CLIMATE VARIABILITY AND CHANGE IN THE CHUSKA MOUNTAIN AREA:
IMPACTS, INFORMATION, AND THE INTERSECTION OF WESTERN SCIENCE
AND TRADITIONAL KNOWLEDGE

by

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LIST OF ACRONYMS

AZ2- Arizona Climate Division 2 (NCDC)
CT- center of mass (stream) flow
DJF- December-February
ENSO- El Niño Southern Oscillation
FILNET- USHCN data set originally missing data filled in using nearby networks
FSA- Farm Security Association
IPCC- International Panel on Climate Change
JAS- July-September
JJA- June-August
MAM- March-May
NCDC- National Climate Data Center
NM1- New Mexico Climate Division 1 (NCDC)
NNDWR- Navajo Nation Division of Water Resources
NNWMB- Navajo Nation Water Management Branch
NOAA- National Oceanic and Atmospheric Administration
NRCS- Natural Resources Conservation Service
PDO- Pacific Decadal Oscillation
PDSI- Palmer Drought Severity Index
PRISM- Parameter-elevation Regression on Independent Slopes Model
SAI- Standard Anomaly Index
SON- September-November
TOBS- USHCN data corrected for time of day bias
USGS- United States Geological Survey
WG1- Working Group 1 (of the IPCC)
WRCC- Western Regional Climate Center
Abstract

Local knowledge can play a role in both complementing quantitative climate data and enhancing understanding of associated impacts relating to climate variability and change. This study focuses on the local knowledge of farmers and ranchers in the Chuska Mountains area of the Navajo Nation. Local climate records in the Chuska mountains area of the Navajo Nation are consistent with published regional trends in hydroclimate, including less snow and earlier runoff into streams. Interview participants identified these recent changes. These accounts illustrate meaningful sectoral impacts. Local knowledge provides two important insights into linked human-environmental systems: 1) stakeholders in agriculture and farming in this region recognize trends in hydroclimate moreso than temperature and 2) this local knowledge reveals economic and cultural impacts of climate variability and change that can improve communication with this sector to address present and future needs relating to enhanced climate information, institutional structure, and infrastructure.
CHAPTER 1: CLIMATE OF THE WEST CHUSKA MOUNTAIN AREA OF THE
NAVAJO NATION: PRESENT, PAST, AND FUTURE

Part one of this study focuses on climate history of the general area of the Chuskas and surrounding areas of the Southern Colorado Plateau. First, a general overview of the location will geographically orient the reader. Next, a discussion of modern climate will detail the general characteristics and processes that influence the local and regional climate. Thirdly, a description of modern climatic variables drawn from multiple data sources will describe the current setting (temperature, precipitation, streamflow, PDSI). After, the past climate description will extend beyond the 20th century as far as the previous 2,000 years based on a comparison of paleoclimate reconstructions. Fifth, a discussion of the impacts of the past and present will illustrate the current impacts of greatest import for the area. Lastly, a description of future projections based on the Fourth Assessment Reprot of the Intergovernmental Panel on Climate Change (IPCC, AR4) model ensembles will introduce the current estimations of climate into the end of the 21st century.

Location and Background

*Diné Bikeyah* (Navajoland) is home to over 183,000 Diné people across the southern Colorado Plateau, an area rivaling West Virginia in size at 69,120 km² (27,000 mi²) (see Figure 1.1). The area of interest for this study lies near the center of the Navajo Nation: the western slope of the Chuska Mountains the northern Defiance Plateau, and Black Creek Valley between the two. The Chuska Mountains straddle the northern border between New Mexico and Arizona, rise to almost 3050 m (10,000 ft), trend NW-SE, and drain into the San Juan River basin. Because of this elevation, they receive more
precipitation annually than any other area on the reservation, and are the source for two thirds of surface water generated within the Navajo Nation (Harshbarger and Reppening, 1954; Pynes, 2001). Geologically, the Chuska Mountains are made of resistant Chuska sandstone and capped by basaltic rock from past volcanic activity (Pynes, 2001). The Defiance Plateau, described as both a monocline and an anticline (Pynes, 2001 and Branch of Forest Resource Planning, 1995, respectively), reside at 2130-2440 m above sea level (7,000-8,000 ft) and receive more precipitation than the surrounding reservation owing to this as well. They rise just over 600 m (3000 ft) from the valley floor on the eastern border and 915 m (2,000 ft) above the valley on the west (Branch of Forest Resource Planning, 1995).

The local vegetation of the Chuska Mountains is diverse and due primarily to the cooler more humid climate (relative to the surrounding area). The Navajo word “Chuska” derives from, “Chooshgai”, and refers to white-colored spruce trees, illustrating the fact that different biomes represented by various coniferous species and a few broadleaf tree species cover the landscape in this high desert (Pynes, 2001). The high diversity present is due mainly to the significant elevation of the rugged Chuskas and corresponding climate gradients. At the lowest elevations of the foothills and valleys, sage (Artemesia spp.) and low-density juniper spp. (Juniperus spp.) dominate (Figure 1.2) while at the next higher above that, Pinyon-Juniper (Pinus edulis, Juniperus spp.) woodlands are prominent. Ascending to higher elevations, one encounters mixed Ponderosa pine forests (Pinus ponderosa) (Figure 1.3), while at the highest Douglas fir (Pseudotsuga menziessii) and Aspen (Populus tremuloides) are the most abundant over-story (Figure 1.4). At the
very highest elevations sit small areas of Spruce-fir forest (Branch of Forest Resources Planning, 1995).

**Modern Climate**

Overall, the modern Navajo Nation has a semi-arid climate that ranges from 18 cm (7 in) of annual precipitation in the west to 51 cm (20 in) higher elevations of the Chuska Mountain area (Navajo Nation DWR, 2003). The major broad-scale climatic characteristics are influenced heavily by latitude and position with regards to moisture sources. The southern Colorado Plateau resides on the northern boundary of the subtropical high and within the dry interior of the North American continent. Being on the fringe of this dry subsiding air means it is on the border of most storm tracks and therefore doesn’t receive reliable precipitation. Taken together, the large-scale circulation resulting from this positioning and its location within the arid continent translates to overall dry conditions and variability. Two climatic modes arising from ocean-atmosphere interactions are often cited as impacting the temperature and precipitation variability in the West. The 1 Niño Southern Oscillation (ENSO) and the Pacific Decadal Oscillation (PDO) operate on interannual and decadal timescales (2-10 years and 20-30 years, respectively), have global teleconnections, and help to increase the predictability of winter precipitation on the Southern Colorado Plateau (Mantua, 1997, Hereford et al., 2002; Navajo Nation DWR, 2003).

In terms of precipitation, this region exhibits a bimodal regime with the largest peak arriving in the summer, while a lower peak occurs in winter (Figure 1.5). The summer precipitation is due primarily to the North American Monsoon though decaying tropical cyclones from the Pacific, and cut-off frontal storms from the Pacific also
contribute (Hereford and Webb, 1992). Differential heating between the continent and the Gulf of California sets up monsoonal circulation in the early summer as the rapid summer heating of the land masses of the Southwest (SW) deserts and plateaus creates a thermal low. This reverses wind direction and brings local, often violent convective storms accompanied by thunderstorms to the Southwest (Adams and Comrie, 1997). Tropical cyclones deliver another source of summer moisture when the few tropical cyclones persist northward off the west coast of Mexico late in the summer (Reyes and Cadet, 1988). Even though in this area winter moisture accounts for less than half of the annual precipitation, it is more effective in terms of its sustained impact. Winter moisture comes from large-scale synoptic storms usually originating in the northern Pacific Ocean and less often in the tropical Pacific (Navajo Nation WDWR, 2003). During El Niño years, the eastern tropical Pacific is warmed and the jet stream shifts southward, bringing relatively high winter moisture to the area. El Niño events also correlate positively with maximum winter temperatures (Woodhouse and Meko, 1997). The Pacific Decadal Oscillation (PDO) is a characterized by temporal variations of sea surface temperature (SST’s) in the North Pacific. It has recognizable winter precipitation impacts on the Southwest, although the 20th century instrumental record shows less than two of its full “cycles” (shifts 1925, 1947, and 1977) due to its multi-decadal period (Mantua et al., 1997). In its positive phase, when the Northeastern Pacific SST’s are warm (with lower pressure over the Northern Pacific Ocean), the winters in the West tend to exhibit higher precipitation. This especially amplifies precipitation in the Southwest when combined with ENSO and conversely, can dampen El Niño effects when it is in a negative phase (cooler western Northern Pacific SST’s) (Sheppard et al., 2002).
On a local scale, these large-scale factors certainly influence weather and climate on all timescales. However, mean differences and precipitation type (snow versus rain) of the Chuska Mountain area is highly influenced by local topography with elevation being the strongest influence on climatic variables (Spence, 2001; Richmond 1987). The Chuska Mountains (almost 3050 m) and Defiance Plateau (~2130-2440 m) create local orographic precipitation accounting for their relatively lush vegetation and diverse biomes as well as the rainshadow on the lee side of the mountains and the dry desert eastward.

Notwithstanding all the climatic influences locally, regionally, and synoptically, there is an upward temperature trend in the West that cannot be accounted for by all of the previously discussed factors (Mote et al., 2005). This warming trend in the West, and locally on the central Navajo Nation, is consistent with global temperature increase attributed to global anthropogenic warming. Global temperature increases over the 20th century also have observable hydroclimatological impacts in the West and are projected to increase due to anthropogenic warming into the next century (Barnett et al., 2005; Hamlet et al., 2005; Knowles et al., 2006; Mote, et al., 2005; Mote, 2006; Service, 2004; Stewart et al., 2004; IPCC WG1, 2007). The following section presents local and regional climate data and analysis to understand the how local temperature changes compare with regional change (annually and seasonally), which data set best represents local changes, and what changes are observed in regional hydroclimatology (i.e., peak streamflow timing and amount, and snow accumulation).
Data: Mean Temperature

The National Weather Service has a series of cooperative stations available from the Western Regional Climate Center (WRCC). Taken together, this climate station network is the most long-standing source of direct station observation on the reservation and represents some of the longest records when compiled, although questions about its reliability due to large dependence upon volunteer observation remain (Richmond, 1987). Additionally, on the Navajo Nation, no one station has been consistently in operation; many are inactive, resulting in limited historic data. The data used here focus on the Chuska Mountains/Defiance Plateau area co-op stations (Ft. Defiance, St. Michael’s, Window Rock, Ganado, and Lukachukai, Fig. 1.6) from 1898-2006. Only months with \( \leq 5 \) days of data missing were used, and no annual values with any months missing were used, as is the practice of the WRCC. The longest running co-op station, Canyon de Chelly/Chinle, is not included among these co-op stations since it is also the USHCN site detailed next.

The U.S. Historic Climate Network is an established network of high quality data sets from reliable long-term weather stations to be used for climate change studies (National Climate Data Center, 2007). There are four different data sets for each station, corresponding to different quality control adjustments: “raw” (areal edited, involving comparison with nearby stations records to remove outliers), “TOBS” (areal edited and adjusted for time of observation bias Karl et al., 1986), “FILNET” (filled missing original data using nearby networks to estimate), and urban-heat adjusted (adjusted to remove outliers, adjusted for time of observation bias, filled in missing data, and adjusted for potential heat-island effects), and. The TOBS data are used in this study for mean, min,
and max temperature rather than the other three (“raw”, “FILNET”, and urban-heat adjusted) as they are believed more appropriate since Chinle is a rural location (little urban heat effect), and because of there is a low density of station networks to reliably fill in missing data in this area. The data after 1928 are most reliable due to an ambiguous station move and observer time prior to 1928. The Chinle site (Fig. 1.6 #20) has moved seven times in its history and has resided between 1650-1710 m (5400-5610 ft) over its operation life. It was originally operated by local clergy early in its history and thereafter by the National Park Service.

The regional records of nearby USHCN sites employed here include: Holbrook, AZ; Lee’s Ferry, AZ; Ft. Valley, AZ; Bluff, UT; Blanding, UT; Canyon de Chelly, AZ; Aztec, NM; and Grand Canyon, AZ (Figure 1.7). These data have gone through the standard quality control adjustments and including estimation of missing dates using a network of correlated sites (FILNET) and have gone through the urban warming adjustment, thus they are serially complete (although values have been estimated). The stations vary in elevation (1550m, 980m, 2240m, 1315m, 1840m, 1710m, 2070m, and 1720m, respectively).

The National Climate Data Center (NCDC) created climate divisions in 1933 and currently provides data sets corresponding to the U.S. climate divisions for mean temperature and precipitation (as well as Palmer drought indices, percent area warm/cold and wet/dry, and other climatic variables). These data sets are only adjusted for time of observation bias and no other homogeneities (instrumentation changes, observer, station and location moves, and changes in station composition) (National Climate Data Center). Also, the number of records available decreases further back in time, and thus the earlier
portion of the record is less reliable. Currently, the AZ Climate Division data draw upon 117 stations within its division’s borders, whereas the smaller NM Division 1 uses 48 stations for its history. Both sets rely heavily upon the NWS Cooperative stations (described earlier). Here I use two climate divisions, Arizona 2, and New Mexico 1, hereinafter referred to as AZ2 and NM1 (Fig. 1.7).

The PRISM data set (Parameter-elevation Regression on Independent Slopes Model, Daly et al., 1994) is different from the previous data in that it combines point climate data and the surrounding topographic influence climatic variables to create estimates of climate variables. The result is a high-resolution 4km x 4km gridded data set of minimum, maximum, and mean temperature and mean precipitation from 1895-present. This is especially useful in areas of high topographic relief (NRCS, 2007). The data used here are from the 4km grid cell in a high elevation valley at the foot of the Chuskas that the coordinates 36° 5′ 49.2″, -109° 7′ 40.8″ occupy (approximately 2200 m above sea level~ 7200 ft) (Fig. 1.6, #6).

Methods

For the WRCC data, all available mean temperature data from the area were utilized. No station record extended the entire length of the series, and all were included (Appendix A) in the normalized composite (See Appendix B: Supplemental Data for graph of raw data of all annual series) (Alexandersson, 1986). To standardize and compile all the station series into one composite, each station record was subtracted from its mean and divided by its standard deviation to get indices for each series. Then all indices were combined and averaged based on the number of stations operating in that year (Katz and Glantz, 1986). This index was then multiplied by the average standard
deviation of all the stations and the average of all stations was added to return to the composite normalized series to units of degrees Celsius.

The NCDC, HCN, and PRISM data were already compiled into single time series. Each series was then compared based on its mean, variation (average standard deviation), correlation coefficient ($r$), and coefficient of determination ($r^2$) to see how well the data relate over the common period. It is important to mention that only the HCN and Co-op series are truly independent. NCDC and PRISM use a combination of station data across a network and thus correlation coefficients and coefficient ($r$) of variation ($r^2$) values between these may seem misleading in their strength.

To determine in which season mean temperature changed the most and the least over the period of record, two methods were used to compare against one another. The first method involved taking the slope of the line (the rate of change) and averaging it across all sites in a given season. The other method was station specific, where the rate of change (slope of the line) was compared across seasons to order them. Thereafter the order of seasonal change was compared across sites to see if the order of change was the same or not.

**Results: Mean Annual Temperature**

All temperature series have mean annual averages between 8.4 - 11.1°C and standard deviations between .61-.93 (Table 1.1). The average mean annual temperatures correlate well year to year ($r$= .61 to.81). The variability in different average means can be explained most by elevation for the regional data as illustrated by the lapse rate ($r^2$ = .91, see Figure 1.15).
All sites show a similar pattern of high temperatures at the turn of the century followed by a decline between 1910-1915 (Fig. 1.9). A rise occurs between 1915 to the early 1930’s followed by a period of semi-stable average temperatures until the mid-1960’s. A cooler period then occurs until the middle-late 1970’s. After this point there is a rise in mean temperature that steepens at all sites in the early 1990’s. The maximum temperatures at this point exceed mean temperature during the entire series’ length for all sites except NCDC’s AZ2 (Fig. 1.8). Note, however, that this climate division data record was extrapolated by statewide temperatures prior to 1931, and thus has to be considered less representative of the Navajo nation region before this time (Personal communication, R. Heim, 2007).

**Seasonal mean temperatures**

**Winter**

Mean winter (December-February) temperature fluctuate between periods of lower average temperatures and higher average temperatures somewhat regularly approximately every 15 years (5-10 years for each period of relatively warm and relatively cool temperatures, Fig 1.10). Recent increasing trends since the early 1990’s show the mean temperatures for 5-year averaged values (Figure 1.10) as approaching 0°C and reaching/exceeding this temperature more consistently since 1995 (for the sites that previously did not exceed an average mean temperature of 0°C even in the “warm periods”). Winter mean temperatures are changing but there is no consensus between data
sets which season is changing most in terms of seasonal mean temperature (Tables 1.2, 1.3).

**Spring**

There is a noticeable upward trend in all spring (March-May) mean temperatures series since 1895. Spring shows the most noticeable warming trend of all seasons. There are two sharp increases in the rate of mean springtime warming apparent in all series around 1920 and 1980 visible (Figure 1.11) of 5-year running means for spring temperature. The latter temperature increase is especially apparent in spring temperatures at all sites and is important in terms of snowpack, melt, and peak flow at this elevation. Winter moisture is very important throughout the rest of the year as it greatly affects surface water supply and availability. This will be discussed in greater detail in the following analysis section.

**Summer**

Mean summer (June-August) temperature shows a gradual but steady upward trend for all series over the entire length with the exception of NCDC AZ2 and, to a lesser extend, NCDC NM1. These sites exhibit temperatures at the turn of the last century that exceed or are equivalent to the most recent high temperatures and dampen any upward trend over the series length (Fig. 1.12). Only the PRISM data also occur at this early period, and while they do show a general pattern of high temperatures at the turn of the last century (1895-1905) the pattern is not nearly as pronounced and the temperatures do not approach those in the recent period (since approximately 1995). The current warming trend seems to have become more pronounced in the early 1980’s across all data sets. The PRISM data and the USHCN data (from which the PRISM data most likely
drew upon) show the summer warming since the late 1990’s as exceptional over the full series length. Earlier in the century, warming is observable in the early half of the last century in the PRISM data set (~1920-1940) and to a lesser extent in the NCDC records but moreso in the late 1950’s (Fig. 1.12).

**Fall**

The fall (September-November) series again shows warm temperatures at the turn of the last century into the early 20th century to varying magnitudes followed by a cooler period until late 1910’s, although WRCC co-op data conflicts with the other series here (Fig. 1.13). This early 20th century period is followed by a warming trend that started around 1920 and lasted into the 1930’s. The next marked change is a decline in mean temperature in the mid 1960’s until the following decade. Since this decline, there has been a steady upward trend similar in rate to that of the 1920’s-1930’s. Compared to the rest of the seasons’ series, no fall series shows exceptional temperatures at the end of its record compared with the rest of the 20th century records (Fig. 1.13).

**Seasons with the Greatest Change**

To examine seasonal temperature change over the period of record by season I performed two analyses. The first ranked the average annual change for each season over all series. Using this method, winter appears to have warmed the most followed by spring, summer, and fall (Table 1.2).

The second analysis created a ranking for each individual data set of seasonal rate of mean temperature change. I compared these data sets’ seasonal rankings for their degree of agreement (Table 1.3). There was a consensus between all data sets that fall temperature has changed least. Thereafter there is less consensus. In general winter and
spring are changing most, though there is little consensus regarding which is changing most (Table 1.3). From Table 1.2, it is evident that spring and winter average rates of change are similar. Unlike the PRISM and NCDC data, it should be noted that the USHCN data and the WRCC Co-op data do not extend the length of the entire period (1895-2005), although the NCDC data are questionable for this region prior to 1931 (Personal communication, Heim, 2007).

**Regional Analysis of Individual Chuska/Defiance Station Records**

Regionally, all the long-term USHCN sites (8 sites) highlighted in Figure 1.15 (except Holbrook) have positive trends for the series length mean (Fig. 1.14). Those with the most change tend to be the higher elevation sites (Fig. 1.15). Specifically, all show a 1990-2005 average as higher than the series mean (including Holbrook slightly). While none of these increases exceeds two standard deviations of its series mean, Canyon de Chelly, Blanding, and Fort Valley averages for this period do exceed one series length standard deviation (1.58, 2.09, and 1.62°C, respectively). Variability does not change greatly over this period although it does vary from site to site. The Holbrook site is different from all the other USHCN stations. It has the most southerly latitude compared to the other stations surrounding the Chuska/Defiance area and has a lower elevation than five of the eight sites. Additionally, on average, it correlates poorly with almost all surrounding sites (average r= .50 compared with other stations’ average correlations with one another of .66 to .85, see Supplemental Table S.1). Additionally, the early 1990’s-2005 shift in higher rate of temperature increase is visible in all data sets (except the USHCN’s Holbrook station).
PRISM Data Most Appropriate for Further Analysis

The PRISM data set for temperature is likely the most representative of the 20th century-present climatic history of the Chuska/Defiance area based on the preceding analysis. First, these data correlate well with the WRCC local data ($r = .81$, $r^2 = .65$), and their mean is the most consistently similar to the co-op data in all seasons. However, it is acknowledged that some of this is likely due to partial usage of the local co-op data sets to compute the PRISM values. Second, the PRISM data, based on their high spatial resolution, take into account topographic relief. Regionally, elevation is the most influential factor affecting climate average mean temperatures and lapse rates (Figure 1.15) for USHCN sites surrounding the Chuska/Defiance Plateau (Fig. 1.15). The PRISM mean temperature data correlates reasonably with most of the regional sites (average correlation $r = .50$ (Supplemental Table S.2) for individual statistics between sites). Lastly, the PRISM temperature data extends from 1895-2007 and includes minimum and maximum temperature series which are useful in the analysis that follow and involve other measures of climate in the area, primarily snowpack and streamflow.

Data: Precipitation, streamflow, and relationship with temperature

The Navajo Nation Water Resources Management Branch acquired control of the manually measured snow course network starting in 1984. The snow courses are checked bimonthly generally from late December until April 1. These are the only known “long-term” snow data for the Chuska Mountains, and all data are currently considered provisional by the Navajo Nation Water Management Branch. There are 8 sites in the snow course network, 7 of which are used in this following analysis based on their completeness (high elevation >2439ft: Bowl Canyon, Hidden Valley, Tsaile, Tsaile III,
Whiskey Creek; low elevation<2439: Fluted Rock, Missionary Springs). Figure 1.6 shows the snow course locations along the Chuska Mountains and one site (Fluted Rock) on the eastern side of the Defiance Plateau to the west of the Chuskas.

PRISM precipitation and temperature (mean, minimum, and maximum) data (Daly et al., 1994a) from the Chuska/Defiance area (as previously described) are likely the most representative of the recent climate of this area. Because of this, in the following analyses, they are used to examine the relationship between temperature and precipitation and trends in snowpack, streamflow timing, and late summer precipitation.

Chinle Creek (station 09379200) streamflow (daily discharge) is available from the U.S. Geologic Survey and extends from 10/1964-present. The basin drains an area of 9344 km² (3650mi²) into the San Juan basin. Its mean basin elevation is 1908 m (6260 ft) (Fig. 1.16). Whereas there are no reservoirs regulating flow there are diversions for irrigation, livestock, and domestic use that influence discharge values. These data have all been approved by the USGS and are used here in the analysis of streamflow timing described below.

**Methods**

To create an aggregated time series for the SWE from the Chuska snowcourse, only "reasonably complete" data (relative to its series length) were used (>65% after Mote et al., 2005) largely between the 1985-2006 periods, although not all series extended the entire period (one low elevation site, Missionary Springs, extended only 1991-2006). No incomplete years were included (except for 2006 as it was uniformly missing the last observation date for all sites, late March), therefore the average of all series does not include every year for each series. Correlations were high between the
five sites, the lowest being .68, the highest .996 inferring that when years of certain sites were absent from the record, the average would still be representative. It should be noted that in 2004, only one site was complete and therefore represents all high elevation sites.

