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THE IMPACT OF SNOWFALL ON THE COLORADO PLATEAU

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by

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Abstract

The Colorado Plateau has been plagued with drought throughout its existence. The lack of snow is ultimately to blame for the dry times. Having such a high dependence on snowfall, makes it vital that climatic research be preformed on this area. This project provides a systematic approach for predicting drought by only observing snowfall information, with the result being a forecast suggesting relief from the current drought will not arrive for several years.

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I. Introduction

Droughts have frequently plagued the United States for as far as anyone can remember. Severe droughts can have devastating impact on an economy. In many cases, long after the environment has recovered, economic troubles are still present. The drought of 2002 was not only the most recent, but one of the worst dry spells this country has ever seen. It has been estimated that the United States lost $11 billion because of the drought. The southwest (Colorado Plateau in particular) is extremely vulnerable to these conditions. Colorado was among the hardest hit in 2002. In the agriculture sector alone, damages have already exceeded $525 million.

The Colorado Plateau encompasses four states which include Arizona, Colorado, New Mexico, and Utah. Its topography varies from mountain ranges, to smaller plateaus, to low lands and covers over 130,000 square miles of terrain. Weather patterns over the area typically steer major storms away from the plateau. This is unfortunate because the region often relies on major winter storms to replenish its water supply.

Mountain snow is the most influential weather condition in this area. The snow that piles up during the winter thaws throughout the year accounting for almost 80 percent of the total water found in surrounding rivers, lakes, and reservoirs. With that holding true, it is imperative that the plateau receives an adequate amount of frozen precipitation during the winter season.

Short term (within five days) forecasting for snow is very accurate by today's standards. Predicting snow for weeks, months, or even years ahead of time is a little bit of a challenge. There are many anomalies that are often difficult to foresee. Snowfall data has been recorded for decades and new technologies have made it possible to receive information from locations that were previously unreachable. Analyzing historic snowfall totals may lead to more precise forecasting of winter precipitation which the region so heavily relies on, leaving the Colorado Plateau more prepared. Having more time to plan could alleviate some of the environmental and economic strain caused by drought.

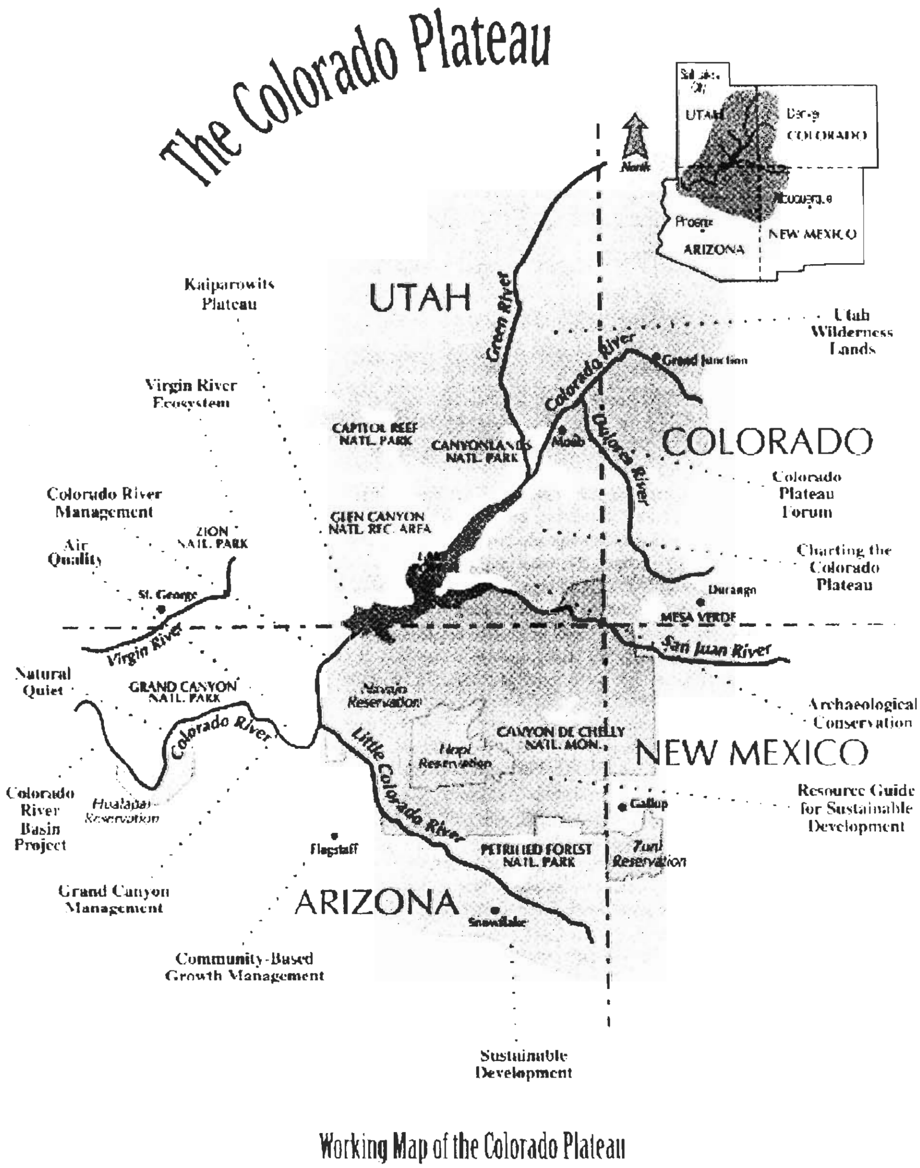

Fig 1.1 The Colorado Plateau consists only of the four corner states.
(http://www.kaibab.org/gct/coloplat.htm)

II. Background

A. The Colorado Plateau

Similar to the amount of terrain that the plateau covers, its history is very extensive. It dates as far back as 400 million years when the continents began to separate themselves and the highland was a shore to a large sea. When the sea subsided, large amounts of sediment had washed up, which eventually transformed into rock. Movement of the tectonic plates, around 80 million years ago, led to the creation of the Rocky Mountains. As the plateau continued to rise, the rivers that were created by the mountains carved deep into the earth creating huge canyons which exposed the sediment that was buried long ago.

Today the plateau has a wide variety of vegetation and topography. Its geological features include mountains, smaller plateaus, flat lands, basins, and fault lines. Vegetation depends on altitude which is directly related to precipitation. Areas below 11,000 ft that have an annual precipitation over 20 inches can expect dense forests. Above that height, bare snow covered mountain peaks are the norm. Desert-like grasslands occupy locations that receive the least amount of rainfall.

The Colorado Plateau is considered to be a dry place with hot summers and cold winters, with upper level winds being the culprit for the lack and infrequent precipitation. As a whole, the Colorado Plateau averages 20 inches of precipitation per year with average annual temperatures ranging from 40 – 55 degrees Fahrenheit. Mountain ranges that exceed 11,000 feet receive around 30 inches, areas between 8,000 and 11,000 feet can usually expect between 20 – 25 inches annually. The lower lying areas, (which is the majority of the two) normally receive about 10 inches per year.

The ratio between snow and rain across the plateau is around 50/50. Higher elevations will receive a greater snow to rain ratio. The converse is true for lower altitudes. With that being said, it is important that the highland receives its normal snowfall totals. To re-enforce this concept, a comparison has been made between Maybell, Colorado and Burlington, Vermont. The city located in Vermont has an average annual snowfall of 76 inches and a mean temperature of 44.6 degrees Fahrenheit. In comparison, Maybell receives 62.1 inches of snow and has an average temperature of 42.4 degrees Fahrenheit annually. One would say that the numbers are fairly close; the real difference is seen in the total annual precipitation. Burlington receives a total annual precipitation of 34.4 inches, while the town in Colorado collects just 12.3 inches per year.

