# Hydroclimate variability influenced social interaction in the prehistoric American Southwest

**Nicolas Gauthier**[1]

[1] Center for Social Dynamics and Complexity, School of Human Evolution and Social Change, 900 S Cady Mall, Tempe, USA

E-mail: Nicolas.Gauthier@asu.edu

**Abstract.** In agricultural societies, farmers rely on their social networks to absorb the impacts of droughts and floods by facilitating resource flows to affected settlements and population flows away from them. These benefits depend on how well one's social network connects populations that experience different weather patterns. Here I use an empirical archaeological case study from the late pre-Hispanic period in the North American Southwest to examine the relationship between drought variability and human social networks over a 250 year period. I analyze 7.5 million artifacts collected from nearly 500 archaeological sites, and estimate how the flow of social information between sites varied as a function of distance and growing-season hydroclimate variability. Interaction between regions experiencing different oceanic and continental influences was often higher than would be expected by chance and distance alone, but the intensity of this influence changes over time. This work highlights the importance of distinguishing between different dynamic origins of hydroclimate variability when considering the social impacts of droughts and pluvials in the past and present.

*Keywords*: drought patterns, archaeological networks, spatial interaction model

## Introduction

Exchange networks are part of the broad toolkit of social and physical infrastructure humans use to manage environmental risk in social-ecological systems (Anderies 2015). The environment can structure these exchange networks by influencing the costs and benefits of social interaction. Recent theoretical and empirical work highlights how spatial, social, and environmental factors interact with networks of exchange and interaction (Fafchamps and Gubert 2007; Bloch et al. 2008; Nolin 2010; Verdery et al. 2012; Freeman et al. 2014; Koster and Leckie 2014; Hao et al. 2015; Schnegg 2015). Distance is a key factor in such systems, making it difficult to monitor conditions in potential migration destinations (Anderies and Hegmon 2011) and know the resources and reputation of potential interaction partners (Fafchamps and Gubert 2007), as well as increasing the metabolic costs of transport (Drennan 1984). For agricultural societies in water-limited environments, hydroclimate variability – changes in the balance of precipitation and evapotranspiration – may be another critical factor. The benefits of interacting with others in distinct drought regimes can outweigh the costs of traveling longer distances. As a consequence, we might expect a greater "investment of social energy in the maintenance of social ties" between populations experiencing poorly or negatively correlated climate variability (Rautman 1993). Norms and institutions that maintain ties between different climate regimes are likely to evolve (Durante 2009). This process is difficult to measure in the present day due to the mismatch between the generational time scale on which cultural evolution occurs and the limited time horizons available to contemporary social sciences. Instead we can turn to the archaeological record.

Archaeology focuses on the material correlates of human behavior and is unique in addressing how social and physical infrastructure modulate human interactions with the environment over long time spans. Not only do archaeologists catalogue the remains of field systems, road networks, canals, and other components of hard infrastructure directly, but also the ceramics, raw materials, and luxury goods that are the material correlates of past networks of exchange and interaction. A powerful idea in archaeology is that, because of the interaction between societies and their biophysical environments, the spatial and temporal patterns of environmental variability can be used to predict "ideal" cultural responses and compared to archaeological observations (Halstead and O'Shea 1989). Yet in practice it is often difficult to find archaeological data fit for purpose, due to the incomplete nature of the archaeological record and the paucity of detailed paleoclimate data at the scales most relevant to human populations.

The North American Southwest is an exception. The climate of this region has been intensively studied by paleoclimatologists and climate modelers (Cook et al. 1999; Sheppard et al. 2002; McCabe et al. 2004; Herweijer et al. 2007; Cook et al. 2011; Bocinsky and Kohler 2014; Coats et al. 2015; Routson et al. 2016; Ault et al. 2018). Additionally, nearly two centuries of survey and excavation have yielded extensive, high quality settlement pattern data (Hill et al. 2004). Rates of archaeological site preservation and recovery in the Southwest are exceptionally high due to the arid climate and comparatively low density of Euro-American occupation. Hence, detailed inventories of material culture at hundreds of archaeological sites provide an unparalleled view of the structure and dynamics of past social networks. This archaeological record attests to extensive exchange networks of durable goods such as ceramics and obsidian (Malville 2001; Taliaferro et al. 2010; Mills et al. 2013a), and there is evidence for the long-distance transport of limited quantities of maize to the large regional center at Chaco Canyon (Benson et al. 2009; Benson 2010). The populations of the Southwest also underwent massive social transformation, migration, and population decline in the late 13th century contemporaneous with one of the worst droughts in the last 1,000 years (Hill et al. 2004). Past work has suggested a relationship between the intensity of social interaction and patterns of drought variability, but has been limited by small sample sizes or sparse climate data (Rautman 1993; Johnson 1990; Cordell et al. 2007). The question is returning to the fore with the advent of high resolution climate observations and reconstructions, facilitating more detailed accounting of the spatial patterns of drought in the North American Southwest (Strawhacker et al. 2017), and more detailed archaeological datasets (Borck et al. 2015). Simulations suggest that the precise nature of environmental variability is critical for exchange dynamics (Freeman et al. 2014). With these advances in our ability to map droughts in space and time comes the need to more precisely define what patterns of climate variability are actually important.