To get a normalized record (Z-score) for each series, the data were normalized by subtracting each series by its mean and then dividing by its standard deviation (SD). These scores were then averaged together and converted back into SWE by multiplying the averaged z-score by the SD of all series’ average and then adding the series’ average mean (Katz and Glanz, 1986 in Mote et al., 2005). This was done for five higher elevation sites that exhibited high and similar mean SWE, as well as for the two lower elevations sites that exhibited much lower mean SWE. One particularly high outlier in 1988 at one site (Whiskey Creek) was removed from the analysis since it was 280% of its’ site average and 260% in excess of the other sites SWE for that year. This regional Chuska SWE series was then examined for trends and variability. To examine the influence of temperature and precipitation on SWE trends, I first obtained the correlation (r) and coefficient of variation (r^2) between SWE and spring (MAM) maximum temperature. I then did the same for SWE and cool-season total precipitation (Nov.-March). I then compared these statistics. Lastly, I examined their combined effect on SWE in a simple multiple regression to see if precipitation or temperature influenced SWE more than the other.

Streamflow timing is also an important hydroclimate variable used to study change, particularly as temperatures increase. Here the USGS Chinle Creek data were converted to centroid of streamflow (Cayan and Stewart, 2004), also known as center of mass flow, hereafter referred to as “CT”. The formula used to arrive at this measure is:
\[ CT = \frac{\sum(t_i q_i)}{\sum q_i} \]

Where \( t_i \) is the time in days from the beginning of the water year (Oct. 1) until the end of the high flow (June 30 = day 273) and \( q_i \) is the streamflow for the day \( i \). So CT is a date given in the number of days since Oct 1 (=day 1) and is thought to reflect the conditions that influence snowmelt-dominated streams. The CT was then compared to a number of spring temperature data sets to see which correlates best, including monthly (March, April, May) and multi-month, (MAM) and mean, minimum, and maximum temperature data sets (WRCC Co-op, USHCN Chinle, PRISM, and NCDC for both AZ2, NM1, and an average of both). Also, to understand the influence of overall cool season precipitation on streamflow timing, precipitation (Nov.-Mar.) was also compared to CT to understand the “bulk” effect of cool season precipitation on CT. To compare the combined influence of both cool-season precipitation and spring maximum temperatures, a simple multiple regression analysis was also employed using JMP statistical software (SAS Institute, 2005) (Stewart and Cayan, 2004 use a hydrological model to examine the effect of both separately and combined).

To examine trends and variability in summer season precipitation, the PRISM data from July-September (JAS) were plotted along with its five-yr running average, series length mean, and most recent mean 1991-2006. To examine changing contributions of each month’s precipitation to the total seasonal (JAS) precipitation, each month’s percentage of total JAS was plotted with a 5-yr running mean and series mean (1895-2006).
Results: Climate and snowfall

There is an overall declining pattern of snowfall at all elevations within the period of available data as seen in Figure 1.17 (1985-2006, NNWMB provisional data). There is also higher variability in the high elevation sites than in the lower elevation sites. As the lower elevation site has a lower mean, in dry years there is essentially no measurable snow accumulation while at the high elevation sites even in dry years, there is still snow accumulation. 1996, 1999, 2000, and 2006 are four such years in the 19 complete years of SWE observation when there was almost no measurable snow accumulated throughout the year at the lower elevations. The latter portion of the record also exhibits more sustained lower SWE compared with the rest of the record where dry years are followed by wet recovery years (though the 1980’s are an anomalously wet period for comparison).

Maximum temperature during the cool-season (November-March) was correlated more strongly with SWE than mean temperature for both lower and higher elevation sites (r = -.50 vs. r = -.68 for high elevations and r = -.79 vs. r = -.82 for lower elevation SWE). Figures 1.18-1.21 show a time series of SWE for high and lower elevations plotted along with maximum cool season temperature and precipitation. Cool-season maximum temperature and precipitation (November-March) do not appear to have the same influence on SWE at both high and low elevations. Considered alone, precipitation and high elevation SWE for this period have a correlation of .8, (r² = .65), whereas maximum temperature for the same period is -.68 (r² = .47). Taken individually, both correlations are significant (p<.001). However, in a simple multiple regression analysis using JMP statistical software to examine the combined effects of cool-season
precipitation on high elevation SWE, maximum temperature was not significant (t = -1.59, p = .13), whereas November-March precipitation was significant (t = 3.71, p = .0014).

At lower elevations, the correlation between SWE and maximum temperature was $r = -.82$ ($r^2 = .67$) and for cool-season precipitation, $r = .58$ ($r^2 = .33$). This suggests that at lower elevations maximum temperature is more influential than precipitation, the converse of the high elevation influences. A simple multiple regression also supports this. For lower elevations, cool-season precipitation was not significant (t = .51, p = .61), whereas November-March maximum temperatures were very significant (t = -4.06, p = .0009). However, high elevation data had a much normal annual distribution than the low elevation data, making such an analysis more suitable for the higher rather than the lower elevation. If the lower elevation annual data were normally distributed enough for the multiple regression analysis to be appropriate, it would support the simple correlations suggesting different influences between high and low elevation SWE.

This potential higher temperature sensitivity at lower sites is consistent with the thinking that temperatures there will be consistently higher than at the sites at greater elevations, which would result in less precipitation falling as snow and higher temperatures that would induce earlier melting (Mote et al., 2005). In terms of its impact on societal and ecological systems, this is generally thought to be of less consequence at lower elevations than in mountains since SWE produces more sustained recharge for aquifers and streams at higher elevations and is therefore a more important in terms of hydrology (Barnett et al., 2005).
Results: Climate and Streamflow

There has been a trend in earlier springmelt pulse timing for Chinle Creek, a waterway that feeds into the San Juan River near Mexican Water, UT and is fed in great part by smaller tributaries coming off of the Chuska drainage area. Figure 1.22 and 1.23 shows this increasingly earlier CT (spring melt pulse) over time. The variability explained by Nov.-Mar. total precipitation and MAM temperature ($r^2 = .45$) suggest that there are other factors influencing the variation in the CT in this period. This makes sense as the watershed is not completely dominated by snowmelt.

Spring maximum temperatures have an inverse relationship and the most correlations with CT compared to other months and minimum and mean temperatures ($r = -.51, r^2 = .26$) and is significant when considered alone ($p < .001$). However, cool season precipitation (Nov.-Mar.) exhibits a stronger positive correlation with CT ($r = .66, r^2 = .44$) and has a similar downward trend and very close year-to-year variations (Fig. 1.23). A simple multiple linear regression analysis using JMP software shows cool season precipitation as being significant while temperature is not when the combined effect is considered (precipitation: $t = 3.8, p < .001$; temperature: $t = -1.2, p = .24$).

Precipitation during the monsoon season (July, August, September), according to the PRISM record from 1895-2006 (Figure 1.24), shows a mean of 127 mm throughout the series, whereas the latter part of the record (1991-2006) shows a lower sustained mean of 107 mm. The late 1960’s to 1980 also has a lower mean than the rest of the century.

Figure 1.25 shows the % of total JAS precipitation that July comprises during the 1895-2007 period. There is an evident decline in the amount of summer precipitation that
July contributes according to this dataset since 1991. The 5-year periods with the lowest contributing July are 1991-1995 followed by 1939-1943.

The earlier period of lower contributing July values is consistent with the regional history of 20th century JAS precipitation. Hereford and Webb (1992) noted an earlier decline in warm-season rainfall on the Colorado Plateau after the early 1930’s and attributed it to declines in tropical cyclones, shifts in meridional circulation in the upper atmosphere, and variability of ENSO conditions. It is important to recall that warm season precipitation includes moisture from the different sources and processes. This local data may also be consistent with Higgins and Shi (2000), showing an abnormally late onset of monsoonal precipitation starting in the early 1990’s.

Discussion

Regional trends for the West and the Southwest are evident in the local data to an extent, though ultimate attribution of cause (e.g. to global climate change) is beyond the scope of this study. The current trends include higher temperatures since the 1980’s, particularly in spring and winter and least in fall that are correlated with an earlier spring melt and less snow (at least since the 1980’s). The snow trend, however, needs to be compared against a longer period since snow-water-accumulation is highly correlated with winter precipitation and the period of observation begins in an anomalously wet period and ends in a drought period.

There is also potential evidence of less or later monsoonal precipitation contributed in July. The monthly data used in this study are not of high enough resolution to determine if this decline may be indicative of a later onset of the North American monsoon or simply a decline in the overall amount of precipitation spread throughout this
month (not necessarily confined to the latter part of July). Therefore, these data are insufficient to determine whether or not this decline in July, over the last two decades in particular, is most attributable to North American Monsoon activity or a combination of other summer rainfall contributors. Higgins and Shi (2000) have recognized a significant (95% level) correlation (-.52) in Arizona and New Mexico between onset date of monsoon and the total warm-weather precipitation received (June-September, using NCDC divisional data 1948-1996). An earlier onset correlates with more overall seasonal rainfall, whereas the opposite is observed as well but to a lesser extent. This correlation is even stronger (-.68) when considering only June-July rainfall and timing onset. If the latter relationship continues, one vital implication for climate-sensitive sectors is that combined with an earlier snowmelt there would likely be an extended dry season.

**Paleoclimate**

There were almost no instrumental climate data in the Southwest prior to the late 19th century as demonstrated in the previous section (Liverman and Merideth, 2002). To understand climate variability prior to the instrumental period, other sources are needed to represent climate variability. Proxies of paleoclimate such as from tree-rings, packrat middens, lake cores, speleothems, and geologic features can help understand the past climate of the American Southwest. Dendrochronology, in particular, has provided long, continuous and high-resolution records of climate here. The Southwest’s aridity in particular and the preservation of archaeological remains (in great part due to its arid climate) has lent itself to preservation of extended chronologies of tree-ring records from which to reconstruct climate (Dean et al., 1985). Many researchers have used tree-ring chronologies to reconstruct the climate of the southern Colorado Plateau extensively,
yielding chronologies and reconstructions of climate variables such as annual precipitation and temperature, Palmer Drought Severity Index (PDSI), streamflow, and precipitation days (e.g., Dean and Robinson, 1978; Dean et al. 1985; Stockton and Jacoby, 1976; Salzer and Kipfmueller, 2005; Woodhouse and Meko, 1997, Woodhouse et al., 2006, Cook et al., 2004).

There are few stations that have long enough instrumental records against which to calibrate reconstructions for the area of interest (the central Navajo Nation). When reconstructing climate, trees are often sampled over a broad area and also correspondingly, calibrated against a regional record, rather than an individual climate station. Thus, the quality of a reconstruction relies on the quality of the observed record against which it is calibrated (Personal communication, 2006, K. Wolter.).

Global change-type drought as described by Breshears et al. (2005) differentiates past droughts in the Southwest from the current drought in terms of increased temperatures in addition to the usual precipitation deficit typical of drought. Natural climatic variability is predicted to combine with anthropogenic atmospheric warming to drive environmental changes distinct from those due to past natural variability alone (Walther et al., 2002). The instrumental data for the Southwest indicates an average surface temperature increase of 1.1°C to 1.7 °C during the last century (Southwest Regional Assessment Group, 2000), and modeled warming forecasts of 1° to 1.5° C for the early 21st century (2020-2029), and 3°-5° C by the late 20th century (2090-2099), relative to late 20th century surface temperatures (1980-1990). The latter modeled projection depends more than the former on the trajectory of future greenhouse gas emissions (IPCC, 2007). Thus, it would seem imperative, in this area of sparse and often
discontinuous instrumental climate records, to utilize the numerous paleoclimatic reconstructions to understand the natural climatic variability. This baseline information can help place future trends in context. This study will focus on characterizing the temporal and spatial drought variability of the central Navajo Nation from the dendroclimatic record and assessing change in the variability over time.

Tree-rings have proven valuable for proxies of past climate. Fritts (2002) describes each tree-ring as an integration of multiple factors affecting the growth in that year. Additionally, each tree species has its own biological character that responds in distinct manner to climate throughout the year, making some trees better indicators of certain climate variables and seasonal conditions during the year (Fritts, 1965, 2001). Since conditions on the ecological boundaries are most limiting, tree-rings from these areas are the most climatically responsive (Fritz, 1985). In the Southwest, tree-rings may offer more information on cool-season precipitation since the nature of the summer precipitation is generally more irregular and spatially heterogeneous compared to the winter precipitation, often rendering warm-season moisture less available to vegetation.

Climatically-sensitive coniferous tree species from this region offer an annually-resolved record of climate. The species most often used in this region for precipitation and PDSI reconstructions are Douglas-fir (Psuedosuga menziesii, PSME), Ponderosa Pine (Pinus ponderosa, PIPO), Pinyon-pine (Pinus edulis, PIED), and various Juniper species (Juniperus, JUN). Fritts (1974) suggests using a diversity of species in dendroclimatic reconstructions because of differing tree-growth responses.
Data

The reconstructed drought data used in this study came from the Southwest Paleoclimate Network Project of the University of Arizona Laboratory of Tree-ring Research (Dean and Robinson 1978). It is comprised of 25 tree-ring chronologies from southern Colorado Plateau sites throughout the Four Corners region (Utah, Colorado, New Mexico, and Arizona). Dean and Robinson combined archaeological chronologies with living tree chronologies from the same or nearby areas and used these site chronologies to reconstruct June PDSI and precipitation, calibrated using Arizona Climate Division 2 data (NCDC, 1999). Since the reconstructed data are based on well-known archaeological sites rather than climatic boundaries, five sites were chosen based on their correlations in order to represent a homogenous climate of the central Navajo Nation (Fig. 1.27). Dean and Robinson (1978) use a diversity of species in their dendroclimatic reconstructions (Table S.3 in Supplementary Figures) of Canyon de Chelly, Chuska Mtn., and Chaco Canyon sites while the two others used in this study (Hopi Mesas, Puerco/Defiance) only incorporated one species, pinyon pine (*Pinus edulis*). The highest correlations among tree-ring reconstructions are found between the three sites in eastern Arizona (Hopi Mesa, Puerco/Defiance, Canyon de Chelly) and two in western New Mexico (Chuska Valley, and Chaco Canyon) (Table S.4, Supplementary Figures; Fig. 1.27).

Cook et al. (2004) reconstructed climate for North America employing a point-by-point local regression, and providing a gridded data set for PDSI (Fig. 1.27). The data were calibrated against instrumental PDSI. Like Cook, Zhang et al. (2004) deliver a grid reconstruction of the conterminous United States, but they use a different method to
arrive at summer (June-August) PDSI from 1700-1895 (thereafter followed by instrumental data from Cook, 1999. The data were calibrated against summer drought using a different algorithm than Cook et al. (Regularized Expectation Maximum) that is meant to capture large-scale patterns rather than local information. Both Cook et al. (2004) and Zhang et al. (2004) reconstructions were obtained at the World Data Center for Paleoclimatology website (NOAA).

Ni et al. (2002) use two different models, neural network, and linear regression to reconstruct climate divisional cool-season (November-April) precipitation data from tree-ring chronologies for the period 1000-1988. The simple average of reconstructions generated with these two methods is used here as recommended by the authors (Ni et al., 2002). These data were also obtained from the World Data Center for Paleoclimatology website (NOAA).

Grissino-Mayer and Holmes (1993) used old-growth conifers (Pseudotsuga menziesii) in El Malpais National Monument (Fig. 1.27) in northwestern New Mexico to reconstruct a long-term precipitation (and fire) history (-136-1992). This area had not been previously subject to known or detectable anthropogenic disturbance. These reconstructed data were also accessed from the World Data Center for Paleoclimatology website (NOAA).

Woodhouse et al. (2006) updated the annual streamflow reconstructions for the Upper Colorado River using 62 tree-ring chronologies to reconstruct flow (billions cubic m/yr converted here to standard anomaly index = “SAI”) at key gauges (including Green River, UT, Colorado River near Cisco, UT, San Juan near Bluff, UT, Colorado at Lee’s Ferry) between 1490-2000m (Fig. 1.27). U.S. Bureau of Reclamation gauges were used
for calibration. Meko et al. (2007) soon after extended the Lee’s Ferry gauge streamflow reconstruction from 762-2005 and employed primarily Douglas fir and pinyon pine (\textit{Pseudotsuga menziesii} and \textit{Pinus edulis}) . Reconstructed data were obtained from the World Data Center for Paleoclimatology website (NOAA).

**Methods**

To describe climate of the Southern Colorado Plateau of the last 2,000 years in terms of variability, particularly regional drought history, all the above data sets were used in a comparative analysis (except the short Zhang et al., 2004 series). While all values are expressed as indices (either summer Palmer Drought Severity Index = “PDSI” or cool-season precipitation Standard Anomaly Index = “SAI”), over their record lengths they still do not have means of 0 or 1. Also, their variability as taken from each series’ standard deviation differs. Therefore, to compare temporal and spatial coherence of decadal drought, I completed an 11-yr running average for each site followed by a ranking of the most severe droughts in each series of the common period mid-600s to the late 20\textsuperscript{th} century. The most severe periods for each series were compared for spatial variability over time. A visual comparison of the fluctuations also aided in illustrating the variability of each series over time. Figures 1.28 to 1.31 show the annual PDSI and SAI values along with the 11-year running averages between the mid 600s AD to late 1900 AD. Both of these comparative methods help to reveal temporal coherence between these reconstructions, particularly in terms of drought, when the tree-ring reconstructions are most representative (rather than the wet periods which are not well represented, Woodhouse and Overpeck, 1998).
Results

Decadal-scale droughts

The most severe decadal-scale droughts of the period 660 AD- 1988 AD from the ranking of the 11-year running mean for the Chuska area (Fig 1.28, top; Table 1.4) occurred the late 1500s and are centered on the most severe years: 1587-1589 AD (approximately 1582-1594 AD). This is followed by the late 1800’s, centered on 1897 AD (approximately 1892-1902 AD). Thirdly is the 1950’s drought, centered on 1954 and ’55 AD (approximately 1949-1960 AD). Noteworthy is the next most severe drought in the early 1200’s, centered on 1217, 1219, and 1220 (approximately 1212-1225 AD). The Chaco chronology (Fig 1.28, second series, Table 1.4) however shows the 1950’s drought as the most severe for that site, centered on the years 1954-’55 AD, and 1951-’52 AD (approximately 1946-1960 AD). The early 1820’s, centered on 1823 AD (approximately 1818-1828 AD) is also the next most severe, followed by the late 1500’s, (approximately 1575-1585 AD). The Hopi Mesas reconstruction (Fig 1.28, third series; Table 1.4) was most responsive to the early 1800’s drought (centered on 1817-1818 AD, lasting approximately from 1812-1823 AD), followed by the late 1200s (approximately 1285-1295 AD). Closely following these is the early 1700’s (approximately 1727-1738 AD), and the early 1800s (approximately 1810-1820 AD). The Puerco/Defiance Plateau site reconstruction (Fig 1.28, fourth; Table 1.4) showed the early 1500s (1518 AD) (approximately 1513-1523 AD) as the most severe decadal drought while the early 11th century ranked second (approximately 1089-1100 AD). The early 1800’s followed (approximately 1817-1827 AD) while a considerable portion following this revealed more high-severity and long-term late 11th and early 16th century droughts. Natural
Bridges (Fig 1.29, second series; Table 1.5), unlike the other local reconstructions shows the early 8th century (approximately 702-712 AD) as having the most severe droughts in both duration and severity while the early 1600s (approximately 1622-1632 AD) and mid-12th centuries (approximately 1144-1156 AD) followed the severity of the 8th century. The Navajo Mountain reconstruction (Fig 1.29, top, Table 1.5) showed the early and late 1600s as the most severe (approximately 1662-1676 AD and 1622-1632 AD) while the late 1800’s (1899 AD) was second in severity to the late 17th century drought. Last of the local Dean and Robinson (1978 AD) PDSI reconstructions; Tsegi Canyon (Fig 1.29, third series; Table 1.5) proves the most sensitive to decadal droughts in the last 10th century (approximately 991-1001 AD), next in severity is the early 8th century (approximately 711-727 AD), the early 1700s (approximately 1727-1737 AD), and the late 13th century (approximately 1273-1283 AD). The El Malpais record (Grissino-Mayer, 1995) shows (Fig. 1.29, fourth series; Table 1.5) the late 16th century (approximately 1576-1592 AD) as dominating in terms of both severity and length, though the shorter period of approximately 737-747 AD also rates as similar in terms of severity only (not duration).

The 20th century droughts do not rank among the most severe of most of these local chronologies, only the Chuska Valley, Chaco Canyon, and Navajo Mountain chronologies show droughts of the 20th century as ranking among the most severe during the 660-1988 AD period. For all reconstructions, the spread between the most severe three drought periods is very narrow, a few tenths to hundredths of the PDSI and SAI index.
The standard anomaly index (SAI) of regional cool-season precipitation reconstruction for AZ2 (Ni et al., 2002) shows the late 1600s (approximately 1661-1672 AD) as the most severely dry period followed closely by a drought centered on 1733 AD (approximately 1728-1738 AD) (Figure 1.30, first series; Table 1.6). The late 1500s and late 1600s also rank firmly in the top four periods of drought for this region (approximately 1583-1593). The late 1500s and 1600s clearly dominate the NM1 decadal drought severity (approximately 1582-1595 AD and 1658-1672 AD) (Figure 1.30, second series; Table 1.6). The late 1700s (approximately 1773-1783 AD) rank next in severity followed by the drought centered on 1220 AD (approximately 1215-1225 AD). The reconstruction of October-July precipitation (SAI) (Salzer and Kipfmueller, 2005) emphasizes the sustained, severe aridity of the late 16th century compared to all other decades (approximately 1575-1593) (Figure 1.30, third series; Table 1.6). The late 1800s (approximately 1893-1904 AD) is the next most severe, though it did not last as long as the late 16th century drought.

The Cook et al. (2004) gridded PDSI reconstructions extend from 650-1988 AD, whereas the Ni et al. (2002) precipitation reconstructions begin at 1000 AD. Most of the Cook et al. data emphasize the aridity before 1000 AD (the 8th, 9th and 10th centuries). However, reconstructed precipitation from Salzer and Kipfmueller (2005) extends to 570 AD and also shows the 16th century droughts as most prominent during its series length like some of the Ni et al. reconstructions. Data from the Cook et al. reconstructed grid point 103 (northwest grid point), centered on the years 1035 AD and 1153 AD, and show a picture of regional drought clearly dominated by the early 10th and mid-11th centuries (approximately 1029-1041 AD and 1146-1158 AD; Figure 1.31, first series; Table 1.7)
(Cook et al., 2004). This reconstruction shows more consistently negative PDSI values than the other Cook reconstructions (nearby grid points 104-SW, 118-NE and 119-SE). The PDSI reconstruction for grid point 104 (southwest grid point) reveals the most intense droughts as centering on 740 AD, 1036 AD and 1256 AD (approximately 734-745 AD, 1031-1041 AD and 1250-1261 AD, respectively; Figure 1.31, second series; Table 1.7). The reconstruction for grid point 118 (northeast grid point) also emphasized the low PDSI during the 11th century and the 12th with mid 8th centuries as very dry (approximately 1029-1041 AD, 1146-1158 AD, and 734-745 AD, respectively; Figure 1.31, third series; Table 1.7). The summer PDSI reconstruction from the last grid point, 119 (southeast grid point) shows a period of continuous 8th century severe drought lasting from approximately 734-753 AD (Figure 1.31, fourth series; Table 1.7).

None of the regional reconstructions (neither PDSI nor SAI) show 20th century droughts as ranking among the most severe in terms of aridity or duration except the late 1800s drought, which lasted until the first few years of the 20th century. However, a few of the local reconstructions do show periods during the 20th century comparable to and exceeding droughts prior to the 20th century on a local level (Chuska Valley, Chaco Canyon, and Navajo Mountain from Dean and Robinson, 1978).

The reconstructed streamflow records across sub-basins of the Upper Colorado River basin show that while there is variation between individual gauge reconstructions, generally there is strong spatial correlation in the basin at the water-year scale (Table 1.8, Figure 1.32). After taking the 11-year running average and converting the streamflow into standard anomaly indices (SAI), the ranking of the low flow years shows slight variability (Tables 1.9 and 1.10). The most prominent low-flow periods across the basin
since 1530 AD include the early 1600s, late 1700s, late 1500s, late 1800s, early 1700s, mid 1800s, and mid-late 1600s (Table 1.9 and 1.10). The 20th century does not rank among the most severely dry decadal periods in any reconstructions except the San Juan River near Bluff, UT and Colorado River near Cisco, UT, gauge reconstructions (1953-1964 for both). Also, the drought extending into the very early 20th century does figure into the driest decadal length droughts of the San Juan River near the Archuleta, Dolores, CO and Lees Ferry, AZ reconstructions as well (Tables 1.9 and 1.10).