To stress the point a little further, the rule of thumb in the meteorological world is that 10 inches of snow is equivalent to one inch of rain. Temperature factors into this ratio as well. The colder it is, the greater amount of snow is needed to equal one inch of rain and *vice versa*. But it is impossible to calculate the snow/water equivalence for a particular day when the data is presented in decades of averaged annual snowfall. Burlington's snowfall would translate to 7.6 inches of water and Maybell's snow converts to 6.2 inches of rain. It's obvious where this is going now. If it did not snow in both places for the entire winter, Burlington would only be down 22 percent of its yearly precipitation while Maybell would discount a staggering 51 percent. A 50% reduction in annual precipitation would be devastating to a community, causing wide spread drought and major economic strain.

The Colorado River Basin is divided into an upper and lower region, which spans over 250,000 square miles. The basin's flow starts off in southern Wyoming, Colorado and Utah. It continues down through Arizona and New Mexico, and just before the river system exits the country into Mexico, it passes through California and Nevada.

The construction of the Hoover Dam and many other dams not only produce large amounts of electricity, they also make it possible to divert the 15 million acre feet of water that is available annually. The water that is diverted, supplies millions of people and thousands of businesses. It is crucial that the area get the water it needs.

B. Drought

There are many distinctly different types of drought. A meteorological drought is a period of abnormally dry weather, with a sufficiently prolonged lack of water, which causes a serious hydrologic imbalance in the affected area. An agricultural drought is defined as a climatic excursion involving a shortage of precipitation sufficient to adversely affect crop production or range production. There is also a hydrologic drought, a period of below-average water content in streams, reservoirs, ground-water aquifers, lakes and soils. Those are all fine definitions but drought can simply be defined as a temporary shortage of rainfall which the Colorado Plateau has dealt with for years. By taking a closer look at the history of drought in this region, we can better understand the economic impacts that they incur.

On the Colorado Plateau, the surrounding economies are continuously affected by the amount of precipitation that falls from the sky. The severity of the impact depends on the type of industry. Businesses that are directly related to tourism and agriculture are very vulnerable.

In Colorado and Utah, tourism employs just under 350,000 people and supplies $8.5 billion and $4.15 billion respectively, into the states' economies. The most likely impacted jobs are those dealing with skiing, outdoor recreation, touring, resorts, and parks. Skiing is the largest contributing recreational subdivision in Colorado, accounting for 19 percent of tourism spending and employs 30,347 people.

In 2002, this region saw one of the worst droughts it has ever seen. Colorado was severely hit. Snow pack levels as of April 1st were 52% lower than average. It was the second lowest since the state first began these measurements, with the record low in 1977 when the snow pack was 46 percent from normal.

With the snow pack being so low, one would think that this would be detrimental to the ski industry and it was in the drought of 1977. The ski industry saw a 40 percent decrease in ticket sales from the previous year and businesses directly related to skiing in Colorado lost almost $100 million in revenues.

The lack of snow was not as much as an issue in 2002. The snowmaking process made it possible for resorts to operate. Ski resorts in Utah saw an 11.2 percent decline in skier visits, while Colorado experienced saw only a 5.1 percentage decrease. The decline probably had more to do with the September 11th tragedy than did the drought, and most likely inflated these numbers.

After the winter ski season of 2001 - 2002 was over, the snow pack that was nearly half of what it was supposed to be, made its way to the rivers and streams. Streamflow forecasts eventually reached record lows, with much of the state being extremely below average (25% - 50%) and a small portion in southwestern Colorado was labeled as exceptionally below average (0% - 25%). This is clearly illustrated in Figure 2.1.

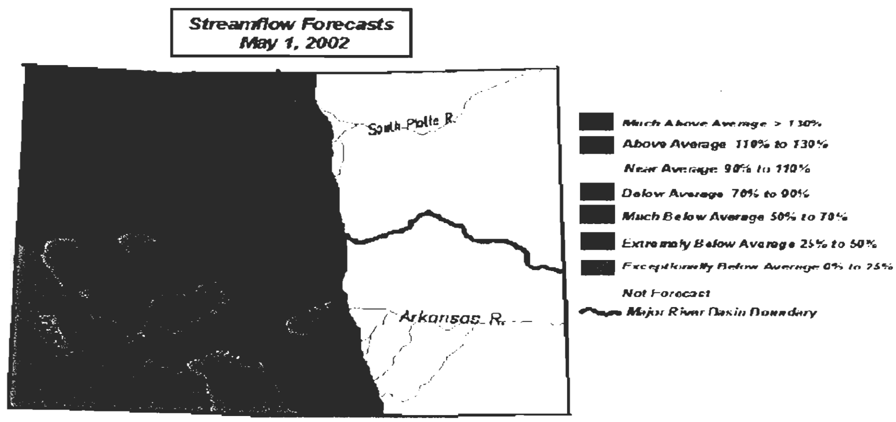

Fig 2.1 Streamflow forecast for Colorado May 1st 2002.
(http://cwcb.state.co.us/owc/Drought_Planning/Drought_Watch_May_8_02.pdf)

Because the streams and rivers were carrying less water than normal, the reservoirs levels began to plummet. After a state wide measurement on October 1st, the reservoirs were down about 50 percent from what is considered to be normal levels. The reservoirs in Utah did not fare much better. As you can see in Figure 2.2, statewide levels steady declined until they hit rock bottom in October of 2002.

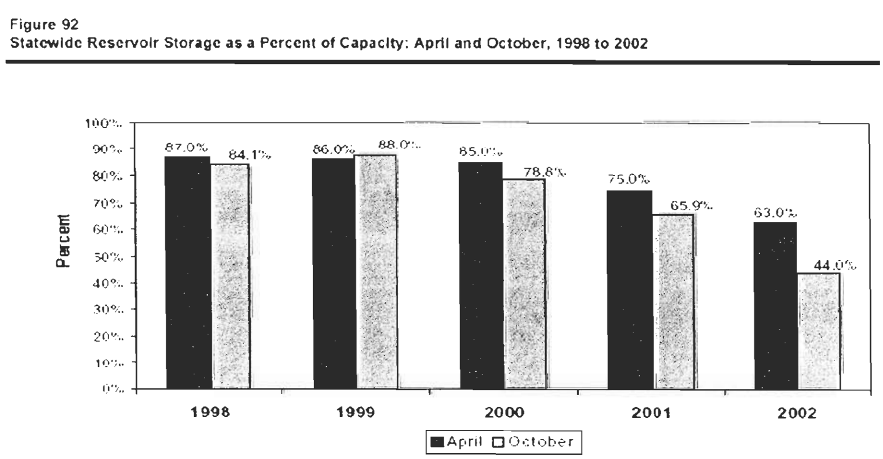

Fig 2.2 Utah's statewide reservoir levels between 1998 and 2002.
(http://governor.utah.gov/dea/ERG/ERG2003/25.EconImpactDrought.PDF)

To stress the severity of this drought a little more, a town just south of Denver, Colorado, called Aurora, receives about 95 percent of their water for the year from snowfall during the winter. Their reservoir dropped to a staggering 27% of capacity. The spokeswoman for Aurora said, "2002 was the driest on record."