Here, I draw on hydroclimate data from the past and present to isolate specific *modes of variability* – reoccurring climate patterns – in the American Southwest. I then compare these patterns to prehistoric social networks, inferred from a dataset of 7.5 million ceramic artifacts from nearly 500 archaeological sites (Figure 1), to examine the relationship between hydroclimate variability, distance, and social interaction over a 250 year span.

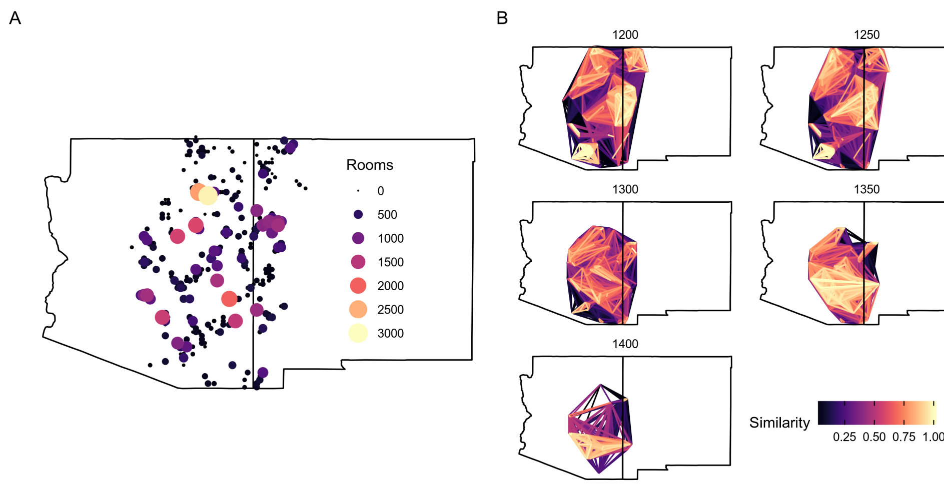


**Figure 1.** The *Soutwest Social Networks* dataset, version 1 (Mills et al. 2013a). A) Site locations for all time periods in the dataset, aggregated into 10km patches to reduce biases from local settlement aggregation and dispersal. Site sizes are estimated from room counts. B) Social networks reconstructed from ceramic assemblage similarity between each pair of sites. A similarity coefficient of 1 means that the sites share the same decorated ceramic wares in the exact same proportions, and a coefficient of 0 means there is no overlap in the ceramic assemblages. The similarity network can be interpreted as the degree of social interaction and cultural transmission between sites, whether via migration, trade, or copying. Networks are shown over successive 50 year time spans, starting at 1200 CE.

## Results

### *Six drought patterns explain 83% of observed drought variability in the American Southwest*

Climate varies across scales for many reasons, both dynamic and stochastic, and it is important to separate climatic signal from noise. Principal Components Analysis (PCA) of spatiotemporal data is a common tool for extracting modes of variability in the climate sciences (Lorenz 1956; Hannachi et al. 2007), but its use for this particular purpose is rare in archaeology (Weiss 1982; Cordell et al. 2007). I used PCA to decompose a 100-year observational record of summer moisture availability into orthogonal modes of variability in order to extract the leading patterns that collectively explained the most variability.

The leading 6 PC time series together explain 83% of the variance in the observational record. The principal components (PCs) represent time series that are maximally representative of the entire data set (Figure 2). I rotated the 6 PCs before mapping, in order to capture more physically meaningful patterns and minimize statistical artifacts. PCs beyond the leading 6 were not retained for rotation and mapping, as they represent spatially and temporally incoherent variability and spurious correlations introduced by sampling error in the observational record.

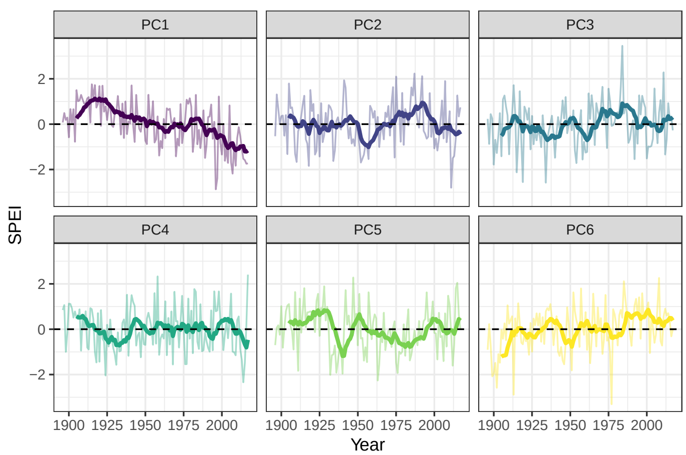


**Figure 2.** Time series associated with the leading 6 PCs for the observational period, after varimax rotation. The y-axis corresponds to the 12 month Standardized Precipitation-Evapotranspiration Index (SPEI), the normalized deviation from the average climatic water balance for a given month on 12 month time scale (Vicente-Serrano et al. 2010). SPEI values can be interpreted as z-scores in a normal distribution (i.e. a value of 1 is one standard deviation wetter than average for that location, -1 is one standard deviation drier). 10 year moving averages superimposed over raw annual values.

