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Navajo Nation, USA, Precipitation Variability from 2002 to 2015

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Abstract: Due to its semi-arid climate, the Navajo Nation, situated in the southwestern United States, is sensitive to small changes in precipitation. However, little information on patterns and causes of rainfall variation is available for this sparsely populated region. In order to study stability and variability over time, this study characterized hydroclimatic changes for the Navajo Nation over timescales of months to years based on data from 90 sites from 2002 to 2015. This research will help local water managers identify related precipitation areas within the region, compare Navajo Nation precipitation with climate indices to ascertain larger-scale atmospheric contributors to precipitation in the Four Corners region, and support future water planning in this understudied region. A vector quantization method, called *k*-means clustering, identified five sub-regions of contrasting precipitation climatology. The regions differed in the timing, magnitude, and relative importance of the winter and summer peaks comprising the bimodal precipitation regime of the area. Correlation examination of spatial and temporal trends of precipitation variability with three climate indices revealed strong winter precipitation relationships to the Pacific North American teleconnection pattern for all regions; summer precipitation teleconnections were weaker and more variable; however, modest correlations with Pacific Decadal Oscillation were observed. Climate field analysis indicates that cold-season precipitation is enhanced by intensification of the Aleutian Low with a storm trajectory into the southwest United States; warm season precipitation is enhanced by poleward shift of the North American monsoon ridge.

Keywords: *Four Corners region, southwestern U.S., climate, hydrometeorological network*

Future climate change is expected to exacerbate variability in precipitation and water resources in many parts of the world. These changes are likely to affect the amount, timing, and intensity of precipitation, possibly increasing the incidence of extreme flooding and drought events (CCSP 2008; Dominguez et al. 2010; Trenberth 2011; Nania et al. 2014). The particular region of our study lies within several recognized Native American reservations. Marginalized populations, including Indigenous peoples, are particularly vulnerable to climate change impacts due to the location of their homelands and ways of life (Redsteer et al. 2013; Wildcat 2013; Bennett et al. 2014; Nania et al. 2014).

The Navajo Nation is a federally recognized tribe whose political boundaries lie within Arizona, New Mexico, and Utah, and the characteristics of the lands they inhabit as well as their resource-based livelihoods cause them to be particularly vulnerable to climate change impacts (Cozzetto et al. 2013). The Navajo Nation has a land base of over 70,000 square kilometers (Navajo Nation Department of Water Resources 2003; Garfin et al. 2007). Nania et al. (2014) suggest the most important resource on the Navajo Nation is water. Navajo Nation residents, wildlife, livestock, and vegetation are highly dependent on water resources including precipitation, surface, ground, and spring waters for vitality (Navajo Nation Department of Water Resources 2003; Novak 2007; Redsteer et al. 2010; Navajo Nation Department of Water

Resources 2011). Navajo livelihoods dependent on water resources include irrigation farming, dry land farming, and ranching (Navajo Nation Department of Water Resources 2003; Navajo Nation Department of Water Resources 2011). Water dependent environmental components significant to Navajo culture are wildlife and plants used for traditional practices. Energy industries, including coal mining and thermoelectric power generation stations, remove water from surface and ground waters for their processes; these industries provide the Navajo Nation with economic revenue (Nania et al. 2014). Monthly, seasonal, and interannual changes in precipitation directly impact ecosystems of the Navajo Nation through a variety of interconnected effects such as groundwater recharge, frequency of dust migration, strength of winds, flow in ephemeral and perennial streams, plant and animal populations, wildfires, change in vegetative cover, and possible alterations in species composition (Hereford et al. 2002; Redsteer 2011).

The climate for the Four Corners region consists of a bimodal summer and winter precipitation distribution, separated by dry spring and fall seasons (Crimmins et al. 2013). Winter season precipitation is derived primarily from synoptic frontal systems originating from the Pacific Ocean, whereas summer moisture arises from localized convection associated with the southwestern summer monsoon. According to the Navajo Nation Water Management Branch's Water Monitoring and Inventory (WMBWMI) Section data, average annual precipitation in the region ranges from approximately 15 centimeters in lower elevation areas to over 40 centimeters in higher elevation areas. Major topographic features, including Navajo, Lukachukai, and Chuska Mountains, are responsible for orographic precipitation (Navajo Nation Department of Water Resources 2003), and combined with summer and winter circulation patterns across the area, are factors that contribute to the spatial and temporal distribution of rainfall throughout the Navajo Nation (Mathien 1985). The Navajo Nation's average annual temperatures vary between 4.4° Celsius in higher elevations to 10° Celsius in valleys and lowlands (Garfin et al. 2007). Given the large size and climatic diversity of the area, there is great potential for climate and environmental change to affect future sustainability for members of the largest land-based tribe, the Navajo.

Various groups have attempted to examine the Navajo Nation's precipitation patterns and changes; however, these studies (Navajo Nation Department of Water Resources 2003; Garfin et al. 2007; Crimmins et al. 2013) have not analyzed data with a level of spatial and temporal resolution necessary to assess variation in precipitation patterns across the area and potential climatic controls on this variation. The Technical Review of the Navajo Nation Drought Contingency Plan – Drought Monitoring, for example, estimated the Standard Precipitation Index for the Navajo Nation using monthly precipitation data from Parameter-Elevation Regressions on Independent Slopes Model (PRISM) gridded climate data to estimate wetness and dryness (Crimmins et al. 2013; PRISM Climate Group 2013). Crimmins et al. (2013) acknowledged that their study provided climate division values useful for drought monitoring at a large-scale spatial resolution but not at the Chapter and Agency levels (corresponding to rural communities and regional areas, respectively), where allocation of resources for water management and water-related environmental impacts occur. Characterization of precipitation at a finer spatial scale is important to Navajo water managers to make decisions in allocating funds to prepare for drought and flood events. Spatial and temporal examination of historical precipitation variability and trends across the Four Corners region is also crucial to characterizing patterns of potential recharge to groundwater, a source the Navajo Nation relies upon (over 90%) for its residents, businesses, and animals (Crimmins et al. 2013).