This did not bode well for the surrounding businesses. Agricultural related companies are by far the most dependent on the reservoirs. They consume about 85 percent of the water available. So it was no surprise that this industry took a heavy hit. As one can see from Table 2.1, Colorado's agricultural sector was estimated to have lost over a billion dollars.

State	Estimate	Sector
Colorado	$1.1 billion $640 million $460 million $1.7 billion $200 million $800,000	Agriculture Crop losses Livestock Tourism Outfitters Fishing licenses
Utah	$250 million	Agriculture

Table 2.1 Major losses in Colorado's and Utah's economy due to drought in 2002
An altered version of the table located at (http://ams.confex.com/ams/pdfpapers/73004.pdf)

As previously mentioned, Colorado has already incurred $525 million in agricultural damages. It may be hard to believe that number could double before it is over, but it must be remembered that the effects of a drought are felt long after the actual drought has past.

This is a real life example of how the drought is affecting the farming community. A farmer in Colorado named Bill Bohn, has been growing corn and hay on his land for the past 41 years. Mr. Bohn knew beforehand that 2002 was going to be rough year. So, at the beginning of the growing season, he decided to plant only 18 acres of corn on his 113 acre farm. When the middle of July rolled around, a reporter asked him how his crop of corn was holding up. Bill replied, "right now, I would say it's 100 percent gone." The time and energy he spent working to make his corn field profitable, was wasted. Stories like this one are all too common through the Colorado Plateau during this time.

When the land is so dry that farmers lose their entire crops, it becomes very susceptible to wild fires. In 2000, Colorado suffered 2 major fires that destroyed everything it came in contact with. Six hundred claims were filed to insurance companies. Who paid approximately18.5 million dollars to their clients. A similar situation arose in Arizona in 2002, where the Rodeo-Chediski wild fire chard 468,638 acres of land. The fires burned through 426 structures that included 250 homes. This fire was far more devastating than the Colorado blaze. Insurance companies paid an estimated $102 million in compensations, the second largest disaster claim in Arizona's history.

With these types of losses, it is not difficult to realize that droughts are a major problem, especially in areas where snowfall is the primary water source. There is no defense for droughts that span three or four years. If scientists and meteorologists could predict a short term drought years in advance, cities and town could be more prepared to deal with upcoming event.

C. Forecasting the Weather

Forecasting weather is a very difficult task because of the countless variables that come into play. Long and short forecasts are now more accurate then ever, due to the constant study of our atmosphere and the improved technologies available. The increasing number satellites, computer models, automated devices, and radar sites (like the one seen in Figure 2.3) are just a few of the innovations that make predicting the weather easier.

Figure 2.3 A radar Facility in Newfoundland, Canada.
(http://www.ns.ec.gc.ca/press/doppler_xme.html)

Short term forecasting, which is predicting the weather within five days, has increased in accuracy over the years. Meteorologists have the ability to precisely calculate the temperatures and amounts of precipitation within those five days. After five days is where it starts to get tricky. Long term forecasts must take into account the averages over years past. They are usually very general by saying temperatures will be below or above average and whether it may or may not rain.

For example, a weather person could predict the weather for the next week, by saying that temperatures will be slightly above average. The next week rolls around and there is a very cold day and all the other days were warm and above average. One may think that the person did a horrible job predicting the weather because of that one cold day, but in essence, the meteorologists accurately predicted the weather because the forecast was for the week and not a specific day.

Long term forecasting has recently included the use of computer models. These models are based on the laws of physics and typical atmospheric trends which have the ability to predict how the storm systems transfer heat and energy. Complex computer models, along with the recent discovery and study of *El Nino*, have made it possible to predict weather not just weeks in advance but seasons.

Breakthroughs in technology, along with extensive research will lead to the fine tuning of long term weather forecasts. Super computers, as mentioned earlier, will not be included in this study. Hopefully, by looking at snowfall and precipitation exclusively over the past 50 plus years will lead to a long term forecast that is useful.

III. Methodology

In order to calculate a snowfall forecast for the Colorado Plateau, it is necessary to sample data from the region. The data I used was extracted from the Western Regional Climate Center. I chose this organization because they had an abundant supply of weather stations that contained large amounts of data for the southwestern United States.

The data that lies within these weather stations are listed by states and not in the geographic region of the plateau. To solve this problem, the climate center had maps of each state with all the stations locations on them. I traced the outline of the plateau onto each state to separate the weather stations that were located within the region, with the ones that were not. After the lines were drawn, there were 234 weather stations located inside the plateau (71 in Arizona, 119 in Utah, 22 in Colorado, and 22 in New Mexico).

In my opinion, the most scientific approach to sample data was to take a systematic random sampling. This type of sampling requires that every item within a known population be distinguished. First, a list of the entire population must be created. After that task is completed and a specific number of samples (x) are desired, divided that number (x) by the total population (t). The value that remains is (n). After (n) has been calculated, go back through the list that was created and take every n*th* item. The items that were chosen are the objects that will be sampled.

I determined, that if I sampled 20 weather stations (5 from each state), I could accurately calculate a trend and eventually be able to forecast snowfall. By placing the stations in an alphabetical list by state, and performing the random sampling just described, I determined which stations I would be able to use.

A few problems arose as a result of the random sampling. I realized that the data in some of the weather stations were not very accurate, with missing data and data ranges being the most troubled areas. Some stations would have entire years of data missing and others would have data for only a few years. This was not the best way to sample information. I realized that the only way to get the most reliable information was to go through each station one by one in each state.

After going through all 234 weather stations, I chose the best five from each state that had data ranging from the second half of 1948 to the first half of 2002. The reason I only went to the first half of 2002 and not continue on to the present, was because the data in almost all the stations I sampled had missing entries and therefore, could not be included in this study.

I analyzed both snowfall and total precipitation data from every station. The precipitation data will be used to back the snowfall measurements. The only problem was that snowfall measurements begin in July and end in June the following year, and precipitation statistics are recorded from January to December. To solve this problem, I had to re-configure the precipitation data to match that of the snowfall. After transforming the data and recalculating the yearly totals, the next step was to calculate an average for each station for both snowfall and precipitation over the 53 years in question.

The goal of the sampling was to determine which stations had above average, normal, or below average readings and when. Since it is highly unlikely that a yearly total will match the average, it was important to have a range that is considered normal. Any yearly total for both snowfall and precipitation that was within 10 percent (plus or minus) of the 53 year average was considered normal. Anything greater would be considered above average, and any reading below the 10% was below average.

When that was completed, I then arranged my data into graphs to make it easier to observe and calculate trends. I constructed graphs for each state and the plateau as a whole. I also divided the Colorado Plateau into regions, the North (Colorado and Utah), the South (Arizona and New Mexico), the East (Colorado and New Mexico), and the West (Arizona and Utah), to see if there was any correlation between geographic location and amount of snowfall.

IV. Snowfall Research

A. Snowfall by States

1. Colorado

The first state that I analyzed is Colorado. The five stations that I chose to extract data from were Altenbern, Cedaredge, Dinosaur National Monument, Grand Junction, and Mesa Verde (National Park). Table 4.1 shows each stations most important data.

Station Name	Longitude /Latitude	Elevation (above sea level)	Average Annual Temp.	Average Annual Precip.	Average Annual Snowfall
Altenbern	39.5 N 108.38 W	5690ft.	46.61	16.22 in	60.02 in
Cedaredge	38.9 N 107.93 W	6200ft.	49.13	12.53 in	49.1 in
Dinosaur National Monument	40.23 N 108.96 W	5920ft.	47.23	11.63 in	43.0 in
Grand Junction	39.1 N 108.53 W	4850ft.	52.79	8.67 in	21.6 in
Mesa Verde	37.2 N 108.5 W	6680ft.	49.32	17.82 in	81.1 in

Table 4.1 Colorado's stations and their data.

