correlation coefficients for each variable at each site with the three-month averaged SOI are shown in Table 3. The sites are arranged roughly in a north to south order to assist in observing the general pattern of positive correlations in the Pacific Northwest and negative correlations in the Southwest. As can be seen from the values in the table, this pattern, which has been generally observed in other studies, is consistent for all of the variables analyzed. In addition, the magnitude of the correlation is also strongest in these regions, although opposite in sign, and is statistically insignificant for the other sites. The strongest correlations with SOI are in the Pacific Northwest where all of correlation coefficients at all of the sites are statistically significant. The Arizona site in the extreme Southwest also exhibits a statistically significant correlation with all variables, and in southern Utah seasonal streamflow volume is significantly correlated. In general, correlation coefficients for all three variables were roughly equivalent in magnitude although streamflow tended to have the highest correlation. Variations are most likely due to individual site characteristics and climatic conditions. March is not always the month of maximum snow accumulation at all sites which may lead to some of the difference between SWE and streamflow. In addition, at least one of the sites (Willamette River, OR) has a substantial amount of the runoff due to low elevation winter rainfall. Finally, there are some significant differences in elevation between the climate stations and snow courses. A particular example is the Wyoming site. In this case a much stronger correlation was observed for streamflow, which results from high elevation precipitation, than for the valley precipitation station. However, the overall strength of the correlations suggests that the SOI is an indicator of the significant role that ENSO plays in the climate of the western United States and in particular the Pacific Northwest and Southwest.

Table 3. Correlation coefficients between SOI and winter precipitation, snow course with maximum principle component loading, and streamflow volume during forecasting period.

STATE NAME	WINTER PRECIPITATION	SNOW COURSE WITH MAXIMUM PC LOADING	STREAMFLOW VOLUME DURING FORECAST PERIOD
WA	.562	.538	.603
OR	.288	.359	.327
ID	.599	.517	.664
MT	.464	.312	.414
WY	.172	.330	.504
CA	.013	-.115	-.027
NV	-.108	-.052	-.294
UT	-.296	-.183	-.413
CO	.188	.293	.137
AZ	-.360	-.342	-.429
NM	-.075	.125	-.078

IMPLICATIONS FOR WATER SUPPLY FORECASTING

The statistical analysis has shown that climate and streamflow in parts of the western United States are related to the occurrence of El Niño or La Niña as described by the SOI. The relationship is limited to winter precipitation and is therefore also related to SWE and snowmelt runoff. The period of maximum correlation of climate or streamflow with SOI occurs when SOI is averaged over a three-month period beginning as early as the previous July in some areas. Statistically significant relationships are mostly observed in the Pacific Northwest and Southwest regions while a broad band across the center of the western United States exhibits little if any association. These results suggest that the SOI may be useful for water supply forecasting.

Improvements in current procedures

As Shaake and Peck (1985) have observed, the principal source of error in early season forecasts is due to the uncertainty in expected future precipitation. Since there is little or no statistically significant persistence in monthly precipitation or SWE increments, conditioning future estimates on an exogenous variable such as SOI could prove useful in decreasing the error. One practice in developing forecast equations has been to use all historic information that proves useful in minimizing the error of the forecast equation. Then, in the application of the equation, if a variable such as April SWE is not yet available, the mean value (or the mean value of the increment between the current month and April) is used in the equation. The correlations of both precipitation and SWE with SOI as observed in the Pacific Northwest and portions of the Southwest would suggest that estimates of future precipitation or SWE could be based on linear relationships with SOI rather than on historic mean values. Alternatively, new methods being used by the Water Supply Forecasting Staff of the Soil Conservation Service will develop equations using only data available up to the time the forecast is made. In this case the SOI has been shown to be a significant predictor of streamflow volume, especially early in the year, and can aid in decreasing the uncertainty involved in estimating expected future climate scenarios.

Extensions of current procedures

Water supply forecasts are used as a basis for reservoir operation in many parts of the western United States. However, the guidance provided by these forecasts does not begin until at least January each year when the first forecasts are issued. For certain regions of the West, in particular the Pacific Northwest, it appears that a significant amount of information may be available as early as October each year with regard to the volume that can be expected in the subsequent year's snowmelt runoff. The use of this information along with a knowledge of the antecedent moisture conditions can provide some guidance to reservoir operators in the Fall and early Winter months prior to the first water supply forecasts. Such information will be particularly useful in mitigating the impacts on secondary uses of the reservoir. For example, if the primary use of a reservoir is flood control, then operation early in the water year will proceed on the assumption that a high flow, based on the historical record, can be expected until information to the contrary becomes available. This operational procedure may result in excessive releases to provide space for flood waters in the event an average or below average flow actually occurs. This type of an operating policy will adversely impact other uses such as hydropower production or water supply. Knowledge of the SOI in the late summer and fall months can provide some guidance as to the nature of the coming water year and can therefore provide some additional information which can in turn increase the benefits derived by the operation of the reservoir. Again, this benefit is restricted to those regions where SOI has a statistically significant association with streamflow.

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