### *Different drought patterns are associated with different zones of oceanic or continental influence*

To reveal the latent spatial structures associated with the temporal modes of variability, I mapped the spatial patterns associated with each of the leading 6 PCs

(Figure 3). The results are robust, recurring patterns of spatially-coherent variability, and can be interpreted as the degree to which the 100 year record at each grid cell correlates with the associated rotated PC time series. These spatial patterns are known as the (rotated) empirical orthogonal functions (EOFs). The patterns are consistent regardless of the exact SPEI time scale used to calculate them, which supports their robustness. The spatial and temporal patterns associated with the leading 6 PCs allows us to trace the sources of each mode of variability back to the global climate system.

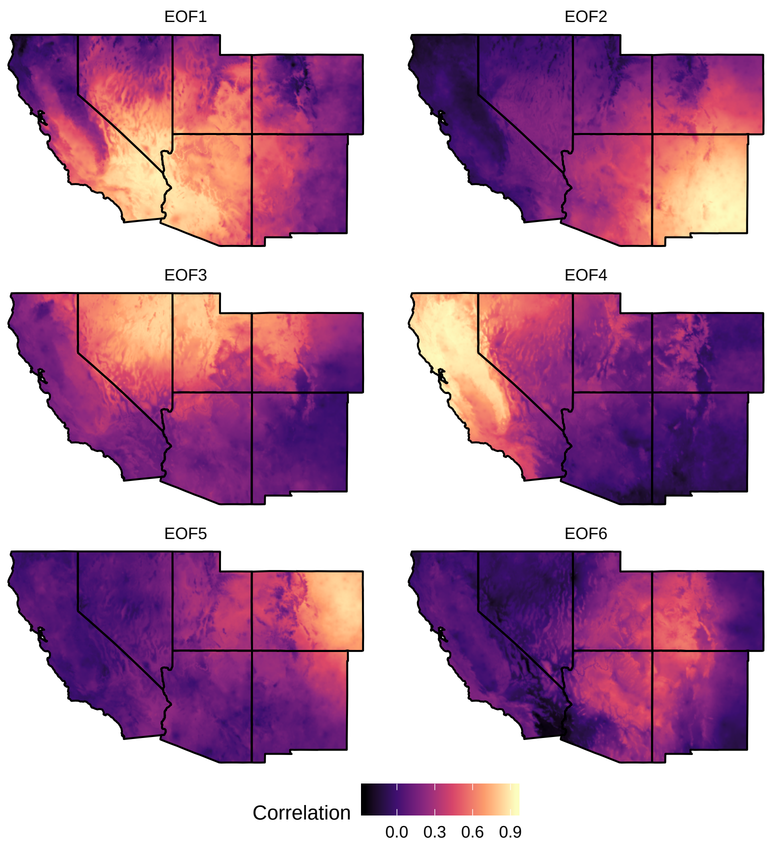


**Figure 3.** Leading 6 rotated empirical orthogonal functions (EOFs), associated with the respective PC time series in Figure 2. These regions represent different oceanic and atmospheric influences; people living in the same EOF will often experience dry and wet years at the same time as one another.

The origins of each drought pattern can be determined by examining the EOF maps, along with the correlations of the PCs to global sea surface temperature and examining extreme dry and wet periods in each observed PC. EOF1 reflects southwesterly flow from the tropical Pacific, bringing moisture across the low desert zones of California and Arizona. The pattern attenuates with gains in elevation, as distance from the ocean increases. PC1 shows an broad drying trend to the present day, possibly related increased evaporative demand due to recent warming. EOF2 similarly represents southeasterly flow from the Gulf of Mexico, centered eastern New Mexico. As with EOF1, the pattern attenuates with increasing elevation and distance from the ocean due to orography and continentality, respectively. It represents cyclonic storms coming from the Gulf of Mexico, in turn influenced by variability in Atlantic sea surface temperatures. PC2 shows a major dry period centered on the Texas/New Mexico drought of 1956. EOF3 represents northerly flow associated with polar continental cold fronts, and its associated PC shows a wet peak in the 1983 Salt Lake City floods. EOF4 represents the influence of westerly flow off the Pacific Ocean and the orographic effect of the Sierra Nevada mountains intercepting this flow, and is associated with coastal droughts in California such as the Dust Bowl and 1924 drought. EOF5 is centered over the great plains and attenuates across the Rocky Mountains, and was most strongly expressed during the Dust Bowl of the 1920s. EOF6 is centered on the the Colorado Plateau, likely reflecting hot continental air masses, and is the only pattern not also visible in coarse-resolution reconstructions.

*The intensity of social interaction decays nonlinearly with distance*

Distance ultimately constrains social interaction, as the further one travels to interact with a partner the greater will be the cost in time, money, and energy. I calculated the cost of moving between each pair of archaeological as the shortest amount of time it would take a foot traveler to move between them. I then used a nonlinear regression model to estimate the functional relationship between distance and interaction.

The null model for the statistical network analysis was that distance alone explains the intensity of social interaction. This null model was sufficient to explain nearly 35% of the variance in archaeological dataset. The empirical distance deterrence function estimated using penalized regression spline (see methods) predicts a falloff in interaction at distances of more than 100 hours (Figure 4). As expected, the resulting distance-based network predicts many strong interactions at close distances, and the residuals of the model show long distance transitive ties.

