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Relationship Between a 700-MB "Dry/Wind" Index and Springtime Precipitation and Streamflow Within Four Snowmelt-Dominated Basins in Northern New Mexico and Southern Colorado

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RELATIONSHIP BETWEEN A 700-MB “DRY/WIND” INDEX AND SPRINGTIME PRECIPITATION AND STREAMFLOW WITHIN FOUR SNOWMELT-DOMINATED BASINS IN NORTHERN NEW MEXICO AND SOUTHERN COLORADO

A Professional Project Report
Submitted

By

Kerry M. Jones

In Partial Fulfillment
of the Requirements for the Degree of
Master of Water Resources
Hydroscience Concentration
Water Resources Program

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RELATIONSHIP BETWEEN A 700-MB "DRY/WIND" INDEX AND SPRINGTIME PRECIPITATION AND STREAMFLOW WITHIN FOUR SNOWMELT-DOMINATED BASINS IN NORTHERN NEW MEXICO AND SOUTHERN COLORADO

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LIST OF ACRONYMS AND ABBREVIATIONS

af	acre-feet
AM	April-May
AMJ	April-June
cfs	cubic feet per second
kaf	Thousands of acre-feet
CD	climate division
DWND	dry/wind index
ENSO	El Niño-Southern Oscillation
mb	millibar
MA	March-April
MAM	March-May
NCAR	National Center for Atmospheric Research
NCEP	National Centers for Environmental Prediction
PDO	Pacific Decadal Oscillation
PDSI	Palmer Drought Severity Index
SD	standard deviation
SMR	snowmelt runoff
SNOTEL	Snow Telemetry
SOI	Southern Oscillation Index
SST	sea-surface temperature
SWE	snow water equivalent
USGS	United States Geological Survey
NOAA	National Oceanic and Atmospheric Administration
NRCS	Natural Resources Conservation Service

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ABSTRACT: Climatic anomaly relationships that could potentially improve seasonal streamflow forecasts in southern Colorado and northern New Mexico were investigated through consideration of meteorological anomalies during the snow ablation season from 1980-2006. Historical relationships between (i) humidity and wind from March-June defined by an index developed for this study, denoted DWND; (ii) springtime precipitation; (iii) departures from expected seasonal streamflow; and (iv) El Niño-Southern Oscillation (ENSO) were examined within four sub-basins in southern Colorado and northern New Mexico: Upper San Juan above Pagosa Springs, Upper Rio Chama above El Vado Reservoir, and Embudo Creek/Rio Pueblo above Dixon. Potentially important links emerged between the DWND index and springtime precipitation. Namely, years that had well-above average DWND index values during April and May recorded below average precipitation if any at all, while years that had a lower average DWND index recorded near normal to much above normal precipitation. Furthermore, the relationship between the DWND index and Niño 3.4 anomalies is better defined than is the relationship between springtime precipitation and ENSO anomalies. This finding may increase confidence that cold (warm) phase ENSO extrema result in a greater (fewer) number of days characterized by low humidity and moderate to strong winds at high elevations in the San Juan and Sangre de Cristo mountains, thereby affecting snowpack and subsequent streamflow.

CHAPTER 1

INTRODUCTION

Snowmelt Runoff: Nature's Elixir in the West

High-elevation watersheds in the western United States possess the most essential component of the water supply forecast system—snow. These snowmelt-dominated basins exhibit a strong seasonality in streamflow such that baseflow conditions from September to March give way to increasing streamflow due to snowmelt runoff (SMR) from April to June with warming temperatures. SMR typically peaks in late May or early June, before streamflow recedes in August.

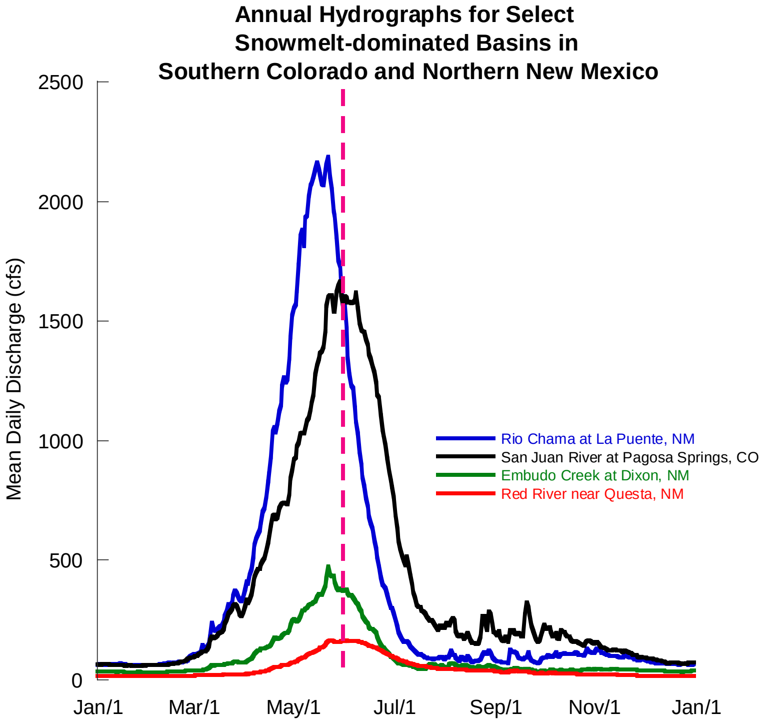


Figure 1. Annual hydrographs for select snowmelt-dominated basins in southern CO and northern NM.

Figure 1 depicts mean annual hydrographs for select snowmelt-dominated watersheds in southern Colorado and northern New Mexico from 1980-2006 (see Fig. 13 for a map of these locations). SMR accounts for as much as 80% of the total annual streamflow volume in these snowmelt-dominated basins (Serreze *et al.*, 1999; Stewart *et al.*, 2005).

The amount of water stored in the mountain snowpack, commonly referred to as snow water equivalent (SWE), has long been measured at high-elevation snow courses throughout the western United States. These permanent sites, usually 1000 feet in length, are typically located within an open meadow that is protected from the wind. Beginning in late fall and continuing through the spring, trained technicians conduct manual surveys where snow depth and SWE are measured around the beginning of each month. There are approximately 100 manual snow course sites in Colorado and New Mexico.

During the late 1970s, the USDA's Natural Resources Conservation Service (NRCS) installed a network of automated Snow Telemetry (SNOTEL) stations to supplement snow course data and, more importantly, to provide daily measurements of SWE. The current SNOTEL system has nearly 700 remote sites in the western United States including Alaska (Schaefer *et al.*, 1996). In northern New

Mexico and southern Colorado, data from nearly 50 automated SNOTEL stations are currently available although fewer than half of these have a period of record greater than 25 years. The Upper San Juan SNOTEL station in southwest Colorado, an original SNOTEL station with a period of record of nearly 30 years, is pictured in Figure 2. Various sensor data that are commonly available at most SNOTEL stations is shown in Table 1.

Figure 2. Upper San Juan SNOTEL.
Photo courtesy of NRCS (2007).

Data from both the automated SNOTEL stations and manual snow courses are an essential component of the NRCS Snow Survey Program. Unlike SNOTEL sites, snow courses do not provide precipitation, temperature or other meteorological data.

TABLE 1. Typical SNOTEL Sensor Array.

Instrument	**Parameter**
Snow Pillow Device and Pressure Transducer	SWE (in.)
Standard 12-inch, all-season, alter-shielded rain gage	Precipitation (in.)
Sonic Sensor	Snow Depth (in.)
Shielded Thermister	Air Temperature (˚C)

The interannual variability of mountain snowpack as measured by the SNOTEL-snow course network can be striking. Time series of daily SWE measured at the Upper San Juan SNOTEL in southwest Colorado, for example, are shown in Figure 3 and Figure 4 to illustrate year to year variability. It can be seen that, on average, SWE typically reaches its peak around or shortly after 1 April. This trend generally holds true for most high-elevation watersheds in the West. However, at relatively low elevation or near the southern edge of the snowpack, such as Gallegos Peak, March SWE may provide a better estimate of peak snowpack conditions (Figs. 5-6). Regardless, relationships between of the amount of snow water in the mountain snowpack by early to mid spring and resultant streamflow during the snow ablation season are well documented (Stewart *et al.*, 2005; Cayan *et al.*, 2001).

In general, as more snow accumulates in the high-elevation watersheds the volume of water ultimately released into the river channels downstream also increases. It will be shown in a later section that simple linear regression based on annual values of 1 April SWE at the Upper San Juan SNOTEL station, for example, accounts for nearly 80 percent of the interannual streamflow variance of the San Juan River at Pagosa Springs, CO.

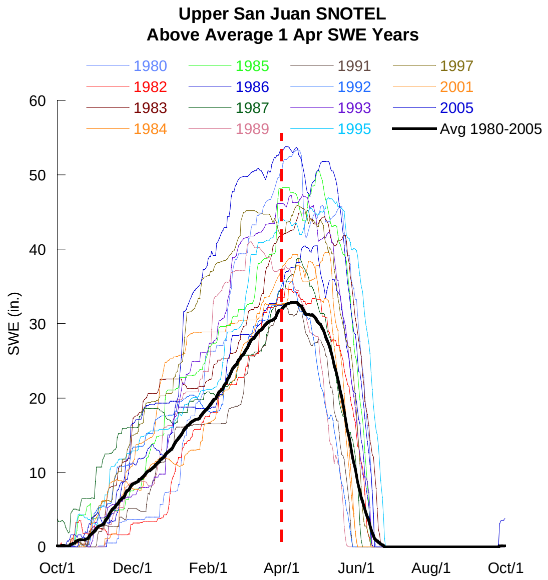


Figure 3. Daily SWE for years with above average 1 Apr SWE, Upper San Juan SNOTEL.