The Navajo Nation WMBWMI Section, acknowledging the continual need to examine its water resources, has monitored and recorded hydrological and meteorological data across the Navajo Nation for decades (Navajo Nation Department of Water Resources 2003; Aggett et al. 2011; Navajo Nation Department of Water Resources 2011). The first gauges in the hydrometeorological network were precipitation gauges at Marsh Pass, Klagetoh, and Little White Cone installed from 1952 to 1962 (Garfin et al. 2007). There was no installation of new precipitation gauges from 1962 to 1983. From 1983 to 2000, the network expanded with new precipitation gauges installed each year (Figure 1). In total, the WMBWMI has managed over 190 precipitation gauges since 1952 (Garfin et al. 2007; Aggett et al. 2011). The WMBWMI has also conducted snow surveys and stream gauging since the 1980s (Tsinnajinnie 2011; Hart and Fisk 2014).

The WMBWMI monitoring network consists of 90 rain gauges, 12 tipping buckets, 8 snow courses, and 8 stream gauges (Figure 2; 2015 water year). Though the network is spatially and temporally extensive, no comprehensive scientific analyses and interpretation of the data has been conducted. Examination of water years 2002 to 2015 was chosen because it was a time period when a relatively extensive and stable network of sites was monitored. Here, we analyze these data to identify regional patterns of precipitation variability using quantitative cluster analysis of monthly, seasonal, and annual precipitation amounts. We then correlate patterns of seasonal precipitation variation for the cluster groups with climatic modes and variables to identify how precipitation in the Four Corners region of the southwestern United States is related to larger climatic patterns. The results of this work demonstrate potential patterns of future precipitation variability in this dynamic and water-scarce region and may serve as a resource for Navajo Nation managers to use for sustainable planning for their water future.

Methods

Precipitation Monitoring

Due to the large size, relatively low population density, and limited electrical and cellular infrastructure of the Four Corners region, the Navajo Nation precipitation network is not automated. Measurements of precipitation are made manually using a U.S. Weather Bureau Type Rain and Snow Gauge 60.96 cm measuring dipstick to determine the volume of water stored in a 20.32 cm diameter rain can; the precipitation amount is calculated using the month-to-month volume difference (Aggett et al. 2011). Mineral oil is used year round to prevent evaporation; during the winter months, a mix of mineral oil

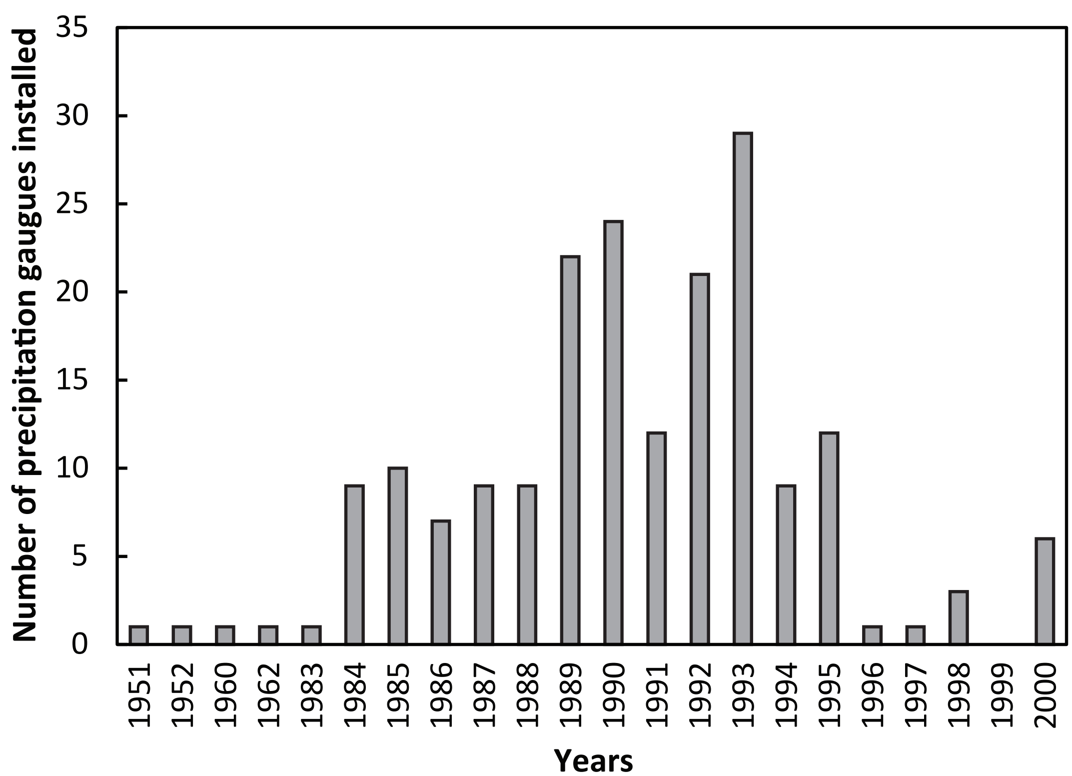


Figure 1. Number of precipitation gauges installed each year from 1951 to 2000.