A comparison of the PDSI, SAI and streamflow records aids in identifying general temporal coherence between different regional climate reconstructions. (Tables 1.4 to 1.7). These regional records show coherence between the most arid periods post-1530 AD (since only one streamflow reconstruction extends prior to this period). The regional reconstructions of climate divisions AZ2 and NM1 (1000 AD-late 20th century, Ni et al., 2002) compare well with the streamflow reconstructions (Table 1.6 compared with Table 1.9). Both reconstructions emphasize the dry conditions during the mid-late 1600s in general as well as the late 1500s and early-mid 1700s. The southern Colorado Plateau reconstruction (Salzer and Kipfmueller, 2005) is also consistent with streamflow, showing the late 1500s and late 1800s as among the driest reconstructed decadal periods in the common period (post 1500-late 20th century, Table 1.6). However, the regional PDSI reconstructions for grid points in the Four Corners region (Cook et al., 2004) extend prior to the 1500s and show the early-mid 11th, early-mid 8th, and early-mid 12th centuries as having the lowest PDSIs compared the rest of the decadally averaged values (Table 1.7). Thus these records cannot compare with the reconstructed streamflow except
to infer that dry decadal-length periods prior to the 1500s were of a much more severe nature than those captured in the streamflow reconstructions after the 16th century.

A comparison between reconstructed streamflow and local reconstructions within and near the Four Corners region by Dean and Robinson (1978) and Grissino-Mayer (1995) shows less consistency with streamflow in terms of decadal drought severity than the regional records. This infers higher variability at the local scale than at the regional scale, showing that dry periods are heterogeneous in their local character (Tables 1.4-1.9). Those local reconstructions that exhibit the most severe decadal droughts consistent with streamflow reconstructions are: Chuska Valley, Navajo Mountain, and El Malpais (Table 1.4, 1.5, 1.9 and 1.10) (Dean and Robinson, 1978; Grissino-Mayer, 1995).

The reconstructed annual mean maximum temperature of the last two millennia shows two dominant periods of high temperature: the early-mid 3rd century and the middle to late 20th century (Table 1.11, Figure 1.33). This applies to the Southern Colorado Plateau and compared with PDSI and precipitation (SAI) reconstructions illustrates that severe decade-length droughts over the reconstructed history (approximately 660 AD- 1988 AD) did not necessarily coincide with high temperatures. However, aside from the 3rd century high temperatures, the 20th century dominates the reconstruction in terms of decades of highest annual mean maximum temperatures (Table 1.11). This temperature reconstruction is unique in the area since it is virtually the only paleotemperature record as there are apparently few options for finding temperature-sensitive tree species on the southern Colorado Plateau.
Discussion

Though the instrumental data may be sparse, there are many records of regional and local climate available for the Four Corners area (within which resides the Navajo Nation). Broad regional drought trends exist, but the local reconstructions (Dean and Robinson, 1978; Grissino-Mayer, 1995) also show that drought character is more heterogeneous at the local scale (Figures 1.28-1.33, Tables 1.4-1.11). Research on Colorado Plateau paleoclimate of the last 2,000 years overall shows that the droughts of the 20th century are in no way comparable to the most severe droughts during this period. The combined duration and severity of the “megadroughts” of the 13th and 16th centuries in the Southwest, as others have noted, greatly exceeds anything experienced in the last century (Woodhouse and Overpeck, 1998; Gray et al., 2003; Kipfmueller et al., 2003; Cook et al., 2004, Gray et al, 2004; Salzer and Kipfmueller, 2005; Woodhouse et al., 2006). Unique to the 20th century (aside from the 3rd century) are the high the decadal-scale mean maximum temperatures compared to the last two millennia that have never been exceeded in this period (except for the very earliest period of reconstruction in the 3rd century which may be questionable due to sparse records). This warming trend is very likely to continue under anthropogenic forcing and is projected to continue into the future, further exacerbating precipitation deficiencies (Hoerling and Eischeid, 2007, Salzer and Kipfmueller, 2005; see next section). As seen in the discussion of instrumental data (see the first section of chapter 1 on modern climate), the majority of regional and local station data in the region of interest all exhibit a positive trend over the 20th century (Figure 1.7-1.12).
The current ongoing drought is often compared to the last severe drought of the 20th century. Because the reconstructions and their running averages don’t extend up to the present, it is valuable to consider current and past droughts in terms of both precipitation deficit as well as temperature for common trends. This, combined with the comparison between the 1950’s drought of the Southwest and a knowledge of the future projections, places the current and future climate in a different category as the past.

**Future Projections**

Knowledge of past, present, and future climate conditions is vital since this knowledge has both global and local consequences. This knowledge can enhance planning and adaptation efforts in the face of social and ecological vulnerability to change. However, in the present context of global climate change, there may not be climate analogs in the past that can adequately represent the conditions ahead (i.e. drought coupled with unprecedented warmth). Climate models of future climate can generate projections on a global scale regarding future climate with considerable skill, but when considering finer-scale regional projections, this skill decreases (Udall and Hoerling, 2005). This is especially the case when fine-scale processes, like topography and cloud cover, greatly influence climate at the regional or local scale, as they do in the West (Garfin and Lenart, 2007). However, projections continue to improve by comparing results from multiple models. Regional models and downscaling techniques continue to improve as well, as does the understanding of finer scale processes and new approaches to deal with uncertainties (Collins, 2007). In this section future projections for the location of interest are presented and discussed.
Data

Hoerling and Eischeid (2007) utilized 42 climate model simulations from an 18-model ensemble that contributed to the IPCC Fourth Assessment (AR4). To generate a regional picture downscaled to streamflow, they calculated PDSI for each simulation from 1895-2060. The 2000-2060 time-span assumed a business-as-usual greenhouse gas scenario to force the model. Also, the annual temperature and precipitation data from the above models were also used in this set of basic analysis from 2005-2099 projections. Hoerling and Eischeid downscaled the data from these modeled projections into data sets corresponding to the NCDC divisional PDSI data sets. Here I used the projection data from AZ2 and NM1 (Hoerling and Eischeid, 2007) as well as the observed data for these same climate divisions from 1895-2006 (Williams et al., 2007).

Methods

In order to evaluate the future PDSI projections, I compared them to the regional observed data (NCDC divisional data for AZ2 and NM1 from 1895-2006). This was accomplished via a basic comparison of statistics for differences in mean and variability (i.e. using standard deviation), coupled with visual comparison of long-term and short-term trends. Following this was a similar examination of mean temperature and precipitation for each season and annually (DJF, MAM, JJA, SON, January-December). Finally, using the results of the annual comparisons, the future temperature and precipitation projections (IPCC, 2007) are assessed and discussed.

Results

From the basic statistics on tables 1.12 and 1.13, one can see AZ2 observations have a slightly higher mean than the modeled PDSI for all annual and seasonal values
whereas NM1 observed and modeled PDSI are essentially the same. For both climate divisions, variability is substantially greater in the observed data than in the simulated records. This is primarily due to higher variability at the regional scale from processes insufficiently represented in the downscaling global-scale models. Correlation coefficients (r) and coefficients of variation (r^2) between observed and modeled data for all seasons and annual values are very low for this time period for both AZ2 and NM1 (Tables 1.12 and 1.13).

A visual observation of the seasonal PDSI values (Figures 1.34-1.41) shows that the modeled PDSI generally fluctuates around the observed mean without capturing the extremes such as the deluge of the 1980’s, or the drought at the turn of the 19th century for both climate division records. In general, Figures 1.34-1.41 illustrate that simulated models probably underestimate decadal variability in future projections since they do not capture near the full range of variability in the observed record. Additionally, the observed PDSI data do not necessarily represent regional climate well throughout the entire series length prior to 1931. NCDC climate division data used all stations in the state to estimate divisional data before this time, therefore, the portion of the series before 1931 is questionable and may neither validate nor discredit modeled data if the fit is poor.

Long-term trends in the observed PDSI are generally very weak for both climate divisions compared to the modeled PDSI over the historic period (1895-2006). Observed PDSI trends are also generally in the opposite direction as modeled PDSI (except for summer in AZ2). Whereas for most seasons the overall trends do not match, some short-term trends do show some coherence in direction between modeled and observed data for many seasons. AZ2 in particular has noticeable downward trends over the final portion of
record (1990-2006) in all seasons except fall (Figures 1.34-1.37). The modeled data does follow this downward trend in all seasons that exhibit it for AZ2. NM1 does not show as much downward trend in its seasons since 1990 except for summer (Figure 1.40), in which case the modeled data follows it reasonably well.

There is a marked decline in projected seasonal PDSI for both climate divisions over 2007-2099 compared to the previous figures of observed PDSI (Figures 1.42 and 1.43). Each season seems to have a rather homogeneous downward trajectory that eventually levels off in the early 2080’s at a very negative PDSI of –9 for AZ2 and –10 for NM1. PDSI values this low are incommensurate with anything experienced in the 20th century, the lowest in both observed records not surpassing –7.6 (AZ2) or 6.1 (NM1) (Tables 1.12 and 1.13). One likely reason the downward trajectory of PDSI values does not continue to decrease linearly past 2080 is likely the fact that it cannot continue decreasing infinitely. PDSI values consistently at or below –10 are unlikely considering the observed PDSI range of variability over the 20th century. Since PDSI is derived from a complicated equation that integrates many factors, including precipitation and temperature, examining them separately may help in determining how reliable these projections are. Temperature is more reliably modeled than precipitation as illustrated in a comparison of the annual temperature and precipitation of both climate divisions (Figures 1.44 and 1.45). The long-term temperature trend is roughly consistent with observed data for both climate divisions (Figure 1.44) whereas simulated precipitation data and long-term trends match poorly with the observed (Figure 1.45). Here, as in the PDSI seasonal figures, the modeled precipitation trends exhibit opposite trends compared to the observed record. With this information, the last set of figures (1.46-1.49) can be
better understood. They illustrate the same IPCC projections used in the projected PDSI (Figures 1.42 and 1.43) but in the original temperature and precipitation parameters. The projections from 2006-2099 (1.47 and 1.49) show the consistent decline in precipitation and the associated increase in temperature projected into the rest of this century. It thus makes sense that the Navajo Nation region will become progressively hotter, drier, and more drought-like in the future.

Discussion

Knowing what parameters are best simulated based on comparison with observed data helps assess the likelihood of future projected temperature and precipitation trends. However, this depends on how representative the observed record is of reality. As with any regional time series that is compiled using other records, the number of records declines as one goes back further in time. Therefore, one should investigate the observed data to see if it is representative throughout its length. This may prove to be an issue in this region where climate division records before 1931 were generated using a regression analysis from statewide records (Personal communication with R. Heim, 2007) that may not be representative of this region.

Another factor that may be influencing the often-poor fit of the modeled data is the topographic complexity of this area. One important influence was discussed earlier in this chapter: the North American Monsoon. It is currently difficult to simulate monsoonal convective storms since this precipitation is rapid, intense, and localized. This is very important in the Southwest, and in the Chuska Mountain area it accounts for approximately half of the overall precipitation received. Monsoonal rainfall is important
for climate sensitive activities like farming and ranching that depend upon seasonal sources of water.

In the likelihood that the Southwest’s climate moves towards an average characterized by temperature-driven rather than precipitation-driven drought, it is prudent to move from the scientific to the social, and to consider potential ramifications. The Southwest has always been characterized by its arid climate, and the resultant landscape, over many thousands of years. Those who have invested their lives here would have experience and knowledge about how climate variability and change impacts society as well the landscape. The next section is devoted to such matters.
CHAPTER 2: LOCAL KNOWLEDGE AND LIVED EXPERIENCE

Populations involved in farming and ranching across the globe are widely recognized as vulnerable to climate variability. Research in different parts of the world has stressed understanding how the vulnerability as a complex relationship of environmental and socio-economic factors with feedbacks that include decisions of the human communities (Adger, 1998, 2003; Conley et al., 1999; Usman et al., 2005; Peilke et al., 2007; Tschakert, 2007). These decisions can act to increase or decrease their vulnerability.

In the context of climate change-driven droughts for the future in the West, it behooves scientists, policymakers, natural resource managers, and the general public to consider adaptation strategies and ways to build more resilient communities to in light of the risks this hazard poses (in addition to climate change mitigation efforts). This chapter focuses on the local knowledge and experience of vulnerable farming and ranching populations on the Navajo Nation as a case study. It addresses questions relating to local how local knowledge can, 1) inform interested communities regarding climatic variability at the local level and 2) illustrate the vulnerabilities and adaptations of this population to climate variability. Tschakert (2007) affirms, “Incorporating the views from the vulnerable is a first step for conceiving feasible and meaningful adaptation options to climate change and extremes that also improve livelihood resilience” (p. 393). While this study is not meant to represent a full-fledged, comprehensive vulnerability study, it ultimately seeks to contribute to studies relating to climate variability and vulnerability.
Local Knowledge

There are many words and phrases often used interchangeably with the phrase “local knowledge and experience”. Traditional ecological knowledge and Indigenous knowledge are two very common terms in development, anthropological, and conservation literature, while indigenous science, endogenous knowledge, and traditional knowledge, amongst others, are also terms in use. These terms do not necessarily refer to knowledge held only by indigenous communities, as its main characteristic is perhaps its locally situated origins, which can be found in all societies. However, while no system of strict definitions to distinguish this vernacular (that is accepted by all of its users) exists, local knowledge escapes some of the connotations that other terms may imply. Some of these potential connotations invoke dichotomies such as Western and non-Western, science versus oral tradition (Antweiler, 2004).

Definitions of traditional ecological knowledge (TEK) also help describe what will be most often referred to as “local knowledge” here. Berkes et al. (1995) and Huntington (1998) broadly define TEK as that which refers to the knowledge, practice, and beliefs regarding relationships between living things and the environment acquired through either first-hand experience or culturally transmitted throughout generations. For this study, a “TEK” may also be used less frequently as a synonym for “local knowledge and experience”.

Interest in TEK has grown especially throughout the 1990’s to the present and has been utilized for multiple purposes, particularly in the enhancement of natural resource management in concert with Western science. It is the intersection between Western science and local knowledge about which its practitioners and critics have raised many
issues. While practitioners emphasize the benefits of its contribution to enhancing management and amplifying perspectives of the natural world, these different sources of knowledge often derive from very different epistemologies whose differences should not be ignored (Huntington, 2000). To avoid this uncritical “integration” of TEK and Western science so that it ultimately results in a more reciprocal exchange that can benefit both “institutions”, but especially the community from whence it originates calls for a critically planned and executed multi-disciplinary study.

Traditional knowledge is often not simple and unambiguous when viewed from a lens outside of the context in which it was created (Posey, 2004). Scholars, indigenous and non-indigenous, have researched and written extensively on the topic of traditional knowledge and its use. Clearinghouses exist all over the world as centers of study of this knowledge and issues surrounding its use. Those who study local knowledge generation cannot avoid the ethical implications of what they are doing, particularly in the current context of globalization, and power structures that have the capacity to hegemonize knowledge systems. Since traditional or local knowledge is generally situated in a specific context (culturally and geographically), the separation of it from this context into categorizations has the capacity to essentially divorce it from the context in which it was created (Semali and Kincheloe, 1999). The fact that it does develop within this context suggests that in essence it “belongs” to that community. Traditional knowledge scholars affirm that because of this, its study should ultimately be directed at how it can benefit those to whom it belongs rather than be appropriated or exploited by academics and others (Cruikshank, 2000). Huntington (1998) however states that in order to analyze TEK, it must be decontextualized and recontextualized for its specific management
purpose while understanding the original context for appropriate analysis. The present study is aware of the concerns of associated with local knowledge and ethical issues associated with its study and intended use. This study is also aimed at understanding how local knowledge can illustrate the nature of impacts related to climate to eventually inform strategies aimed at increasing adaptive capacity of these communities.

**Local Knowledge and Western Science**

In general, local knowledge is often distinguished from other forms of knowledge like Western science in its contextual development. These origins are important because as such, it serves the community in its ability to help organize reality from the local perspective. Semali and Kincheloe (1999) describe this:

*...indigenous knowledge...is an everyday rationalization that rewards individuals who live in a given locality. In part... indigenous knowledge reflects the dynamic way in which the residents of an area have come to understand themselves in relationship to their natural environment and how they organize...knowledge...to enhance their lives* (p. 3).

Local knowledge often is defined as integrated experience over time involving problem-solving *in situ* by peoples globally (Bicker et al., 2004). This crucial emphasis on the experiential rather than the experimental distinguishes it from Western science. Further, local knowledge is often ascribed as adaptable and non-static knowledge that serves the community. It is often contrasted with western science as a holistic, rather than compartmentalized and categorized knowledge system. For this study, the concept of time is also important. While Western science, and particularly climate science in this case, view time as a linear quantity that is necessarily ordered sequentially for research and interpretation of patterns, local knowledge does not necessarily view time as linear. In particular, Navajo culture views time in a more cyclical manner in often a very literal
sense. For instance, the lunar cycles and appearance of certain constellations traditionally
guided the seasonal agricultural practices, rather than relying on a strict Gregorian
calendar: certain ecological and cosmological indicators often signaled the timing of
important events such as migration to different winter or summer camps (Aronilth, 1991,
McMillan, 2000). The latter is most evident in the known Navajo calendar, whose
“months” or seasons are named for those ecological or climatic features that are part of
the annual cycle. Also relevant to the present study is the inherent morality and
accountability of human actors within the natural system of many traditional knowledge
systems, as opposed to the more modern self-perception of humans as objective
bystanders in the natural world (insofar as there is not direct manipulation) (Ermine et al.,
2005, Cruikshank, 2001). This is exemplified in Diné culture through the ongoing
importance of ceremony to preserve balance or correct imbalance.

In the recognition of general characteristics of local knowledge and those which
distinguish it from other knowledge systems like western science, it is easy to create
mystification and ambiguity and tempting to assume mutual exclusion and simple
dichotomies (Anteweiler, 2004, Vayda et al., 2004). However, to do so risks binding the
hands of factions who wish to pursue paths towards enhanced empowerment and overall
sustainability, and results in stranding local knowledge on the banks of relativism
(Cruikshank, 2000). Understanding this need to translate local knowledge into a useful
context for practical management, Vayda et al. (2004) discuss a more rapid approach that
emphasizes a focus on how and why the knowledge is used to make decisions rather than
an attempt to understand the complex of the ethnographic background of the knowledge.
This overwhelming task then tends to produce results that are not effective in practical
goals of sustainability. This study also recognizes the value of local knowledge and its
distinctive qualities, but it does not attempt an understanding of the deep ethnographic
background as it was exploratory in nature and impractical considering time and
resources available.

The distinguishing characteristics noted earlier are obviously not concrete as
systems of knowledge in essence are adaptable in a changing world and serve those by
whom they were created. However, it is still important to recognize these general
differences, particularly the locally situated character of local knowledge. These
distinctions can prove useful in elucidating the differences that can be viewed as
strengths and weaknesses of the systems. This view can create a more apparent
complementary relationship useful in identifying overarching mutual goals such as to
better understand earth processes and how they affect, and are affected by human
communities for sustainability (Novak, 2002, unpublished; Bicker et al., 2004). Despite
the present ethical issues that necessarily must be wrestled with and resolved, proponents
of local knowledge in general see promise in applying new ways of thinking and
approaching modern socio-environmental issues using lessons from these systems. In
fact, Bicker et al. (2004) affirm that, “local knowledge needs to interface with global
scientific knowledge, each drawing upon the other to effect sustainable adaptation to
changing natural and socio-economic environments” (p. xi).

Local knowledge and experience can contribute a unique local perspective and an
additional line of evidence to increase the coherency of patterns and processes across a
region. Aside from its recognized inherent and independent value, it can be combined
with data from scientific monitoring and methods to achieve the overall objective of
enhancing understanding of human-earth systems. Some researchers have proposed that TEK be examined as a promising source of hypotheses for testing, using the scientific method as a potential “short-cut”, where appropriate (Thorpe, 2000; Posey, 2004).

Although lacking a single accepted and concrete definition, local knowledge and TEK will be used here to refer to local experience and observation, be it first-hand or transmitted from prior generations. It will focus on the Navajo (Diné) community members involved in farming and ranching who reside in the chapters of interest in the Chuska Mountain and Defiance Plateau vicinity (especially the Tsaile-Wheatfields and Crystal Chapters and to a lesser extent, the Lukachukai Chapter). Navajo Nation chapters were created earlier in the 20th century and constitute community boundaries with their own local centers of government much as one might think of states.

In trying to better understand of the way climate is changing in this area and the impacts and perceptions of those effected, one of the ultimate objectives of this study is to contribute to efforts aimed decreasing the vulnerability of these communities. Though there are many challenges presented with its use, the researcher tried to choose those intersections where complementarities between Western climate science and local knowledge exist, to be discussed in greater detail in Chapter III.

**Navajo Farming and Ranching**

The Navajo Nation is home to many communities who depend on the land for part of their livelihood and/or cultural practices. Farming and raising livestock have been long standing practices with which Navajos still identify regardless of their current activity level. In an atmosphere of changing global climate and the downscaled regional projections for a drying and warming West, the observations and perspectives derived
from local experience of vulnerable communities can enrich research on climate change and impacts. With the expectation of climate change and its impacts on sensitive communities, the biggest contribution local knowledge ethically has, is in the ways it can help these communities to adapt and persist in a changing world by involving and empowering them (Huntington, 2000; Parker et al. 2006).

The Navajo have a long history of farming on the southern Colorado Plateau, since at least the 16th century. Their fields were once found in the rich lands of Dinétah, an area in proximity to the San Juan River in present-day northwestern New Mexico. However, by the mid-18th century, raiding from neighboring Ute and Comanche tribes initiated a move westward and a lifestyle more heavily reliant upon livestock. Inherent in the change from a focus on farming to a mix of farming and livestock was the move from a sedentary to a more seasonal migratory way of life, with summer and winter camps to take advantage of seasonally available forage grounds (Kelley and Whiteley, 1989).

Crops and livestock production were primarily for household consumption before the 20th century with little trade. After return from Fort Sumner in 1868, governmental food rations supplemented these food sources, particularly in times of drought-induced crop failure (or other natural phenomena). The arrival of the Atlantic and Pacific Railroad in the late 1800’s encouraged a more market-based economy, encouraging more trading posts and an outlet for Navajos to sell wool to the market. Throughout the 20th century, the market-based economy grew, as did limited industrialization with the discovery of oil and coal deposits on Black Mesa and the southern Utah portion of the reservation. These changes brought on by exterior governmental and economic forces influenced the
economic dependence of agriculture and livestock on Navajoland (Kelley and Whiteley, 1989).

Today, while the overall Navajo economy may not depend on farming and ranching to the extent that it did a century ago, farming and livestock-raising continues to comprise an important role in Navajo life and economy. It now includes not just sheep, goats and horses, but also cows and even a few llamas belonging to a few of the most experimental Navajo ranchers. The total estimated worth of all the livestock on the reservation was $20 million in 2000, most of which came from cattle ($16 million) (Navajo Department of Economic Development, 1989 in Navajo Nation Drought Contingency Report, 2002). Additionally, annual income spread between personal livestock raisers in 1997 amounted to approximately $15 million. Farming income is also important for many Navajos. Annually, the income generated from traditional agricultural crops approximates $2 million (Eckert, 1989 in NN Drought Contingency Report, 2002). This also constitutes one of the longest-standing and most successful activities on the reservation (Navajo Nation Water Strategy Report, 2000).

Culturally, livestock and farming continue to be significant activities with which most Navajos identify, even those not directly involved in either activity. Sheep, in particular, have had a central role in transmission of Navajo culture. Their wool was used in rug weaving, a practice rife with symbolism of Navajo cosmology. Additionally, social and cultural activities during the year often require families to provide animals.