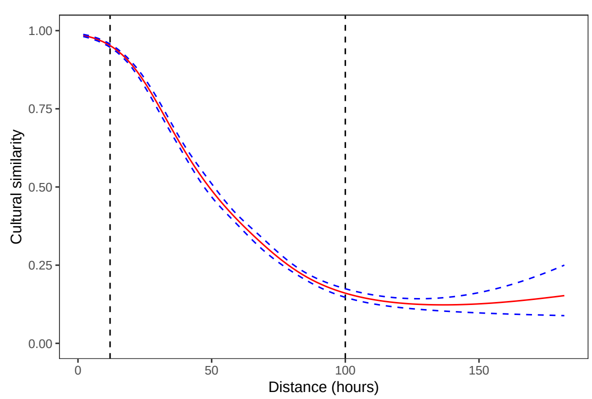


**Figure 4.** Empirical distance deterrence function estimated with a generalized additive model, describing how the intensity of social interaction, measured as the cultural similarity between two settlements, decreases as a function of distance. Dashed lines indicate key thresholds in the function at 10 and 100 hours.

*Hydroclimate variability explains a moderate but clear proportion of the intensity of social interaction*

A model predicting cultural similarity using distance and climatic dissimilarity, measured as the absolute difference between the EOF loadings of a pair of sites, explains approximately 41% of the variance in the ceramic similarity data. The increase over the distance-only null model is moderate but statistically significant, and the EOF model is superior in all measures of parsimony and goodness-of-fit.

The smooth functions estimated in the EOF model are all close to piecewise linear on the scale of the linear predictor, but the intensity of these functional relationships varies smoothly over time and across EOFs (Figure 5). Increasing distance along a particular EOF sometimes increases the intensity of social interaction, as was expected ahead of time, but some EOFs appear to inhibit social interaction. The smoothness penalty also selects some EOFs out of the model entirely by estimating functions close to a horizontal line, and almost all the functions are flat when the climate differences are less than 0.2. Surprisingly, the fluctuations in the effect size of a particular EOF have no clear association with the sign of the associated PC amplitude time series reconstructed for each period, suggesting that additional dynamic processes are in effect on time scales longer than a single generation.

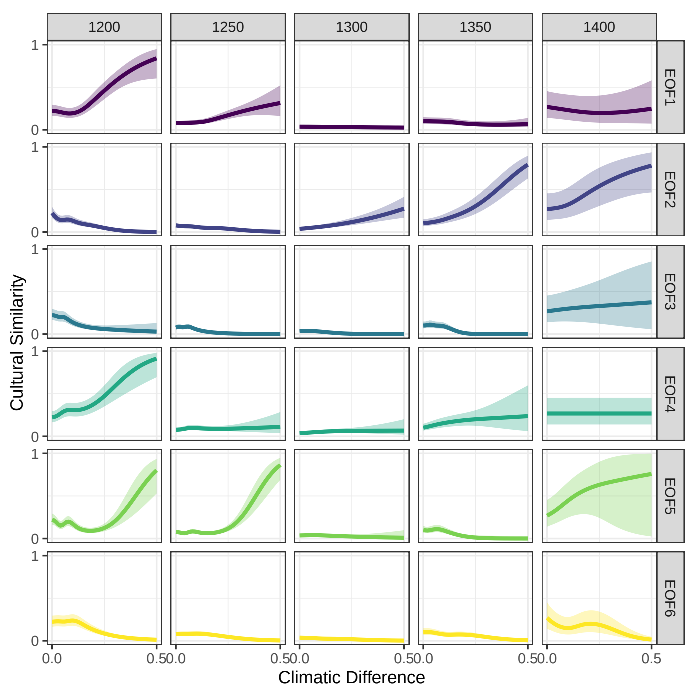


**Figure 5.** Estimated smooth functions describing how the intensity of social interaction increases or decreases with increasing distance along each of six spatial drought patterns from Figure 3, compared over five time steps. Shaded regions correspond to the 95% confidence intervals for the smooth functions.

**Discussion and Conclusions**

The six spatial patterns of hydroclimate variability isolated here are consistent with the general mechanistic understanding of hydroclimate variability in the American Southwest. These patterns represent different zones of moisture transport, reflecting the influence of topography and marine or continental moisture sources (Liu et al. 2010; Hu et al. 2011). These spatial and temporal drought patterns, and their hypothesized forcings from the global climate system, are largely consistent with those from other studies using varied observational data and time windows (Comrie and Glenn 1999; Cook et al. 1999; McCabe and Dettinger 1999; McCabe et al. 2004; Ryu et al. 2010; Seager and Hoerling 2014; Herrmann et al. 2016). These same patterns from the observational period also appear in drought reconstructions spanning the past millennium, emphasizing the fact that these are robust, time invariant spatial modes.

Objective measures of hydroclimate variability, rather than point-to-point sample correlations, allow us to isolate the most important drivers of that variability. Droughts and pluvials associated with tropical Pacific and Atlantic influences seem to have been most important for structuring social interaction, with ties connecting these regions greater than expected by chance and distance alone. Tropical Pacific sea surface temperatures are known to be the primary driver of variability in Southwest, with additional influences from moisture sources in the North Pacific and Atlantic (McCabe et al. 2004). A disruption in these patterns is thought to be one reason why droughts in this period led to such social transformation, as the networks of social infrastructure that had developed over previous centuries were unable to adapt fast enough to unusual conditions (Cordell et al. 2007).