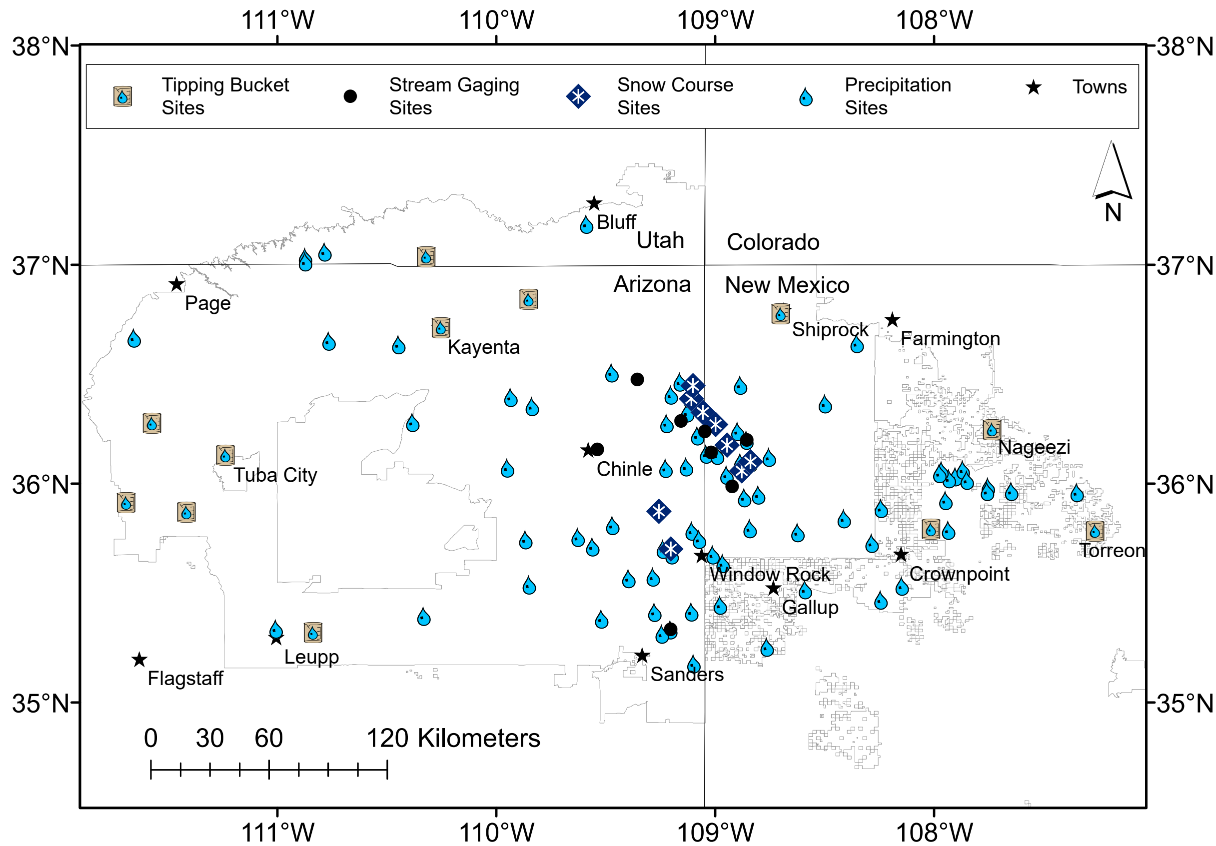


Figure 2. Navajo Nation Water Management Branch's Water Monitoring and Inventory Section hydrometeorological sites in Water Year 2015 included 90 rain gauges, 12 tipping buckets, 8 snow courses, and 8 stream gauges.

and biodegradable antifreeze is used to prevent freezing (Aggett et al. 2011). WMBWMI personnel record the date, time, air temperature, wind speed, and precipitation amount during each monthly site visit (Garfin et al. 2007; Aggett et al. 2011). Data are recorded into the Navajo Nation Precipitation Database managed by the WMBWMI.

Spatiotemporal Analysis

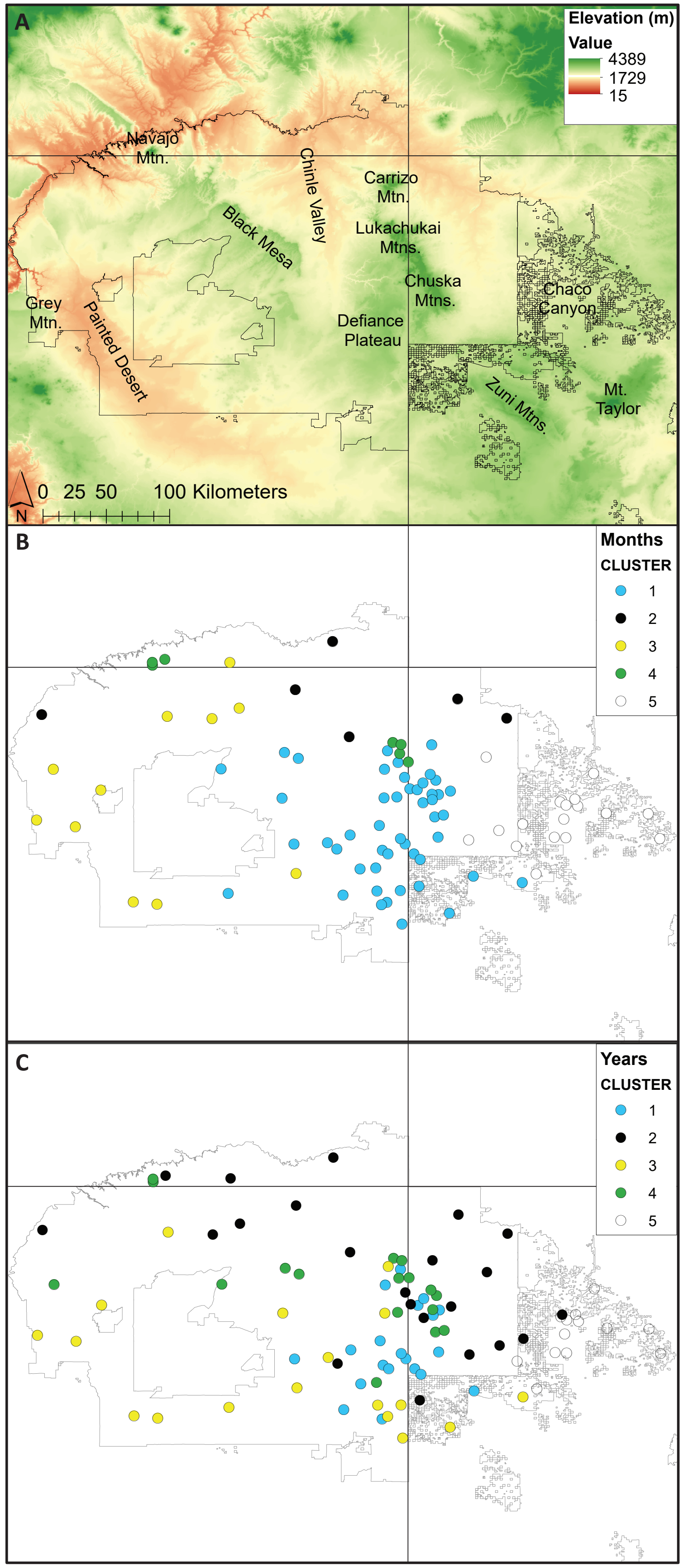
We used Hartigan-Wong's *k*-means clustering algorithm (Hartigan and Wong 1979; R Core Team 2013) to identify common patterns of variation in the multi-site precipitation dataset and group these sites into geographic clusters with common precipitation patterns. *K*-means clustering is a method of vector quantization that creates *k* clusters by maximizing between-group dissimilarity relative to within-group dissimilarity (Hartigan and Wong 1979). Clustering was conducted using both climatic (precipitation) and geographic (latitude, longitude, elevation) variables in order to identify spatially coherent clusters with common precipitation patterns. Data were standardized to dimensionless *z*-scores using