Historically, it is important to note the changes that took place in the 1930’s. Driven by the Great Depression and the 1928 Boulder Dam survey that blamed range deterioration from overgrazing upstream for the high sediment loads threatening the dam,
the BIA instituted livestock reduction program on the Navajo Nation. This unilateral and mandatory reduction between 1935-1940 reduced Navajo livestock by more than a third through forced sales and outright termination (Kelley and Whiteley, 1989). This event still represents a dark and bitter memory for many Navajos. From this point on, wage work began to overtake livestock raising and farming as the principal economic activity since many were unable to subsist on diminished herds. Coinciding with this period and its events, the BIA created grazing districts and a permit system that stopped the seasonal migration of herders to seasonal ranges outside the boundaries of the new districts (except for adjacent districts in some cases. This traditional seasonal movement is thought to have constituted a range conservation practice that reduced range degradation caused by confining livestock to one area year round (Kelley and Francis, 2001).

The imprudent implementation of the 1930’s stock reduction program on the Navajo Nation has been named as a culprit in the failure of later attempts to implement successful rangeland policies. In 2002, the level of overstocking of the rangelands was estimated at 40% (not including non-reported livestock). Overstocking increases the vulnerability to drought both economically and ecologically, for example, if water sources are depleted in a drought, water hauling activity can become economically prohibitive while livestock decrease in value from undernourishment. Ecologically, drought-stressed land cannot support as many livestock, much less excessive amounts (Navajo Nation Drought Contingency Report, 2002).

Methods

James et al. (2006) and Kelley and Francis (2001) are two studies that investigate climate change and impacts on the Southern Colorado Plateau. Both implement
individual and group interviews. James uses them to inform natural history and the human impacts felt from associated changes in this history while Kelley and Francis use them in more focused group interviews on ranching practices, range management, and climate, which are most germane to the present study.

This study utilized semi-structured and open-ended interviews with 20 individual community members of three Chapters in the western Chuska Mountain region (Crystal, Lukachukai, and Tsaile-Wheatfields). The main chapters represented in this study are Tsaile-Wheatfields (10 participants), and Crystal (7 participants). Every individual had some history of involvement in either farming and/or ranching, as did their families preceding them. The sample was non-random as individuals participated on a voluntary basis and were either self-identified or identified through knowledgeable community members such as grazing representatives and chapter officials, these factors prevent extrapolation to a wider population.

Interview questions related to the respondents’ backgrounds and provided basic information such as livelihood and activities, perceptions of climate trends, responses to climatic impacts, forecasting methods, and use and access to climate information (see Appendix F for interview protocol). Questions relating to climatic trends were designed to inquire about recent climate-related trends observed in the West and those projected. I took careful notes of participants’ responses throughout each interview and compiled responses to individual questions (transcripts of interviews will be archived in the Navajo Nation Historic Preservation Office in Window Rock, AZ for future research possibilities). Additional relevant information mentioned elsewhere throughout the interview was also noted and categorized in the appropriate section. All participants were
categorized using background information and input into spreadsheet format. Categories included: chapter, age, years involved in farming and/or ranching cumulative time involved in farming and/or ranching activities, and recent activity level (anytime between 1995-2005). Present activity levels of 0-3 were then assigned to each participant for their level of present activity at the time of the interview (Sept.-Dec. 2006) in their respective activity. 0 indicated little to no present involvement for multiple decades, 1 indicates low involvement (e.g. was more involved prior to present but now only has a small garden). Level 2 was given to those moderately involved at present (2006) (e.g. involved on a weekly basis though not dependent upon it, for example, another means of primary income exists). Level 3 was ascribed to those participants involved on roughly a daily basis in farming and/or ranching.

No statistical analysis was possible due to the small, non-random sample of participants. Rather, the analysis utilized an approach similar to a comparable study by West and Vásquéz-León (2003) where responses to questions were all categorized and accorded weight by frequency of response (respective of each question, no arbitrary frequency cutoff). In some cases, where few participants responded similarly (low frequency) and where these responses did not contradict other participants’ and were offered by participants with a high level of experience, they were included. In cases where responses were heterogeneous, this was noted as such and no generalizable response was assumed. Respondents could have more than one response to each question depending on the nature of the question and so long as they were not conflicting. For example, if there were multiple reasons for loss over time, they were all included,
categorized, and analyzed for their frequency to determine if they merited import on a local scale.

**Results**

**Background**

Almost all participants (19/20) consider themselves to be native to the area though most left at some point for work and/or school. Almost all participants (19/20) have generational ties to the area, with at least one parent (if not both) from the area and at least one set of grandparents from the general area (18/20). The two generations prior to the participants’ (parents and grandparents) had extensive involvement in farming and ranching both (except one whose family only ranched). The average time spent in farming or ranching activities accrued over one’s lifetime was 40 and 42 years, respectively. This was estimated by averaging the time between childhood and present age, or age at cessation of farming and ranching activity (minus prolonged periods spent off-reservation for wage work or education).

**Loss and Present Activity**

**Ranching Loss**

Ranching loss refers to any sort of loss in livestock on a large or small scale, related to natural or other cause, including socio-economic. There are no obvious trends among the participants based on responses to inquiries about type and reason for loss, nor the timing of these losses. Rather than a common trend regarding loss, the responses seemed to indicate instead a fairly heterogeneous experience among participants. This is seen in the fact that there were 12 main reasons for loss mentioned between the 18 participants still involved in ranching on some level; only three participants at most
mentioned the same reason for loss. Interestingly, almost all of the reasons for loss were directly or potentially indirectly related to climate (e.g., excessive snow, voluntary reduction during drought, lack of water in grazing areas, ingesting of toxic plants, disease, conflict with other ranchers, disease, predation by coyotes, and competition for grass from deer).

**Ranching Activity**

While most have experienced loss, most participants’ overall activity with livestock has remained stable (see Table 2.0). Only one participant has stopped ranching altogether on advice from the Natural Resources Conservation Service (NRCS). However, this participant plans to begin ranching again once more implements are acquired (cross-fence, water, water tanks. Three others who ranch less noted different reasons for decreasing ranching: age/energy level (1), and expense (1), and need for more implements such as fencing, and water tank (1).

**Farming Loss**

Farming loss refers broadly to any decrease in crops over a season from any source, be it natural or socio-economically-driven. For this study, participants’ responses concentrated on three main categories of loss type: fewer crops, limited growth, and completely lost crops. Included are participants who have been active at some point between 1995-present. Each participant may have experienced more than one type of loss. The main reasons cited were drought (5), freeze (1), wildlife (5) and a combination of both drought and dam construction (1). Participants often connected wildlife to the climate (drought) via decreasing forage available to wildlife.
There was a more recognizable time period in which participants experienced widespread farming loss compared to the more widely spread and heterogeneous ranching losses. 14/20 of the participants were actively involved in farming up until at least some point within the last 10 years (Table 2.0). Over participants’ experience, nine reported 16 different types of loss with the most common time period encompassing these losses being between 1996-2006. In fact, participants reported losses occurring within the last 10 years, even though the question asked each participant was about any loss, not just recent loss (except for one participant noting loss in 1935, ’40, and ’44). Three of the participants active in the last 10 years didn’t mention loss or stated no major loss.

**Farming activity**

Of the 14 participants active in farming within the last 11 years (1995-2006), six stopped between 1998-2006. These are all long-term farmers with histories between 20-69 years of involvement. Age was the primary reason for two of the six, though one of the two recognized lower creek levels as a burden on irrigation (just not as the primary reason for cessation of farming activity). The other 4/6 mentioned lack of water from the drought as the main reason for halting or severely decreasing farming activity (one also noted a combination of drought and dam diversion wear-down). Those who have stopped farming all lived in the same chapter (Crystal) and relied primarily on dryland, and irrigation from spring runoff and small creek diversions.

Narratives from those who stopped farming provide insight into the factors involved in their reasons for ceasing farming activity:

The ground is dry. There used to be deep snow about 2 ft. By April the soil was still moist, now it’s dusty and sandy. …
Some little runoffs have disappeared; even reservoirs up in the mountains are gone. There was 3-4 feet of snow in the mountains that made for plenty of water. The meltwater snow disappeared around March; it kept things moist.

Now 037 is not farming, there is no water because the diversion near 037’s fields (~9 acres) is not repaired unlike the upper diversion from Crystal Creek. … It broke down in ~1999. There were two places where the diversion wore out in 1999. The upper diversion was repaired in 2003. Now 037 is not farming because there is no water, the upper diversion that is repaired is not close to 037’s farming area. There’s no water in the reservoir because of breakage and weardown. And from ~1999-present there has been very little snow to fill the reservoir, so 037 has not planted. Also, even though the upper diversion is fixed, there is still not enough water to farm. It (the creek) just goes a short way from the mountain and goes underground or dries up. The water was consistent before ~1999.

038 has farmed and ranched all life and currently has animals, but since the drought hasn’t planted due to lack of rain for the last ~8 years. The last time 038 planted ~8 years ago, crops wouldn’t grow. 1998 was the last big loss. It didn’t rain all summer and the corn and oats didn’t grow, so 038 stopped altogether. … Mom would say you have to watch out for the climate. She said not to plant [when it was bad].

Currently 039 has animals, but since the drought 039 has not planted. The rain stopped about 8 years ago, which is the last time 039 planted. … There’s no running water nearby so 039 relies on the snow and rainfall in the summer to fill the arroyo.

044 quit farming because of health, the water is still there to farm, though the creek doesn’t run as it used to. ~ 9 years ago the rain and creek both decreased and people stopped farming down to Canyon de Chelly.

Water Source

The water source is no doubt one of the, if not the most important factor, in determining the viability of the farming and ranching activity. Sources differ by

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* Indicates that from here forward, indented and italicized comments refer to direct quotes and non-italicized and indented comments refer to a paraphrased comment.
reliability and convenience for farming and ranching. The most convenient sources are surface waters, which are also often the least reliable, particularly those from alluvial and ephemeral streams (NN DWR, 2002). The most reliable sources are generally groundwater, and are often more inconvenient to access as they often require hauling, which can become economically prohibitive. Additionally, they may depend upon poor or failing infrastructure that decreases or prevents access.

**Farming and Water Source**

There were 2-4 water sources available for farming mentioned by participants (Table 2.1). There are two main types of water users in the case of farming activity: irrigators and dryland farmers. Both rely on winter and spring moisture to plant. Irrigators rely on rain to water the fields when streams are low, and dryland farmers needing rain as the direct water source for the fields. The two main precipitation peaks play a role in water supply that farmers and ranchers in this region depend upon. The role of winter moisture is illustrated below, though it is not clear if “rains” refer to non-winter moisture in particular for each participant:

- **The ground is dry, there used to be deep snow ~ 2 ft. By April the soil was still moist, now it’s dusty and sandy. ... There was 3-4 feet of snow in the mountains that made for plenty of water. The meltwater snow disappeared around March; it kept things moist. -35**

- **You don’t really need water for corn, potatoes, or squash in the spring because the ground is moist. It stays moist until the rain comes…. You can’t plant if there’s not moisture from winter. -38**

- **When there’s a big snow it saturates. ... There’s no running water nearby so 039 relies on the snow and rainfall in the summer to fill the arroyo. … The creeks coming out of the mountain and arroyos bring water. –39**

- **There’s no water in the reservoir because of breakage and weardown. And from ~1999-present there has been very little snow to fill the reservoir, so h/ has not**
planted. Also, even though the upper diversion is fixed, there is still not enough water to farm. It (the creek) just goes a short way from the mountain and goes underground or dries up. -37

Blackrock has no perennial streams and is on the other side of the mountain from Tsaile and Wheatfields, so water would have to be pumped up the mountain, which isn't happening so they irrigate by hand when there's no rain. –43

**Ranching and Water Source**

There are numerous sources of water on the western side of the Chuska mountains area available for livestock. People seldom mention the same source and people always mentioned more than one source of water. 19 different sources were mentioned for livestock among Tsaile Chapter participants, common sources being Tsaile Peak, Wheatfields Creek, various windmills (Table 2.1). In the Crystal Chapter area, 14 livestock water sources were mentioned. There were only three interviews conducted with Lukachukai Chapter members, therefore, the fact that only 4 water sources were mentioned should not suggest that there are fewer sources.

These numbers together could only be an underestimation, as people may have not recalled other sources they use and have used. As more people were interviewed, the number of different water sources mentioned increased. Participants provided essentially the same responses regarding reliability of livestock water sources.

**Local Perspectives of Climate and Environmental Change**

Although there were no explicit questions relating to the perceived cause of recent climate and landscape changes, this information was often inherently communicated in descriptions of change over time. Some of the more traditional community members mentioned traditional reasons for the observed change, while others noted global causes
from anthropogenic climate change related to them by family or media. The best
eamples of this are given in the following narratives.

You don’t plant in the full moon or the corn will be small. You go from the sliver
to the full moon, that is the traditional [way]. You use the moon, even for
ceremonies, you don’t do a ceremony in the full moon. “We don’t use those
anymore.
You do it in all things, the sliver to the full moon, even traditional storytelling is
based on the sliver or full moon. There are specific months you do storytelling.
Summer stories too. String figures are for the winter. As soon as you hear thunder
you put away your string figures. All this is mixed up- they do it in any season.
It’s caused our air and everything to be mixed up. There is no more respect for the
seasons and times. It’s caused us to have no rain and ruined it. Up to the time
[Navajo people] started working and stopped teaching [our] kids the times when
you do things [it started mixing things/seasons up]. -035

There’s an early frost yearly, you never know when it will come around. It was
the same during 039’s mom’s time. When the yei bi che dance begins it gets cold.
When it starts too early (and it’s harvest time) it makes frost too early. -039

*The rain was nice back then. The earth was like a newborn, young. Even the
lightning was even-keeled. We were always working and stored food for winter —
044.*

There is more warmer weather now, even though there’s cold weather. ... It is true
here, and scientists say that ice is melting, maybe it’s the ozone? It’s a little too
warm for the snow to come. [Now] we are off balance between summer and
winter. …Now it is dry. I guess it is more or less global warming.
We may not have another round [of El Niño]; it is flooding in the East and there is
a drought here. Maybe the earth will rotate and will come back in favor of the
SW. -027

**Climate and landscape changes**

Table 2.2 details some of the most commonly reported changes in landscape and
climate. The most widely noted changes had to do with vegetation and wildlife. Many
participants attributed their observation of less vegetation to drought and poor forest
management. The increased wildlife was most often related to sightings at lower
elevations and often in the fields of participants. Participants most often attributed the
increased presence of wildlife (over various timescales) to drought stress on vegetation at higher elevations. Almost half of the participants noted warmer conditions while few reported colder conditions. Often the warmer conditions, and even the few reports of colder conditions were also associated with perceived changes in extremes and unpredictability. Death of trees, particularly pinyon was noted locally at lower elevations rather than higher over the last 2-5 years (2001-2004), but a few participants noted that pinyon mortality was much more severe in lower elevation areas such as Ganado (further south).

Most reported less precipitation and many noted “harder rain”. This question was in response to an inquiry of more “male” or “female” rain, the prior being associated with hard, intense, destructive rain, while female rain is described as being more gentle and prolonged so that it sinks into the earth. Participants reported this change as having occurred approximately within the last 12 years (1994-2006).

**Traditional Knowledge of Weather and Climate Predictors**

There are multiple traditional indicators of climate and weather conditions that participants noted in response to questions relating to climate predictors and indicators. Earlier generations used these prior to modern weather forecasts. The majority of participants noted that the shape and clarity of the moon predicts and indicates weather conditions (12/20). While not all respondents mentioned what weather coincided with what moon shape, 6/12 did mention a corresponding condition. The most prevalent mention of moon shapes was an upturned crescent, this denoted cold weather while a crescent open to its side was indicative of warm weather. Responses were consistent with
shape and coinciding weather condition. This is highly [understandable] since traditional Navajo farmers utilized the moon cycle in timing agricultural activities (Aronilth, 1991).

The next most common climate indicator was vegetation. Navajos use some grasses as indicators for the following winter rather than an immediate, or proximal/short-term weather condition. There is a certain kind of grass whose height indicates how high the snow will be. Assuming the 5 respondents who mentioned this were talking about the same type of grass, its Navajo name is tlo/llo nast’asi, ntesí. More research into the cycles of this plant might be initiated to indeed see its value and/or connection to climatic cycles and predictors.

Weather and Climate Information Use and Access

Participants in this study mentioned specific and non-specific information they get and ways they use climate forecast information. These represent portions of strategies to help plan and adapt activities to climate thereby decreasing loss:

<table>
<thead>
<tr>
<th>Type of forecast</th>
<th>Knowledge and Related Decisions and respondents (in parentheses)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Seasonal: summer moisture</td>
<td>• Cattle reduction (talk and plan with family) (27, 29)</td>
</tr>
<tr>
<td></td>
<td>• Assuring a dependable truck and tank to haul water (e.g., knowing if it will be necessary) (27, 45)</td>
</tr>
<tr>
<td></td>
<td>• Contacting appropriate entity to inquire about compensation availability (27)</td>
</tr>
<tr>
<td></td>
<td>• Preparing oneself for the elements on multi-day work outdoors (46)</td>
</tr>
<tr>
<td></td>
<td>• Animal welfare (e.g., hard rain provides water for livestock) (41)</td>
</tr>
<tr>
<td></td>
<td>• Know about fields and grass availability from snow (livestock forage and farming) (40, 41)</td>
</tr>
<tr>
<td>Seasonal: winter conditions</td>
<td>• Care for livestock (e.g., bring livestock more hay, break ice in cold spells for livestock water, monitor lambing at night in winter as cold temperatures cause lamb mortality, know when it is all right to put ewes and rams together to avoid lambing in cold temperatures) (28, 29, 30, 35, 39, 42, 46, 30, 46).</td>
</tr>
<tr>
<td>(temperature and snow)</td>
<td>• Prepare home with chopped wood for fire (29, 38, 39, 42, 45)</td>
</tr>
</tbody>
</table>
• Know and prepare for field conditions (e.g., if snow is deep it helps) (41).

Short-term forecasts

• Know travel conditions (e.g., to travel to get food for family, get hay out to livestock if necessary as deep snow covers forage, move livestock) (27, 28, 29, 30, 38, 39, 41, 42, 44, 45).
• Perform certain activities when weather permits (e.g., seeding, knowing if adequate seed supply and rain for livestock so one can buy hay, seed just before moisture comes so it sinks in, cutting and baling hay if it’s sunny) (27, 29, 32).
• Wind doesn’t help farming and ranching (37, 40).
• Hard rain helps animals (41).

Two participants are unaware that long term forecasting of conditions is even possible.

There were seven main modes of attaining weather information mentioned among participants (Table 2.3). They are, from most common to least:

- Radio, television, word of mouth, newspaper, personal observation, the Internet, county fliers (Apache County, St. John’s is county seat), and ranching magazine. Note: county fliers generally come from the Farm Service Agency and other governing organizations meant to offer information on climate conditions relevant to their respective assistance programs. These programs are charged with a responsibility to farmers and ranchers belonging to their constituencies.
- Word of mouth is very common and involves information exchange with friends and relatives most often, but also in fewer cases with agency personnel from the local Natural Resources Conservation Service (NRCS).

One of the final questions during the interview pertained to ways to improve weather and climate forecasts. There were few explicit mentions regarding ways to improve the information as seen in the list below. Only 5 (out of 20) participants mentioned way to improve the information. Improvements mentioned:

• Economic information: brochure or newsletter with weather and price of hay and grain (27),
• Timeliness: often, county information doesn’t get to the chapter houses on time; feed stores have information but they might be out of feed if you didn’t get the information on time (27),
- Communication: a mailing list would be wise so they can get information sooner (27),
- Rural vs. urban: a focus on the reservation would be useful, not just the (off-reservation) towns (32),
- Long-term: it would help to get long-term information (information on the next season) (37, 42) and,
- Graphics: clear information and the inclusion of graphics would help with reports (41).

Participants (14) indicated that the reliability of current climate information is adequate for their needs (9 noted that it is at least moderately reliable while four noted it is sometimes reliable). Some commented with statements such as “sometimes they lie”.

Discussion

Water Source and Loss

The availability and number of water sources for livestock can be seen as a factor in adaptability and vulnerability in changing availability of water. Even between chapters (primarily Tsaile-Wheatfields and Crystal), the sources weren't always the same, though the major creeks and reservoirs were important, and generally have higher levels of reliability than the other surface sources such as ephemeral streams running through arroyos and stock ponds. Reliability can also be related to different causes that should be mentioned, for example, infrastructure quality in delivering water and direct evaporation/vulnerability of the water source to climatic conditions. Farming options for water supply were fewer. This important resource is vital to the well being of these practices since most farmers use irrigation in some form, be it a simple diversions
adjacent to a creek or piping and sprinkler systems. However, many use a mix of dryland and irrigated agriculture, particularly the eldest participants who grow food crops. Having fewer sources of water for farming (compared to ranching) increases vulnerability. Non-climatic factors such as lack of infrastructure and jurisdictional issues combine with climatic variability and change to compound vulnerability.

Another possible factor included in the number of losses reported (aside from few participants and a heterogeneous landscape) is rooted in cultural norms. There is an important belief held by many Navajos (particularly the elder generation) that it is not appropriate to talk about or emphasize the negative. Thus, this brief survey could only represent an approximation of the loss and the reason for loss, particularly for the earlier generation that were more likely to adhere to more traditional values of the parent’s and grandparent’s generation.

Overall, compared to ranching, the farming loss generally seems to be impacted most by drought and wildlife/insect damage, as well as an occasional freeze at this altitude (while ranching loss had no common source). In terms of impacts, the drought was the main reason for loss and long-time farmers decision to stop farming.

**TEK and Western Science**

Local knowledge is often seen as incommensurate with scientific understanding. The most pressing issue and criticism of the local experience, or reason to ignore the potential contribution of this knowledge in scientific questions, is the belief that these two sources of knowledge come from fundamentally distinct and therefore incommensurate paradigms (Cruikshank, 2002). Moreover, rather than “distinct” many see local knowledge on a lower status compared to Western knowledge systems such as science.
Similarly Huntington (2000) sees the lack of incorporation as linked the issue of discomfort with methods outside the fields of physical science (e.g. social science methods). I wanted to explore the intersections of these tools (local knowledge with scientific observation and understanding). In using this framework, I sought to intersect the fundamental ideas surrounding the causation of local climate and global change held by the mainstream scientific community and those from the Navajo elders’ perspectives. A central question then is whether or not, in Cruikshank’s words, “there are ways of speaking about global issues such as climate change that accord weight to culturally specific understandings as well as to the universalistic frameworks of science” (Cruikshank, 2002, p. 389).

In the example of comparing the attribution of climate change offered by local Navajo elders and scientific community, there is need for decontextualization and recontextualization. “Times are changing, it is happening.” This phrase is used often with almost biblical undertones by older Navajos. It is not used in a context referring to direct and isolated climate change, but within a larger epistemological view of socio-cultural change, of which climate change is one element and/or result. These broad changes are attributed to a change of people’s behavior that then sets in motion an imbalance that extends to weather and climate. For example, in discussing observed changes over their lifetimes, many respondents (generally older, more traditional Navajos) cited that people’s values were changing, that they are now lazy, lack cooperation and community cohesiveness, and are not being taught “the old ways and how to work”. Notably linked to these issues of social change are cultural changes strongly related to sustaining balance or creating imbalance in the natural world. In particular, Navajo culture ascribes a
seasonal timing to ceremonies and activities to perpetuate balance in the world. When these activities are neglected, done incompletely, or out of season, traditional views hold that imbalance results and extends to weather and climate changes. These are fundamentally different than the physical mechanisms for the climate change as explained by Western science. In this traditional view, local socio-cultural changes are the culprit rather than a global phenomenon resulting from industrial development paths. One way to view the question of addressing global climate change that includes this particular culturally specific understanding lies in a decontextualization, and recontextualization of the traditional view held by many Navajo elders. There is a thread though in these different contexts of attribution that links the root cause of climate change from both perspectives: the matter of social action and accountability. This idea asserts that human actions have a consequential role in climate rather than as objective or isolated bystanders. The Navajo attribution doesn’t elaborate on an intermediary mechanism between actions and consequences, whereas in the scientific view, amplified greenhouse gas concentrations primarily define and explain the relationship between human actions and the consequence- global warming. However, currently, many advocating change are addressing climate change as a moral issue, which bears similarity to Navajo explanation as moral attribution. In this way perhaps a communication route may be opened for a dialog to begin between these local communities (stakeholders) and practitioners of Western science (in the academy and/or in natural resource management roles). This dialog could address the causes, effects, and most importantly the potential strategies to cope with and adapt to changes on a local level that matters to people. It is important for scientists to understand the paradigm differences and to appreciate them for
what they are, not needing to necessarily supplant one view for another, particularly when it is beyond its purview. There is a potential problem in “integrating” science and TEK in that it implies that traditional knowledge will conform to Western conceptions of knowledge, thereby subjugating the one and veiling the real differences between the two rather than addressing and respecting them (Nadasdy, 1999). In this particular example, both views recognize change and the need to plan for the future. Dialog between these oft-disparate groups (local, traditional stakeholders and practitioners of Western science) would help ensure mutual respect and reciprocity in determining which course to follow under changing climate conditions, and help empower the local community in deciding on the best courses of action to follow.