Populations in the late pre-Hispanic Southwest were clearly out of equilibrium (Hill et al. 2004). Exchange networks take time to develop and effort to maintain. Social dynamics such as free-riding can lead to the breakdown in this critical social infrastructure when it is most needed (Kohler and West 1996). Yet the change of the functional forms for the EOF patterns over time still points to dynamics occurring longer than our 50 year time scales. Future studies should leverage these findings to construct dynamic simulation models. It will be important to model the evolution of social flows and physical paths separately (Bevan and Wilson 2013) in order to capture this time lag effect. A simulation approach would be better able to capture the influence year-to-year variability, as well as the time averaging and bias introduced by the use of archaeological similarity data to represent dynamic social processes (Crema et al. 2014; Crema et al. 2016).

In spite of the robustness of these spatial patterns, there remains considerable diversity in the functional responses of human social networks to these drought patterns. Differences in drought regime are just as likely to inhibit social interaction as they are to enhance it. One possible explanation is that large-scale climate regimes also influence the formation of ethnolinguistic groups. Kinship, or perceived kinship (ethnicity) are important for structuring social exchanges (Nolin 2010). Small-scale, quotidian interactions may have tracked shared ethnolinguistic affiliation, while interregional exchange may have occurred higher up a sociopolitical hierarchy. The flows of goods and information often proceeded hierarchically, a dynamic poorly-captured in simple spatial interaction models (Crumley 1979). Perhaps then the strongest flows were between sociopolitical elites at terminal sites.

The residuals from the fitted network models retain unexplained structure. These broadly correspond to large cultural clusters, a common feature in social networks that is not accounted for by either distance or drought variability. On a microscale, the residuals display a pattern of high transitivity and triad closure, which is to say there are a great many more closed triangle structures than would be expected by chance. Although this feature is common in human social networks, it is also to be expected from the semi-metric nature of the data, as full transitivity is to be expected in a metric with subject to the triangle equality. Statistical methods specifically designed for such structures may be preferable in future work (Stillman et al. 2017). In addition, the archaeological data are not spatially extensive enough to sample the full range of hydroclimate variability. Given the relative spatial scales of our environmental and cultural data, there is a risk that many different correlated climate patterns will be indistinguishable at the scale of the cultural data. Correlation between competing hypotheses as a source of error in model selection using information criteria (Shirk et al. 2018). In spite of these shortcomings, these results highlight two more novel points: the importance of objective, physically-meaningful measures of drought spatial variability and that social interaction dynamics are out of equilibrium with the biophysical environment.

These results refine our understanding of the geography of human adaptation to climate and climate change. Prehistoric exchange infrastructure evolved in part in response to robust, time-invariant spatial climate structure. The EOF patterns acted as the selective environment in which norms and institutions regulating social interaction emerge. Social responses adapted to a particular mode of variability can be fragile to changes in that variability (Janssen et al. 2007). These findings emphasize the importance of institutional evolution in the developing world, that increases the robustness of human populations to environmental variability. Much of the world's food is still grown on small farms, and these farmers rely on complex networks of formal and informal arrangements in much the same way as their forbears have for 1,000s of years. Tracing the flows of information and energy within these complex social-ecological systems is essential for understanding their long-term behavior, and leveraging our archaeological understanding of why societies succeed or fail will be critical to anticipating the impact of impending climate changes on farming communities in the developing world.

## Data and Methods

### *Hydroclimate Variability*

I analyzed a 100-year record of the Standardized Precipitation-Evapotranspiration Index (SPEI) calculated from interpolated weather-station data over the states of Arizona, New Mexico, Colorado, Utah, and California (Daly et al. 1997). SPEI is the normalized deviation from the average climatic water balance for a given month on varying time scales (Vicente-Serrano et al. 2010). I focused on the 12-month SPEI calculated in the August of each year, as agricultural droughts during the summer growing season would have been most relevant to societies practicing small-scale maize agriculture. I calculated the empirical orthogonal functions (EOFs) of the SPEI data via a singular value decomposition of the space time covariance matrix ‡, multiplying each grid cell by the cosine of latitude to account for areal distortion. Then, I selected the leading eigenvalues for rotation, using both a scree test and North's

‡ This step is equivalent to working on the correlation matrix, as SPEI is already standardized to unit variance at each location.

rule of thumb (North et al. 1982), which accounts for autocorrelation in the observed data. I rotated the leading eigenvalues using a varimax rotation in order to relax the spatial orthogonality constraints of the PCA analysis to reveal coherent, physically meaningful patterns (Richman 1986). The resulting eigenvectors were then multiplied by the square root of the corresponding eigenvalues to yield correlation coefficients, and were mapped in space. I refer to these resulting spatial patterns as EOFs, and their associated time series as PCs (principal components). The PC amplitude time series were then compared to the observational record, and the signs of the eigenvalues and vectors were reversed to match the historical record (so that a positive time series value corresponded to a positive SPEI and *vice versa*). To determine whether these patterns were robust over time, the observed EOFs were compared to the EOFs of a SPEI reconstruction over the past millennium (Steiger et al. 2018).