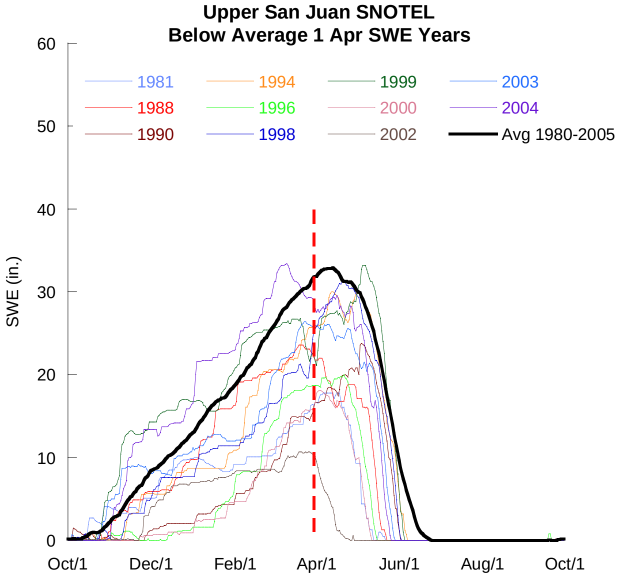


Figure 4. Same as Fig. 3 except for below average years. Location of the Upper San Juan SNOTEL site is shown in Fig. 13.

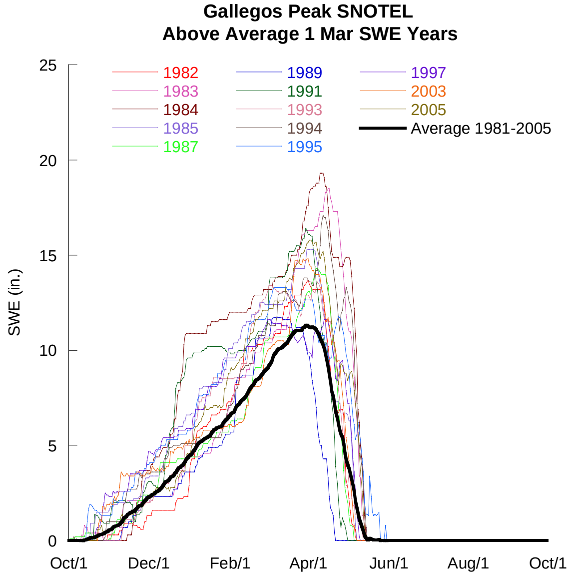


Figure 5. Daily SWE for years with above average 1 Mar SWE, Gallegos Peak SNOTEL.

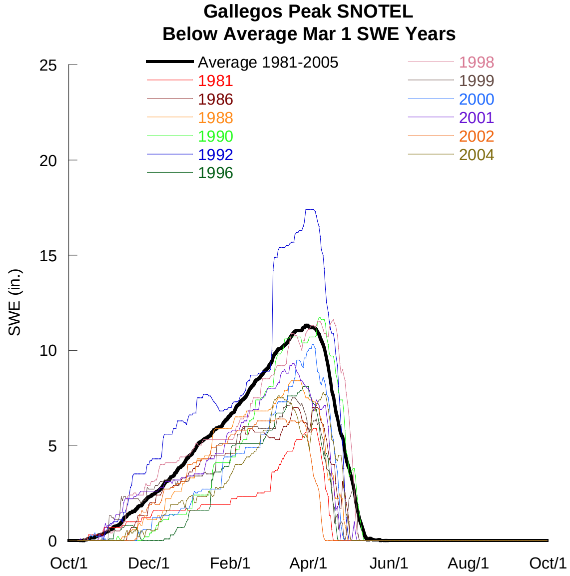


Figure 6. Same as Fig. 5 except for below average years. Location of the Gallegos Peak SNOTEL site is shown in Fig. 13.

A close inspection of Fig. 4 reveals one year, 2004, when SWE remained above-average from October to March only to end up below average on 1 April. During that year, anomalous snow ablation processes may have resulted in accelerated loss of snowpack just before 1 April. How did spring streamflow respond during that year and other similar years? Conversely, how might streamflow respond during years that observe above-average SWE on 1 April, but the ensuing April-June period is unusually dry and/or windy? In the absence of anomalous snow ablation processes, such as consecutive days of unusually dry and windy weather or short-duration heat waves during March and April, accumulation-based water supply forecasts work reasonably well much of the time (Pagano, 2004). Investigating these anomalous ablation processes and exploring possible answers to the aforementioned questions could potentially result in more skillful streamflow forecasts.

Mountain Snowpack: Atmospheric and Hydrologic Forcings

Atmospheric and hydrologic variables that govern the evolution of mountain snowpack and subsequent SMR are complex. During the snow accumulation season, for example, the frequency of precipitation events, ambient air temperature and boundary layer winds are key atmospheric variables that affect the rate at which mountain snowpack develops. Other atmospheric-related forcings such as the turbulent transfer of heat and moisture and radiative exchanges are also important (Gray and Male, 1981). The effects of topography and land surface variables such as slope, aspect, elevation, and vegetation also greatly determine the spatial distribution of snow cover in any alpine or sub-alpine watershed.

The rate at which snow melts in late spring and early summer is principally driven by increasing solar radiation and warming temperatures (Elder *et al.*, 1991). Decreasing snow albedo, wind-driven sublimation, and heat exchange between the atmosphere and snow surface are also important snow ablation processes. A recent study by Painter *et al.* (2007) found that the deposition of dust, originating from the high desert and Colorado Plateau of northern Arizona and the Four Corners region, on snowpack in high-elevation watersheds of the San Juan Mountains in southwest Colorado resulted in snow melting out nearly a month earlier than normal. However, depending upon the density and ripeness of the snowpack, melt water may not be immediately released to the underlying surface. Soil moisture is an important hydrologic variable that can modulate the rate at which the mountain snowpack releases its snow water to stream channels.

Despite these inherent complexities, seasonal water supply forecasts jointly issued by NRCS and NOAA's National Weather Service (NWS) have generally improved throughout the western United States since the early 1980s (Pagano, 2004). Trends in population growth coupled with a greater number of studies documenting the effects of climate change on mountain snow pack and SMR in recent years have elevated the need for additional improvement in skill of water supply forecasts to critical levels. For example, Stewart *et al.* (2005) and Cayan, *et al.* (2001) revealed that peaks in runoff associated with snowmelt had shifted earlier in the snowmelt period for many rivers in the western United States.

The Forecast Challenge

The relationship between mountain snowpack and snowmelt runoff is especially interesting in northern New Mexico and southern Colorado, where the effects of soil moisture deficits and dry, windy springtime periods often coexist (i.e. this region is very sensitive to warm spells or extensive sublimation events). SWE measured and/or independently sampled near the beginning of each month is the foundation upon which seasonal water supply forecasts are based. Given the uncertainty of future precipitation during both the accumulation and ablation seasons (see Figs. 3-6), water supply forecasts based upon 1 February SWE, for example, are often less skillful than those based upon 1 March or 1 April snowpack data (Pagano, 2004).

Despite known inputs, such as 1 April SWE, departures between observed and predicted streamflow at a particular station can be significant irrespective of the statistical methodology used. While precipitation after 1 April through the end of the forecast period naturally accounts for a significant portion of these departures (Pagano, 2004), the effects of anomalously warm or cold temperatures, soil moisture (either surpluses or deficits), sublimation and accelerated ablation, although difficult to quantify, also contribute to streamflow forecast errors. Other sources of forecast error include rare and unusual weather events that are not possible to predict three months or more in advance and are not accounted for in statistical forecast methodologies.

Weather events, such as excessive precipitation or an anomalously cold period followed by rapid warming in Apr-Jun, can result in significant under-forecasts of streamflow. Pagano (2004) found that significant under-forecast events from 1982-2003 in the western U.S. were characterized by below average snowpack conditions on 1 April followed by above-average precipitation in Apr-Jun.

Conversely, forecast overestimates are more often than not the result of average or slightly above average snowpack conditions followed by anomalously warm, dry, and windy weather. A forecast of streamflow that exceeds what is actually observed would be troublesome for water managers since water allocation could potentially be impacted.

El Niño-Southern Oscillation and Pacific Decadal Oscillation

During the past decade, a considerable amount of climate-related research has focused on the El Niño-Southern Oscillation (ENSO) cycle and Pacific Decadal Oscillation (PDO). The cause and effect relationship between tropical wind fields and warm/cold phases of ENSO have been well documented. Rasmusson and Carpenter (1982) demonstrated that the onset of the warm phase of ENSO (El Niño) is strongly correlated with a weakening of the trade winds over the equatorial Pacific. This decrease in wind stress acts to diminish the upwelling of colder waters off the Peruvian coast, resulting in an anomalously warm pool of water over the eastern tropical Pacific (Fig. 7). Subsequent studies have correlated these anomalously warm Pacific sea-surface temperatures (SST) to a large-scale pattern of sea-level pressure anomalies at Tahiti and Darwin, Australia, called the Southern Oscillation (SO) (Walker, 1924).

The PDO is derived from monthly SST anomalies in the North Pacific, poleward of 20˚ North latitude. The warm (cold) phase of the

PDO (Fig. 8) occurs when North Pacific SST anomalies are negative (positive) (Mantua *et al.*, 1997). The PDO has an equatorial Pacific expression that can interfere either constructively or destructively with ENSO anomalies. PDO events persist for considerably longer periods (20 to 30 years) than do ENSO events, which typically persist anywhere from 6 to 18 months. Therefore, the effects of La Niña on southwestern North America during a warm PDO phase, for example, may be different than during a cold PDO phase. Indeed, some scientists argue that a warm PDO phase is simply a larger scale La Niña and links between ENSO and PDO are not well understood. Another important distinction between the PDO and ENSO is the fact that the PDO relates SST anomalies across the North Pacific, which is much larger in areal coverage than the relatively narrow region of the tropical Pacific associated with ENSO.