$$z = \frac{x - \overline{x}}{\sigma} \qquad \text{Equation 1}$$

where x is the station value and $\overline{x}$ and σ are the mean and standard deviation across the dataset, respectively.

We performed two versions of the clustering. The first used monthly averaged precipitation data across the study period (Figure 3B) to identify clusters that exhibited common patterns of intra-annual variation; the second used precipitation data summed to obtain an annual total for each year (Figure 3C) in order to identify groups with similar interannual variation. Both versions of the clustering produced similar results, and subsequent analyses used cluster groupings based on monthly

Figure 3. (A) Map of Navajo Nation geographical features; (B) cluster group assignments for precipitation sites based on latitude, longitude, elevation, and climatological average monthly precipitation amount; and (C) cluster group assignments for precipitation sites based on latitude, longitude, elevation, and total water year precipitation amount time series.



analysis grouping (Figure 3B). The number of sites in each cluster is not equally distributed, rather, they are grouped in a cluster where their individual characteristics are similar to other sites. The asymmetrical distribution of the number of sites in each group may show more precipitation variability in a smaller group than a group with more sites. We elected to use five clusters based on the sum of squares (SS) method (Hartigan and Wong 1979); the internal cohesion and external separation ratio (between SS/total SS) decreased rapidly below five clusters and slowly above five clusters. To validate the robustness of the *k*-means clustering, Principal Components Analysis (PCA) was also conducted; results from PCA exhibited similar grouping and boundaries.

Correlation Analyses

To further examine the climatology of the Navajo Nation and associations between cluster groups, we developed correlation matrices using group-average monthly precipitation values. Correlation matrices were produced for annual, winter, and summer seasons, where the seasonal analyses used the sum of precipitation amounts from November to May and June to October for each water year, respectively. The months for each season were chosen to include the beginning and end of each seasonal precipitation cycle for all the groups.

We evaluated extra-regional climate system controls on the patterns of interannual precipitation variability observed during the dominant summer and winter precipitation seasons and across the different cluster groups by creating correlation matrices. Correlation matrices were calculated between precipitation and the Pacific North American index (PNA; Leathers et al. 1991), Pacific Decadal Oscillation index (PDO; Mantua and Hare 2002), and East Central Tropical Pacific SST (Niño 3.4; Rayner et al. 2003). Correlation matrices were calculated for winter and summer separately. Climate indices data were retrieved from the National Oceanic Atmospheric and Administration Climate Prediction Center. We further investigated the dynamical associations of observed Navajo Nation precipitation patterns by mapping anomalies of 500-hPa geopotential height associated with especially wet or dry periods during the winter and summer. Geopotential height data were obtained at monthly resolution on 2.5º grids from the NCEP-DOE AMIP-II Reanalysis (R-2) (Kanamitsu et al. 2002), provided by NOAA/OAR/ESRL PSD at http://www.esrl.noaa.gov/psd. To illustrate winter patterns, the four driest and four wettest January-February periods were identified based on precipitation averaged across the five cluster groups; likewise, summer patterns were analyzed using July-August precipitation data.

Results

Navajo Nation Cluster Groups

K-means clustering using monthly precipitation data divided the dataset into five groups containing 48, 6, 11, 7, and 18 sites, respectively (Figure 3B). Group 1 included sites across the southern area of the Navajo Nation, going as far north as the Chuska Mountains and Defiance Plateau; Group 2 covered the northern part of the Navajo Nation and part of the Chinle Valley; Group 3 consisted of the Painted Desert and Grey Mountain areas in the western Navajo Nation; Group 4 primarily comprised sites in the high elevation areas of the Chuska and Lukachukai Mountains and Navajo Mountain; and Group 5 contained sites within the eastern portion of the Navajo Nation, east of the Chuska Mountains and including Chaco Canyon (Figure 3A). The areas covered by the regional groups vary in topography, land-surface characteristics, and vegetative cover, with noticeable variations in amounts for monthly, seasonal, and interannual precipitation. Clustering using annual precipitation time series yielded a similar overall pattern, with a slight expansion of the northern and western groups (2 and 3) at the expense of the southern and eastern groups (1 and 5) (Figure 3C).

Precipitation Climatology of the Four Corners Region

Precipitation totals varied substantially between years and among the cluster groups, with group-average individual month totals ranging from 0.56 cm to 6.15 cm ($\bar{x}$ = 2.31 cm, σ = 1.43 cm) (Figure 4; Table 1). The highest water year total precipitation amounts were observed for the high-mountain cluster group (Group 4; $\bar{x}$ = 42.39 cm), whereas the lowest totals occurred in the northern (Group 2)