*Archaeological Interaction Networks*

The Southwest Social Networks (SWSN) database is a compendium of material-culture data from nearly 1,000 well-dated archaeological sites west of the Continental Divide in Arizona and New Mexico (Mills et al. 2013b; Mills et al. 2013a; Peeples and Haas 2013; Borck et al. 2015; Hill et al. 2015; Mills et al. 2015). The SWSN project recorded nearly 4.7 million ceramic artifacts and nearly 5,000 obsidian artifacts (Mills et al. 2015). Version 1.0 of the SWSN database provides quantitative estimates of the topology of the region-wide social network during five 50 year time steps spanning the period 1200-1450 CE (Mills et al. 2013a). I aggregated the point-based SWSN data into 10km grid cells§ so that the network estimates were less sensitive to local settlement dispersal or aggregation as reflected in the assemblages at individual sites (Paliou and Bevan 2016). Then I calculated the modified Jensen-Shannon divergence between the empirical frequency distributions of 15 decorated ceramic wares at each of the grid cells as

$$D_{ij} = H\left(\pi_1 P + \pi_2 Q\right) - \pi_1 H(P) - \pi_2 H(Q), \tag{1}$$

where $D_{ij}$ is the divergence between the empirical frequency distributions of ceramic wares at sites $i$ and $j$, and $H(P) = -\sum_i p_i \ln_2 p_i$ is the Shannon entropy of $H$ measured in bits, and $\pi_1 = \pi_2 = 0.5$ are equal weights for the probability distributions. This equation measures the information flow based on the distributions of the ceramic types shared by both sites and the types exclusive to each (Masucci et al. 2011). Analogous to the use of divergence measures in population genetics, divergence here is a proxy for information flow. The index can be loosely interpreted as a probability of interaction between two sites, with identical patterns of ceramic discard indicating a high probability of interaction via either direct migration and trade or indirect cultural diffusion.

*Least-Cost Networks*

I calculated the least-cost network between all sites in the SWSN network. The topography of the study area was represented using 90m SRTM DEM, resampled to 250m to reduce computation time and reduce fine-scale topographic noise. A cost

§ The choice of 10km grid cells yields areas consistent with the distance traveled by farmers for farming and raw material collection, so the procedure effectively smooths over the approximate area of each site's resource catchment (Varien 1999).

matrix was calculated containing, for each DEM cell, the amount of time in seconds it would take a foot traveler to move to each of the 16 neighboring cells. Time costs were calculated using a version of Tobler's hiking function, which estimates walking speed from terrain slope. The function was modified to make it isotropic (i.e. averaging the uphill and downhill walking speeds) and adding an extra penalty to very steep slopes consistent with human cognitive biases (Pingel 2010). This cost matrix (time) was then inverted to represent conductance (speed), facilitating a sparse matrix representation and estimation of least cost paths using efficient graph theoretic algorithms (Etten 2014). The resulting transition matrix was used to calculate all pairwise isotropic least cost paths between the centroids of each pair of 10km grid cells containing archaeological materials.

*Spatial Interaction Models*

Spatial interaction models are used across the social and natural sciences (Wilson 1971; Fotheringham and O'Kelly 1989; Sen and Smith 1995; Bavaud 2008; Murphy et al. 2010; Head and Mayer 2015). In a regression context, a spatial interaction model estimates the pairwise flow – resources, migrants, information – among entities as a multiplicative function of predictors influencing the production and attraction of flows as well as measures of their mutual separation or other generalized costs of moving. Archaeologists have used *statistical* spatial interaction models sparingly (Tobler and Wineburg 1971; Hodder 1974; Johnson 1990) because of the rarity of archaeological data on social interaction strength, although the method is common in simulation studies where data quality is less of a restriction (Bevan and Wilson 2013; Evans et al. 2011; Davies et al. 2014; Paliou and Bevan 2016). The conceptual justification for the use of spatial interaction models on archaeological networks is similar to that used in molecular ecology (Murphy et al. 2010), with information flows among a spatially-structured metapopulation measured by the divergence of those populations (Mesoudi 2018). Data of this type have three features that make traditional statistical spatial interaction modeling difficult. These are: 1) the data are bounded between 0 and 1, 2) the measures are pairwise symmetric 3) we have no exact functional expectations for the specific terms in the spatial interaction model because empirical work on this scale and type is rare. To address these issues, I used a generalized additive model (Wood 2006), a semiparametric extension to generalized linear models useful for more complex spatial interaction models (Lebacher et al. 2018).

Specifically, I fit models of the form

$$logit\,(D_{ijt}) = f(dist_{ij}) + f_t(EOF_{ij}) + \tau_{it} + \tau_{jt} + \epsilon_{ijt}, \tag{2}$$

where the logit function maps the data from $[0, 1]$ to $[-\infty, +\infty]$, $t$ is the time step, $f()$ is an arbitrary function estimated during model fitting using penalized cubic regression splines, $\tau_i$ and $\tau_j$ are time-varying random effects for the nodes incident on each edge, and $\epsilon$ is Gaussian error. This model assumes only that information flows are at equilibrium with settlement population, not that the populations themselves are at equilibrium (Wilson 2008). The $\tau$ terms account for the non-independence of edges that share a node, and were estimated using a maximum likelihood population effects correlation structure appropriate for pairwise data (Clarke et al. 2002). I compared the AIC, BIC, and $R^2$ of models fit using maximum likelihood with and without the EOF terms, and refit the best performing model using restricted maximum likelihood (Clarke et al. 2002; Shirk et al. 2018).