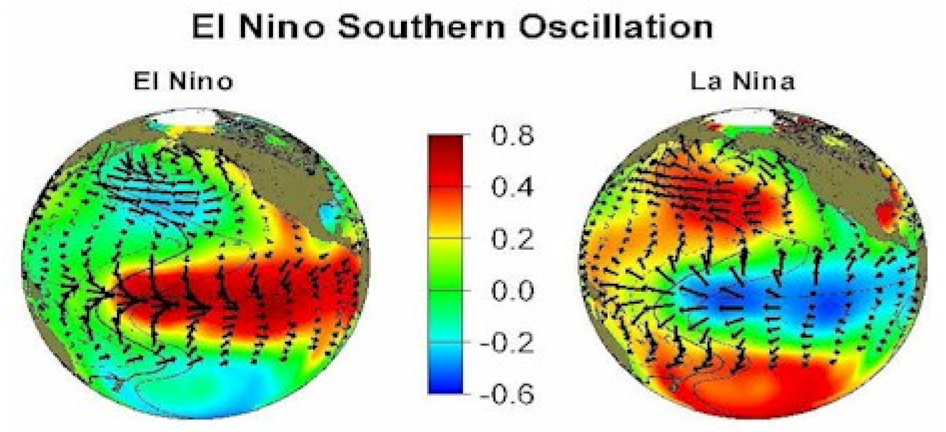


Figure 7. Sea-surface temperature anomalies and surface wind vectors associated with ENSO extrema: El Niño (warm) and La Niña (cold). Source: http://jisao.washington.edu/

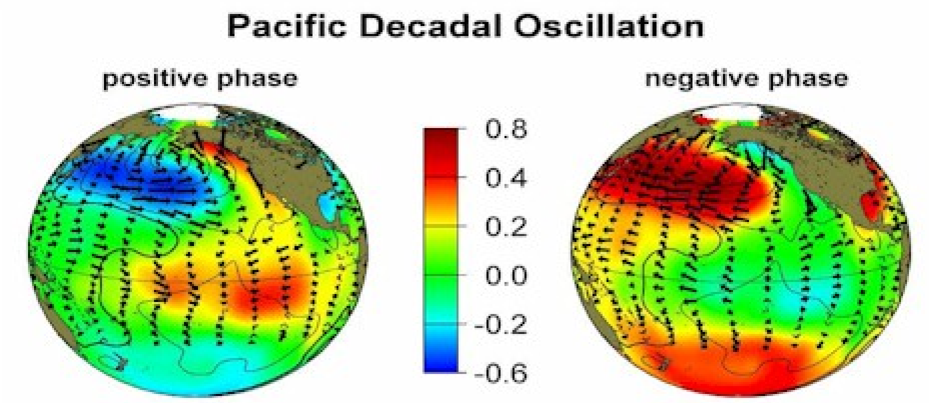


Figure 8. Sea-surface temperature anomalies, sea-level pressure and surface wind associated with Pacific Decadal Oscillation (PDO) extrema: positive (cold) and negative (warm).
Source: http://jisao.washington.edu/

Fluctuations in sea-surface temperatures (SST) and the resultant larger-scale shifts in surface pressure patterns in the tropical Pacific basin are continually monitored to assess the strength of ENSO from season to season. The Southern Oscillation Index (SOI) and equatorial Pacific SST anomalies are the two best known indicators.

SST anomalies associated with the ENSO cycle can have significant impacts on winter precipitation across the western U.S. (Andrade *et al.*, 1988; McCabe *et al.*, 1999). Andrade and Sellers (1988) established a connection between ENSO cycles and the seasonal distribution of precipitation in Arizona and southwest New Mexico such that warm ENSO phases (El Niño) produced above average precipitation while cold ENSO phases (La Niña) produced below average precipitation.

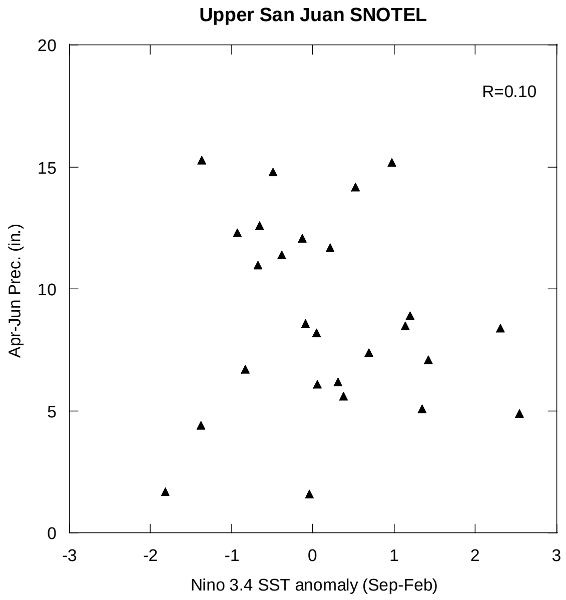
Cayan and Webb (1992) examined relationships between the SOI and April 1 SWE, and between the SOI and annual runoff in the western U.S. They found that SWE and annual runoff were negatively correlated with the SOI in the southwestern U.S., which suggests that El Niño (La Niña) events result in increased (decreased) SWE and annual runoff. Bradshaw (1994) in an unpublished study examined the impact of warm ENSO years on New Mexico snowfall and found that positive relationships exist between warm ENSO cycles and increased snowfall for parts of the state. According to Bradshaw (1994), the weakest correlations were found to be over the northwest plateau and northwest mountains while the greatest positive influences were over the northeast highlands and plains, southern mountains, southwest deserts and central valleys where snowfall totals averaged 200 to 300 percent of normal.

Gutzler *et al.* (2002) found that the “ENSO-based predictability seems to undergo a profound decadal modification that might be associated statistically with the Pacific Decadal Oscillation (PDO) but the physical link to North Pacific ocean temperatures is problematic.” Studies have found that significantly positive PDO years favor above-normal winter precipitation, while significantly-negative PDO years favor below-normal precipitation (Guan *et al*., 2005; Liles, 1999).

During negative PDO years, Liles (1999) found that annual precipitation in New Mexico climate division 2 (Northern Mountains; see Fig. 14) was 90 percent of normal compared to 124 percent of normal during positive PDO years.

When relating ENSO and streamflow directly, Ropelewski and Halpert (1986) found that the Pecos River basin in New Mexico is very near the northern and eastern limit of the Southwest U.S. ENSO influence. A subsequent study by Molles and Dahm (1990) found similar results and demonstrated that streamflow in the Gila River basin of southwest New Mexico responded more favorably to warm ENSO cycles than did the Pecos River basin, although the Pecos River basin still exhibited a very significant ENSO-related response.

While important links between ENSO and precipitation variability in the southwest U.S. have been documented, especially during the fall and winter, confidence integrating long-lead precipitation outlooks into late winter and early spring water supply forecasts for northern New Mexico and southern Colorado is low. This is due in large part to a statistically insignificant relation between ENSO anomalies (e.g. SOI and Niño 3.4 SST indices), upon which seasonal precipitation outlooks are almost exclusively based, and springtime precipitation at high elevations in the San Juan and Sangre de Cristo Mountains of southern Colorado and northern New Mexico (Figs. 9-12).



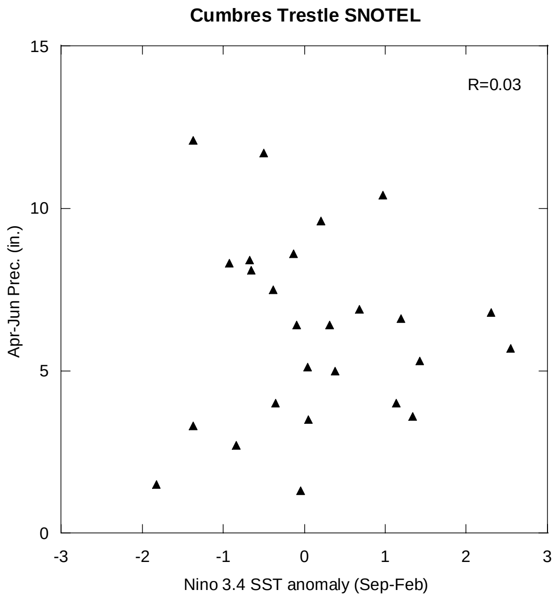
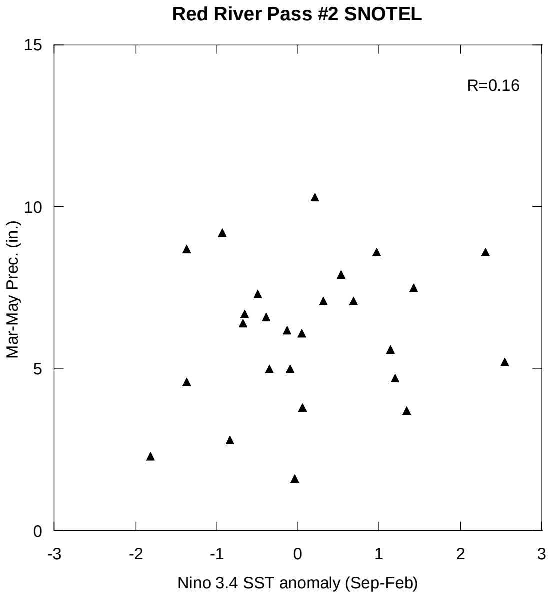


Figure 9. Nino 3.4 SST anomalies vs. AMJ precipitation at the Upper San Juan SNOTEL.

Figure 10. Same as in Fig. 9 except for Cumbres Trestle SNOTEL.



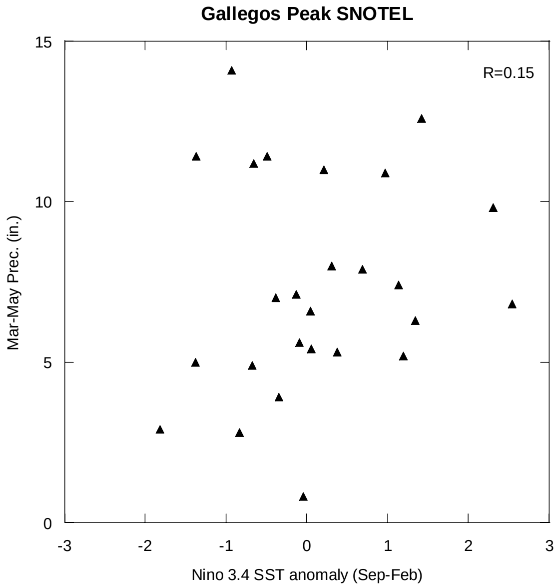


Figure 11. Same as in Fig. 9 except for Red River Pass #2 SNOTEL.

Figure 12. Same as in Fig. 9 except for Gallegos Peak SNOTEL.