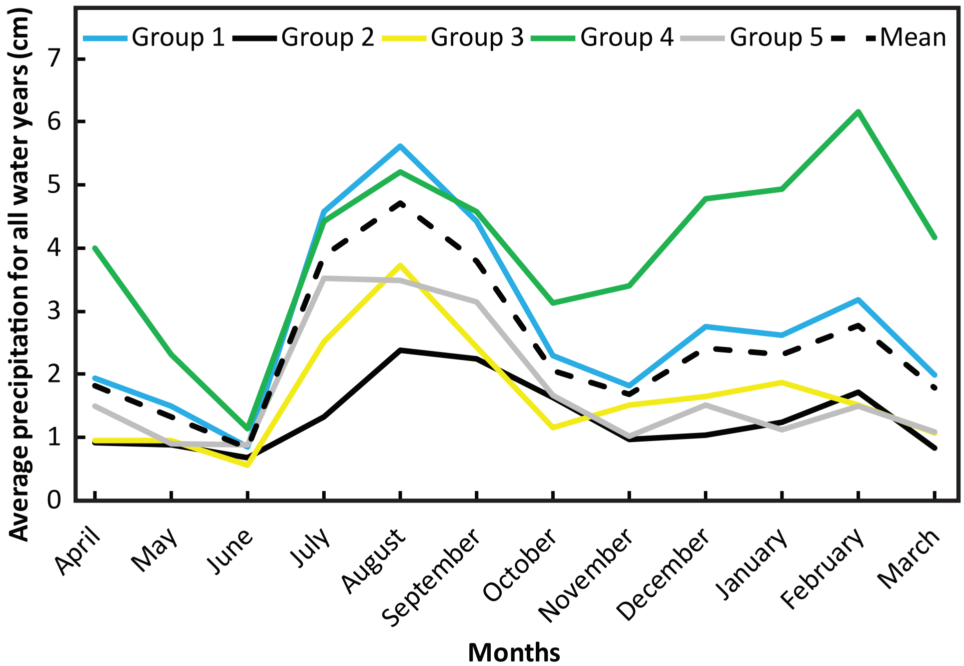


Figure 4. Annual cycle of Navajo Nation precipitation for objectively determined clusters.

Table 1. Mean and [standard deviation] of Navajo Nation precipitation for objectively determined clusters (Groups 1-5).

Months	Group 1 (south)	Group 2 (north)	Group 3 (west)	Group 4 (mountains)	Group 5 (east)
April	1.95 [0.25]	0.91 [0.11]	0.95 [0.18]	3.99 [0.49]	1.50 [0.17]
May	1.49 [0.18]	0.88 [0.09]	0.96 [0.16]	2.31 [0.26]	0.91 [0.07]
June	0.84 [0.10]	0.67 [0.05]	0.56 [0.07]	1.14 [0.13]	0.89 [0.11]
July	4.58 [0.41]	1.33 [0.09]	2.51 [0.32]	4.42 [0.55]	3.52 [0.32]
August	5.61 [0.50]	2.38 [0.07]	3.73 [0.47]	5.21 [0.71]	3.49 [0.37]
September	4.43 [0.31]	2.25 [0.10]	2.43 [0.24]	4.58 [0.54]	3.15 [0.21]
October	2.30 [0.23]	1.63 [0.10]	1.16 [0.11]	3.12 [0.32]	1.66 [0.14]
November	1.81 [0.19]	0.96 [0.08]	1.51 [0.19]	3.40 [0.32]	1.02 [0.07]
December	2.75 [0.31]	1.04 [0.05]	1.66 [0.23]	4.78 [0.52]	1.52 [0.09]
January	2.63 [0.28]	1.25 [0.05]	1.88 [0.23]	4.93 [0.40]	1.11 [0.10]
February	3.19 [0.44]	1.71 [0.09]	1.51 [0.23]	6.15 [0.53]	1.49 [0.12]
March	1.98 [0.29]	0.84 [0.05]	1.07 [0.20]	4.17 [0.53]	1.09 [0.10]

region ($\bar{x}$ = 16.87 cm). In the northern (Group 2), southern (Group 1), and western (Group 3) parts of the Navajo Nation, peak precipitation occurred in August, with amounts ranging from 2.38 cm to 5.61 cm ($\bar{x}$ = 3.91 cm, σ = 1.32 cm). For the eastern region (Group 5), summer precipitation was again dominant, but the summer peak (3.52 cm) occurred one month earlier, in July. Eastern, southern, and high-elevation groups showed a similar, abrupt onset of summer precipitation in July, with the northern and western areas showing a more gradual transition, and July precipitation totals similar to or less than 50% of the August summer maximum (Figure 4). In the western and high elevation areas the summer monsoon season ends abruptly, with a pronounced precipitation minimum in October. In contrast, the monsoon withdrawal is more gradual in the northern, southern, and eastern regions, where the fall precipitation minimum occurs in November. June is the driest month in the Navajo Nation, with rainfall ranging from 0.56 cm to 1.14 cm ($\bar{x}$ = 0.82 cm, σ = 0.20) across all groups. The high elevation mountain cluster group was the only group dominated by winter precipitation, with a peak value of 6.15 cm in February.

Temporal Precipitation Patterns

Although total annual precipitation amounts and seasonal patterns varied widely among regions, temporal trends across years were similar for all regions (Figure 5A). High annual precipitation totals were observed across most or all subregions in 2005, 2007, 2010, and 2015, with relatively low totals occurring during water years 2002, 2006, and 2008-2009. Group 2 showed the strongest interannual variability (relative σ = 0.28 cm). The least variable interannual water year precipitation totals in the Navajo Nation were found in the eastern region (relative σ = 0.20 cm).

Summer (June - October) precipitation across the Navajo Nation ranged from 3.12 cm to 26.59 cm ($\bar{x}$ = 13.53 cm, σ = 5.19 cm) (Figure 5C), and showed lower interannual variation, with relative values between 0.19 and 0.32, than winter (November - May; relative σ = 0.29 to 0.40 cm; Figure 5B). Year to year patterns of variation in summer and winter season precipitation were weakly correlated (Figures 5B and C). Both seasons contribute to the variability in annual totals (Figure 5D), with some anomalously wet years reflecting higher-than average winter precipitation (e.g., 2005) and some high summer precipitation (e.g., 2007). Similarly, dry years could be attributed to both low winter (e.g., 2006) and summer (e.g., 2008-2009) totals.