After placing all the data into a bar graph, I began to notice some tends. Snowfall between 1952-1953 and 1971-1972 was predominately below average as can be seen in Figure 4.1.

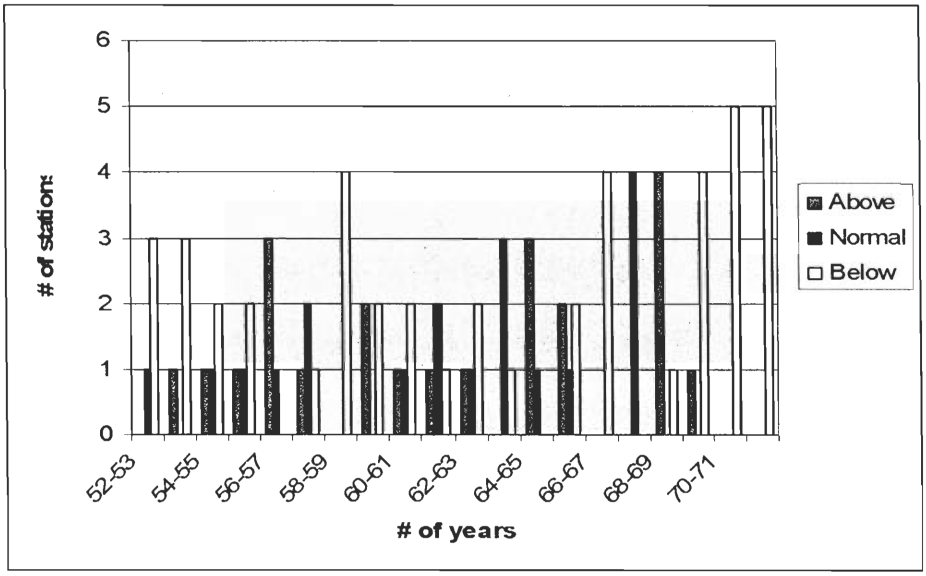

Fig 4.1 Snowfall in Colorado from 1952 until 1972

The snowfall was below or equal to, with above average reports, 17 out of the 20 years. I think it would be safe to say that this was a dry time period for Colorado by just analyzing the snowfall.

There are three time periods left. I will first start with 1948-49 to 1951-52. During this short time the stations' totals reported above average snowfall readings for every year. The years from 1972-73 to 1988-89, also produced above average snowfall. Over those seventeen years, thirteen of them had above or equal to the below average readings. With that said, it is apparent that these eras have to be considered a period of above average snowfall.

Below is Figure 4.2, which is the snowfall for the last stretch of time, the second half of 1989 to June of 2002. Every year, except for two, had below average information reported from the stations.

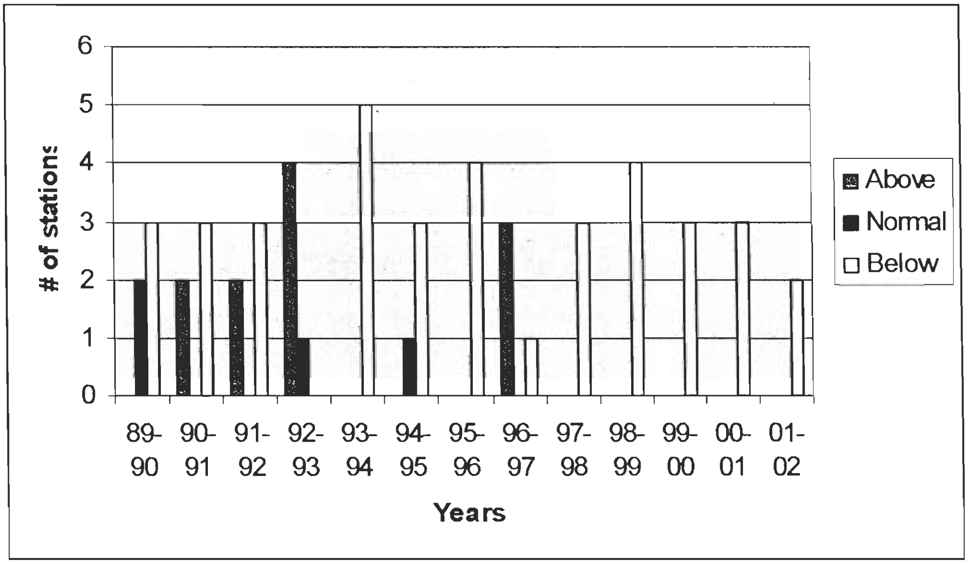

Fig. 4.2 Snowfall from 1989 until 2002 in Colorado.

With this graphic, one can clearly see why Colorado had so many problems in 2002. It was not just one season of lacking snowfall, it was eleven. This type of prolonged drought can be extremely detrimental to an area.

I also looked at the Colorado yearly precipitation and compared it with the snowfall data. The results do not exactly line up. From 1950-51 to 1963-64 was a period of below average precipitation, with nine years out of the 14 reporting sub-par readings. The data between 1964-65 and 1980-81 does not support any sort of trend. Above average snowfall was reported for 6 years and below average for 8 years. There are three years when the above and below data were equal, but there were no patterns and the results were scattered throughout this length of time. A trend reforms starting in the middle of 1981, and ends in the middle of 1999, where there were 13 years of above average precipitation. From that point onward and finishing in 2002, there were below average readings.

The precipitation data in no way backs up the snowfall data because some of the snowfall deficits were offset by rainfall during the rest of the year. But historically, droughts have been directly related to snowfall.

It is my conclusion that the snowy and dry periods last an average of 18 years each. That is not to say that during an above average period of snow, that there will not be some below average years, because there will be. But as a whole, these periods last about 17 to 20 years in Colorado. Presently Colorado is about 13 years into one of the dry cycles, so they can expect dry times to continue for at least the next 4 years.

2. Utah

Moving west into Utah, I chose the stations at Alton, Ferron, Jenson, Manti, and the Zion National Park. Each site expects to receive 88.35, 28.34, 21.33, 54.62, and 9 inches of snowfall per year respectively. Table 4.2 shows some of the stations statistics.

Station Name	Longitude /Latitude	Elevation	Average Annual Temp.	Average Annual Precip.	Average Annual Snowfall
Alton	37.43 N 112.5 W	7040 ft	45.59	16.23 in	88.35 in.
Ferron	39.08 N 111.13 W	5940 ft	48.43	8.34 in	28.34 in.
Jenson	40.36 N 109.36 W	4750 ft	46.10	8.00 in	21.33 in.
Manti	39.25 N 111.63 W	5680 ft	47.70	12.85 in	54.62 in.
Zion National Park	37.22 N 113.00 W	4050 ft	61.30	14.81 in	9.00 in.

Table 4.2 Utah's Stations and their data.

When I took a close look at the Utah data, I found the data to be remarkably similar to Colorado's. Utah experienced the same extensive dry period during the 50's, 60's and ending early in the 1970's. From 1955-56 to 1970-71, a period of 16 years, Utah's weather stations reported 12 years of below average snowfall, which is comparable to Colorado's 20 year dry spell that began in the second half 1952.

The next fifteen years yielded an extremely snowy period for Utah. As one can see on the chart below, during this period, above average snowfall fell in 12 of the 15 years. As one can also see in Figure 4.3, every station reported below average snowfall during 1976-77 winter season. It was the worst snowfall deficit on record, but 4 out of the 5 years previous and three years after this drought, Utah had above average readings. This leads me to believe, while this drought produced an extreme decline in snowfall for that one year, the effects were short lived.