Figures 9 through 12 depict the relationship between springtime precipitation and ENSO anomalies for the four SNOTEL stations used in this study. Note the lack of correlation between Niño 3.4 SST anomalies in the six months preceding spring SNOTEL precipitation. That said, days characterized by little or no measurable precipitation and low humidity are more common than wet days in the spring. Moreover, low humidity days are often windy, which can accelerate the loss of snowpack through sublimation processes and result in less-than-expected streamflow particularly early in the forecast period. It is therefore instructive to collectively investigate relationships between dry, windy Apr-Jun periods and springtime precipitation, departures from expected seasonal streamflow and ENSO.

CHAPTER 2

DATA

Study Area

Four snowmelt-dominated watersheds in the San Juan and Sangre de Cristo mountains of southern Colorado and northern New Mexico were chosen for this study (Fig. 13). These high-elevation basins were carefully selected so that a long-term SNOTEL station, with a historical record extending back to at least 1981, was paired with an unencumbered stream that was gauged near the outlet of the same sub-basin for an equally long period of time. Despite the fact that historical records of SNOTEL stations are considerably shorter than snow courses, SNOTEL data were used in this study since, in addition to SWE, daily precipitation was a critical element. The selected basins are geographically diverse in terms of meridional orientation (i.e. north to south), elevation and areal extent (Table 2).

Historical measurements of 1 March and 1 April SWE, cumulative precipitation and streamflow volume from April-June, as well as 700-mb mean values of air temperature, zonal wind and relative humidity within each of the four high-elevation watersheds were analyzed between 1980 and 2006.

TABLE 2. Description of Study Basins.

	Drainage Area (mi²)	**Latitude** SNOTEL [Stream Gauge]	**Longitude** SNOTEL [Stream Gauge]	**Elevation / Datum** SNOTEL [Stream Gauge]
Upper San Juan above Pagosa Spgs.	772	37.48˚N (37.26˚N)	106.83˚W (107.00˚W)	10200 ft. MSL (7058 ft.)
Rio Chama above El Vado Reservoir	480	37.02˚N (36.66˚N)	106.45˚W (106.23˚W)	10040 ft. MSL (7084 ft.)
Red River above Questa	113	36.68˚N (36.70˚N)	105.33˚W (105.57˚W)	9850 ft. MSL (7452 ft.)
Embudo Creek above Dixon	305	36.18˚N (36.21˚N)	105.55˚W (105.91˚W)	9800 ft. MSL (5859 ft.)

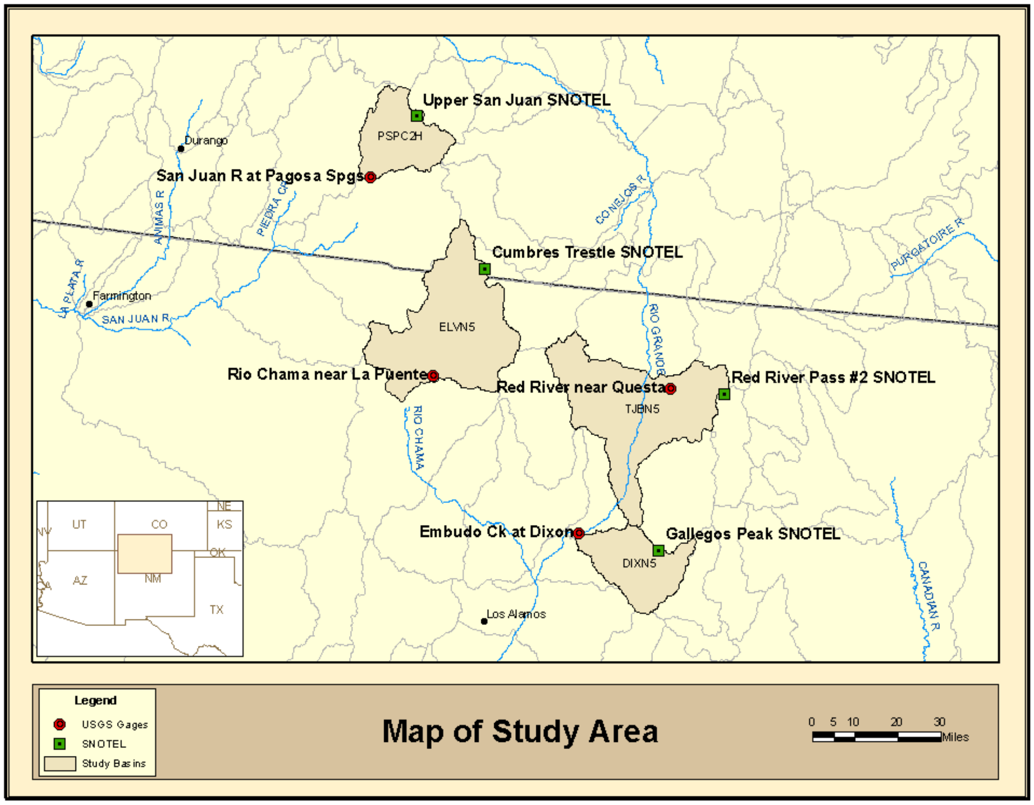


Figure 13. Location of snowmelt-dominated basins, SNOTEL stations and USGS stream gauges used in this study.

USGS Daily Streamflow

Mean daily streamflow data obtained from the U.S. Geological Survey online database (http://waterdata.usgs.gov/nwis/sw) for the San Juan River at Pagosa Springs, CO (USGS ID 09342500), Rio Chama near La Puente, NM (USGS ID 08284100), Red River near Questa, NM (USGS ID 08265000), and Embudo Creek at Dixon, NM (USGS ID 08279000), were combined into April-June flow volumes in thousands of acre-feet (kaf). The April-June period was chosen to better isolate runoff that could be more strongly attributed to snowmelt versus runoff from convective precipitation events that are predominant during the summer (July-September) thunderstorm season.

SNOTEL Precipitation and Snow Water Equivalent

Daily measurements of snow water equivalent (SWE) and precipitation obtained from the NRCS for the Upper San Juan SNOTEL (CO06M03S), Cumbres Trestle SNOTEL (CO06M22S), Red River Pass #2 SNOTEL (NM05N11S) and Gallegos Peak SNOTEL (NM05N18S) were parsed into 1 March SWE and 1 April SWE values, and monthly and seasonal precipitation (e.g. MAM, AMJ). See Fig. 13 for SNOTEL station locations. Data were obtained from the NRCS at: ftp://ftp.wcc.nrcs.usda.gov/data/snow/snotel/table/history.

NCEP/NCAR Reanalysis Datasets

Daily composites of analyzed air temperature, mean relative humidity, and the zonal (east-west) component of the horizontal wind at 700-mb from 1980-2006 were obtained from the NOAA/ESRL Physical Sciences Division web site (http://www.cdc.noaa.gov). These widely-used datasets were compiled by the NCEP/NCAR Reanalysis Project (Kalnay *et al.*, 1996) and are mapped to a 2.5° latitude x 2.5° longitude global grid. A locally created PHP script extracted daily temperature, mean relative humidity, and zonal wind values from the global data file for points nearest the SNOTEL locations used in this study. The 700-mb level was chosen as it best represents free-air conditions near mountaintop level in the study area (elev. ~3000 m or ~10,000 ft MSL). Nearly 2,500 days were examined.

Climate Division Precipitation and Palmer Drought Severity Indices

Mean monthly precipitation and Palmer Drought Severity Index (PDSI) values for Colorado Climate Division 2 (Colorado Drainage Basin), Colorado Climate Division 5 (Rio Grande Drainage Basin), and New Mexico Climate Division 2 (Northern Mountains) obtained from the NOAA/ESRL Physical Sciences Division web site (http://www.cdc.noaa.gov) (NCDC, 1994) were aggregated into various seasonal (e.g. MAM, AMJ) periods for comparison to SNOTEL precipitation. Figure 14 shows the location of Colorado and New Mexico climate division boundaries. It is important to note that various observational networks are used in climate division data, with most observations located in populated areas resulting in values that are biased towards low-elevations.

The PDSI is a meteorological drought index based on temperature and precipitation data and the local available water content of the soil. It is useful for monitoring long-term, hydrological drought. Negative (positive) PDSI values indicate drought (wet) conditions. To capture trends during the baseflow period (fall/winter) preceding the peak SMR period, a mean seasonal Sep-Feb PDSI value was computed.

Figure 14. Colorado and New Mexico climate division boundaries.

CHAPTER 3

METHODOLOGY

Relationships between snowpack, streamflow, and sublimation processes were diagnosed using least-square linear regression. The main predictor variable for streamflow in each study basin was 1 April (or 1 March) SWE at a single SNOTEL station near the time of peak snow accumulation (1 April or 1 March). This defines "expected" streamflow.

Relationships between springtime precipitation and departures from expected streamflow were then examined. Precipitation data from both the SNOTEL gauge (e.g. high elevation, point value) and corresponding climate division (e.g. lower elevation, areal average) were compared to the residuals to determine how much of the streamflow variance could be explained by precipitation alone, and whether using an areal average value that incorporates lower elevation data yields better results than simply knowing a single, high-elevation point value.

To isolate days that were characterized by low relative humidity and moderate to strong winds near mountaintop-level, a simple, dual-parameter dry-wind atmospheric index (herein referred to as DWND index) was created by dividing the daily values of 700-mb zonal wind by the 700-mb relative humidity and multiplying by 100. An average

DWND index for the reanalysis grid cell containing each SNOTEL site (e.g. lat/lon pair) was computed for various monthly combinations such as March-April (MA), April-May (AM), March-May (MAM) and April-June (AMJ) for each year. Relationships between the DWND index and springtime precipitation, seasonal departures from expected streamflow and ENSO were examined.

Because the purpose of this study is to analyze the processes that cause departures from streamflow expected based on 1 Apr SWE, rather than to minimize forecast standard error, a single predictor variable was used to keep the calculations simple and easy to interpret. Multiple linear regressions were employed to determine how much additional variance, if any, of the crucial streamflow residuals could be explained by the PDSI, Niño 3.4 SST anomalies, or the DWND index developed as part of this study.