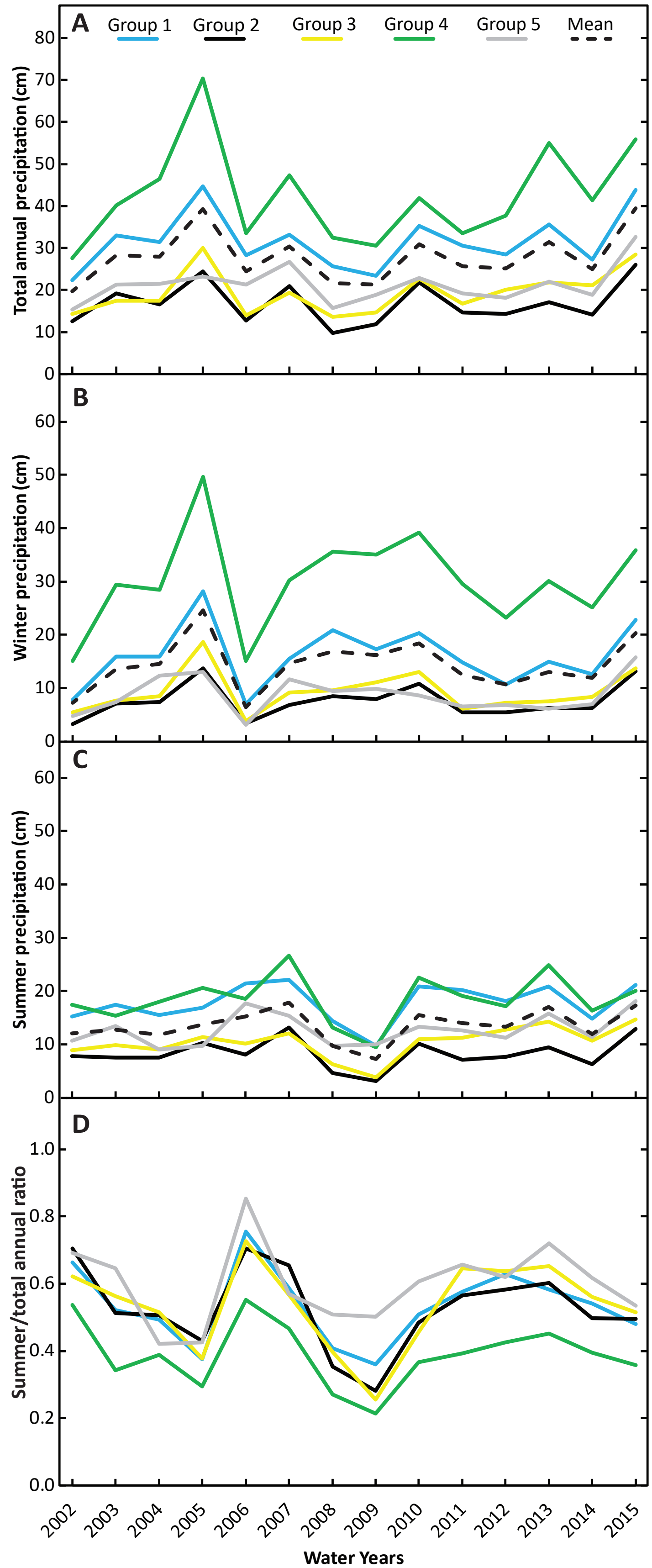
Correlation analysis reinforced the observed similarity of interannual variation among cluster groups (Figure 6). Correlations for winter season precipitation were highest, with correlation coefficients exceeding 0.9 for all comparisons except those involving group 5 (eastern region). Summer season correlations among groups were somewhat weaker, with the eastern region again exhibiting the lowest coefficients. Analysis of annual data showed strong correlations between the three groups covering the southern part of the Navajo Nation, but relatively weak correlation between the high elevation group and other regions; the high elevation group correlations were weaker for the annual average comparisons than for either of the individual seasons.

Teleconnections

Correlation results suggested much stronger teleconnections for Navajo Nation winter precipitation than for summer; teleconnections describe the persistent and recurring large-scale patterns of climate anomalies (Figure 7). Winter precipitation totals were moderately well correlated with all climate indices, but the strongest correlations (0.46 to 0.63) were observed relative to the PNA index (Figure 7A). Among the cluster groups, the PNA was most strongly correlated with winter precipitation totals for the northern and western regions (Groups 2 and 3; r = 0.63 and 0.59, respectively). Moderately strong correlations were observed between summer precipitation and PDO (positive correlation) for the northern and PNA for the western (negative correlation) regions (Figure 7B).

Analysis of geopotential heights showed that high-precipitation winters are associated with enhanced troughing over the North Pacific (Figure 8A), indicating a deepened Aleutian Low with negative Z_{500} anomalies extending into the southwestern United States (Figure 8B). Low-precipitation winters are, by contrast, associated with weakening of the trough over the North

Figure 5. Precipitation time series showing cluster group averages for (A) water year, (B) winter, (C) summer, and (D) precipitation totals and the summer contribution to total water year precipitation.



Pacific (Figure 8A) and positive Z_{500} anomalies extending into the study region (Figure 8C). The finding that Four Corners winter precipitation is positively correlated with the strength of the Aleutian Low is consistent with the positive climate index correlations in Figure 7A because these indices, in their positive polarity, feature a strengthened Aleutian Low, meaning negative Z_{500} anomalies (e.g., Nigam 2003).

High-precipitation summer months are associated with poleward displacement of the mid-tropospheric subtropical ridge (STR; e.g., Carleton et al. 1990) over the southwestern United States, as illustrated by the 5900 isopleth of Z_{500} in Figure 8D. With corresponding Z_{500} anomalies being positive to the east and negative to the west (Figure 8E), poleward displacement of the STR exposes the study region to southerly geostrophic wind anomalies conducive to delivery of warm, moist air and hence convective storminess. Low-precipitation summer months are, by contrast, associated with equatorward displacement of the