**Weather and Climate Information Use and Access**

Studies of agriculture and climate around the world identify communication of weather and climate information as a vital factor. Having timely access to it, assuming it is adequately communicated, can decrease vulnerability, granting there is enough flexibility in the system allowing the agents to adapt and use the information (Nicholls, 1999; Lemos et al., 2002; Usman et al., 2005; Tschakert, 2007). There is also an emphasized need to understand the local experience to effectively communicate weather and climate information, particularly in a reality of global climate change.

Knowledge of the main modes of communication for rural community members involved in sensitive practices is valuable for further research of ways to enhance climate information dissemination in a more efficacious manner. Most Navajos have access to radios and television though it might be at a nearby relative or neighbors home. However certain challenges exist for some Navajo-speaking members of the older generation with
regard to understanding English-language television communications. The radio can provide a means of reaching all Navajos though, regardless of the primary language on the reservation, as KTNN, the “Voice of the Navajo Nation” provides music, news and weather in both English and Navajo. However, in terms of rapidly broadcasting urgent climate information such as severe drought, there is apparently a complicated process to place public announcements on the air (NNWMB, 2003). This sort of delay could compromise the response time that vulnerable community members need to plan for the events mentioned above.

The fact that television is becoming so ubiquitous is evidence of socio-cultural change that doesn’t necessarily require leaving the reservation. Generally, the television might be viewed as a negative impact of culture, fostering movement towards the American mainstream and a loss of cultural identity. However, in this case, perhaps this medium could help to improve communication of climate information and reduce climate related vulnerability of culturally important activities.

Some community participants responded that television is a good means of communication because it supplies images that can provide useful tools to communicate climate data. Another participant noted, however, that network television forecasts focus on more specific weather conditions in urban areas, and often neglect conditions in rural areas.

Word of mouth was the third most widely noted means of attaining climate information. The advantage of this mode is that it does not necessitate ownership or access to radio and television, though likely, the majority of information spread from this
mechanism most likely originates from one of the other sources (radio, television, newspaper, personal observation, etc.).

The lesser-mentioned modes of communication include the newspaper (4), personal observation (4), county leaflets (2), the Internet (2) and ranching magazines (1). The disadvantage of the newspaper is difficulty in reaching all the constituents in a rural area on a regular basis. Also, difficulties arise in communicating more specific information with non-English speakers who read neither English nor Navajo (a phonetic language generally not read by the elderly). However, the images supplied in forecasts are most likely helpful in communicating simple short-term conditions. Personal observation may be an area of greater concentration to study that relates more to local knowledge as these community members might be more keenly aware of local environmental indicators of weather and climate changes closely associated with agricultural and ranching activities that could be used in concert with climate data for more holistic communication.

One of the challenges in perception of forecasted climate information that came up multiple times was reliability of the climate data. This reliability of course depends on for what they are using the information. It should be noted that some of the final questions regarding climate information use and access took place at the end of a period of over an hour in almost all cases, and exceeding two hours rare cases. This may have led to interviewer fatigue. Multiple “ok” and “sometimes” responses received (5/15) were brief. Though most participants noted comfort with the present amount and reliability of climate data, at the same time, some made comments such as “they lie” (31, 32, 35) when referring to this same forecasted information. This, along with the “ok”, and “sometimes”
responses seems to convey acquiescence to the unreliable nature of the information. However, assumption of simply unreliable information could lead to its disregard in decisions that it could actually help better inform if communicated in a meaningful way and used properly.
CHAPTER 3: ALIGNING LOCAL EXPERIENCE AND CLIMATE INFORMATION

The objective of this section is to examine how local knowledge (i.e., TEK) and information from climate science intersect in each of the following themes: scale, vulnerability, communication, perspectives in the context of climate variability and change. First a background of the past research on climate science and TEK in the West will establish the contributions of past research and its potential. Second, the methods and results of the most appropriate alignments of climate data and narrative will highlight those intersections that complement and enrich one another. A discussion follows regarding the contribution of the local knowledge to the above named themes.

Background

Past Research on Climate and TEK

To date, the majority of climate change research incorporating TEK has taken place in the Arctic, where the first and most dramatic changes and impacts have taken place. In the West, observations support change occurring already, however, unlike the Arctic, climate studies the West have not included local knowledge and experience to the same extent. Traditional, land-dependent communities are assumed to be more sensitive to changes that affect the land and to recognize change outside of normal variability of their experience and transmitted experience from prior generations. This intersection could yield more holistic research that identifies local scale patterns and changes that are meaningful to communities and stakeholders. This synthesis could enrich and inform local and regional decision-making processes, because while climate change is a global phenomenon, “it has profoundly local consequences” (Cruikshank, 2001).
Research Examples Around the World

Elsewhere around the globe there has also been research in climate-society studies that has made use of local knowledge. West (2001) shows that subsistence farmers in Burkina Faso, West Africa, do perceive long-term climatic variability as trends, rather than just simple events that can be verified by meteorological data. The author also confirms that perceptions have more value than simply validating their experience against meteorological data. These perceptions can contribute to an understanding of the concerns they face and help inform vulnerability work, particularly as it pertains to the effectively communicating climate information for decision-making.

Tschakert (2007) also investigated the relationships between climate and the local experience. Tschakert employed interviews and workshops with community members in Senegal (Sahel Desert of Africa) and explicitly states the need to move from a sectoral approach to climate change vulnerability studies. The sectoral approach focuses on technical solutions compared to an emerging type of assessment that focuses on the real population as agents rather than victims and seeks ways to increase their adaptive capacity rather than decrease vulnerability. Tschakert affirms, “Incorporating the views from the vulnerable is a first step for conceiving feasible and meaningful adaptation options to climate change and extremes that also improve livelihood resilience” (p. 393).

Lemos et al. (2002) describe the challenges of relatively recent advent of a 6-month climate forecasting in northeastern Brazil, a region often ravaged by drought. They performed extensive interviews with leadership and decision making entities at all scales be they economic, political, non-governmental, emergency services-related, land
managers, clergy, the media, and agriculturalists. Information from these interviews helped illustrate the fact that climate information dissemination and communication occurs in a socio-economic context that can compromise its value to the end user if there is an atmosphere of mistrust of the political (or presumably scientific) body controlling and disseminating the information as well as misunderstandings of the nature of the information. It especially emphasizes the need for interaction between end-users, policymakers, and climate scientists in making these products useful. Like Lamb (1981 cited in Nicholls 1999), they affirm that perfect forecasts alone wouldn’t necessarily translate into use and decreased vulnerability if socio-economic limitations exist that prevent acting on the information.

Adger (1998) used local knowledge and experience in northern Vietnam to understand the influence changing social structures through political transition alters vulnerability. Through his study, he affirms that institutional adaptations mediate vulnerability to environmental change.

Usman et al. (2005) looked at creating a new conceptual framework that is more useful to agricultural needs in Africa. Surveys from local farmers helped to identify what sorts of climate information would be helpful. They found that also including information regarding seasonal agricultural activities along with the seasonal forecast would be a useful addition and enhance communication of the forecast between climate scientists, intermediaries, and end users (farmers).

Human dimensions of climate change have been studied more extensively in the Arctic than anywhere else. Here, there exists the most dramatic environmental change as well as sensitive populations who often depend upon that environment for their
continuing lifeways. Not surprisingly then, as mentioned earlier, Arctic research in this realm has recognized and utilized local knowledge the most, thus contributing to the development of frameworks and methodologies for its usage (e.g. Cruikshank, 2000, Huntington, 1998, 2000, Ermine et al., 2005, Gearhead et al., 2004).

There exist common threads between what Huntington et al. 2007 found in examination of five studies in various locations in the Arctic to understand human dimensions of Arctic climate change. These are:

- marginalized communities with little economic and political control over outside influences,
- heterogeneous impacts across a similar climate and terrain and,
- combining and/or interacting environmental and human influences that acted to increase vulnerability, but that have the potential to decrease vulnerability.

These threads bare much semblance to the circumstances on the Navajo Nation as well. The Navajo Nation is a marginalized community, as are Indian tribes across the United States. They are generally heavily reliant upon federal monies to provide for infrastructure and much of the wage work found on the reservation. On the Navajo Nation, by contrast, partial reliance upon natural resources often helps to supplement wage work. Additionally, as this study illustrated for the farming and ranching sectors, impacts at the local scale across adjacent communities can be heterogeneous, due to terrain and other non-environmental factors. These non-environmental factors, inasmuch as they are a matter of local human decision-making, do combine with environmental variability and change as was illustrated in the examples of unreliable water sources due
to factors such as vandalism, and lack of, or prolonged maintenance schedules, of water
supplying infrastructure.

**Research in the Southwest**

Little research has occurred regarding the contribution of the cumulative
experience of these ongoing lifeways in the Southwest in the context of climate change.
The most specific of these is by Kelley and Francis (2001), who studied weather and land
use changes via interviews on the Southwestern Navajo Nation (Chzhin Bii’) as part of a
larger USGS project. Their main objective was to determine the relationship between
land use changes and climate changes, and resulted in a list of local changes that reflect
the local experience and interpretation of regional changes. They included: an overall
drier climate, a decline in farming and livestock, the disuse of government irrigation
projects, a change from farming and livestock to wage labor, a decline in social and
cultural practices (cooperation, less sharing within the extended family, lack of prayers
for rain and snow) that were once attached to land dependence. The perception among
their interview participants was that these changes resulted in social ills and drought.

Another study in the same region by James et al., (2006) is much less specific and
focuses more on the utility of oral histories from long-time residents as a complement
other techniques designed to determine ecological change in northern Arizona. West and
Vásquez-Léon (2003) applied similar methods as West (2001, mentioned earlier in
Burkina Faso example), to agriculturalists in southeastern Arizona. From these interviews
with residents, they found, similarly as in west Africa, that this sector does recognize
entitled “Circles of wisdom: Native peoples-native homelands climate change”,

supported by the U.S. Global Climate Research Program. The report summarized feedback from this workshop on changes and impacts recounted by Native participants from all over the U.S., including the Southwest.

Some studies have focused on archived work rather than direct accounts of local knowledge. For example, McMillen (2000) used a historical archive search to understand the climatic and social circumstances around which the early Indian Service (now Bureau of Indian Affairs) irrigation projects failed at the turn of the 19th century for the Navajo and neighboring tribes. McMillen details the impacts of severe drought on farming and pastoral practices during this time at the turn of the century. For the purposes of this study, McMillen gives an idea of how the past climate differentially impacted farming and ranching compared to the current period. Overall, McMillen describes a people and practices almost completely dependent upon the fluctuations of precipitation. The above average precipitation between 1905-1930 peaked from 1905-1907 and coincided with the highest Colorado River flows in the last 500 years. Interestingly, in the broader region, these were also the conditions under which Colorado River water was quantified and appropriated in the Colorado Compact.

**Intersections and scale**

As discussed, local knowledge in other areas of the world has informed researchers, and hopefully the pertinent decision-makers from the local level upwards, regarding the diverse impacts from climate and non-climatic influences. This is important because of the diverse vulnerabilities that populations around the world face. This third chapter is meant to emphasize the potential complementary nature of local knowledge intersections with climate data. It has the potential to inform its community at the local
level as well as a wider audience more familiar with climate data who can gain a better understanding of potential impacts on this population. Connecting this local experience and its associated local climate data can bring into focus the human experience of climate variability and change, particularly in the context of forecasted climate-change induced drought.

**Intersections of Local Knowledge and Climate Data in the Chuska Mtns.**

On the Navajo Nation, the long-term climate stations that do exist are few, short, and often discontinuous. These stations are not representative of the topographic complexity of the entire 69,900 km² (27,000 mi²) of the Navajo Nation (NNWRMB, 2002). On the other hand, the more spatially comprehensive NNWMB climate monitoring equipment have only operated since the 1980's, are dependent up on regularity of direct measurements and consistent calibration, and are often subject to vandalism, and of questionable quality (Personal communication with N. Selover, 2007).

Two main objectives of this chapter are to examine how local knowledge compares with the local climate data as an additional line of evidence that could support the sparse climate data and aid in communication of change. The second objective is an examination of how its qualitative nature contributes meaningful information of change by including narrative that describes its sectoral impacts. As discussed, these impacts do not result from a simple cause and effect relationship, there are non-climatic influences that temper or exacerbate impacts in a complex web of interactions that is beyond the scope of this research. However, a better understanding of these impacts and influences (climatic and non-climatic) from this preliminary research are useful in assessing vulnerability and ways to increase adaptive capacity in future studies.
Challenges to Recognize

The intersecting of traditional knowledge and Western science poses some challenges that no doubt contribute to its underutilization due to requiring multidisciplinary approaches involving very disparate disciplines. Because traditional knowledge originates in its own unique political, epistemological, spiritual, and historical context, its employment naturally carries some challenges in comparing it to other forms of knowledge that should be addressed (Huntington, 2006). In general, local knowledge and experience is often heterogeneous due to the other multitude of contributing factors that differ person to person. Obtaining and recording these experiences requires social science methods and the interaction between the researcher and the participant can never be completely objective. A discussion of conflicting data and a description of factors affecting response are given in the discussion section following the results.

Methods

I return to the local trends (PRISM data) presented in Chapter I that are consistent with regional trends attributed to climate change. I align this data with the local knowledge information from interviews. The main method for aligning the climate data with the interview data consists of first identifying the most consistent trends in the interview data (Chapter II) and coupling narratives representing these trends adjacent to the climate data in graphical form (from Chapter I). I then offer a description of how the specific interview data enriches the understanding of the climate data.
Results

Decreased Farming and Drought

A majority of Crystal chapter farmers who have been involved in farming over much of their lives up until at least the mid 1990’s have stopped farming between 1999-present. 4/6 in the sample who stopped reported that drought was the main factor in this decision. Figures 3.1 and 3.2 show the coinciding temperature trend during this time of drought while the narrative excerpts below detail the local description and impact.

…it was balanced between warm and cold, now in the afternoon you could wear shorts. It changed when the drought came, it brought warm weather in the late 90’s. You used to get chased into the ice water, now there is none [with 027’s grandsons]. -27

*It used to be hot at 70 degrees, now it’s 100 degrees. In the past summers, it has been hot and fire hazardous.* -28

A long time ago the weather was nice, there was rain and tall grasses, now it’s dry and hot. They [029’s parents] said this ~mid-1980’s. -29

*It seems like it’s really warmed up since ~20 years ago.* -30

*It gets hot, windy and there’s less rain. Sometimes the rain comes down a lot but the ground is too dry and it dries up.* -45

Many of the quotes above mention timing of noticeable warming. The time frames differ between participants, some noticing the change occurring in the mid-1980’s (at least two participants, one being from parent’s comparison to their lifetime~ presumably the bulk of the 20th century). The first quote belongs to a farmer/rancher who noticed the change in the late 1990’s, coincident with the onset of the most recent drought. This could provide evidence from local knowledge for recognition of the difference that distinguishes the present drought from past droughts: the high temperatures. Figure 3.3 illustrates recent shifts in the mean temperature over the last century. There are three means indicated, one for the entire series length (8.50°C), another from 1980-2007
(9.19°C), and the last from 1998-2007 (9.72°C). The shifts over the last three decades support the possibility that the participants who mention different timing for temperature increases are recalling real but different shifts depending on their memories and experiences.

The second quote mentions one of the most immediately detrimental impacts associated with drought and high temperatures: forest fires. The third quote connects decreased vegetation with the temperatures, though the timing associated with this, the mid-1980’s is generally associated with a pluvial in the SW, which should have positively impacted vegetation.

**Decreased Snowfall and Agricultural Impacts**

The accounts below of less snow combined with the Figure 3. 4 of snow-water-equivalent (SWE) indicate downward trends over the last two decades at high elevations as well as lower elevations nearer where people in this area live. All of the narratives describe how the snow fed creek levels have decreased, one mentioning the timing of this steep decrease, which is consistent with monitored observations (1999). The first quote especially insinuates the dependence of soil on snowpack, which may also be referring to lower elevation receipt of snow, which theoretically would be affected sooner than higher elevations since the temperatures are higher at lower elevations. This is a potential impact on agriculture aside from the irrigation issues that less snowpack brings as described in the second and third quotes regarding reservoir levels and snow-fed creeks.

The ground is dry, there used to be deep snow ~ 2 ft. By April the soil was still moist, now it’s dusty and sandy. The melt from the mountain comes down here and stops [now]. [The creeks] have all changed now; they’re tiny. There was 3-4 feet of snow in the mountains that made for plenty of water. The meltwater snow
disappeared around March; it kept things moist. -35

...from 1999 to the present there has been very little snow to fill the reservoir…[the creek] just goes a short way from the mountain ... and dries up. -37

There’s no irrigation for these crops. In the spring the alfalfa field is irrigated by spring melt that flows into a creek. -38

**Snowfall and Maximum Temperature**

The first two statements and the fourth by 27, 28, and 38 (following this paragraph) illustrate the relationship between temperature and snowmelt as illustrated in Figures 3.5 and 3.6 and, that warmer conditions prevent snow from accumulating in the first place and additionally promote earlier melt. These comments don’t explicitly mention snowfall becoming rainfall in the presence of high temperatures as found in climate research in the West (Mote et al., 2005). Additionally, the second quote suggests that farming and ranching depend on winter snowfall that persists and until melting mid-late spring. When snowmelt is decreased, there is indeed a longer dry period to survive through between when the snow melts earlier in the spring and when the monsoon storms arrive late in the summer. The third quote, about the timing of the decrease in snowmelt, correlates well with the timing from the coinciding figures of a steep decrease in 1999 (interviews took place between Aug.-Dec. 2006). The invoking of an 8-year cycle with precipitation may be referring to the El Niño effect on SW winter precipitation, but this was the only mention out of all interviews to such a cycle. It also emphasizes the cultural changes that are not climatic in nature but social and economic between different generations.

*It is warmer and snow depth decreases and melts in a day. If snow decreases,*
the water levels just keeps decreasing until the monsoon. -27

I remember we always had moisture but now there’s no snow to begin with and it melts right away and it’s hot and we finally get some when fall comes so if you plant they die of heat first. -28

~8 years ago the snow decreased (only 1-5 inches). Back in the old days there was big snow. Now they say “it was planned that way”- the old people really know. They say every 8 years there would be a lot of rain and livestock, it changed. No we’re losing, it’s “another day, another dollar’. -31

Now there’s not much snow for the melt and if it’s warm it melts it right away. -38

Later Arrival of Summer Rainfall

The amount of precipitation falling in June has a downward trend compared to the relatively stable August and September (Figure 3.8). Half of the participants noted a later arrival of summer rains over varying or unmentioned timescales (8 out of 16 responding: 27, 30, 33, 35, 37, 40, 43, 46). No reasons were offered. Figure 3.7 shows a decline in the precipitation received over the typical monsoon period, July-September. Figure 3.8 shows a pattern of decline in the percent of JAS precipitation received in July. The black triangles in Figure 3.8 represent reported timing of change when 5/7 participants began to notice a later arrival of summer rains, which varied (“early 1970’s, ~20 years ago, the last 10 years, last 5-10 years, and ~1997/98). Participants implicitly or explicitly noted impacts linked with the extension of the dry season on agriculture:

If snow decreases, the water levels just keep decreasing until the monsoon. -27

I remember we always had moisture but now there’s no snow to begin with and it melts right away and it’s hot and we finally get some [moisture] when fall comes so if you plant they die of heat first. -28

The spring melt used to last until June~July in the mountains. Now it’s all melted by April or May. The monsoon in summer comes in July-August. Now there’s no rain in June or July. -30
Usually there’s an abundance of green grasses in midsummer. In my younger times there was quite a bit of summer rain. Now one day there’s a lot, the next day there’s nothing. The moisture isn’t consistent. -32

The snow melts in ~March and finishes in April. In the summer the rains come ~June, but now they are coming later like in July. -35

In the parents’ and grandparent’s days there was snow that stayed until May. There was still water. In July there was still a little ice in the mountain on the shady side. Today it changed, from April to May the snow melts/gone, but if there isn’t even any snow, there’s nothing to melt. For the last ~10 years it’s been sporadic. In the parents’ and grandparents’ days the summer rains would come in July, now it is August, it seems to have changed ~10 years ago. -37

In summer it rains in July-August. It kept coming later in the last 5-10 years. -43

It seems like it [rain] came in September but it wasn’t that much. It used to come around July and Aug, it’s getting to the point where it’s coming later started ~1997-1998. [For parents’ and grandparents] used to come around June and July then, that’s why they had good crops. Now it’s different. Back then when we got out of boarding school the melons would be out and the corns would be ready. We’d have kneel down bread. But now it won’t even come until 9 weeks into school. -46

Discussion

Summer rainfall throughout July, August, and September is coincident with the North American Monsoon (NAM) in this area. There are other sources of summer precipitation as mentioned earlier though they are not specifically addressed in this study. However, participants do not distinguish between sources of precipitation in this research so in order to compare the responses with the data, total JAS rainfall is most appropriate.

In the West, regional hydroclimate and vegetation changes in response to temperature rise are particularly researched in current literature (Milly et al., 2005, Mote et al., 2005, Schmidt and Webb, 2001, Service, 2004, Stewart et al., 2004), and current best models downscaled to the Southwest project regional drought in response to overwhelming temperature increases (IPCC, 2007, Hoerling and Eischeid, 2007).
Participants notice the greater effectiveness of snow for irrigation and increased soil moisture and do recognize that spring and summer moisture play an important role in agriculture and livestock. The quotes offered imply or explicitly mention that when summer rains come later, there is a longer dry season that impacts crops. This is only exacerbated when the snowmelt comes earlier as well. As stated in section 1, Higgins and Shi (2000) found that later onset of summer rainfall correlated with a drier summer and more especially an early onset of precipitation correlated to a wetter summer (significant at 95% level, r = -.52).

If the seasonal distribution and magnitude of precipitation is changing, a landscape response via soil moisture, growing season length and nutrient cycling is likely. For example, the types of plant species (woody C3 shrubs vs. summer C4 grasses) respond to different seasonal precipitation regimes (Schmidt and Webb, 2001). This distribution would certainly have an impact on agriculture and ranching activities. Additionally, extending the dry season as the climate data imply will have an effect on farming and ranching practices as well, as can be garnered from the quotes of those affected above. Since this data is monthly however, it is difficult to know what part of the month it fell, the earlier or latter part. To further investigate this observation, higher resolution precipitation data and the source of each storm are needed.

Communicating with this sector via these interviews conveys their perspectives, observations, and experiences and gives the researcher a better understanding about those things that are important to them as stakeholders. This local scale information can be used to create a more meaningful manner of communicating future projected change. For example, since we know at what point in general community members began noticing
piñon pine mortality, one can examine the climate conditions (primarily temperature) under which this occurred and extrapolate roughly into the future based on climate modeled forecasts to explain future climate in terms more meaningful than simply degrees Celsius.