CHAPTER 4

RESULTS

SWE vs. AMJ Streamflow Volume

Relationships between AMJ streamflow and SWE on 1 March and 1 April were examined for the four study basins, and a subset of these results is shown in Figures 15-19. A strong relationship between AMJ volume of the San Juan River flow at Pagosa Springs, CO and 1 March SWE, with an R^2 value of 0.59, is evident in Figure 15. The relationship between AMJ volume and 1 April SWE (Fig. 16) is even stronger with an R^2 value of 0.79 (statistically significant at a 5% level) due to additional snow accumulation in March. This indicates the level of skill of a seasonal streamflow forecast that could potentially be derived from a perfect snow accumulation forecast, without regard for snow ablation processes after 1 April. Results for the Upper Rio Chama above El Vado Reservoir, NM (Fig. 17) indicate a similar positive correlation ($R^2=0.73$) for 1 April SWE. Red River above Questa, NM (Fig. 18) and Embudo Creek above Dixon, NM (Fig. 19) demonstrate positive relationships that are somewhat weaker.

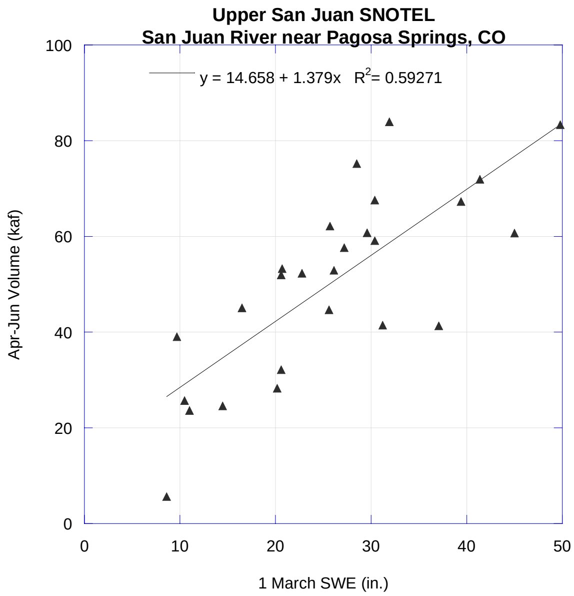


Figure 15. 1 Mar SWE vs. AMJ streamflow volume for the Upper San Juan River above Pagosa Springs, CO.

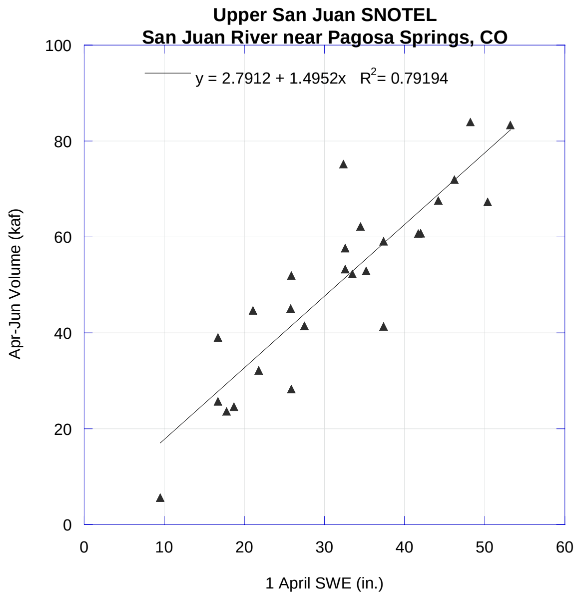


Figure 16. Same as in Fig.15 except for 1 Apr SWE.

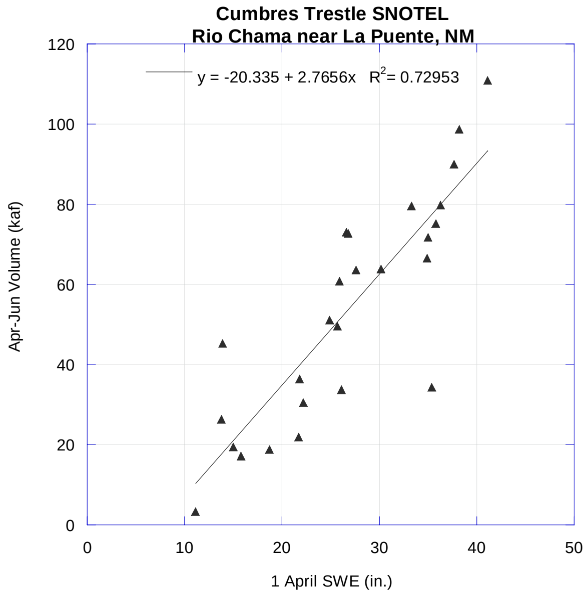


Figure 17. 1 Apr SWE vs. AMJ streamflow volume for the Rio Chama above El Vado Reservoir, NM.

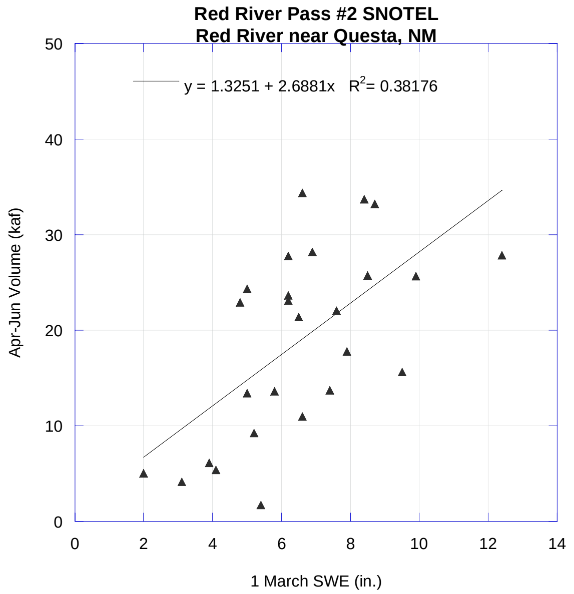


Figure 18. 1 Mar SWE vs. AMJ streamflow volume for the Red River above Questa, NM.

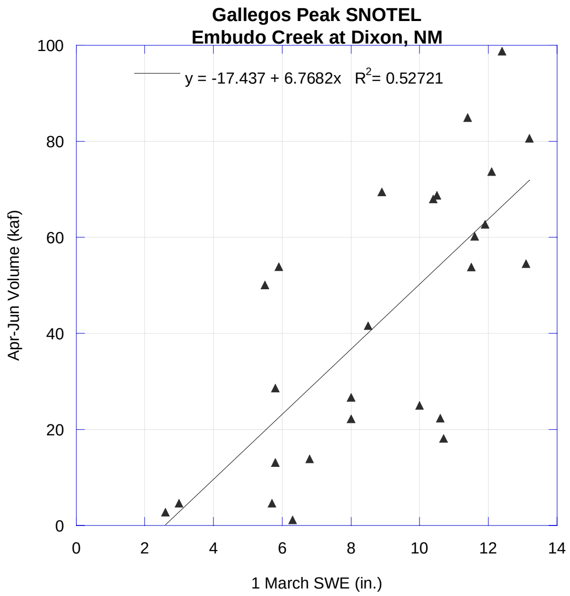


Figure 19. 1 Mar SWE vs. AMJ streamflow volume for Embudo Creek above Dixon, NM.

A summary of R² values resulting from simple linear regression calculations used to relate SWE and AMJ streamflow for each of the four high elevation watersheds is provided in Table 3. Each of these values is statistically significant at the 5% level but the magnitude of the linear relationship varies considerably.

TABLE 3. Coefficient of Determination (R²) Values for SWE vs. Volume Plots.

Basin	1 MAR SWE	1 APR SWE
Upper San Juan above Pagosa Spgs.	0.59	**0.79**
Rio Chama above El Vado Reservoir	0.55	**0.73**
Red River above Questa	**0.38**	0.36
Embudo Creek above Dixon	**0.53**	0.47

R^2 values for the SWE vs. volume plots were highest for the Upper San Juan above Pagosa Springs and Rio Chama above El Vado Reservoir, implying a relatively close fit to the observed data. R^2 values quickly dropped off for the two New Mexico SNOTEL locations. At these more southerly, lower elevation basins the better correlation shifted from 1 April SWE to the earlier 1 March SWE values, which suggests that AMJ volume might be better predicted using snowpack conditions earlier in the melt season. This result is consistent with the notion that snowmelt in northern New Mexico typically occurs earlier than it does farther north in Colorado (Figs. 3-6).

Of particular interest for this study are those years that had near-normal 1 April SWE values, but subsequent AMJ streamflow volumes that were starkly different from what would have been expected through use of simple linear regression based on 1 Apr SWE. As mentioned previously, precipitation (or lack thereof) after 1 Apr likely explains a significant portion of these departures as will be seen in the next section, but other meteorological anomalies should be examined. Figure 20 and Figure 21 show a comparison of daily 700-mb temperature traces for the months of April and May in years that had near-normal 1 April SWE values but subsequent streamflow volume was either well-below expectation or well-above expectation for the Upper San Juan above Pagosa Springs, CO and Embudo Creek above Dixon, NM, respectively. Note in both time series, evidence of short-duration (5 to 10 consecutive days) heat waves in April of years when Apr-Jun streamflow volumes were well-below average: 1989 for the Upper San Juan above Pagosa Springs, CO and 2003 for Embudo Creek above Dixon, NM. The number of consecutive days that the mean 700-mb temperature remained above average during the same periods is also significant.

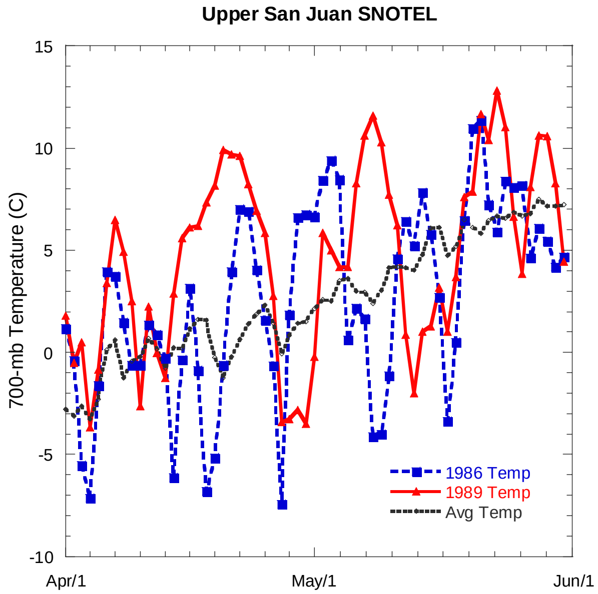


Figure 20. Time series of AM 700-mb temperature for 1986 (strong positive residual), 1989 (strong negative residual), and 1980-2005 average at the Upper San Juan SNOTEL.