## References

Anderies, John M. (2015). "Understanding the Dynamics of Sustainable Social-Ecological Systems: Human Behavior, Institutions, and Regulatory Feedback Networks". In: *Bulletin of Mathematical Biology* 77.2, pp. 259–280.

Anderies, John M. and Michelle Hegmon (2011). "Robustness and Resilience Across Scales: Migration and Resource Degradation in the Prehistoric US Southwest". In: *Ecology and Society* 16.2, p. 22.

Ault, Toby R., Scott St George, Jason E. Smerdon, Sloan Coats, Justin S. Mankin, Carlos M. Carrillo, Benjamin I. Cook, and Samantha Stevensong (2018). "A robust null hypothesis for the potential causes of megadrought in Western North America". In: *Journal of Climate* 31.1, pp. 3–24.

Bavaud, François (2008). "The endogenous analysis of flows, with applications to migrations, social mobility and opinion shifts". In: *Journal of Mathematical Sociology* 32.4, pp. 239–266.

Benson, L. V., J. R. Stein, and H. E. Taylor (2009). "Possible sources of archaeological maize found in Chaco Canyon and Aztec Ruin, New Mexico". In: *Journal of Archaeological Science* 36.2, pp. 387–407.

Benson, Larry V. (2010). "Who provided maize to Chaco Canyon after the mid-12th-century drought?" In: *Journal of Archaeological Science* 37.3, pp. 621–629.

Bevan, Andrew and Alan Wilson (2013). "Models of settlement hierarchy based on partial evidence". In: *Journal of Archaeological Science* 40.5, pp. 2415–2427.

Bloch, Francis, Garance Genicot, and Debraj Ray (2008). "Informal insurance in social networks". In: *Journal of Economic Theory* 143.1, pp. 36–58.

Bocinsky, R. Kyle and Timothy A. Kohler (2014). "A 2,000-year reconstruction of the rain-fed maize agricultural niche in the US Southwest". In: *Nature Communications* 5, p. 5618.

Borck, Lewis, Barbara J. Mills, Matthew A. Peeples, and Jeffery J. Clark (2015). "Are Social Networks Survival Networks? An Example from the Late Pre-Hispanic US Southwest". In: *Journal of Archaeological Method and Theory* 22.1, pp. 33–57.

Clarke, Ralph T., Peter Rothery, and Alan F. Raybould (2002). "Confidence Limits for Regression Relationships Between Distance Matrices : Estimating Gene Flow With Distance". In: *Journal of Agricultural, Biological, and Environmental Statistics* 7.3, pp. 361–372.

Coats, Sloan, Jason E. Smerdon, Benjamin I. Cook, and Richard Seager (2015). "Are Simulated Megadroughts in the North American Southwest Forced?" In: *Journal of Climate* 28.1, pp. 124–142.

Comrie, A. C. and E. C. Glenn (1999). "Principal components-based regionalization of precipitation regimes across the southwest United States and northern Mexico, with an application to monsoon precipitation variability". In: *Climate Research* 10.3, pp. 201–215.

Cook, Benjamin I., Edward R. Cook, Kevin J. Anchukaitis, Richard Seager, and Ron L. Miller (2011). "Forced and unforced variability of twentieth century North American droughts and pluvials". In: *Climate Dynamics* 37.5, pp. 1097–1110.

Cook, Edward R., David M. Meko, David W. Stahle, and Malcolm K. Cleaveland (1999). "Drought reconstructions for the continental United States". In: *Journal of Climate* 12.4, pp. 1145–1163.

Cordell, Linda S., Carla R. Van West, Jeffrey S. Dean, and Deborah A. Muenchrath (2007). "Mesa Verde settlement history and relocation: Climate change, social networks, and Ancenstral Pueblo migration". In: *Kiva* 72.4, pp. 379–405.

Crema, Enrico R., Anne Kandler, and Stephen Shennan (2016). "Revealing patterns of cultural transmission from frequency data: Equilibrium and non-equilibrium assumptions". In: *Scientific Reports* 6.39122.

Crema, Enrico R., Tim Kerig, and Stephen Shennan (2014). "Culture, space, and metapopulation: a simulation-based study for evaluating signals of blending and branching". In: *Journal of Archaeological Science* 43, pp. 289–298.

Crumley, Carole L. (1979). *Three Locational Models: An Epistemological Assessment for Anthropology and Archaeology*. Vol. 2, pp. 141–173.

Daly, Christopher, George Taylor, and Wayne Gibson (1997). "The Prism Approach to Mapping Precipitation and Temperature". In: *10th AMS Conference on Applied Climatology* 1, pp. 1–4.

Davies, Toby, Hannah Fry, Alan Wilson, Alessio Palmisano, Mark Altaweel, and Karen Radner (2014). "Application of an entropy maximizing and dynamics model for understanding settlement structure: The Khabur Triangle in the Middle Bronze and Iron Ages". In: *Journal of Archaeological Science* 43.1, pp. 141–154.

Drennan, Robert D. (1984). "Long-distance transport costs in pre-Hispanic Mesoamerica". In: *American Anthropologist* 86.1, pp. 105–112.

Durante, Ruben (2009). "Risk, Cooperation and the Economic Origins of Social Trust: An Empirical Investigation".

Etten, Jacob van (2014). "R Package gdistance: Distances and Routes on Geographical Grids". In: *Journal of Statistical Software* 59.10.