Conflicting Accounts and Contradictory Information

There will be cases when accounts of local knowledge will differ from one another, and when accounts will differ from data derived from Western science. The simplistic question: “What about when local knowledge is ‘wrong’?” fails to grasp the nature of local knowledge as experiential and situated in space. Perhaps a better question to ask is: “Why did this person experience this differently than the data or another individual?” First, in distinguishing between local knowledge and Western science, West and Vasquéz-León (2003) distinguish the differences between the two by describing the prior accounts as “interpretive” vs. the latter (e.g., data from the meteorological data) as “descriptive”. They are interpretive because, as Roncoli et al. (2003) put it, “Recollections of the past, observations of the present, and expectations of the future shape our experience of climate phenomena and our understanding of climate information” (p. 181). This is one main reason why local knowledge may differ among individuals as well as from Western science-derived data.

In the previous description of local knowledge, one of its characteristics was its diversity and adaptability, these qualities being used to serve those from whom it originates. As a product of the environment filtered through non-environmental filters of individuals and groups, it is in “continual negotiation between stakeholders” (Campbell, in Bicker et al., 2004, p. xiii). This diversity may result in there being no consensus
among individuals in a community because “local stakeholder knowledge is rarely
homogeneous” (Sillitoe and Barr, 2003 p. 62).

How then, for practical purposes, are we to evaluate local knowledge between
differing accounts among its holders and between it and scientific data? First it is
important here to return to the affirmation elaborated earlier regarding the strengths and
weaknesses of both knowledge systems. Since they possess their own strengths and
weaknesses, in seeking their respective contribution to a particular overarching question,
they will be employed depending on how the strengths appropriately address the question
at hand. After this determination an examination follows regarding the motivation for
study. This will help direct the choosing of suitable methods and analysis. For example, if
the purpose is a vulnerability project through a sustainability context, an understanding of
the degree of heterogeneity is vital as an indicator of ecological and social vulnerability.
This would then help to understand more appropriate approaches for increasing adaptive
capacity. More in-depth interviews and analyses to understand the ethnographic backdrop
to decisions is vital. This illuminates understanding as to why accounts (perceptions)
differ and how this reflects important factors that shape vulnerability like access to
resources (i.e., “entitlements”) (Adger, 1998). For example, Adger (1998) noted that
while external reviews “invalidated” local accounts of climate change in his particular
study, this knowledge was important and valid for understanding perceptions of the
climate.

Another motivation, as in portions of this study, is to understand how people
recognize environmental change and what changes are most common. In this case, the
degree of consensus is important to see if local characterization and experience can
complement a regional trend in meteorological or ecological data. Here, one is basically assessing or “validating” the knowledge for this purpose. Again, here the term is not meant to ascribe value to local knowledge, just to examine for this particular question if it has an appropriate contribution.

Another way of evaluating conflicting accounts among holders of local knowledge aside from majority or consensus is to examine background information of respondents. Participants who have had a long and less interrupted personal and family history in the practice of interest as well are likely to have a long-term baseline by which to compare their current knowledge and observations (Dagel, 1997). However, one should still be aware of non-environmental factors that influence perceptions as described earlier. In this analysis, one way to understand local knowledge accounts that are less influenced by non-climatic information is to recognize indicators that are less likely to be influenced by socio-economic or cultural influences. For instance, in this research, certain indicators mentioned included a shallower depth of fence posts, which was related to soil moisture depth; the lesser amount of water melted off of snow in a pot, relating to drier snow; and certain landmarks, for example, boulders where floods reached when one participant was younger that are much higher than present stream levels and recent floods. These are experiential qualitative indicators more directly related to climate than other accounts. While they are not completely free from individual error and circumstances, compared to simple answers like, “it doesn’t rain here as much as it used to” or “it is warmer in the summer now” they appear more robust. Participants in general however, had some sort of experience to back up their perceptions of change, though some were also influenced by non-climatic factors. The following section provides more
specific confounding influences that were encountered in this study, and those data that it most likely influences.

**Potential Sources of Error Present**

In recording and analyzing information, it is important to be aware of potential sources of error. Huntington (2006) addresses the need to recognize diverse perspectives among participants before and during analysis. This may be easier in some cases (age, gender, language differences) than others (temporal/spatial perspectives, epistemological assumptions, individual and factional motivations, cognitive and motivational differences). Lack of consideration of such factors can cause misinterpretation while a careful consideration can enrich the research process and acknowledge its broader context. Linked with the discussion of contradictory information between participants and between participants and scientific data are more specific examples from this study. The heterogeneity in this sample in part emanated from diversity of individual, social, and cultural, and environmental influences. Those identified are described below.

**Circumstances that Remove One from Agricultural Activity**

Individual life experience differences may have resulted in a changing baseline. For example, some participants mentioned personal illness and accident as factors that increased or decreased their involvement in farming and ranching. Also other participants had moved out of the area time, a few for the majority of their lives up to this point, before returning to the area. This can result in the participant a having a different perspective and potentially another baseline for judging changes in the environment, inclusive of the weather.
Language Translations

Many of the more elder participants preferred that the interview be conducted in Navajo. Navajo is a very descriptive language, but often there are no words to directly translate terms in English, and vice versa. This often required the translator to come up with translations for participants on the spot when confusion or questions as to clarity arose. Though I was careful to consult with multiple Navajo speakers regarding the appropriateness of the interview protocol as it translated to Navajo, in addition to my interpreter having an advanced degree in social sciences and being aware of bias issues in interview protocols, there still may have been a small degree of bias in these questions in the case of confusion and clarification for the participant. This would have affected the Navajo speakers most and overall the potential effect is unknown as it may have affected answers differently.

Interview Fatigue

Interview fatigue is simply the fatigue resulting from the length of an interview exceeding the interest, patience, or mental acuteness of the participant, and perhaps the interviewer as well. This would have most likely affected especially the final portions of the interview protocol. The interviews that took place in Navajo at the request of the participant tended to last longer than the average interviewer, one lasting approximately three hours. While it was affirmed that Navajo elders are patient and will take time (personal communication, C. Chee), this length was in great excess of the anticipated time required.

Cultural Teaching Regarding the Negative

As mentioned briefly in Chapter II, there is a Navajo cultural teaching that one
should not focus on the negative. This belief may have resulted in a discontinuity of transmission of earlier particularly difficult periods. Evidence of this may be the very few mentions regarding the infamous livestock reduction program begun in the 1930s (discussed in Chapter II). However, as this sort of information is important, the belief in emphasizing the good may have resulted in transmittance of teachings to prepare for change, but not a keen memory of the specific change itself. This is more likely to have impacted those answers relating to loss and would have caused a general underestimation.

**Proprietary information**

Proprietary issues may arise, particularly with knowledge regarding traditional knowledge as opposed to everyday information less likely to have proprietary concerns (e.g., questions relating to importance of modern weather information use and access). In one particular case, after offering some traditional methods of predicting weather, and being asked further about such information, the participant playfully, yet firmly, responded that in every family, there are things that you keep and pass just in your family, knowledge you are “stingy” about. This may have been the case for others who seemed to not know or share little, though some openly said they didn’t pay enough attention, but that they should have. This is more likely to have affected the responses regarding the more specific traditional predictors of climate and would most likely have decreased the amount of detailed information and the overall frequency.

Overall, a study such as this that seeks to intersect local knowledge and climate science in an overarching question of local scale change and associated impacts has the potential to open dialog between the two disparate forms of knowledge. To science,
insights from the local experience could help guide research questions and include impacts and perspectives that help make climate science more meaningful to society in general (Cohen, 1997). For the local scale, climate science contributions qualitative data that can be used to help create specific guidelines for management plans and decision-making as well as connecting local level changes to global phenomenon (Jurgens, 2002). This perspective could help in articulating problems and solutions in a broader context but in a manner relevant to those it affects most. This intersection has the capacity to engage communities and increase the qualities of self-determination and resilience that American Indian tribes continually struggle to affirm (Lazrus, 2005).
CHAPTER 4: SUMMARY OF FINDINGS AND RECOMMENDATIONS FOR FUTURE RESEARCH

In a world of changing climate, some scientists are calling for a larger emphasis on adaptation (in addition to mitigation), particularly at multiple levels (Peilke Jr. et al., 2007). Regardless of mitigation activity, temperatures are still projected to rise over the next half century. Therefore, the most vulnerable communities would especially benefit by implementing adaptation activities (Adger et al., 2003). For the Navajo Nation, this makes sense when one considers the already present rapid and deleterious impacts of drought on the most sensitive sectors, not to mention drought exacerbated by anthropogenic climate change. In addition, residents of the reservation are not believed to have as high a "carbon footprint" compared with the rest of the Nation considering that approximately 37% of the Navajo Nation residents did not have access to electricity in 2000 compared to 1.4% nationally (DOE, 2000). Thus on average, individuals (rather than government entities which hold more power over oil and gas resources) on the reservation do not have as many options to contribute to mitigation activities since per capita resource use including fossil fuel emissions is much lower than the average American.

It is widely assumed that the most impoverished of society will be disproportionately affected by a warming climate and thus need to address adaptation at a meaningful and measurable scale (local-regional). For the sectors described in this study, an examination of the controllable factors (notwithstanding financial resources) that compounded the impacts these communities experienced may be valuable. Coupled with
the findings of a drought report of the Navajo Nation (2000), the following section offer recommendations based on Chapters I-III.

**Improvement of Infrastructure**

There are many factors that are non-climatic that combine with and compound climatic impacts increasing the vulnerability of vulnerable communities (Pielke Jr. et al., 2007). The vulnerable farming and ranching sector on the Navajo Nation is an example of such a society. Identifying and addressing these non-climatic factors in such a way so as to minimize overall vulnerability is a potential route that would decrease the risks posed by climate change on land-dependent communities in this area. There is also the potential for abrupt changes caused by non-linearities within the climate system that cannot be adequately anticipated though they have occurred in the past and are thought to become higher probability possibilities through anthropogenic forcing (Alley, et al., 2003). As such risks exist, it would only further add emphasis on the need for adaptation measures.

Infrastructure enhancement, particularly in the case of water resources is also a factor that can decrease overall vulnerability as evidenced by the differences between the viability of farming and ranching practices here. Ensuring a more reliable source of water is part of the goal of the ongoing water rights quantification settlement between the Navajo Nation and the surrounding states that share basins with the Nation (Arizona, New Mexico, and Utah). However, improvement of the current water supply does not need to rest completely on the large-scale decision-making at the nation and state level. It can also be improved by improving local management such as in the formation of water users’ associations and improving community awareness and protection of water sources
from controllable threats such as vandalism, that can compromise quality and quantity (NNWMB, 2002).

Many participants in this study mentioned the lack of certain resources and infrastructure that have contributed to their farming and ranching loss. For example, one participant mentioned more cross-fencing, and water pumps as implements that in this particular case study, would increase the range health and improve access to water. Since overstocking range is also known as a factor that amplifies vulnerability in drought (NNWRMB, 2002), and drought it is projected to increase in the region, these might be non-climatic factors that could increase the resilience of these sectors.

**Management Scale and Heterogeneity**

Heterogeneity has been established as a crucial characteristic of both local knowledge and vulnerability that needs to be given further study at local and broad scales to determine at what scales risks should be approached and managed. The Huntington et al. (2007) comparison described in Chapter III illustrates a potential example for further studies in the Southwest, and other comparable arid environments across the world that are at risk to future projected drought due to global climate change. Future academic endeavors in the human dimensions of climate change in such environments could help identify the degree of heterogeneity between communities, which would be very useful in projecting future impacts. In addition to recognizing the heterogeneity of local systems, it could also identify common threads across temporal and spatial scales that link similar processes. Such information could help increase sustainability of both the human and environmental systems, thereby decreasing vulnerability through identification and institution of policies at the regional, national, or global scale that would address
common circumstances. This type of large-scale study of local systems bears similarity to ecosystem studies at the meso-scale, where such a scale allows for identification of broad patterns over longer time periods (Swetnam and Betancourt, 1998). However, rather than seeing heterogeneity in the local level variability as “noise”, it would instead represent an important scale of change better managed for by local decision-making entities such as the chapter and tribal-level, while efforts to address the larger scale would be better managed by a coordinated network involving multiple agencies and stakeholders (including tribal).

**Communication of Climate Information**

Climatic factors obviously can increase vulnerability as exemplified by the fact that the farming and agricultural sectors almost disappeared during the 1996 drought (WRMB, 2002). Yet these activities continue presently, suggesting these sectors are highly sensitive to year-to-year changes and can rebound from difficult periods. As such, dissemination of reasonably accurate and meaningful climate information soon after it is available is vital for informed decision-making regarding annual and seasonal planning.

Chapter II detailed the mediums of communication that agriculturalists in this region use most frequently, yet there were procedural difficulties with using the most widely recognized mode of weather information communication, the radio (NNWMB, 2002). In light of the importance of climate information to public welfare, perhaps an arrangement could be made between the disseminators of information and the NNWMB or other producers of climate information. This is, presently, perhaps the most efficacious means of increasing public awareness of climate conditions and forecasts (long and short-term) because of its accessibility to almost all Navajo Nation members as a bilingual AM
station broadcast in this rural area. This is supported by the fact that the overwhelming majority of the participants (16/20) receive climate information from radio broadcasts. Those who did not note the radio as a source of weather information did not note any means of climate information (instead responding “too busy” to pay attention to weather information, 36, 43). Thus this number doesn’t reflect only those with access to a radio, but only those who specifically mentioned receiving climate information from the radio. Most likely, all participants have access to the radio and utilize it on at least a semi-regular basis. Also, KTNN is well established on the reservation and broadcast from Window Rock (the capitol of the Navajo Nation) by members of the Navajo Nation. Therefore, rather than an outside, less familiar communication source and medium, perhaps this is the first and best existent widespread network to utilize in climate information dissemination. Das et al. (2005) and Weiss et al. (2000) note that television and radio are the best modes of communication for rural populations as they are rapid and if in the appropriate language, can reach the most people. One disadvantage compared to leaflets and the Internet, amongst other sources is the limited amount of time that they are available, versus the longer lifespan of an image or document which to reference over longer periods of decision-making.

Word of mouth was the third most noted mode of receiving weather information, after radio, and television. This method of communication could further be studied through networks analysis research, which seeks to understand how information is disseminated in a network and who the influential sources are (Wasserman and Faust, 1994; Freeman, 2004; Cross and Parker, 2005). Identification of the influence certain individuals have in these networks, be they members of the general community, or
Chapter-level, tribal-level, state, university extension, or federal agency employees, could prove an efficacious means of continuing and enhancing information diffusion. An understanding of who these individuals are could help in creating collaborations or supplying support to increase their capacity to supply efficacious information. The idea of these people as “boundary workers” here is helpful as these individuals, if comfortable and educated in land and/or water management, and/or climate science and comfortable in the community could serve as “information brokers”. They would optimally, be better able to translate concepts between the field of climate science and the reality of the local stakeholders.

Work in development, particularly agricultural development has recognized the great need for “boundary workers”. Human dimensions of climate change research could also greatly benefit from such expertise, particularly in rural communities where use of local knowledge is part of the research framework. Boundary workers, such as “técnicos” in Latin America, are college-educated professionals who live and work in rural communities and have an understanding of local knowledge and practices. This understanding of both the practices of Western science and those of the local experience allow them to be potential “information brokers” who are able to translate concepts between the two systems knowing, though they are underutilized in research of local knowledge (Bentley et al., 2004).

In this study, one particular participant proved very insightful commentary on change and reasons for change. This participant had not been active in farming or ranching since a young adulthood, when boarding school led h/ away during the school year and finally when college and the professional career led h/ away from farming and
ranching year round. This college education as well as familiarity with the life that accompanies farming and ranching for Navajos (siblings were still involved with the practices) helped this participant easily understand the topics and questions and provide meaningful explanations that were very consistent with the local climate data in spite of no longer being active in those practices.

In the U.S., extension workers are often seen as “boundary workers”, or “information brokers” as their position requires their involvement and assistance with local agriculturalists and public. In the realm of climate change studies, boundary workers have the capacity to provide their expertise and provide timely results for informed decision-making. Decisions on the Navajo Nation generally do not have a history of being made in a timely fashion. In the past, this has often been due to a convoluted interface between government and tribal agencies (NNWRB, 2002). In terms of working in studies that address local knowledge and natural resources, this has also been due to unfamiliarity and hesitancy to work through the perceived complexities of the human subjects protocols required on the Navajo Nation for any research dealing with human subjects (personal communication Gerald Moore, 6/2006).

Integration of multiple perspectives in improving climate forecasting and communication is strongly suggested by many (Usman et al., 2005). These perspectives could be better integrated by communication modes such as county leaflets that incorporate visual aids of seasonal activities and recommendations depending on the climate information. Extension agents would be in a prime position to contribute such information as would trusted community representatives and Diné College students studying agriculture or climate-related sciences. A leaflet could provide a physically
lasting and more detailed source of climate information specific to farming and livestock interests that could be dispersed to chapter houses easily and timely via facsimile. However, according to interview data currently few (2/20) participants mentioned use of such information though one of these (27) mentioned that often this information does not get to the Chapter house in time for farmers and ranchers to respond appropriately. Perhaps the improvements mentioned could help increase its demand and use.

Climate Information Use Training for Agriculturalists

Further research into reasons why people might not actively use climate forecasts in decisions could prove useful in understanding people’s perceptions of climate forecasting and their expectations to improve communication of this information (Nicholls, 1999). Such information would help create more useful products to help people make more informed decisions by better understanding the information. Provide training or perhaps better communication format that addresses the misunderstandings of concepts like probability (Nicholls, 1999, Hansen, 2004). Das et al. (2003) propose aspects that should be included to effectively teach about probabilistic information in agriculture including presentation of information in frequencies (e.g. 100 mm of rainfall about every 10 out of 20 years). They also emphasize relating this information to experience of the agricultural community to “map” this information using their experience. Lastly, they emphasize the creation of trust and transparency by describing the comparing forecasts to observations and clarifying in basic terms how forecasts are created. These steps have been utilized in diverse places such as Kenya to Florida in teaching farmers about probabilities of weather forecasting to augment their informed usage of this information (Das et al., 2003).
Although most participants noted contentedness with the present amount of climate information received, there are two reasons that strongly suggest the increasing need of useful climate information to decrease vulnerability. First, there are a great number of activities related both to everyday life as well as agricultural and ranching previously mentioned by participants that presently rely on climate information. Second, the new context of climate change projected to bring warmer, drier conditions to the West is a topic of which few participants made any mention throughout the interviews.

**Creation of More Useful Climate Indices Tailored to Agriculture**

All agricultural indices relate to precipitation and crop rainfall requirements, as opposed to indicators of meteorological drought, which is only related to rainfall relative to itself, not another variable. This creates a complexity for those wishing to choose an index that appropriately captures the most important dimensions of drought impacts to those who are most vulnerable.

The Navajo Nation has used the Standard Precipitation Index since approximately 1998, on advice from the Bureau of Reclamation. It is a parsimonious index that relies only on normalized precipitation. As opposed to PDSI, it is more sensitive to abrupt onset of drought and can be calculated at different time scales depending on the needs of the sector. Because it is only reliant upon rainfall records, it is suitable to this data-sparse region. The SPI is currently the index the Navajo Nation is using in drought declaration and the subsequent response chain, though federal programs on the reservation may use other indices more suitable for their purposes. In 2002, the NNWRMB indicated plans for creating Standardized Precipitation Indices (SPI) specific to each of five agencies on the
Navajo Nation for enhanced local governance and decision-making. Currently this is an ongoing effort (NNWMB, 2002).

The ability of the SPI to be easily computed for different sectors depending on the timescale of interest is a benefit, and this is intended to help agriculturalists. However, in the research conducted for this paper, no farmers or livestock owners mentioned use of this index. Research on climate information needs and communication shows that interaction between the end-users, those who disseminate climate information, and those who produce the information is vital (Lemos et al., 2002). More research on how end-user needs and climate science producer ability can converge would greatly increase the utility of this information. Whatever the outcome of such research, certainly the interaction would prove to enhance communication of climatic information for agriculture and ranching in a more standardized and useful format that incorporated meaningful variables and that reflected sectoral-specific activities.

Traditional climate predictors may also prove insightful avenues for future research on biological indicators of climate change. Chapter II detailed those mentioned by participants, including interestingly the grass some Navajos have used in the past, as indicators for the following winter rather than an immediate, or proximal/short-term weather condition. Though it was not widely understood and used by participants in this sample, many at least had knowledge of its existence and use in the past (5). More research into the cycles of this plant might be initiated to indeed see its value and/or connection to climatic cycles and predictors. Uses of indicators such as this along with climate data could provide more holistic manner of communicating climate information and enhance community monitoring.
**Improved Land Management**

In the past farming and ranching fluctuated at the seeming mercy of the climate. It’s evident that the options in the past were far fewer as the infrastructure for resources such as water and hay to buy from outside the region were not available as they are today. In addition to low forage, McMillen mentioned archives that indicated that during the deepest droughts, animals died of thirst as well, a condition not described by any farmers in this study (McMillen, 2000). In general, compared to the past the vulnerability of the Navajo people to climate stresses has decreased. However, there are still debates regarding current land management versus traditional and customary land use. Some argue for the value of declining traditional practices and their influence on land health and community welfare (Kelley and Francis, 2001, Kelley and Whitely, 1989). It is difficult to quantitatively research these traditional practices and they constitute a set of activities that could influence the viability and vulnerability of the agricultural sector. This is an area that could benefit from more multi-disciplinary research, particularly as climate projections suggest conditions that will place this sector under increasing vulnerability. However, suffice it to say that for the present study, these contributions and questions are acknowledged as valid, but are beyond the scope of this study in terms of recommendations for the future in decreasing vulnerability in a context of climate change.

Improvement in land use management is no new recommendation, but it is still worthy to mention since it is key when considering the heightened risks brought about by increased temperatures and longer dry seasons between spring melt and rains. Range management in particular is germane to the current study since wise grazing practices can
decrease land degradation that compounds the effects of drought. Examination of forest
management practices would also be useful for considering the severe fire hazards that
drier conditions pose to communities, the environment, and the economy.

Conclusions

Global and regional climate is changing and is projected to continue to change in
a manner that may have no global analog that humans have been around to experience. In
the Southwest since people can remember, drought has been a common threat that has
required adaptation. And in the Southwest forecasts call for exacerbation of these dry
conditions. It is therefore worthwhile to research the most vulnerable communities and
understand what changes they are noticing, as well as how they have experienced
impacts.

This study emphasized the value of this local knowledge and experience, for
many reasons, in the context of climate change. First enhancing an understanding of local
conditions and how they may or may not be consistent with regional and global trends
has helped establish connections between local conditions and regional conditions.
Second, the experience and perspectives at the local level can help define the nature of
impacts on local populations, and in this case, impacts upon the most sensitive sector.
This knowledge can help in identifying adaptation possibilities by understanding past
events, impacts, and actions. Third, this knowledge and experience can intersect with
contributions from Western scientific study to communicate change and impacts in a
meaningful way. This intersection between the local, qualitative, and integrated
experience and the large-scale quantitative knowledge can help translate into relevant
decision-making for overall increases in community capacity to adapt in a changing climate.
APPENDIX A: Figures from Chapter 1

QuickTime™ and a TIFF (Uncompressed) decompressor are needed to see this picture.