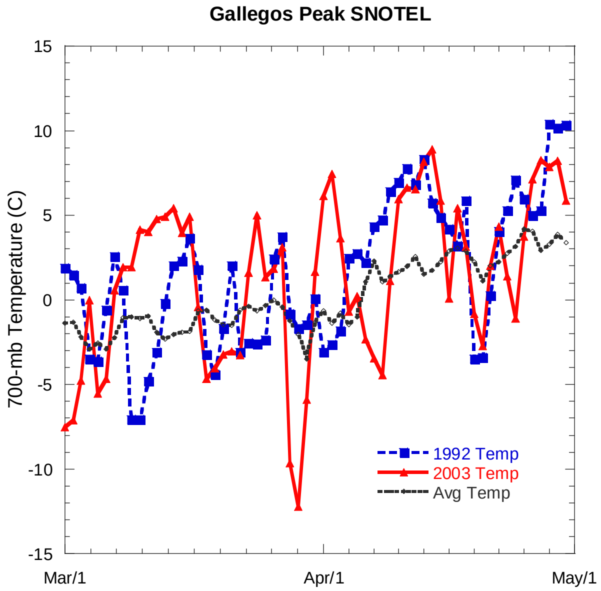


Figure 21. Time series of MA 700-mb temperature for 1992 (strong positive residual), 2003 (strong negative residual), and 1981-2006 average at the Gallegos Peak SNOTEL.

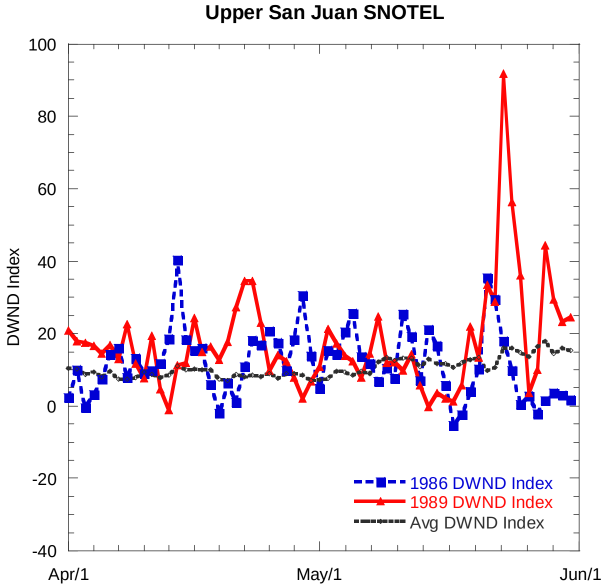


Figure 22. Same as in Fig. 20 except for a time series of DWND index.

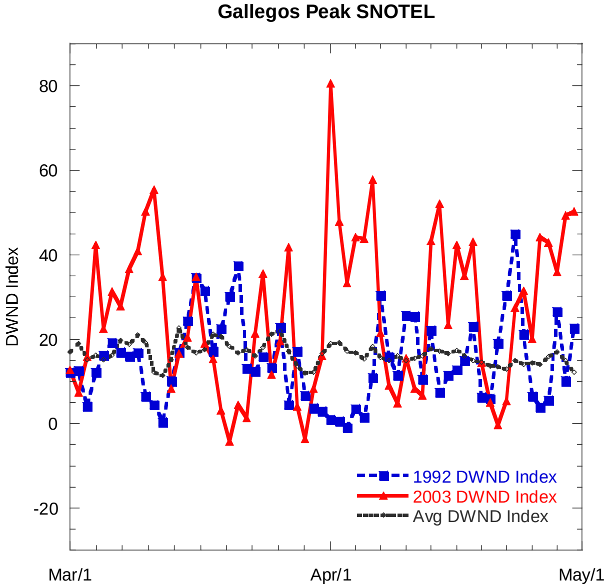


Figure 23. Same as in Fig. 21 except for a time series of DWND index.

Similarly, Figure 22 and Figure 23 are the same as Figs. 20-21 except for the DWND index for years that had near-normal 1 April SWE values but subsequent streamflow volume was either well-below expectation (red lines, closed triangles) or well-above expectation (blue lines, closed boxes) for the Upper San Juan above Pagosa Springs, CO and Embudo Creek above Dixon, NM, respectively.

Precipitation vs. Streamflow Residuals

Precipitation data from both the individual SNOTEL gauge (e.g. high elevation, point value) and corresponding climate division (e.g. lower elevation, areal average) were compared to the streamflow residuals to assess how much of the streamflow variance could be explained by precipitation alone.

Table 4. Coefficient of Determination (R^2) Values for SNOTEL (Climate Division) Precipitation vs. Residual Plots. Values represent the percent of interannual streamflow variance explained by precipitation alone. Values in parentheses represent precipitation for corresponding climate divisions.

Basin	Mar-Apr	Mar-May	Mar-Jun	Apr-May	Apr-Jun
Upper San Juan above Pagosa Spgs.	--	--	--	**0.37** *(0.35)*	0.36
Rio Chama above El Vado Reservoir	--	--	--	**0.66** *(0.53)*	0.61
Red River Above Questa	0.68	0.82	**0.85** *(0.67)*	--	--
Embudo Creek Above Dixon	0.61	**0.66** *(0.50)*	0.65	--	--

Correlations between cumulative precipitation after 1 March or 1 April and departures from predicted streamflow varied considerably from basin to basin as seen in Table 4. This finding is not surprising. Interestingly, 82% (85%) of the streamflow variance for the Red River above Questa, NM could be explained by cumulative Mar-May (Mar-Jun) SNOTEL precipitation, respectively (Figs. 24 and 25). These relatively high R^2 values can, in part, be explained by the fact that the Red River above Questa sub-basin had the poorest relationship between 1 Mar SWE and AMJ streamflow. Thus, residuals were significantly higher as compared to other basins in the study.

The more interesting trend was the fact that June precipitation contributed to explaining streamflow variance only at Red River. 700-mb winds from the northwest and “backdoor” cold fronts are common across northeast New Mexico during June. These patterns favor convective precipitation along the east slopes of the Sangre de Cristo range, which includes the Upper Red River sub-basin. In contrast, knowing June precipitation for the other three basins did not explain any additional streamflow variance. This finding supports the notion that little if any effective precipitation falls during the month of June west of the Sangre de Cristo range, where June climatologically is among the driest months of the year.

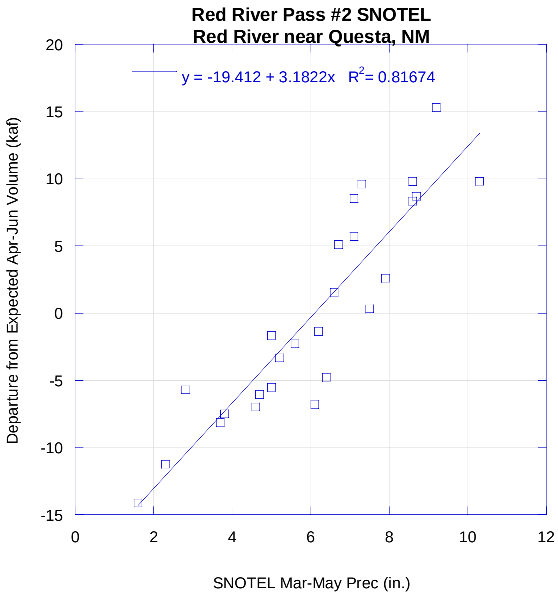


Figure 24. Mar-May precipitation vs. departures from expected streamflow for the Upper Red River above Questa.

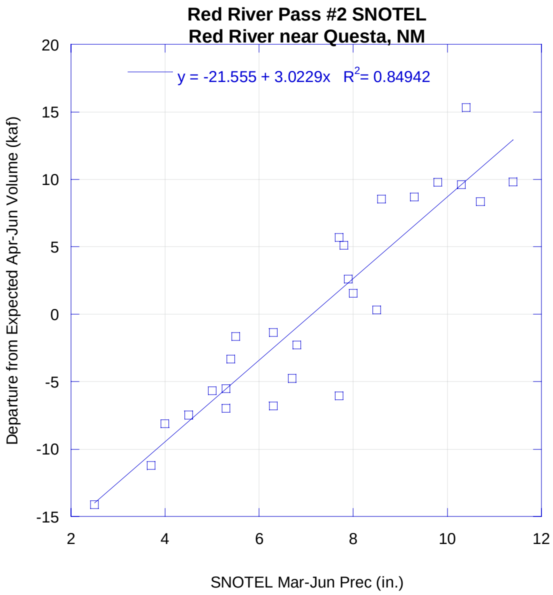


Figure 25. Same as in Figure 24 except for Mar-Jun precipitation.

Meanwhile, the Rio Chama above El Vado Reservoir and Embudo Creek above Dixon had similar results in that 66% of the streamflow variance could be explained by Mar-May and Apr-May cumulative precipitation, respectively. The poorest correlation between precipitation and departures from expected streamflow was in the Upper San Juan above Pagosa Springs (Table 4). One explanation might be the fact that this particular basin had an especially strong relationship between 1 Apr SWE and AMJ streamflow and thus residuals were comparatively small.

Another potentially important finding was the fact that corresponding climate division precipitation explained less streamflow variance in all cases than a single, high-elevation point value from a SNOTEL station. As a result, incorporating precipitation data from lower elevation stations (e.g. climate division areal average) appears to dilute or dampen important terrain-driven influences on precipitation at high elevations.