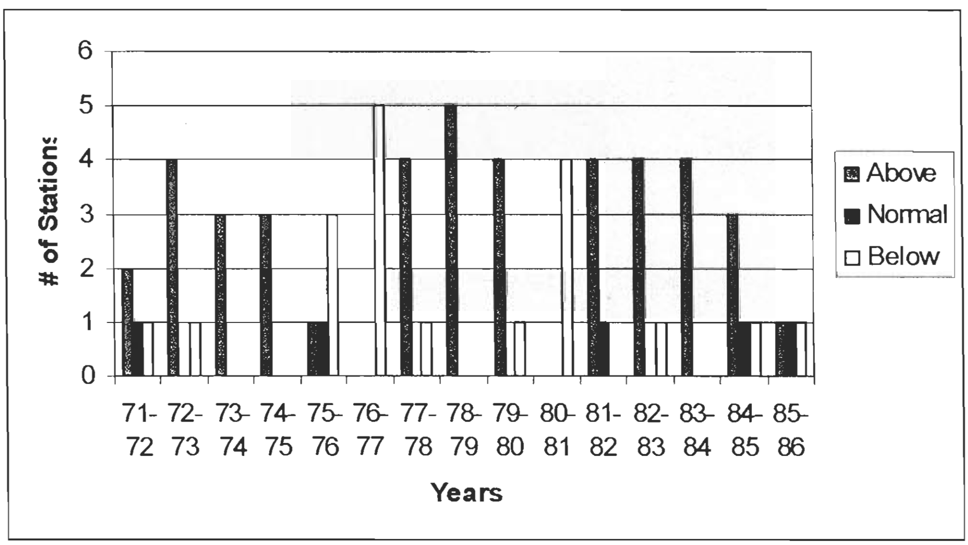

Fig 4.3 Above average snowfall in Utah, 1971-86

The 1985-86 winter season marked the transition from the wet period to another dry one which lasted until 2002. During these 16 years, thirteen years were considered to have received below average snowfall. So, it comes as no surprise that Utah was having problems with water in 2002.

Next, I studied Utah's total yearly precipitation to see if it coincided with the snowfall data. Like Colorado, the wet and dry intervals were completely different and difficult to decipher. According to the data, Utah underwent dry times between 1950 and 1961, recording 10 years of below average precipitation. The next 8 years were moisture rich, followed by another 8 years of dry weather. The waterless trend seemed to halt in 1978, where the next 10 out of 11 years had above average precipitation. That eventually led to the dry years of 1989 to 1996. From the mid-90's onward, the data did not support any type of trend, for 3 years there was above average readings and 3 years there were below average readings.

The snowfall data has more weight than does the precipitation, and since it does not match up with the snow statistics, I will disregard it in my forecast for Utah. It is evident from my research that the wet and dry cycles last about 16 years, which is four years less than that of Colorado. Since the latest dry cycle began in 1987 for this state, I expect there will be a transition into a snowy period within the next year or so, that will last for another 16 years.

3. Arizona

Arizona is located in the southwest portion of the Colorado Plateau and is the next state that I examined. The five stations I used are listed in Table 4.3 along with their characteristics.

Station Name	Longitude /Latitude	Elevation	Average Annual Temp.	Average Annual Precip.	Average Annual Snowfall
Betatakin	36.68 N 110.53 W	7290 ft	49.81	11.77 in	56.28 in.
Fort Valley	35.16 N 111.73 W	7350 ft	42.92	22.2 in	88.89 in.
Montezuma Castle National Monument	34.62 N 111.83 W	3180 ft	61.48	12.92 in	2.33 in.
Petrified Forest National Park	34.80 N 109.88 W	5450 ft	54.68	9.51 in	8.88 in.
Wupatki National Monument	35.50 N 111.36 W	4900 ft	57.98	8.19 in	6.85 in.

Table 4.3 Arizona's stations and their data.

As I began to look over the results for this state, the results did not appear to be as clear cut as the previous two states. Arizona had a dry spell that lasted all of the 1950's. There was not one year where the snowfall was considered above average. This is clearly illustrated in Figure 4.4 below.

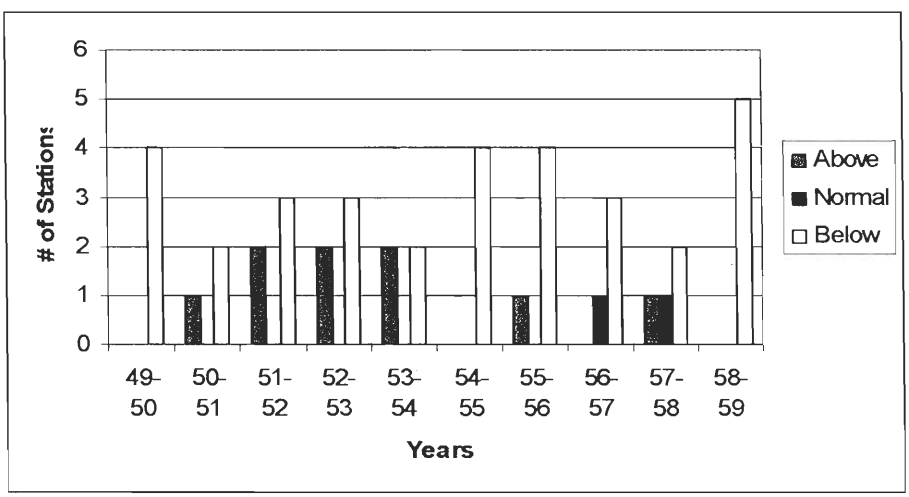

Fig 4.4 Arizona's below average snowfall from 1949 to 1958

The period of time between 1960 and 1976 has to be categorized as above average, because eleven out of the 17 years were on the plus side. As I moved through the data, I noticed that the next ten years recorded below average readings seven times.

This occurred again from 1993 until 2002, the only difference being that 8 out of the 10 years were below normal. Sandwiched in between those two periods, was a stretch of 7 years that saw five years of above average figures.

I then, proceeded to analyze the precipitation data for Arizona. The data yielded an array of trends. Above average snowfall existed between 1949-55, 1965-68, and 1978-01. That left only two below average periods, covering a span of eight and nine years each. The first two above average periods seemed to be equal to all the other trends calculated, but the third lasted 24 years. Out of those 24 years, nineteen of them were considered to have above average or equal to the below average readings. Figure 4.5 depicts this wet period of time very well.