Figure 1.1: The Navajo Nation lies primarily in northeastern Arizona but also extends in to southern Utah and northwestern New Mexico. The Chuska Mountains are located in the eastern portion of the reservation, straddling the border between Arizona and New Mexico (Source map: http://www.bible.ovc.edu/missions/indians/navajres.htm)

Figure 1.2: Sage and low-density juniper at low elevations below Chuska Mtns. (Novak, 2007)
Figure 1.3: Ponderosa Pine in mid-elevation Chuska meadow (Novak, 2007)

Figure 1.4: Mixed Ponderosa Pine, Douglas fir high elevation forest (Novak, 2007)

Figure 1.5: Chuska/Defiance Plateau climograph 1895-2007 (Source: Daly et al., 1994)
**Legend**

**Co-op Stations (WRCC, 2007)**
1. Fort Defiance
2. St. Michael’s
3. Window Rock
4. Ganado
5. Lukachukai

**PRISM (Daly et al., 1994)**
6. (near) Tsaile, AZ

**Navajo Nation Snow Course Data (NNWMB, 2006)**
7. Bowl Canyon
8. Hidden Valley
9. Tsaile
10. Tsaile III
11. Whiskey Creek

**USGS Streamflow (USGS, 2001)**
12. Fluted Rock
13. Missionary Springs
14. Chinle Creek gauge at Mexican Water, AZ

**Figure 1.6:** Instrumental climate data in and near the Chuska Mountains and Defiance Plateau from local records (Data Sources: Daly et al., 1994a (PRISM); NCDC, 1999; Williams et al., 2007 (USHCN); WRCC, 2007); (Map Source: University of Arizona. RangeView, 2004)
**Legend**

USHCN Station (Williams et al., 2007)
15. Holbrook, AZ
16. Lee’s Ferry, AZ
17. Ft. Valley, AZ
18. Bluff, UT
19. Blanding, UT
20. Canyon de Chelly, AZ
21. Aztec, NM
22. Grand Canyon, AZ

**Figure 1.7**: Instrumental climate data in and near the Chuska Mountains and Defiance Plateau from regional US Historical Climatology Network (USHCN) records (Data Sources: Williams et al., 2007 (USHCN)); (Map Source: University of Arizona. RangeView, 2004)
Figure 1.8: Arizona and New Mexico Climate Divisions, those of use here are Arizona 2 and New Mexico 1 (NCDC, NOAA: ncdc.noaa.gov)

Figure 1.9: All instrumental data series (PRISM, WRCC, USHCN, NCDC-AZ2 and NM1) mean annual temperature and 5-yr running averages for the Chuska/Defiance area 1895-2006 (Sources: Daly et al., 1994a (PRISM), NCDC, 1999; Williams et al., 2007 (USHCN); WRCC, 2007)
Figure 1.10: Winter mean temperature (5-yr running mean) for all data series (PRISM, WRCC, USHCN, NCDC-AZ2 and NM1) of the Chuska/Defiance area, 1895-2007 (Sources: Daly et al., 1994a (PRISM); NCDC, 1999; Williams et al., 2007 (USHCN); WRCC, 2007)

Figure 1.11: Spring mean temperatures (5-yr running mean) for all data series (PRISM, WRCC, USHCN, NCDC-AZ2 and NM1) of the Chuska/Defiance area 1895-2007 (Sources: Daly et al., 1994a (PRISM); NCDC, 1999; Williams et al., 2007 (USHCN); WRCC, 2007)
Figure 1.12: Summer mean temperature (5-yr running mean) for all data series (PRISM, WRCC, USHCN, NCDC-AZ2 and NM1) of the Chuska/Defiance area, 1895-2007 (Sources: Daly et al., 1994a (PRISM); NCDC, 1999; Williams et al., 2007 (USHCN); WRCC, 2007)

Figure 1.13: Summer mean temperature (5-yr running mean) for all data series (PRISM, WRCC, USHCN, NCDC-AZ2 and NM1) of the Chuska/Defiance area, 1895-2007 (Sources: Daly et al., 1994a (PRISM); NCDC, 1999; Williams et al., 2007 (USHCN); WRCC, 2007)
Figure 1.14: Mean annual temperature and trend lines for USHCN sites surrounding the Chuska/Defiance area, 1895-2006 (Source: Williams et al., 2007)

Figure 1.15: Regional lapse rate for mean annual temperature of USHCN sites surrounding Chuska/Defiance area (Source: Williams et al., 2007)
**Figure 1.16:** Gauged Arizona basins (Source: US Geological Survey 2001; Note: Chinle drainage is located in the northeastern corner of Arizona, station 09379200)
Figure 1.17: Snow water equivalent (SWE) decline since 1985 from five aggregated high elevation (>2440m) sites in the Chuska Mountain snow course and two aggregated lower elevation sites (<2440m) (Source: NNWMB provisional data, unpublished)

Figure 1.18: Relationship between high elevation SWE values and November-March precipitation at high elevation sites (Source: Daly et al., 1994a (PRISM); NNWMB provisional data, unpublished)
**Figure 1.19:** Relationship between high elevation SWE values and November-March maximum temperature (Source: Daly et al., 1994a (PRISM); NNWMB provisional data, unpublished)

**Figure 1.20:** Relationship between low elevation SWE values and November-March precipitation (Source: Daly et al., 1994a (PRISM); NNWMB provisional data, unpublished)
Figure 1.21: Relationship between low elevation SWE values and November-March maximum temperature (Source: Daly et al., 1994a (PRISM); NNWMB provisional data, unpublished)

Figure 1.22: Center of flow in days for Chinle Creek USGS gauge station at Mexican Water between October-June and relationship with maximum spring (March-May) temperature 1965-2006 (Source: Daly et al., 1994a, USGS, 2006)
Figure 1.23: USGS gauge station at Mexican Water between October- June and relationship with cool-season (Nov-Mar) temperature 1965-2006 (Source: Daly et al., 1994a; USGS, 2006)

Figure 1.24: Total annual late summer (July-September) precipitation 1895-2006, 5-yr running average, series length mean (1895-2006), and mean of most recent period (1991-2006) (Source: Daly et al., 1994a)
Figure 1.25: The fraction of July precipitation contributing to late summer (July-September) precipitation 1895-2006), 5-yr running average of July fraction, and mean of July/JAS fraction 1895-2006 (Source: Daly et al., 1994a)

Figure 1.26: Late summer (July-September) monthly contributions to overall July-September precipitation (e.g. July precipitation/July-September precipitation) July is the only month with a declining trend over this period (Source: Daly et al., 1994)
Figure 1.27: Paleoclimatic data locations for local and regional reconstructions (Sources: Dean and Robinson, 1978; Grissino-Mayer, 1995; Cook et al., 2004; Woodhouse et al., 2006; Meko et al., 2007)

Note: reconstructions from Ni et al. (2002) and Salzer and Kipfmueller (2005) are not included since their reconstructions cannot be expressed as points. Ni et al. Corresponds to NCDC climate divisional data (AZ2 and NM1, see Figure 1.8 for boundaries) and the latter represents the southern Colorado Plateau (Map source: University of Arizona. RangeView, 2004)
**Legend**

**Local Paleoclimate Reconstructions**

Dean and Robinson (1978)
1. Chuska Valley
2. Chaco Canyon
3. Hopi Mesas
4. Puerco Valley/Defiance Plateau
5. Navajo Mountain
6. Natural Bridges
7. Tsegi Canyon

8. El Malpais

**Colorado River flow reconstructions**
Woodhouse et al., 2006; Meko et al., 2007
9. Green River, Green River, WY (not pictured in figure)
10. Green River at Green River, UT
11. Colorado River, Glenwood Springs
12. Gunnison River, Crystal
13. Gunnison River, Grand Junction
14. Dolores River at Dolores, CO
15. Colorado River near Cisco, UT
16. San Juan River Archuleta, CO
17. San Juan River near Bluff, UT
18. Colorado River at Lee’s Ferry, AZ

**Cook et al., 2004 2.5 x 2.5 grid PDSI reconstructions**
19. Grid point 103 (2.5 x 2.5 grid surrounding point)
20. Grid point 104 (2.5 x 2.5 grid surrounding point)
21. Grid point 118 (2.5 x 2.5 grid surrounding point)
22. Grid point 119 (2.5 x 2.5 grid surrounding point)

Tribal land boundaries

**Regional Paleoclimate Reconstructions**
Figure 1.28: Reconstructed annual June PDSI (Palmer Drought Severity Index) from local tree-ring chronologies for the central, western and northern Navajo Nation vicinity and nearby during the common period 660 AD-1988 AD. Heavy black lines indicate the 11-year running average of PDSI reconstructions (CHU = Chuska Valley, CHA = Chaco Canyon, HM = Hopi Mesas, P/D = Puerco/Defiance Plateau) (Source: Dean and Robinson, 1978)
Figure 1.29: Reconstructed annual June PDSI (Palmer Drought Severity Index) from local tree-ring chronologies for the central, western and northern Navajo Nation vicinity and nearby during the common period 660 AD-1988 AD. Heavy black lines indicate the 11-year running average of PDSI reconstructions (NB = Natural Bridges, NAV = Navajo Mountain, TC = Tsegi Canyon, MLP = El Malpais) (Sources: Dean and Robinson, 1978; Grissino-Mayer, 1995)
**Figure 1.30:** Reconstructed precipitation standard anomaly index (SAI) (cool-season for Ni et al., 2002; October-July for Salzer and Kipfmueller, 2005) from tree-ring chronologies for northeastern Arizona (Arizona climate division 1, Ni et al., 2002) and northwestern New Mexico (New Mexico climate division 2, Ni et al., 2002) during the period 1000 AD-1988 AD (Ni et al., 2002) and the southern Colorado Plateau during 650 AD-1987 AD (Salzer and Kipfmueller, 2005). Heavy black lines indicate the 11-year running average of SAI (AZ2= Arizona Climate Division 2 and NM1= New Mexico Climate Division 1, S&K = Salzer and Kipfmueller) (Sources: Ni et al., 2002; Salzer and Kipfmueller, 2005)
**Figure 1.31**: Regional summer Palmer Drought Severity Index (PDSI) reconstructions from tree-ring of the Four Corners region during the period 650 AD-2004 AD. Heavy black lines indicate the 11-year running average of PDSI (Cook 103 = northwest grid point of the area, Cook 104 = southwest grid point of the area, Cook 118 = northeast corner of the area, and Cook119 = southeast corner of the area) (Sources: Cook et al., 2004)
Figure 1.32: Standard anomaly index (SAI) of reconstructed streamflow in the Upper Colorado River Basin 1530-2000 AD. Dark heavy lines indicate 11-year running averages. (GR-WY = Green River, at Green River, WY; GR-UT = Green River at Green River, UT; CR-Gldw = Colorado River, Glenwood, CO; GU-Crystal = Gunnison River at Crystal, CO; GU-GndJct = Gunnison River at Grand Junction, CO; Dolores = Dolores, CO; CR-Cisco = Colorado River near Cisco, UT; SJn-Archuleta = San Juan at Archuleta, NM; SJn-Bluff = San Juan River near Bluff, UT, Lees Ferry = Lee’s Ferry, AZ) (Sources: Woodhouse et al., 2006; and Meko et al., 2007)
Figure 1.33: Annual mean maximum temperature for the Southern Colorado Plateau from 250 BC to 1996 AD (Salzer and Kipfmueller, 2005)
Future Projections

Figure 1.34: AZ1 Winter observed vs. modeled PDSI 1895-2006 (Source: Hoerling and Eischeid, 2007)

Figure 1.35: AZ1 Spring observed vs. modeled PDSI 1895-2006 (Source: Hoerling and Eischeid, 2007)
Figure 1.36: AZ2 Summer observed vs. modeled PDSI 1895-2006 (Source: Hoerling and Eischeid, 2007)

Figure 1.37: AZ2 Fall observed vs. modeled PDSI 1895-2006 (Source: Hoerling and Eischeid, 2007)
Figure 1.38: NM1 winter observed vs. modeled PDSI 1895-2006 (Source: Hoerling and Eischeid, 2007)

Figure 1.39: NM1 spring observed vs. modeled PDSI 1895-2006 (Source: Hoerling and Eischeid, 2007)
Figure 1.40: NM1 summer observed vs. modeled PDSI 1895-2006 (Source: Hoerling and Eischeid, 2007)

Figure 1.41: NM1 fall observed vs. modeled PDSI 1895-2006 (Source: Hoerling and Eischeid, 2007)
Figure 1.42: AZ2 modeled seasonal PDSI 2007-2099 (Source: Hoerling and Eischeid, 2007)

Figure 1.43: NM1 modeled seasonal PDSI 2007-2099 projections (Sources: (Source: Hoerling and Eischeid, 2007)
Figure 1.44: AZ2 and NM1 annual (calendar year January-December) observed vs. modeled mean temperature during the historic period of record 1895-2005 (Sources: NCDC, 2007; IPCC, 2007)

Figure 1.45: AZ2 and NM1 annual (water year October-September) observed vs. modeled mean precipitation during the historic period of record 1895-2005 (Sources: NCDC, 2007; IPCC, 2007)
Figure 1.46: AZ2 modeled annual temperature and precipitation 1895-2006 (Source: Hoerling and Eischeid, 2007)

Figure 1.47: AZ2 modeled annual temperature and precipitation 2007-2099 (Source: Hoerling and Eischeid, 2007)
**Figure 1.48:** NM1 modeled annual mean temperature and precipitation 1895-2006 (Source: Hoerling and Eischeid, 2007)

**Figure 1.49:** NM1 modeled annual mean temperature and precipitation 2007-2099 (Source: Hoerling and Eischeid, 2007)
APPENDIX B: Chapter 1 Tables

Table 1.1 Basic statistics of climate data encompassing the Chuska/Defiance area, average, standard deviation (SD); station data correlations and coefficient of variation (Sources: Daly et al., 1994a (PRISM); NCDC, 1999; Williams et al., 2007 (USHCN); WRCC, 2007)

<table>
<thead>
<tr>
<th></th>
<th>PRISM Ann</th>
<th>WRCC Ann</th>
<th>NCDC (AZ2)</th>
<th>NCDC (NM1)</th>
<th>USHCN (Tobs)</th>
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<tbody>
<tr>
<td>Average</td>
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<td>9.14</td>
<td>10.61</td>
<td>9.43</td>
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<tr>
<td>SD</td>
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<td>0.82</td>
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<td>0.93</td>
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</tbody>
</table>

Correlation coefficients (r)

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<th>WRCC Ann</th>
<th>NCDC (AZ2)</th>
<th>NCDC (NM1)</th>
<th>USHCN (Tobs)</th>
</tr>
</thead>
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<td>1.00</td>
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<td>0.77</td>
<td>0.82</td>
</tr>
<tr>
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<tr>
<td>NCDC (NM1)</td>
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<td></td>
<td></td>
<td>1.00</td>
<td>0.82</td>
</tr>
<tr>
<td>USHCN (Tobs)</td>
<td>1.00</td>
<td></td>
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Coefficient of variation (r-sq.)

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<tr>
<th></th>
<th>PRISM Ann</th>
<th>WRCC Ann</th>
<th>NCDC (AZ2)</th>
<th>NCDC (NM1)</th>
<th>USHCN (Tobs)</th>
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<td>0.60</td>
</tr>
<tr>
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<td>0.58</td>
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<td>0.71</td>
</tr>
<tr>
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<td>1.00</td>
<td>0.66</td>
</tr>
<tr>
<td>NCDC (NM1)</td>
<td>1.00</td>
<td></td>
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</tr>
<tr>
<td>USHCN (Tobs)</td>
<td>1.00</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 1.2: Ranking of seasonal mean temperature by averaging across the seasonal change of each data set (Source: Daly et al., 1994a (PRISM); NCDC, 1999; Williams et al., 2007 (USHCN); WRCC, 2007)

<table>
<thead>
<tr>
<th></th>
<th>DJF</th>
<th>MAM</th>
<th>JJA</th>
<th>SON</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average seasonal rate of change (°C/yr)</td>
<td>0.015</td>
<td>0.014</td>
<td>0.009</td>
<td>0.006</td>
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</tbody>
</table>

Table 1.3: Ranking of seasonal mean temperature by comparing the degree of seasonal ranking agreement between data sets (Source: Daly et al., 1994a (PRISM); NCDC, 1999; Williams et al., 2007 (USHCN); WRCC, 2007)

<table>
<thead>
<tr>
<th></th>
<th>PRISM</th>
<th>WRCC</th>
<th>NCDC (AZ2)</th>
<th>NCDC (NM1)</th>
<th>USHCN (Tobs)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rank of seasonal rate of change for each data series (deg C/yr)</td>
<td>MAM</td>
<td>JJA</td>
<td>DJF</td>
<td>MAM</td>
<td>DJF</td>
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<tr>
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<tr>
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<td>0.013</td>
<td>0.011</td>
<td>0.011</td>
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<td>0.003</td>
<td>0.006</td>
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<td>0.004</td>
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<tr>
<td>SON</td>
<td>0.011</td>
<td>0.003</td>
<td>0.001</td>
<td>-0.004</td>
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</table>
Table 1.4: The 10 most severe 11-yr drought periods and coinciding average PDSI (Palmer Drought Severity Index) from an 11-year running average of PDSI reconstructions from local tree-ring chronologies for the central, western and northern Navajo Nation vicinity during the common period 660 AD-1988 AD (CHU = Chuska Valley, CHA = Chaco Canyon, HM = Hopi Mesas, P/D = Puerco/Defiance Plateau) (Source: Dean and Robinson, 1978)

<table>
<thead>
<tr>
<th>Years of drought (11yr)</th>
<th>CHU Ave. PDSI</th>
<th>Years of drought (11yr)</th>
<th>CHA Ave. PDSI</th>
<th>Years of drought (11yr)</th>
<th>HM Ave. PDSI</th>
<th>Years of drought (11yr)</th>
<th>P/D Ave. PDSI</th>
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</thead>
<tbody>
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<td>1513-1523</td>
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<tr>
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<td>1950-1960</td>
<td>-1.89</td>
<td>1812-1822</td>
<td>-2.12</td>
<td>1089-1099</td>
<td>-2.25</td>
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<tr>
<td>1892-1902</td>
<td>-1.67</td>
<td>1818-1828</td>
<td>-1.73</td>
<td>1285-1295</td>
<td>-2.11</td>
<td>1090-1100</td>
<td>-2.17</td>
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<tr>
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<td>-1.73</td>
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<td>-2.13</td>
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<td>-1.62</td>
<td>1575-1585</td>
<td>-1.62</td>
<td>1286-1296</td>
<td>-2.04</td>
<td>1512-1522</td>
<td>-2.11</td>
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<tr>
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<td>1951-1961</td>
<td>-1.61</td>
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<td>-1.98</td>
<td>1091-1101</td>
<td>-2.08</td>
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<tr>
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<td>-1.60</td>
<td>1817-1827</td>
<td>-1.59</td>
<td>1287-1297</td>
<td>-1.94</td>
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<td>1772-1782</td>
<td>-1.59</td>
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<td>1085-1095</td>
<td>-1.98</td>
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<tr>
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<td>-1.55</td>
<td>1894-1904</td>
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<td>1084-1094</td>
<td>-1.98</td>
</tr>
<tr>
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<td>1948-1958</td>
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<td>1817-1827</td>
<td>-1.85</td>
<td>1088-1098</td>
<td>-1.97</td>
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Table 1.5: The 10 most severe 11-yr drought periods and coinciding average PDSI (Palmer Drought Severity Index) from an 11-year running average of PDSI reconstructions from local tree-ring chronologies for the central, western and northern Navajo Nation vicinity during the common period 660 AD-1988 AD (NB = Natural Bridges, NAV = Navajo Mountain, TC = Tsegi Canyon, MIP = El Malpais) (Sources: Dean and Robinson, 1978; Grissino-Mayer, 1995)

<table>
<thead>
<tr>
<th>Years of drought (11yr)</th>
<th>NB Ave. PDSI</th>
<th>Years of drought (11yr)</th>
<th>NAV Ave. PDSI</th>
<th>Years of drought (11yr)</th>
<th>TC Ave. PDSI</th>
<th>Years of drought (11yr)</th>
<th>MIP Ave. SAI</th>
</tr>
</thead>
<tbody>
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<td>991-1001</td>
<td>-1.80</td>
<td>1578-1588</td>
<td>-1.35</td>
</tr>
<tr>
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<td>1894-1904</td>
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<td>711-721</td>
<td>-1.79</td>
<td>1579-1589</td>
<td>-1.34</td>
</tr>
<tr>
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<td>-1.18</td>
<td>1663-1673</td>
<td>-1.51</td>
<td>1727-1737</td>
<td>-1.75</td>
<td>1582-1592</td>
<td>-1.34</td>
</tr>
<tr>
<td>703-713</td>
<td>-1.14</td>
<td>1622-1632</td>
<td>-1.48</td>
<td>712-722</td>
<td>-1.71</td>
<td>1574-1584</td>
<td>-1.32</td>
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<tr>
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<td>1292-1302</td>
<td>-1.47</td>
<td>714-724</td>
<td>-1.70</td>
<td>1575-1585</td>
<td>-1.30</td>
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<tr>
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<td>-1.13</td>
<td>1748-1758</td>
<td>-1.46</td>
<td>1273-1283</td>
<td>-1.70</td>
<td>737-747</td>
<td>-1.29</td>
</tr>
<tr>
<td>1146-1156</td>
<td>-1.13</td>
<td>1893-1903</td>
<td>-1.38</td>
<td>716-726</td>
<td>-1.68</td>
<td>1577-1587</td>
<td>-1.28</td>
</tr>
<tr>
<td>1144-1154</td>
<td>-1.05</td>
<td>1666-1676</td>
<td>-1.38</td>
<td>717-727</td>
<td>-1.67</td>
<td>1576-1586</td>
<td>-1.27</td>
</tr>
<tr>
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<td>-1.03</td>
<td>1953-1963</td>
<td>-1.38</td>
<td>1140-1150</td>
<td>-1.64</td>
<td>1581-1591</td>
<td>-1.26</td>
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<tr>
<td>974-984</td>
<td>-1.02</td>
<td>1291-1301</td>
<td>-1.37</td>
<td>704-714</td>
<td>-1.64</td>
<td>1572-1582</td>
<td>-1.22</td>
</tr>
<tr>
<td>1287-1297</td>
<td>-0.99</td>
<td>1892-1902</td>
<td>-1.37</td>
<td>715-725</td>
<td>-1.63</td>
<td>1573-1583</td>
<td>-1.20</td>
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</table>
Table 1.6: The 11 most severe 11-yr drought periods and coinciding average cool-season SAI (Standard Anomaly Index) for the Ni et al. and Salzer and Kipfmueller precipitation reconstructions from an 11-year running average of SAI reconstructions from regional tree-ring chronologies of the Four Corners area (SW Colorado, NW New Mexico, NE Arizona, and SE Utah) during from 660 AD-1988 AD (Sources: Ni et al., 2002, Salzer and Kipfmueller, 2005) Note: The Ni et al., 2002 PDSI reconstructions from NM1 and AZ2 begin at 1000AD rather than prior to 650AD as do the Salzer and Kipfmueller (2005)

<table>
<thead>
<tr>
<th>Years of drought (11yr)</th>
<th>Ni AZ2 Ave. SAI</th>
<th>Years of drought (11yr)</th>
<th>Ni NM1 Ave. SAI</th>
<th>Years of drought (11yr)</th>
<th>Salzer &amp;Kipfmueller SAI of precip.</th>
</tr>
</thead>
<tbody>
<tr>
<td>1662-1672</td>
<td>-1.28</td>
<td>1583-1593</td>
<td>-1.33</td>
<td>1582-1592</td>
<td>-1.15</td>
</tr>
<tr>
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<td>-1.25</td>
<td>1662-1672</td>
<td>-1.24</td>
<td>1583-1593</td>
<td>-1.14</td>
</tr>
<tr>
<td>1728-1738</td>
<td>-1.21</td>
<td>1661-1671</td>
<td>-1.24</td>
<td>1894-1904</td>
<td>-1.09</td>
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<tr>
<td>1583-1593</td>
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<td>1660-1670</td>
<td>-1.21</td>
<td>1580-1590</td>
<td>-1.08</td>
</tr>
<tr>
<td>1663-1673</td>
<td>-1.16</td>
<td>1584-1594</td>
<td>-1.21</td>
<td>1579-1589</td>
<td>-1.06</td>
</tr>
<tr>
<td>1664-1674</td>
<td>-1.14</td>
<td>1582-1592</td>
<td>-1.21</td>
<td>1581-1591</td>
<td>-1.06</td>
</tr>
<tr>
<td>1660-1670</td>
<td>-1.12</td>
<td>1585-1595</td>
<td>-1.20</td>
<td>1578-1588</td>
<td>-1.03</td>
</tr>
<tr>
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<td>1659-1669</td>
<td>-1.11</td>
<td>1575-1585</td>
<td>-1.00</td>
</tr>
<tr>
<td>1727-1737</td>
<td>-1.06</td>
<td>1658-1668</td>
<td>-1.11</td>
<td>1576-1586</td>
<td>-0.99</td>
</tr>
<tr>
<td>1582-1592</td>
<td>-1.05</td>
<td>1773-1783</td>
<td>-1.10</td>
<td>1577-1587</td>
<td>-0.99</td>
</tr>
<tr>
<td>1285-1295</td>
<td>-1.01</td>
<td>1215-1225</td>
<td>-1.10</td>
<td>1893-1903</td>
<td>-0.98</td>
</tr>
</tbody>
</table>