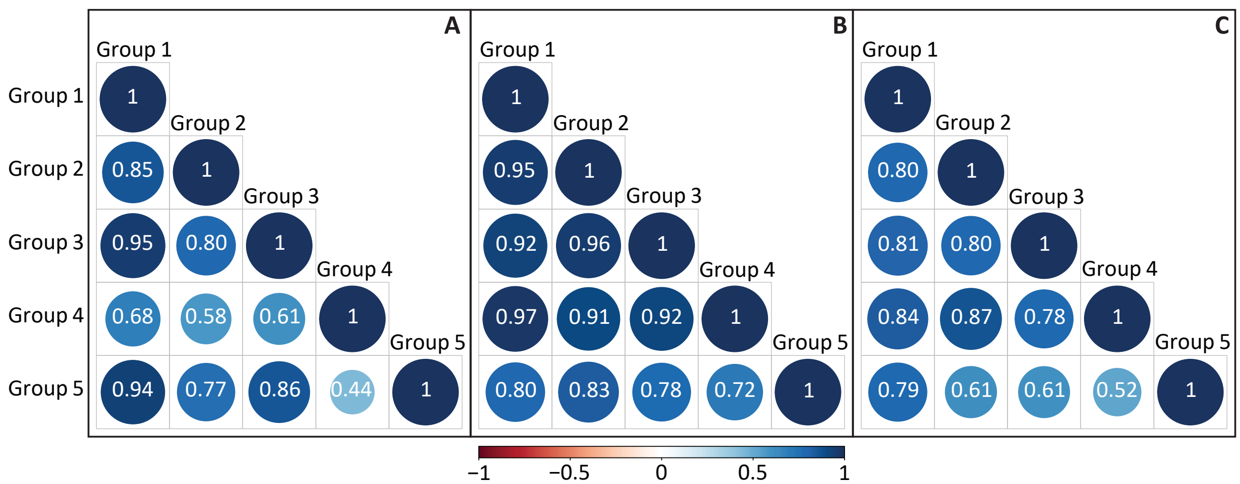


Figure 6. Correlation matrix for interannual timeseries using (A) annual; (B) winter; and (C) summer cluster group average values.

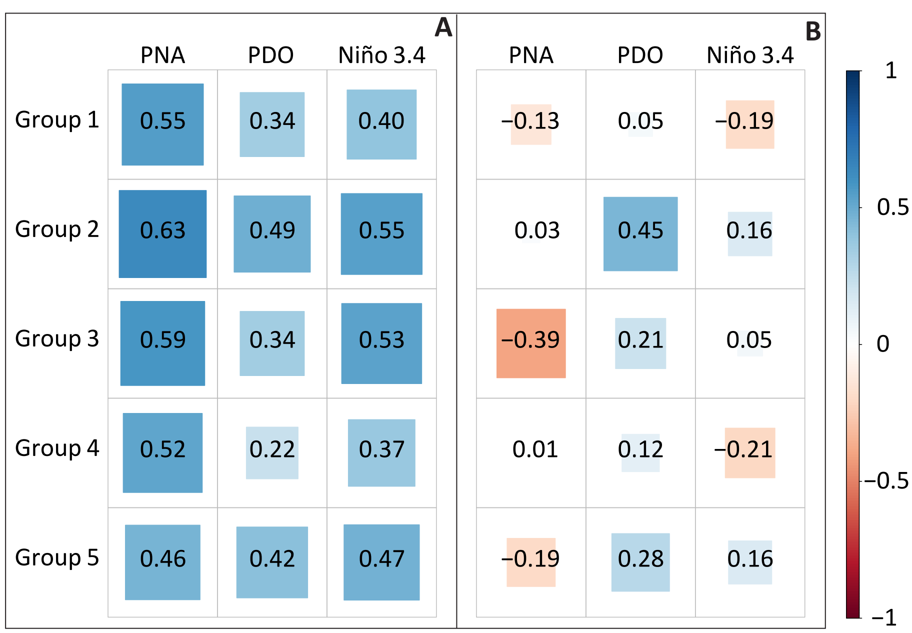


Figure 7. Interannual correlation of precipitation with climate indices for (A) winter months and (B) summer months.

STR (Figure 8E) and westerly geostrophic wind anomalies conducive to delivery of drier air. The STR is sometimes referred to as the monsoon ridge (e.g., Lahmers et al. 2016), and the anomaly patterns in Figure 8 are noted to closely resemble corresponding analysis in the review by Adams and Comrie (1997; Figure 8).

Discussion

Our cluster analysis shows several distinct and spatially-clustered modes of precipitation amount variability across the Navajo Nation, and suggests that the spatial distribution of these modes is similar for intra- and interannual precipitation variability. Differences in the seasonal precipitation cycle relate to comparing the importance of winter vs. summer precipitation in different parts of the study area, and show that although both wet seasons contribute significantly to the total precipitation received, the importance of each season varies substantially between high- and low-elevation and northern and southern sites (Figures 3 and 4). For example, high-elevation mountain areas receive peak precipitation from the winter season and low-elevation areas are dependent on summer precipitation contributions. The similarity in group membership for the cluster analyses using climatological monthly and annual average time series data (Figure 3B and C and Figure 6) suggests that the same climate system factors that control seasonal patterns of precipitation also structure variation in interannual precipitation amounts across the region.

Despite precipitation variability across the region, correlation analysis suggests that coherent patterns of interannual precipitation variability are expressed across the entire study area, particularly in the winter season. Winter precipitation is derived dominantly from cold-season synoptic-scale frontal systems arriving from the North Pacific (Cayan et al. 1998; Schwinning et al. 2008). The observed similarity in interannual variation of winter precipitation across the region, together with the strong correlations with the PNA index and PNA-like pressure patterns, is consistent in