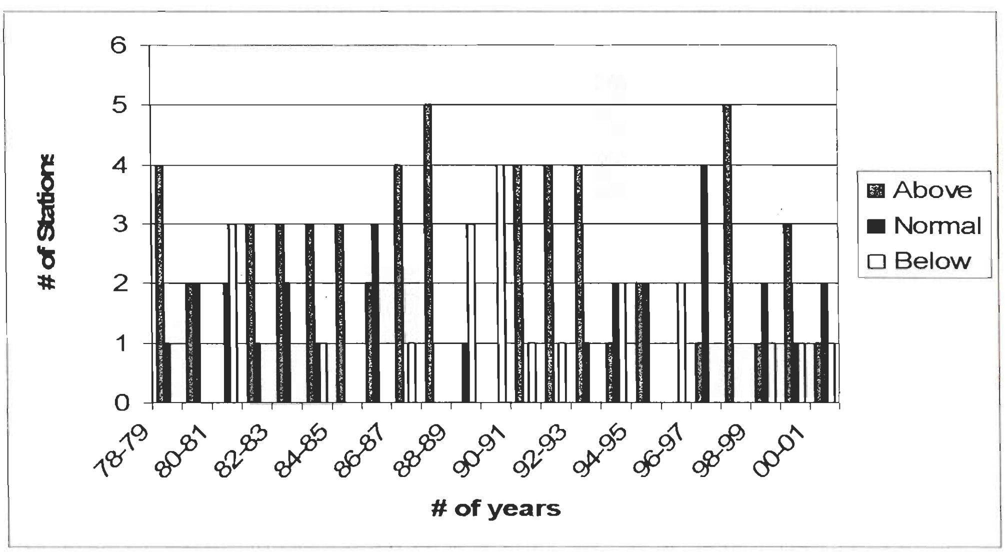

Fig. 4.5 Stations reporting snowfall in Arizona, 1978-2002

Arizona's precipitation data had the same fate as Colorado's and Utah's and does not help support the snowfall measurements. Therefore, by concentrating only on snow, a trend appeared. With exception of the long wet period between 1960 and 1976, each portion of the wet/dry cycle seems to last approximately 8-10 years. Since there was a dry period lasting 9 years from 1994-2002, this leads me to believe that the dry period is coming to a close. Before I finish with Arizona, I would like to mention that 3 out of the 5 stations that were responsible for reporting above or below average data had an average annual snowfall less than 9 inches per year and one site that was less than 3 inches. This means one major storm, or no snow at all, could seriously influence the data. Nevertheless, I am predicting that Arizona can expect snowfall to rebound into the above average level in the next year or two.

4. New Mexico

The last state to be examined was New Mexico. The Aztec Ruins National Monument, Bloomfield, Chaco Canyon National Monument, Star Lake, and Zuni are the five stations that I selected out of the southeast corner of the Colorado Plateau. Data crucial to the stations is listed in table 4.4.

Station Name	Longitude /Latitude	Elevation	Average Annual Temp.	Average Annual Precip.	Average Annual Snowfall
Aztec Ruins National Monument	36.83 N 108.00 W	5640 ft	51.52	9.91 in	15.10 in
Bloomfield	39.67 N 107.96 W	5800 ft	52.47	8.59 in	11.50 in
Chaco Canyon National Monument	36.03 N 107.90 W	6180 ft	49.49	8.85	14.60 in
Star Lake	35.93 N 107.46 W	6640 ft	47.43	9.21	19.10 in
Zuni	35.08 N 108.80 W	6440 ft	50.77	12.06 in	17.20 in

Table 4.4 New Mexico's Stations and their data.

For New Mexico, I am going to work from 2002 backwards until 1953. Figure 4.6, below is a graph of the first two dry and wet spells. As one can see, the period with little snow began in the 1992-93 season and finished in the middle of 2002, which is a span of ten years. Over those ten years, nine of them were considered below average. The next block of time is considered above average, covering a span of 6 years.

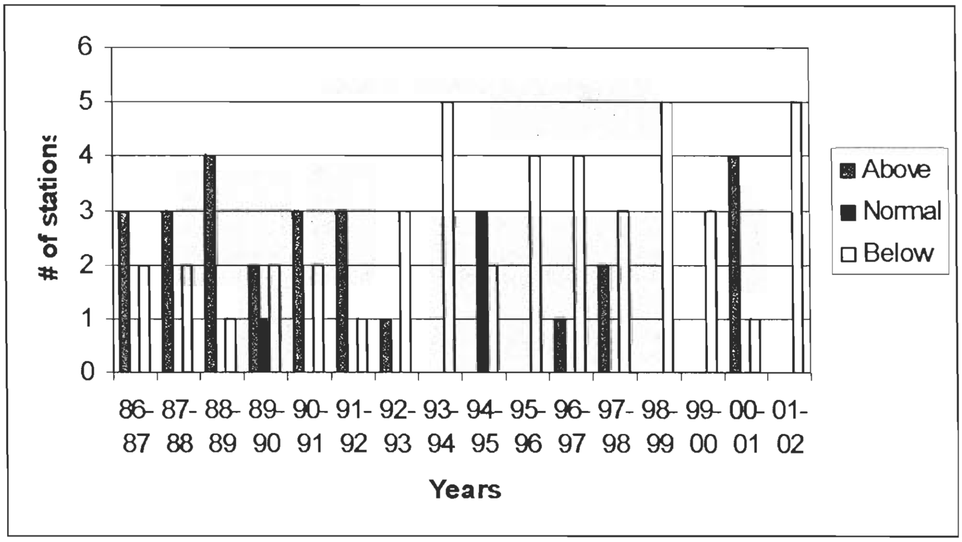

Fig 4.6 An above/below average cycle for New Mexico, 1986-2002

After 1987, the data revealed that there were three additional wet/dry cycles, with the dry years taking place from 1980-87, 1970-72, and finally 1954-62. Below average readings were reported in every year in the assigned dry periods expect for one. During the nine year stretch from 1954-62, seven were considered to be below normal. Snowfall measurements were above normal starting in 1973 and lasting until 1979. The next was a 7 year period from 1963-69, and final snow-filled cycle lasting from 1949-53. Similar to the dry times above, every year was considered to be above average except for the seven year period between 1963 and 1969 where only four years were above normal.

I then considered the New Mexico precipitation data. In total, there were two cycles that occurred. The first began in 1949 and ended in 1973. The first sixteen years were determined to be dry, while the last nine had above average precipitation. The next cycle spanned 25 years from 1974 until 2000, with the first eight years lacking moisture, followed by 19 years of wet weather.

As the three states previous, New Mexico's precipitation did not back up the snowfall data that was given. By analyzing the snowfall, it seemed very clear to me that the cycles lasted approximately 12-15 years, with the dry and wet seasons sharing equal amounts of time. New Mexico is currently in a dry pattern that has lasted for 10 years, which is a little longer than expected. This state should see an increase in the amount of snowfall within the next year or so.

B. Snowfall by Regions

After analyzing the four states, I thought it was necessary to divide the Colorado Plateau into regions, to see if snowfall relates to a larger area than just a single state. I created the North, which is a combination of Colorado and Utah, followed by the South, which contains Arizona and New Mexico. Colorado and New Mexico were combined to form to the East. The final region I formed was the West, which includes Utah and Arizona. I decided not to include precipitation data during this study because it was of no use when evaluating the states.

I started by evaluating the Northern area. There were two dry periods, one lasting 20 years and the other stretching seventeen years. The only major above normal snowfall was between 1973 and 1985, where ten out of the 13 stations had readings on the plus side.

The Southern portion of the Colorado Plateau was next. Contrary to the North, the southern area had much smaller intervals for above and below cycles. Each appeared to last no more than 13-15 years, which are clearly obvious from Table 4.5.

South	Years							
Above Average Snowfall	1949 - 1953	-----	1960 - 1966	-----	1973 - 1979	-----	1987 - 1993	-----
Below Average Snowfall	-----	1954 - 1959	-----	1967 - 1972	-----	1980 - 1986	-----	1993 - 2002

Table 4.5 Snowfall in the southern region of the plateau.

Moving on to the western half of the plateau, there were only three noticeable trends. There were two sub-par snowfall periods that wrapped around one above normal length of time. The wet/dry cycle appears to repeat itself every 36 years, starting in 1950.