A pronounced example of the impact that springtime precipitation can have on streamflow was in 1986. Although 1 April SWE was very close to average that year for the Upper San Juan SNOTEL station, the two-month Apr-May period was one of the wettest on record, with 12.3 inches of precipitation recorded at the SNOTEL station, nearly double the long-term average of 7.4 inches. The corresponding climate division precipitation for the same period (Apr-May) was 3.29 inches compared to an average value of 2.78 inches. Not surprisingly, the observed streamflow was significantly higher than would have been predicted using simple linear regression. Official streamflow forecasts were likely closer to what was actually observed, but this case draws attention to the need for additional studies that focus on potential links between ENSO and high-elevation meteorological anomalies.

DWND Index and PDSI

The process of changing phase directly from a solid to a gaseous state is called sublimation. When the ambient air temperature is less than the temperature of a snow surface, then heat fluxes will be upward-directed (both sensible and latent heat of sublimation). Conversely, if the air temperature is warmer than a snow surface, sensible heat transfer will be directed downward from the atmosphere to the snowpack. The direction of the latent heat transfer will depend upon the humidity of the air immediately above the snow surface. Drier air near and just above a snowpack that has a snow surface temperature of 0˚ Celsius will result in sublimation (Satterlund *et al.*, 1992).

Generally speaking, faster wind speeds above a snowpack result in increased potential for sublimation particularly when the snow surface temperatures are between -5˚C and 0˚C (Satterlund *et al.*, 1992). However, the actual amount of water vapor exchanged between the snowpack and the atmosphere through wind-driven sublimation is still not well understood. Hood *et al.* (1999) found that in a continental, alpine climate like the Colorado Rockies, using data from the melt season to predict sublimation over the entire snow season (i.e. accumulation and ablation) will most likely result in an underestimation of sublimation, perhaps to quite a large extent.

Although no direct link between potential sublimation and the DWND index is established in this study, it is plausible that high DWND index days may be closely associated with increased potential for sublimation due to strong westerly winds and low humidity.

The relationship between the DWND index and Niño 3.4 anomalies appears to be better defined than is the relationship between AMJ precipitation and Niño 3.4 anomalies (Figs. 26-29). This finding may increase confidence that cold (warm) phase ENSO cycles result in a greater (fewer) number of relatively dry (low humidity), windy days during the springtime when snow ablation processes are at their most critical period. The statistical relationship between DWND and ENSO implies that DWND is potentially predictable months in advance.

Such predictability could lead to improvements in streamflow forecasting, because potentially important links emerged between the DWND index, ENSO and springtime precipitation. With very few exceptions, years that were characterized by below average 700-mb humidity and a moderate to strong zonal wind component during April and May at any of the four sites recorded below average precipitation if any at all. Similarly, with very few exceptions, years that had below-average DWND indices recorded near normal to much above normal precipitation (Figs. 30-33).

TABLE 5. Percent of Interannual Streamflow Variance Explained by the DWND, PDSI, and combined DWND & PDSI compared to SNOTEL Precipitation.

	DWND	PDSI	DWND & PDSI	Prec.	DWND, PDSI & Prec.
Upper San Juan above Pagosa Spgs.	0.10	0.17	0.20	0.37	0.44
Rio Chama above El Vado Reservoir	**0.37**	0.22	**0.49**	0.66	0.75
Red River Above Questa	0.14	**0.27**	0.28	**0.85**	0.86
Embudo Creek Above Dixon	0.28	0.22	0.35	0.66	0.67

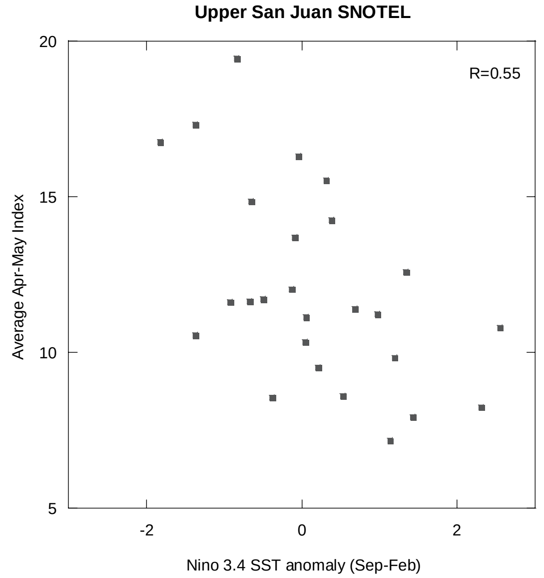


Figure 26. Nino 3.4 SST anomalies vs. DWND index at Upper San Juan SNOTEL.

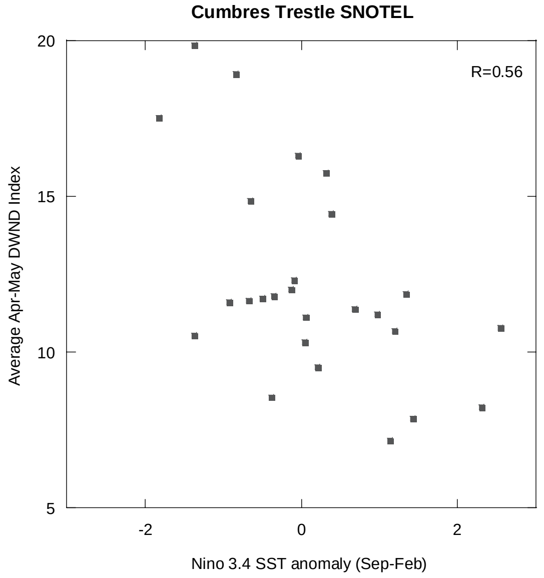


Figure 27. Same as in Fig. 26 except for Cumbres Trestle SNOTEL.

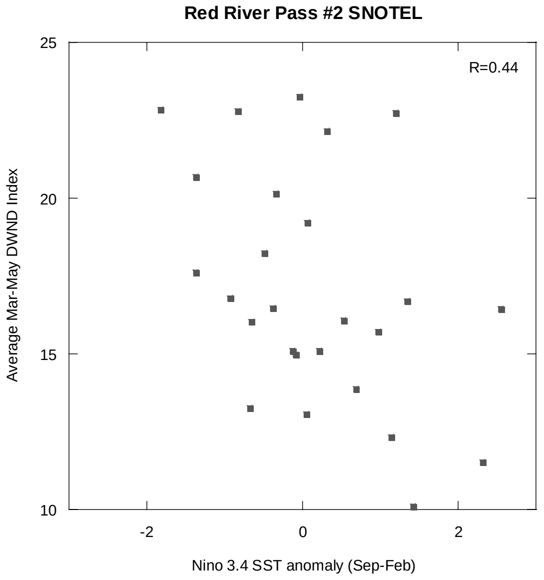


Figure 28. Same as in Fig. 26 except for Red River Pass #2 SNOTEL.

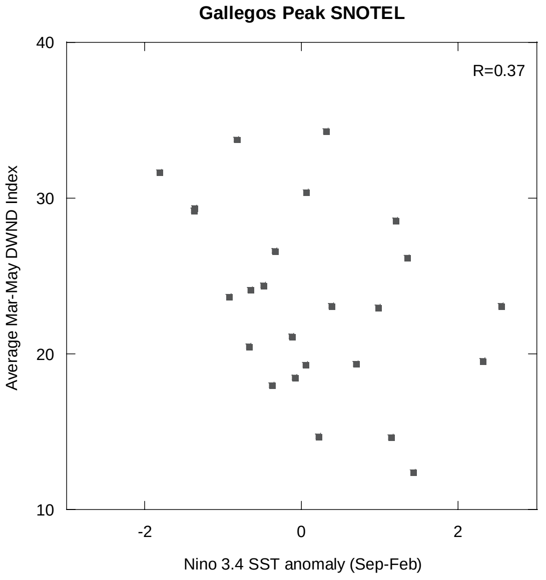


Figure 29. Same as in Fig. 26 except for Gallegos Peak SNOTEL.

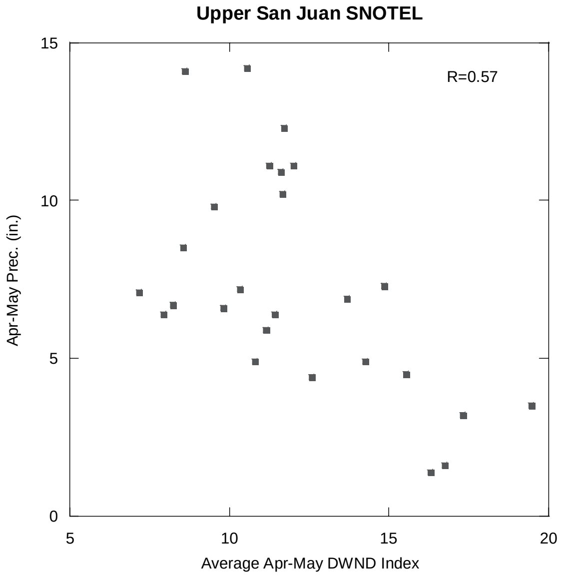


Figure 30. Avg. AM DWND index vs. AM precipitation, Upper San Juan SNOTEL.

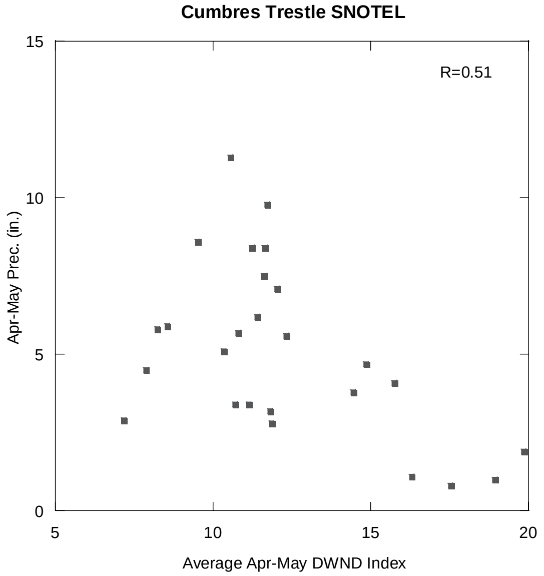


Figure 31. Same as in Fig. 26 except for Cumbres Trestle SNOTEL.