Table 1.7: The 11 most severe 11-yr drought periods and coinciding average PDSI (Palmer Drought Severity Index) from an 11-year running average of PDSI reconstructions from regional tree-ring chronologies of grid points (103, 104, 118, 119) within the Four Corners area (SW Colorado, NW New Mexico, NE Arizona, and SE Utah) during 650 AD-1988 AD (Source: Cook et al., 2004)

<table>
<thead>
<tr>
<th>Years of drought (11yr)</th>
<th>Cook 103 Ave. PDSI</th>
<th>Years of drought (11yr)</th>
<th>Cook 104 Ave. PDSI</th>
<th>Years of drought (11yr)</th>
<th>Cook 118 Ave. PDSI</th>
<th>Years of drought (11yr)</th>
<th>Cook 119 Ave. PDSI</th>
</tr>
</thead>
<tbody>
<tr>
<td>1030-1040</td>
<td>-4.26</td>
<td>735-745</td>
<td>-2.74</td>
<td>1030-1040</td>
<td>-3.16</td>
<td>738-748</td>
<td>-3.31</td>
</tr>
<tr>
<td>1148-1158</td>
<td>-4.15</td>
<td>734-744</td>
<td>-2.59</td>
<td>1146-1156</td>
<td>-3.12</td>
<td>741-751</td>
<td>-3.07</td>
</tr>
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<td>1251-1261</td>
<td>-2.55</td>
<td>735-745</td>
<td>-3.12</td>
<td>735-745</td>
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<td>-3.10</td>
<td>737-747</td>
<td>-3.03</td>
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<td>-3.98</td>
<td>738-748</td>
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<td>948-958</td>
<td>-2.51</td>
<td>734-744</td>
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<td>743-753</td>
<td>-2.53</td>
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</table>
Table 1.8: Relationship between reconstructed water-year streamflow (October-September) at gauged sites on the Upper Colorado River basin during 1525-1999 AD (correlation coefficients and coefficients of variation). (GR-WY = Green River, at Green River, WY; GR-UT = Green River at Green River, UT; CR-Glwd = Colorado River, Glenwood, CO; GU-Crystal = Gunnison River at Crystal, CO; GU-GndJct = Gunnison River at Grand Junction, CO; Dolores = Dolores, CO; CR-Cisco = Colorado River near Cisco, UT; Sjn-Archuleta = San Juan at Archuleta, NM, Sjn-Bluff = San Juan River near Bluff, UT, Lees Ferry = Lee’s Ferry, AZ) (Sources: Woodhouse et al., 2006; and Meko et al., 2007)

<table>
<thead>
<tr>
<th>Correlation coefficients (r)</th>
<th>GR-WY</th>
<th>GR-UT</th>
<th>CR-Glwd</th>
<th>GU-Crystal</th>
<th>GU-Gnd Jct</th>
<th>Dolores</th>
<th>CR-Cisco</th>
<th>Sjn-Archulta</th>
<th>Sjn-Bluff</th>
<th>Lees Ferry</th>
</tr>
</thead>
<tbody>
<tr>
<td>GR-WY</td>
<td>1.00</td>
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<td>0.75</td>
<td>0.79</td>
<td>0.79</td>
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<td>0.80</td>
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<td>0.66</td>
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<td>0.88</td>
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<td>0.88</td>
<td>0.67</td>
<td>0.66</td>
<td>0.66</td>
<td>0.85</td>
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<tr>
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<td>0.89</td>
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<td>0.83</td>
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<td>0.98</td>
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<tr>
<td>Sjn-Bluff</td>
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<td></td>
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<td></td>
<td>0.84</td>
<td></td>
</tr>
<tr>
<td>Lees Ferry</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<td></td>
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</table>

<table>
<thead>
<tr>
<th>Coefficient of variation (r²)</th>
<th>GR-WY</th>
<th>GR-UT</th>
<th>CR-Glwd</th>
<th>GU-Crystal</th>
<th>GU-Gnd Jct</th>
<th>Dolores</th>
<th>CR-Cisco</th>
<th>Sjn-Archulta</th>
<th>Sjn-Bluff</th>
<th>Lees Ferry</th>
</tr>
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Table 1.9: The most severe (approximately) 11-year drought periods and coinciding average streamflow standard anomaly index (SAI) from an 11-year running average of regional streamflow reconstructions from tree-ring chronologies of the Upper Colorado River Basin area from 1530-late 20th century (GR-WY = Green River, at Green River, WY; GR-UT = Green River at Green River, UT; CR-Glwd = Colorado River, Glenwood, CO; GU-Crystal = Gunnison River at Crystal, CO; GU-GndJct = Gunnison River at Grand Junction, CO; Dolores = Dolores, CO; CR-Cisco = Colorado River near Cisco, UT; Sjn-Archuleta = San Juan at Archuleta, NM, Sjn-Bluff = San Juan River near Bluff, UT, Lees Ferry = Lee’s Ferry, AZ) (Sources: Woodhouse et al., 2006; and Meko et al., 2007)

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Table 1.10: The most severe (approximately) 11-year drought periods and coinciding average streamflow standard anomaly index (SAI) from an 11-year running average of regional streamflow reconstructions from tree-ring chronologies of the Upper Colorado River Basin area from 1530-late 20th century (GR-WY = Green River, at Green River, WY; GR-UT = Green River at Green River, UT; CR-Glwd = Colorado River, Glenwood, CO; GU-Crystal = Gunnison River at Crystal, CO; GU-GndJct = Gunnison River at Grand Junction, CO; Dolores = Dolores, CO; CR-Cisco = Colorado River near Cisco, UT; Sjn-Archuleta = San Juan at Archuleta, NM, Sjn-Bluff = San Juan River near Bluff, UT, Lees Ferry = Lee’s Ferry, AZ) (Sources: Woodhouse et al., 2006; and Meko et al., 2007)

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Table 1.12: AZ2 annual and seasonal correlations between observed PDSI (Palmer Drought Severity Index) and modeled PDSI 1895-2006 to evaluate which seasons are best modeled (January-December, Water-year: October-September, December-February, March-May, June-August, September-November) (Sources: Williams et al., 2007; Hoerling and Eischeid, 2007)

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Table 1.13: NM1 annual and seasonal correlations between observed PDSI (Palmer Drought Severity Index) and modeled PDSI 1895-2006 to evaluate which seasons are best modeled (January-December, Water-year: October-September, December-February, March-May, June-August, September-November) (Sources: Williams et al., 2007; Hoerling and Eischeid, 2007)

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**APPENDIX C: Chapter 1 Supplemental Tables**

**Table S.1:** Basic statistics and correlations of mean annual temperature for USHCN sites and PRISM data (average, standard deviation, simple correlation, coefficient of variation) to determine regional homogeneity among regional sites and with PRISM data (Source: Daly et al., 1994; Williams et al., 2007)

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<th>G Canyon</th>
<th>Lees Ferry</th>
<th>Bluff</th>
<th>Blanding</th>
<th>Aztec</th>
<th>Cyn de Chelly</th>
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<td>Aztec</td>
<td>0.93</td>
<td>0.85</td>
<td>0.93</td>
<td>0.85</td>
<td>0.93</td>
<td>0.86</td>
<td>0.82</td>
<td>0.82</td>
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</tr>
<tr>
<td>Cyn de Chelly</td>
<td>0.93</td>
<td>0.85</td>
<td>0.93</td>
<td>0.85</td>
<td>0.93</td>
<td>0.86</td>
<td>0.82</td>
<td>0.82</td>
<td></td>
</tr>
<tr>
<td><strong>Coefficient of variation (r-sq.)</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Holbrook</td>
<td>1.00</td>
<td>0.04</td>
<td>0.01</td>
<td>0.30</td>
<td>0.44</td>
<td>0.03</td>
<td>0.51</td>
<td>0.02</td>
<td>0.06</td>
</tr>
<tr>
<td>Ft. Valley</td>
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<td>0.94</td>
<td>0.88</td>
<td>0.85</td>
<td>0.94</td>
<td>0.93</td>
<td>0.86</td>
<td>0.82</td>
<td>0.38</td>
</tr>
<tr>
<td>Grand Canyon</td>
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<td>0.51</td>
<td>0.37</td>
<td>0.52</td>
<td>0.55</td>
<td>0.30</td>
<td>0.37</td>
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<td>0.45</td>
<td>0.82</td>
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<td>0.23</td>
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<tr>
<td>Blanding</td>
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<td>0.29</td>
<td>0.72</td>
<td>0.23</td>
<td>0.23</td>
<td>0.72</td>
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<td>1.00</td>
<td>1.00</td>
<td>1.00</td>
<td>1.00</td>
<td>1.00</td>
<td>1.00</td>
</tr>
<tr>
<td>Cyn de Chelly</td>
<td>1.00</td>
<td>1.00</td>
<td>1.00</td>
<td>1.00</td>
<td>1.00</td>
<td>1.00</td>
<td>1.00</td>
<td>1.00</td>
<td>0.21</td>
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</table>
Table S.2: Basic statistics and correlations (average, standard deviation, simple correlation, coefficient of variation) between summer (June-August) mean temperature at Chuska/Defiance sites and surrounding series over the 20th century to 2006 (Sources: Daly et al., 1994a (PRISM), NCDC, 1999; Williams et al., 2007 (USHCN); WRCC, 2007)

<table>
<thead>
<tr>
<th></th>
<th>PRISM</th>
<th>WRCC</th>
<th>NCDC (AZ2)</th>
<th>NCDC (NM1)</th>
<th>USHCN (Tobs)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average</td>
<td>18.79</td>
<td>19.69</td>
<td>20.83</td>
<td>20.37</td>
<td>22.33</td>
</tr>
<tr>
<td>SD</td>
<td>0.95</td>
<td>0.80</td>
<td>0.81</td>
<td>0.68</td>
<td>1.14</td>
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<tr>
<td>Correlation coefficients (r)</td>
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<tr>
<td>PRISM</td>
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<td>0.71</td>
<td>0.55</td>
<td>0.68</td>
<td>0.74</td>
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<td>WRCC</td>
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<td>0.61</td>
<td>0.85</td>
<td>0.78</td>
<td></td>
</tr>
<tr>
<td>NCDC (AZ2)</td>
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<td>0.85</td>
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<td></td>
</tr>
<tr>
<td>NCDC (NM1)</td>
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<td></td>
<td>1.00</td>
<td>0.79</td>
<td></td>
</tr>
<tr>
<td>USHCN (Tobs)</td>
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<td></td>
<td></td>
<td>1.00</td>
<td></td>
</tr>
<tr>
<td>Coefficient of variation (r²)</td>
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<td></td>
<td></td>
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<td></td>
</tr>
<tr>
<td>PRISM</td>
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<td>0.50</td>
<td>0.30</td>
<td>0.46</td>
<td>0.54</td>
</tr>
<tr>
<td>WRCC</td>
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<td>0.38</td>
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<td>0.28</td>
<td></td>
</tr>
<tr>
<td>NCDC (AZ2)</td>
<td></td>
<td>1.00</td>
<td>0.72</td>
<td>0.62</td>
<td></td>
</tr>
<tr>
<td>NCDC (NM1)</td>
<td></td>
<td></td>
<td>1.00</td>
<td>0.64</td>
<td></td>
</tr>
<tr>
<td>USHCN (Tobs)</td>
<td></td>
<td></td>
<td></td>
<td>1.00</td>
<td></td>
</tr>
</tbody>
</table>
Table S.3: Dean and Robinson site chronology details: site, parameter reconstructed, length, elevation, location, species used, calibration data, and calibration data elevation (Note: CDC= Canyon de Chelly, CHA= Chuska Valley, HM= Hopi Mesas, PD= Puerco Defiance, PDSI= Palmer Drought Severity Index, Ppt= precipitation, PIED= Pinus edulis, PIPO= Pinus ponderosa, PSME= Psuedosuga Mensiezi; AZ2= Arizona Climate Division 2) (Sources: Dean and Robinson, 1978; NCDC, 1999)

<table>
<thead>
<tr>
<th>Authors</th>
<th>Site Chronology</th>
<th>Reconstructed Variables</th>
<th>Reconstructed Years</th>
<th>Elevation of site chronology (m)</th>
<th>Species Used</th>
<th>Calibration Record</th>
<th>Calibration Record Elevation</th>
</tr>
</thead>
</table>

Table S.4: Correlations between reconstructed PDSI (Source: Dean and Robinson, 1978)

<table>
<thead>
<tr>
<th>Chuska Valley</th>
<th>Chaco Cyn</th>
<th>Hopi Mesas</th>
<th>Puerco/Defiance</th>
<th>Natural Bridges</th>
<th>Navajo Mtn</th>
<th>Tsegi Cyn</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chuska Valley</td>
<td>1</td>
<td>0.72</td>
<td>0.71</td>
<td>0.75</td>
<td>0.68</td>
<td>0.63</td>
</tr>
<tr>
<td>Chaco Cyn</td>
<td>1</td>
<td>0.63</td>
<td>0.75</td>
<td>0.58</td>
<td>0.57</td>
<td>0.61</td>
</tr>
<tr>
<td>Hopi Mesas</td>
<td>1</td>
<td>0.77</td>
<td>0.71</td>
<td>0.69</td>
<td>0.7</td>
<td></td>
</tr>
<tr>
<td>Puerco/Defiance</td>
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<td>0.65</td>
<td>0.61</td>
<td>0.62</td>
<td>0.67</td>
<td></td>
</tr>
<tr>
<td>Natural Bridges</td>
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<td>0.71</td>
<td>0.67</td>
<td>0.66</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>Navajo Mtn</td>
<td>1</td>
<td>0.66</td>
<td>1</td>
<td>1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tsegi Cyn</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>1</td>
</tr>
</tbody>
</table>
**APPENDIX D: Chapter 2 Tables**

**Table 2.0:** Farming and ranching activity change for those farmers and ranchers most recently active the most recent period (1995-2005) in the Chuska area for Tsaile-Wheatfields and Crystal chapters participants

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Tsaile-Wheatfields</td>
<td>6</td>
<td>7</td>
<td>10</td>
<td>9</td>
</tr>
<tr>
<td>Crystal</td>
<td>6</td>
<td>0</td>
<td>5</td>
<td>5</td>
</tr>
</tbody>
</table>

*Note: Table does not include Lukachukai as it only constitutes 3 participants, only one of whom was active in farming during the last 10 years.*

**Table 2.1** Number of farming and ranching water sources for Tsaile-Wheatfields, Crystal and Lukachukai.

<table>
<thead>
<tr>
<th>Chapter</th>
<th>Farming water source</th>
<th>Ranching water source</th>
<th>Interviewees in farming</th>
<th>Interviewees in ranching</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tsaile-Wheatfields</td>
<td>4†</td>
<td>19</td>
<td>6</td>
<td>9</td>
</tr>
<tr>
<td>Crystal</td>
<td>4†</td>
<td>14</td>
<td>0</td>
<td>5</td>
</tr>
<tr>
<td>Lukachukai</td>
<td>2</td>
<td>4</td>
<td>N/A</td>
<td>N/A</td>
</tr>
</tbody>
</table>

† Represents an approximation

*Note: There were very few interviews in Lukachukai and currently only 1/3 Lukachukai participants is still ranching to a degree, so it is omitted (e.g. “N/A”) to prevent misrepresenting the commensurability of chapter data. There were more interviews with Tsaile-Wheatfields than Crystal (10 vs. 7) and the fewest with Lukachukai (3).*
Table 2.2: Most frequently noted changes in local landscape, wildlife, and climate changes among participants in the Chuska/Defiance area

<table>
<thead>
<tr>
<th>#Participants Reporting Change</th>
<th>Change</th>
<th>Reasons Offered</th>
<th>Impact Mentioned</th>
<th>Location</th>
<th>Timing</th>
</tr>
</thead>
<tbody>
<tr>
<td>17</td>
<td>Less rain</td>
<td></td>
<td>Increased erosion from less grass, damaged roads</td>
<td></td>
<td></td>
</tr>
<tr>
<td>15</td>
<td>More wildlife</td>
<td>Less forage at higher elevations</td>
<td>Less forage for livestock</td>
<td>Lower elevations</td>
<td>Varies</td>
</tr>
<tr>
<td>14</td>
<td>Less vegetation</td>
<td>Drought, increased competition, less management, sawmill closure</td>
<td>Lost livestock, more dead wood, more erosion</td>
<td></td>
<td></td>
</tr>
<tr>
<td>14</td>
<td>Harder rain</td>
<td></td>
<td>Increased erosion, less grass, damaged roads</td>
<td></td>
<td>Last ~12 yrs</td>
</tr>
<tr>
<td>13</td>
<td>Dying trees, especially pinyon</td>
<td></td>
<td>More dead wood, more erosion</td>
<td>Lower elevations</td>
<td>2-5 yrs ago</td>
</tr>
<tr>
<td>12</td>
<td>Less snow</td>
<td></td>
<td></td>
<td>8 yrs ago and gradually over a generational timescale</td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>Warmer</td>
<td></td>
<td></td>
<td>Past 3 years (since 2003) or gradually over generational timescale</td>
<td></td>
</tr>
</tbody>
</table>
Table 2.3: Communication media that participants use to obtain climate and weather information.

<table>
<thead>
<tr>
<th>Weather information medium</th>
<th># Participants who use medium</th>
</tr>
</thead>
<tbody>
<tr>
<td>Radio</td>
<td>16</td>
</tr>
<tr>
<td>Television</td>
<td>10</td>
</tr>
<tr>
<td>Word of mouth</td>
<td>7</td>
</tr>
<tr>
<td>Newspaper</td>
<td>4</td>
</tr>
<tr>
<td>Observation</td>
<td>4</td>
</tr>
<tr>
<td>County fliers</td>
<td>2</td>
</tr>
<tr>
<td>Internet</td>
<td>2</td>
</tr>
<tr>
<td>Ranching magazine</td>
<td>1</td>
</tr>
</tbody>
</table>
APPENDIX E: Chapter 3 Figures

**Figure 3.1:** Annual mean temperature trend in the Chuska Mountains area (~2200 m elevation) 1895-2006 (Source: Daly et al., 1994)

**Figure 3.2:** Seasonal T increase 1895-2007 (~2200 m) (Source: Daly et al., 1994)
Figure 3.3: Annual mean temperature rise in the Chuska Mountains area 1895-2006, with successively higher means since 1980 (Source: Daly et al., 1994a (PRISM))

Figure 3.4: Snow water equivalent (SWE) decline since 1985 from five aggregated high elevation (>2440m) sites in the Chuska Mountain snow course and two aggregated lower elevation sites (<2440m) (Source: NNWMB provisional data, unpublished) (Note: same as figure 1.17)
Figure 3.5: Relationship between high elevation SWE values and November-March maximum temperature (Source: Daly et al., 1994a (PRISM); NNWMB provisional data, unpublished) (Note: same as figure 1.19)
Figure 3.6: Relationship between low elevation SWE values and November-March maximum temperature (Source: Daly et al., 1994a (PRISM); NNWMB provisional data, unpublished) (Note: same as figure 1.21)

Figure 3.7: Total annual late summer (July-September) precipitation 1895-2006, 5-yr running average, series length mean (1895-2006), and mean of most recent period (1991-2006) (Source: Daly et al., 1994a) (Note: same as figure 1.24)
Figure 3.8: The fraction of July precipitation contributing to late summer (July-September) precipitation 1895-2006, 5-yr running average of July fraction, mean of July/JAS fraction 1895-2006, and when participants began to identify change (black triangles) (Source: Daly et al., 1994a) (Note: same as figure 1.25)
APPENDIX F: Interview Protocol

Interview Protocol for Vulnerability and Traditional Knowledge Research

Participants: Farmers and Ranchers

Locations: Navajo Nation residents who reside in and/or participate in activities in the Chuska Mountain region

Number: Approximately five participants from each two activities per study area (Chapter); three Chapters total over the course of the study

Contributes to studies focused on: assessing the vulnerability of rural livelihood operations to climate variability and change; also contributes to studies focused on the intersection of traditional knowledge and western science in and climate variability and change studies

Selection process: Interviews may have been (a) self-identified through attendance at Chapter meetings attended by project researcher or (b) recommended by Chapter officials, other knowledgeable Chapter members or (c) recommended by knowledgeable Navajo Nation agency employees or university extension affiliates

Section 1: General Background

The first set of questions is about your family’s background in this area and about your activities and experience in this area.

Code #:
Date of interview:
Month/Year of birth:

Do you always speak Navajo?

What language do you prefer to speak in this interview, English or Navajo?

1. How long have you lived in this area, and your family before you?

2. How long have you been involved in farming and/or ranching activities?
   a. (optional) How much have you been involved in the last 10 years?

3. What type of livestock do you raise/crops do you plant?

4. Do you farm/ranch as your
• main source of income
• side source of income/ additional income/ part-time income
• just for your own household (subsistence)?

**Section 2: Responses to Impacts/Changes**
These questions will help me understand the resources you depend on to farm and/or ranch and if they have changed over time.

5. Did your parents and/or grandparents farm/ranch?
   a. Do you farm/ranch the same area as your parents and/or grandparents?  
      Why/Why not?
   b. Do you farm/ranch the same plants/raise the same livestock they did?  
      Why/Why not?

6. Has the amount of time (you/your parents/grandparents’ generation) spend (spent) on any farming or ranching activities changed?
   a. How?
   b. When did this change occur?

7. (Optional if not answered earlier) Have you ever suffered major crop/livestock losses? Please describe.

8. For your farming/ranching, what is your water source?
   If you have been farming/ranching on the same area:
      a. Is the amount of water consistently dependable?
      b. Is the quality consistently dependable?

   If you have moved to a different farming/ranching area:
      c. Did you change where you farm/ranch because of water or plant availability?

9. Has there ever been a time when there was no water available for your crops/livestock?
   a. When?
   b. How long did it last?
   c. What did you do?

10. If engaged in ranching activities:
    a. When do (did) you (your parents/grandparents’ generation) usually sell your (their) livestock?
    b. Have there ever been any changes in the timing when you (they) sell your (their) livestock?

11. If engaged in farming: [quality and quantity]
a. What changes have you (your parents/grandparents’ generation) noticed in amount and quality of crops you (they) produce per growing season?

**Section 3: TEK**
This section will help me understand how the landscape may have changed over time from your observations.

12. Have there been any noticeable changes in trends here over the years in:
   a. plant and general forest health
      i) When?
      ii) During parents/grandparents’ generation?
   b. animal health (domestic and wildlife)
      i) When?
      ii) During parents/grandparents’ generation?
   c. temperature (how hot, warm or cold it has been)?
      i) When?
      ii) During parents/grandparents’ generation?
   d. how wet or dry it has been?
      i) When?
      ii) During parents/grandparents’ generation?
   e. the type of rain (male/female)?
      i) When?
      ii) During parents/grandparents’ generation?
   f. the amount of rain compared to snow?
      i) When?
      ii) During parents/grandparents’ generation?
   g. the length of time between when the snow melts and when the summer rain arrives?
      i) When?
      ii) During parents/grandparents’ generation?
   h. the temperature in the winter
      i) When?
      ii) During parents/grandparents’ generation?
   i. flooding?
      i) When?
      ii) During parents/grandparents’ generation?
   j. dust storms?
      i) When?
      ii) During parents/grandparents’ generation?

**Section 4: Climate Information**
These questions are designed to assess your use and access to weather information.
13. Was (long and short-term) weather information important to your parents/grandparents?
   a. What did they use for predicting future conditions for farming/ranching?

14. Is (long and short-term) weather information important to your farming/ranching activities?

15. What type of (long and short-term) weather information is most important to you as a farmer/rancher?

16. Where do you get information on (long and short-term) weather?

17. How often do you get this information? [daily, 1/week, 1/month, 1/season, 1/year, only in times of severe events]

18. Is the (long and short-term) weather information you are getting meeting your needs?
   a. If not, how could it be improved?

19. Is there information on weather conditions and forecasts you would like to get?

20. Do you keep any type of records of how the weather is here (temperature or precipitation)?
   a. May I have access to that information?
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