The last section includes New Mexico and Colorado, the states making up the east side of the plateau. As one can see from Table 4.6 below, snowfall was on the positive side during the years from 1949-52 and 1973-1993. With below averages reading being reported in 20 and 8 year spans.

East	Years			
Above Average Snowfall	1949 – 1952	-----	1973 - 1993	-----
Below Average Snowfall	-----	1953 - 1972	-----	1994 - 2002

Table 4.6 The snowfall trends that were evident in the eastern section of the plateau.

The forecast for these regions is as follows. The north (Colorado and Utah) can expect conditions to improve within the next 1 to 2 years. The cycle lasts about thirty four years and is currently 17 years in the latest dry pattern. The southern and western states can also look for conditions to improve very soon, probably within the year. Similar to the north, the west has a 34 year cycle and is presently seventeen years into dry times. The eastern states are a bit of a different story, their above and below seasons last approximately 20 years each and at the moment they are only nine years into the most resent snow lacking episode.

C. Snowfall on the Plateau

After compiling and analyzing the data for each state, I combined the states' measurements to calculate the trends on the Colorado Plateau as a whole. I believe the results from this research will be more concrete due to the fact that there are now a total of 20 stations contributing to the data, instead of just five when I researched the states. I broke down the Colorado Plateau snowfall into the four figures below, two of which I considered to be dry and the two which I believed to be wet.

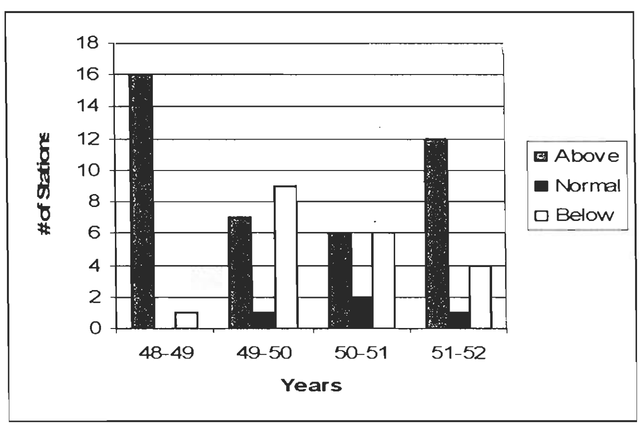

Fig 4.7 Snowfall on the Colorado Plateau between 1948 and 1952

Figure 4.7 is a chart of the first snowy period on the plateau. Even though it was a very brief stretch of time, three out of the four years were above average or equal to the below average reports. The next 20 years that followed were predominately below normal snowfall expectations. Fifteen out of those twenty years were considered to be below average, which is visible in the bar graph below.

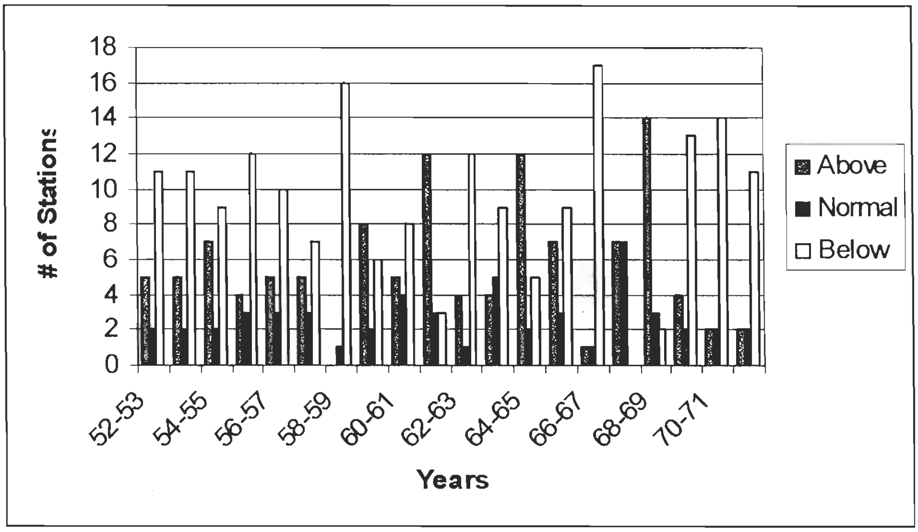

Fig 4.8 Below average snowfall on the plateau, 1952-72

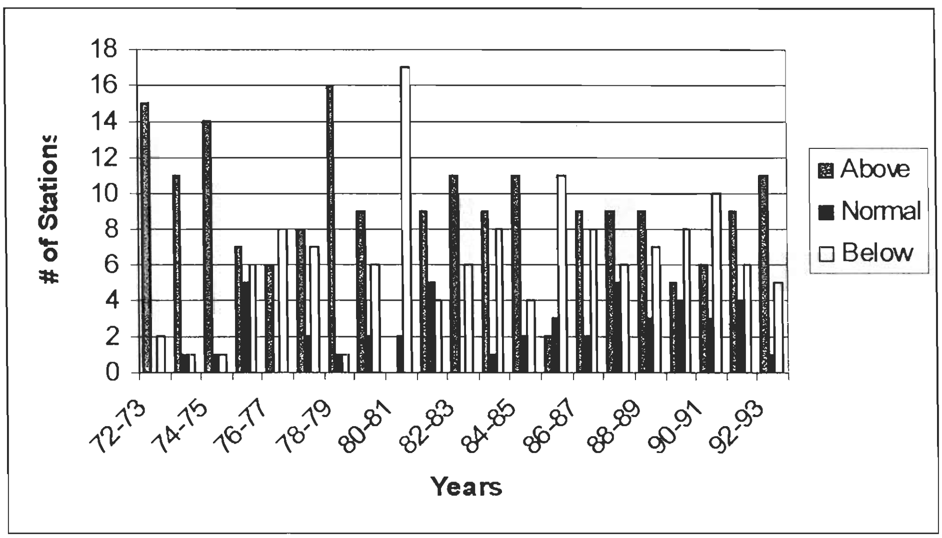

Fig. 4.9 Above average snowfall for the plateau.

After the 1972-73 winter season, there was a transition into an above average pattern that lasted a total of 21 years before ending in 1993. The snowfall during this time was found to be greater than normal, 15 out of the 21 years. Figure 4.10 is a chart that is nine years in duration, from 1993-2002. During this time, there was only one year that received an above average amount of snow, which was in the 1996-97 season.

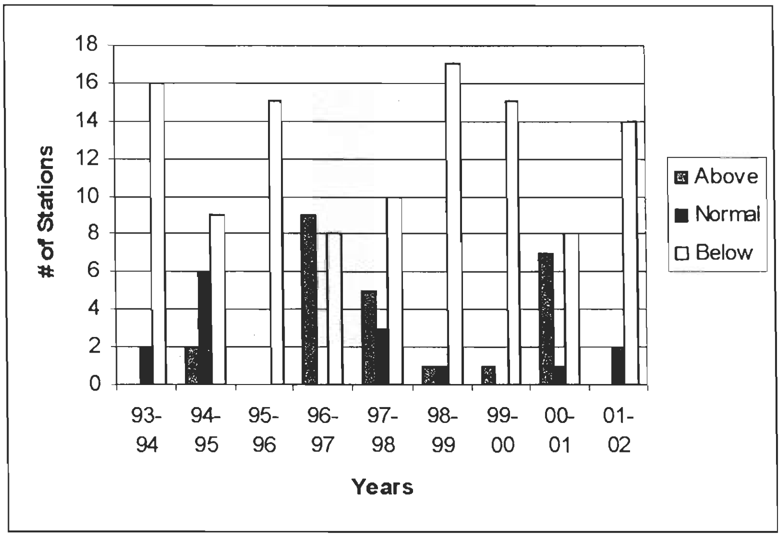

Fig. 4.10 The most recent dry spell on the plateau.