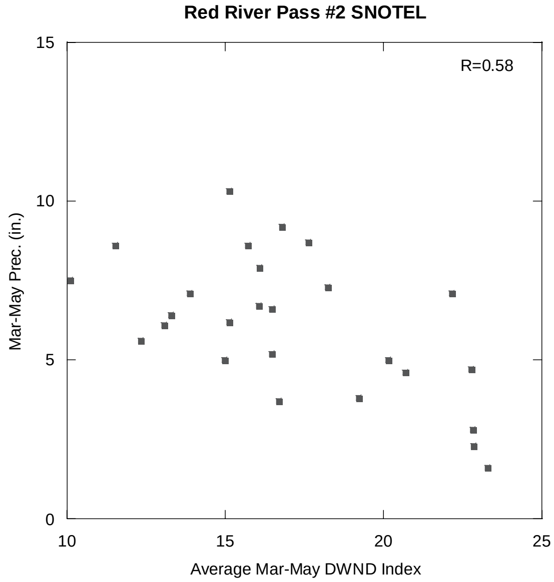


Figure 32. Same as in Fig. 26 except for Red River Pass #2 SNOTEL.

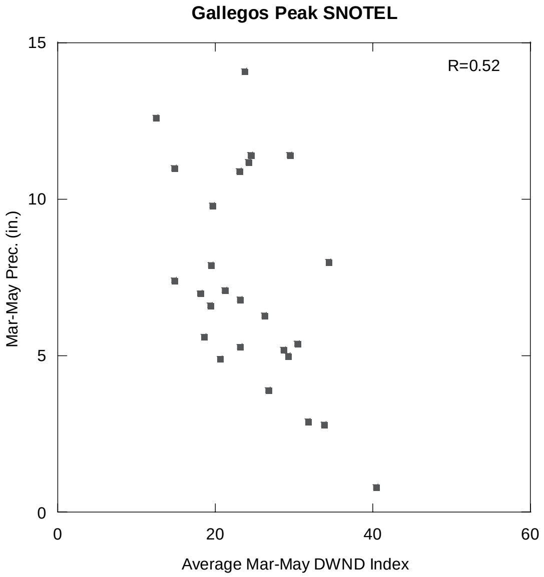


Figure 33. Same as in Fig. 26 except for Gallegos Peak SNOTEL.

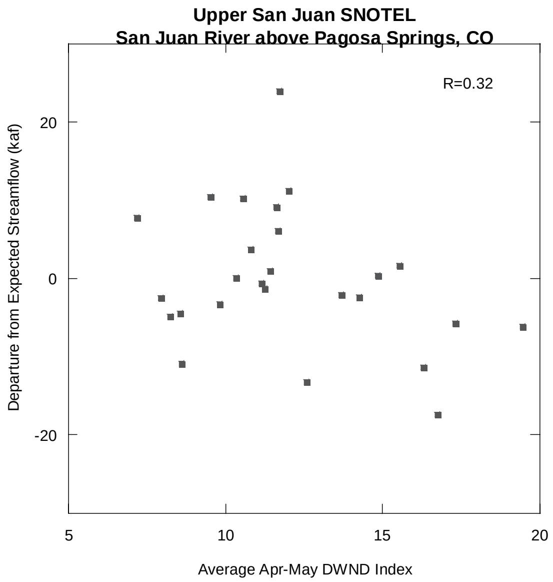


Figure 34. Average Apr-May DWND index vs. residuals, Upper San Juan above Pagosa Springs, CO.

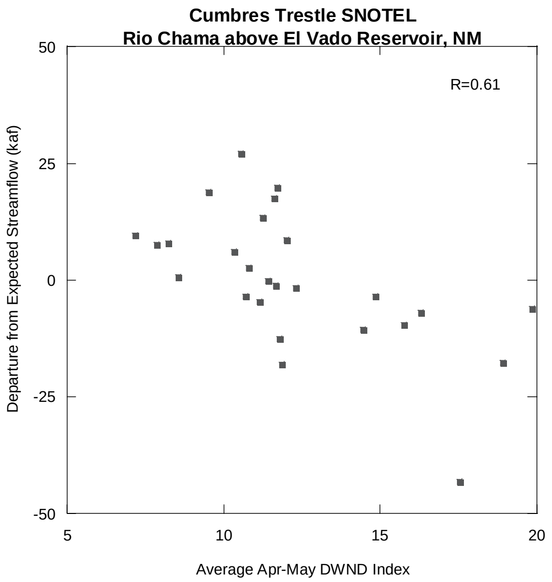


Figure 35. Same as in Fig. 30 except for the Rio Chama above El Vado reservoir, NM.

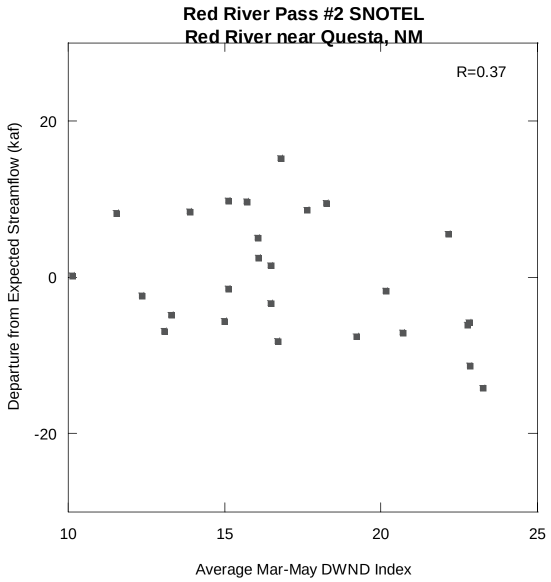


Figure 36. Same as in Fig. 30 except for Red River above Questa, NM.

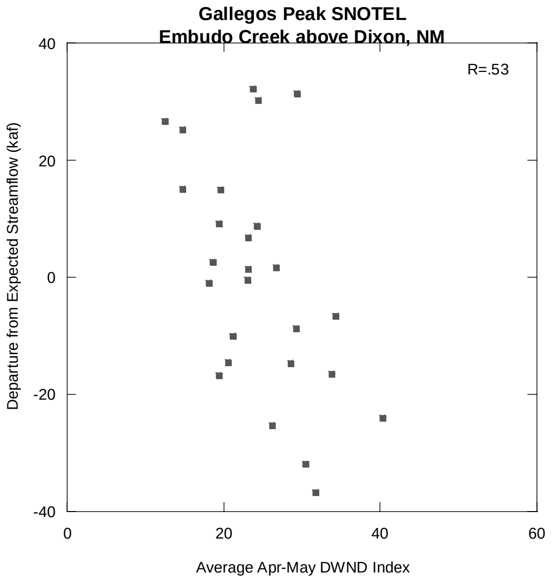


Figure 37. Same as in Fig. 30 except for Embudo Creek above Dixon, NM.

CHAPTER 5

CONCLUSIONS AND FUTURE WORK

In this study, meteorological anomalies during the snow ablation season were investigated within four snowmelt-dominated basins in southern Colorado and northern New Mexico. These included historical relationships between (i) humidity and wind from March-June as defined by the DWND index; (ii) springtime precipitation; (iii) departures from expected seasonal streamflow; and (iv) El Niño-Southern Oscillation (ENSO). Several parameters that could potentially lead to improved streamflow forecasts in southern Colorado and northern New Mexico were documented.

One of the more interesting results of this study is that the relationship between the DWND index and Niño 3.4 anomalies appears to be better defined than is the relationship between springtime SNOTEL precipitation and Niño 3.4 anomalies. This finding may increase confidence that cold (warm) phases of ENSO result in greater (fewer) number of days characterized by above (below) normal windiness and low (high) humidity at high elevations in northern New Mexico and southern Colorado in the springtime. Moreover, three or more consecutive days of unusually dry, warm and windy weather early in the ablation period, which are partially captured in a monthly or multi-monthly DWND index, appear to be related to significant negative departures of expected streamflow. Additional studies need to be conducted to better and more accurately describe these events.

Another potentially important finding was that climate division precipitation explained less streamflow variance in all basins than did using a single, high-elevation point value. Therefore, utilizing climate division precipitation data that is weighted more strongly toward lower elevation stations versus higher elevation stations appears to dampen the terrain-enhanced precipitation signal just enough to degrade a streamflow forecast. Moreover, with the exception of the Upper Red River above Questa, incorporating precipitation data for June did not explain any additional streamflow variance above that of the MAM or AM periods.

When considered together, the DWND index and PDSI explained between 20 to 49 percent of the interannual streamflow variance compared to 37 to 85 percent when precipitation alone was considered. Since potential predictability of the DWND index appears to be higher than for high-elevation springtime precipitation based on ENSO, this finding suggests the need for additional studies to examine 700-mb height anomalies over the Pacific preceding years that exhibited high Mar-May DWND index values (Fig. 38). Relationships, if any, between excessive dust deposition and dry, windy springtime periods (i.e. high DWND indices) would also be especially interesting to examine further.

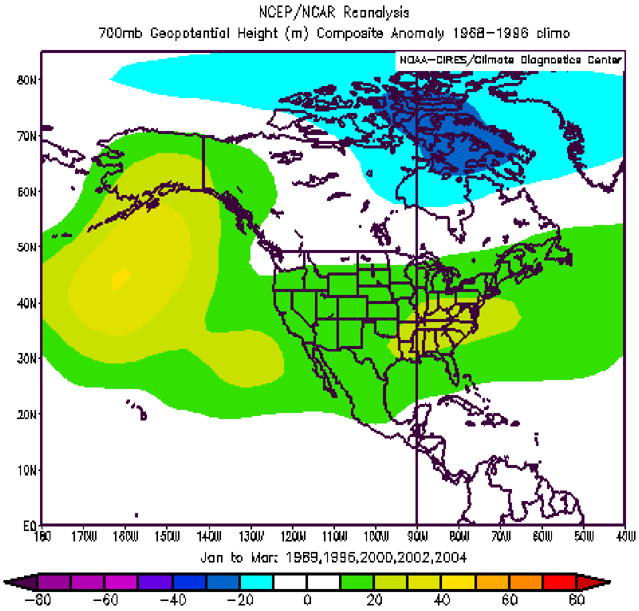


Figure 38. Jan-Mar 700-mb height anomalies preceding years with well-above average Apr-May DWND index values. Source: http://www.cdc.noaa.gov/Composites/Day/

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