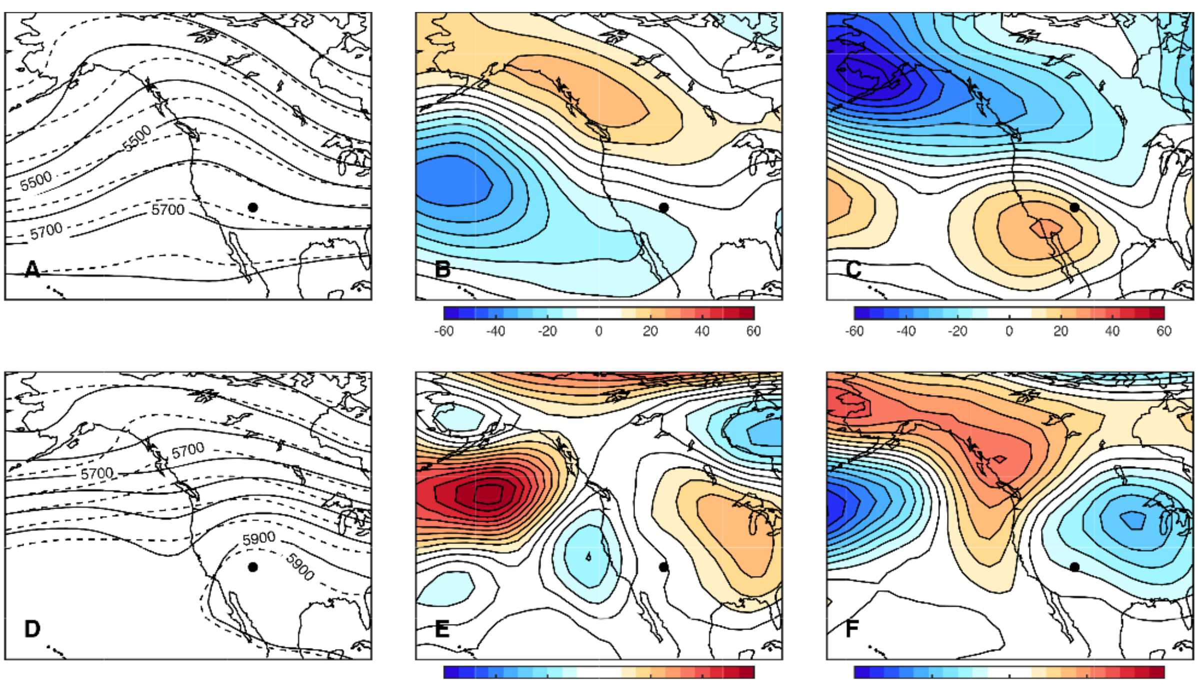


Figure 8. (A) Geopotential height of the 500-hPa isobaric surface (Z_{500}) for the wettest four (solid contours) and driest four (dashed contours January - February periods, contoured every 100 geopotential meters. Z_{500} anomalies associated with the (B) wettest and (C) driest four January - February periods. (D-F) Same as A-C but for July - August. In each panel, the filled circle is centered on the study region.

suggesting that large-scale circulation controls strongly influence winter moisture delivery to the Navajo Nation and dominate winter-season precipitation anomalies. The weakest response to these factors was observed in the eastern part of the region, which is sheltered from westerly winter systems by high topography.

Water year precipitation totals across the Navajo Nation are also strongly influenced by summer season rainfall, however, summer storms are the dominant source of precipitation in four of the five cluster group regions. Variation in warm-season precipitation totals is much less coherent across the region, consistent with the more localized, convective nature of the monsoonal precipitation arriving during the summer season (Favors and Abatzoglou 2013; Carillo et al. 2016). Although no strong teleconnections were observed for summer precipitation variability, our analysis showed that pressure patterns over the western interior correlate with summer precipitation amounts. Different subregions of the Navajo Nation also exhibited different influence of early vs. late-season summer precipitation, suggesting that the mechanisms driving summer rainfall deficit or surplus may be heterogeneous across the study area. Western and northern parts of the Navajo Nation, for example, appear likely to be less sensitive to failure of the early monsoon as they receive the majority of their summer precipitation later in the monsoon season (Figure 4).

Correlations to non-local climate indicators help identify climate drivers responsible for precipitation in the Navajo Nation, and may be useful for forecasting precipitation anomalies in support of regional water management. The PNA index is the strongest overall indicator of winter precipitation in the Four Corners region (Figure 7). PNA is known to exert strong control over winter storm tracks across North America (Wallace and Gutzler 1981). Previous work has suggested a weak association between PNA and 20th-century winter precipitation anomalies (Leathers et al. 1991) in the southwestern USA, although long-term paleoclimate data have suggested that variation in PNA is correlated with drought in the region over the past millennium (Liu et al. 2017). This correlation suggests that long-term trends in the PNA pattern, such as those suggested by paleoclimate records (Liu et al. 2014), could impact future winter precipitation and water resources in the Navajo Nation.

Connections between precipitation and dominant climate modes were weaker for summer than winter. Although summer monsoonal variations have been linked to sea surface temperatures, El Niño-Southern Oscillation (ENSO)-like variations, and possibly also different phases of the PNA pattern (e.g., Adams and Comrie 1997), the overall effect of these large-scale modes on summer circulation variability is less prominent than in winter. We did find, however, that summer precipitation was strongly correlated with a coherent pattern of large-scale pressure anomalies over the North American continent, consistent with previously observed effects of the "monsoon ridge" on summer moisture delivery to the southwestern USA (Lahmers et al. 2016).

Conclusions

We have described and examined precipitation amount variability across the Navajo Nation based on data from a spatially extensive network of monitoring stations. We identify regionalization of seasonal precipitation patterns across the area, with regions differing in terms of absolute precipitation amounts, the relative importance of summer and winter precipitation, and the timing and abruptness of summer monsoon onset and termination. Although year-to-year variations in precipitation amount are highly correlated across the study area, we also find regional structure in the interannual precipitation time series which matches that observed for the seasonal pattern. This, together with our observation that extremes in summer and winter precipitation are independent of each other, implies that future changes in water availability may be different in various parts of the Navajo Nation. Therefore, livelihoods in each region of the Navajo Nation may be differently impacted. Understanding the climate system influences driving summer and winter precipitation variability will thus be critical for accurate regional prediction of precipitation patterns. To this end, we have demonstrated that winter precipitation across the region is most sensitive to variation in the PNA pattern and winter storm-tracks, whereas summer monsoon precipitation appears to respond only weakly to major climate modes and is sensitive to summer pressure patterns steering monsoonal flow over the western USA. This analysis has improved current knowledge by defining improved regional precipitation patterns and changes at monthly, seasonal, and annual timescales within the boundaries of the Navajo Nation. Past and future variability in these climate patterns is a likely driver of water resource variations across the Navajo Nation, and could be a target for improved understanding of water availability in this arid region.

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