With the snowfall data analyzed, I then switch over to the precipitation data for the Colorado Plateau. The results were no different from the individual states. There was only one cycle that I could extract from the data over the past 53 years. There was one dry period lasting from 1949 to 1977 and one wet period starting in 1978 that seemed to last 18 years and ended in 1999. With that being said, I will solely be looking at the snowfall to make a forecast for the entire plateau.

As mentioned earlier, there was a dry time lasting 20 years and a snowy period lasting 21 years. The total cycle lasted 41 years, from 1953 to 1993. Currently the plateau is only nine years into the dry portion of the sequence, so I do not expect conditions to change anytime soon. As a whole, the plateau is looking for at least 10 more years of dry times before it starts to see a change over.

D. El Nino

It has been suggested that theories like global warming and the sunspot cycle have been the main causes for the drought that has plagued the American southwest for decades. These theories may be true, but I believe El Nino may play a roll in this as well.

El Nino, more commonly referred to as ENSO (El Nino Southern Oscillation) by researchers, is an environmental phenomenon that resides in the Pacific Ocean along the equator. Before I proceed any further, it is important understand how the ocean works under normal circumstances. During a typical year, there is a stream of cold water that rides up the coast of Chile that eventually makes its way west after passing the equator. The water starts to warm up as it moves west, with the warmest residing north of Australia. This difference in sea temperatures results in an easterly wind. When wind and warm water join, typically thunderstorms follow. But, due to the easterly wind, these storms are usually confined to the western pacific. Figure 4.11 depicts normal and El Nino conditions.

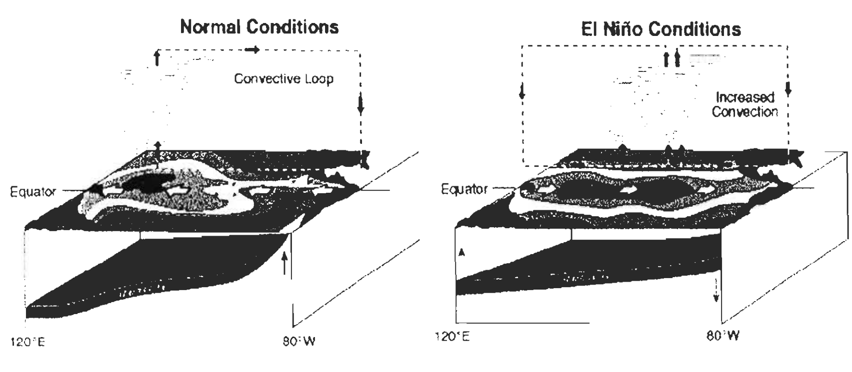

Fig. 4.11 Pacific Ocean, normal and El Nino conditions
(http://www.pmel.noaa.gov/tao/elnino/gif/ElNino.gif

In an El Nino year, the cold water that normally flows along the west coast of South America to the equator, slows down. The reason the cold water slows down has yet to be discovered. As a result, surface sea temperatures begin to rise from west to east. With the difference in sea temperatures now lost, the easterly wind that was present, now relaxes and in some severe cases of El Nino, reverse directions. This nullifying of the wind makes it possible for the thunderstorms to drift east, towards North and South America.

The flip side to El Nino is La Nina. Contrary to El Nino, in La Nina years, the cold water that flows from the Antarctic strengthens, which in turn causes the Pacific Ocean to be cooler than normal. Below average surface sea temperatures relates to an intensification of the easterly wind. As a result, the strong storms are inherently restricted to extreme western areas of the Pacific.

Having defined El Nino and La Nina, I wanted to see if they had any impact on the snowfall on the Colorado. I formed a hypothesis on how the two would affect the weather conditions. Since El Nino causes the easterly winds to relax, which allows storms to move east, I predicted that the weather phenomenon would increase precipitation and that La Nina would have the opposite affect.

In trying to prove my theory, I first had to determine when each occurred. Below is Table 4.7 that depicts the presence of El Nino and La Nina over the last 50 years.

	Years
El Nino	1957-58, 1965-66, 1972-73, 1982-83, 1987-88, 1991-92 1992-93, 1994-95, 1997-98
La Nina	1950-51, 1955-56, 1956-57, 1964-65, 1970-71, 1971-72 1973-74, 1974-75, 1975-76, 1988-89, 1998-99, 2000-01

Table 4.7 El Nino and La Nina years.

Having knowledge of when they occurred, I went back into the snowfall data I had collected from the previous research. I chose to analyze each state and the plateau as a whole. The results were the same for all. The existence of El Nino and La Nina ultimately had no effect on snowfall. There was just about an equal amount of above and below average years of snowfall during El Nino and La Nina, which is shown in the Table 4.8 below.

	Colorado	Utah	Arizona	New Mexico	Colorado Plateau
El Nino years - snowfall (+,-,=)	4+ 3- 2=	3+ 3- 3=	4+ 4- 1=	5+ 3- 1=	5+ 4- 0=
La Nina years - snowfall (+,-,=)	6+ 4- 2=	3+ 6- 3=	4+ 7- 1=	6+ 3- 3=	5+ 6- 1=

Table 4.8 Snowfall years above, below, or equal during El Nino and La Nina.

The results being what they are, I would have to say my hypothesis was incorrect and the data proves that. Just to reiterate, in nature, the presence of El Nino and La Nina have zero effect on the amount of snow the Colorado Plateau receives.

I also checked to see if El Nino had any impact on the total precipitation for Colorado Plateau. Going back through the data, I found that every year that El Nino was present, there were above average reports. La Nina was just the opposite, below average reports were found every year except for one. With that said, I believe that while El Nino does not affect snowfall, it most certainly affects the amount of rainfall in the area.

V. Conclusion

It is difficult to comprehend that in today's technologically advanced culture, we are still dealing with water shortages in some parts of the world when two thirds of it is composed of water. Unfortunately, that is reality and the Colorado Plateau is one of those unfortunate regions. It is often said to be one of the most beautiful places in the world, but as the saying goes, every rose has its thorns.

Based on the research that was performed, snowfall for the plateau will not be above average for at least the next ten years due to the fact that this area is currently in the middle of a 20 year dry cycle. But oddly enough, when one breaks the data down into states, the trends are much different, and three out of the four (Arizona, New Mexico, and Utah) can expect improvements in the next few years. Colorado is expecting improvements to be in the three to four year range.

The presence of El Nino was also discussed in this report and contrary to my previous belief; it ultimately, had no affect on the snowfall of the plateau. This research leads me to ask the question, "what other powerful force created by Mother Nature is responsible for this?" I trust that someday we may find that answer.

Whether or not we find out what is causing these harsh conditions, it is imperative that the plateau region have a plan to ease the difficult times. Although water restrictions and/or bans have been in place during the dry periods, it is almost impossible to bare the severe droughts that have become more frequent in recent history.

An increasing population is just one of the many factors contributing to the water shortage. Since 1940, Arizona's population has increased by an astonishing 1000%. A similar situation in Colorado has occurred, where the upper regions of the state have seen the population double in the past 30 years. Unfortunately, there is a limited amount of water and it is fixed. It does not increase with the growing number of people.

For centuries, the plateau has been a place that has dealt with drought and will most likely continue to feel its wrath for years to come. Hopefully, through continued research scientists and experts in this field will discover new techniques to improve the quality of life for all those who inhabit this area.

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