Evans, T., R. Rivers, and C. Knappett (2011). "Interactions In Space For Archaeological Models". In: *Adv. Complex Syst.* 15.September, pp. 1150009+. arXiv: `1102.0251`.

Fafchamps, Marcel and Flore Gubert (2007). "The formation of risk sharing networks". In: *Journal of Development Economics* 83.2, pp. 326–350.

Fotheringham, Stewart A. and Morton E. O'Kelly (1989). *Spatial interaction models: formulations and applications*. Kluwer Academic Publishers.

Freeman, Jacob, John M. Anderies, Andrea Torvinen, and Ben A. Nelson (2014). "Crop Specialization, Exchange and Robustness in a Semi-arid Environment". In: *Human Ecology* 42.2, pp. 297–310.

Halstead, Paul and John O'Shea (1989). "Introduction: cultural responses to risk and uncertainty". In: *Bad Year Economics: Cultural Responses to Risk and Uncertainty*. Ed. by Paul Halstead and John O'Shea. Cambridge: Cambridge University Press. Chap. 1, pp. 1–7.

Hannachi, A., I. T. Jolliffe, and D. B. Stephenson (2007). "Empirical orthogonal functions and related techniques in atmospheric science: A review". In: *International Journal of Climatology* 27, pp. 1119–1152.

Hao, Yan, Dieter Armbruster, Lee Cronk, and C. Athena Aktipis (2015). "Need-based transfers on a network: A model of risk-pooling in ecologically volatile environments". In: *Evolution and Human Behavior* 36.4, pp. 265–273.

Head, Keith and Thierry Mayer (2015). *Gravity Equations: Workhorse,Toolkit, and Cookbook*. Vol. 4. Elsevier B.V., pp. 131–195.

Herrmann, Stefanie M, Kamel Didan, Armando Barreto-Munoz, and Michael A Crimmins (2016). "Divergent responses of vegetation cover in Southwestern US ecosystems to dry and wet years at different elevations". In: *Environmental Research Letters* 11.12, p. 124005.

Herweijer, Celine, Richard Seager, Edward R. Cook, and Julien Emile-Geay (2007). "North American Droughts of the Last Millennium from a Gridded Network of Tree-Ring Data". In: *Journal of Climate* 20.7, pp. 1353–1376.

Hill, J. Brett, Jeffery J. Clark, William H. Doelle, and Patrick D. Lyons (2004). "Prehistoric Demography in the Southwest: Migration, Coalescence, and Hohokam Population Decline". In: *American Antiquity* 69.4, pp. 689–716.

Hill, J. Brett, Matthew A. Peeples, Deborah L. Huntley, and H. Jane Carmack (2015). "Spatializing Social Network Analysis in the Late Precontact U.S. Southwest". In: *Advances in Archaeological Practice* 3.1, pp. 63–77.

Hodder, Ian (1974). "Regression analysis of some trade and marketing patterns". In: *World Archaeology* 6.2, pp. 172–189.

Hu, Qi, Song Feng, and Robert J. Oglesby (2011). "Variations in North American summer precipitation driven by the Atlantic multidecadal oscillation". In: *Journal of Climate* 24.21, pp. 5555–5570.

Janssen, Marco A., John M. Anderies, and Elinor Ostrom (2007). "Robustness of Social-Ecological Systems to Spatial and Temporal Variability". In: *Society & Natural Resources* 20.4, pp. 307–322.

Johnson, John R (1990). "Chumash social geography: A quantitative analysis". In: *Proceedings of the Society of California Archaeology* 3, pp. 149–173.

Kohler, Timothy A. and Carla R Van West (1996). "The calculus of self-interest in the development of cooperation: sociopolitical development and risk among the Northern Anasazi". In: *Evolving complexity and environmental risk in the Prehistoric Southwest.* Pp. 169–196.

Koster, Jeremy M. and George Leckie (2014). "Food sharing networks in lowland Nicaragua: An application of the social relations model to count data". In: *Social Networks* 38.1, pp. 100–110.

Lebacher, Michael, Paul W. Thurner, and Göran Kauermann (2018). "International Arms Trade: A Dynamic Separable Network Model With Heterogeneity Components". In: arXiv: `1803.02707`.

Liu, Zhongfang, Gabriel J. Bowen, and Jeffrey M. Welker (2010). "Atmospheric circulation is reflected in precipitation isotope gradients over the conterminous United States". In: *Journal of Geophysical Research Atmospheres* 115.22, pp. 1–14.

Lorenz, E N (1956). *Empirical Orthogonal Functions and Statistical Weather Prediction.* Tech. rep. Scientific Report No. 1, Statistical Forecasting Project, p. 52.

Malville, Nancy J. (2001). "Long-Distance Transport of Bulk Goods in the Pre-Hispanic American Southwest". In: *Journal of Anthropological Archaeology* 20.2, pp. 230–243.

Masucci, Adolfo Paolo, Alkiviadis Kalampokis, Victor Martínez Eguíluz, and Emilio Hernández-García (2011). "Wikipedia information flow analysis reveals the scale-free architecture of the semantic space". In: *PLoS ONE* 6.2. Ed. by Matjaz Perc, e17333. arXiv: `1102.0651`.

McCabe, G. J., M. A. Palecki, and J. L. Betancourt (2004). "Pacific and Atlantic Ocean influences on multidecadal drought frequency in the United States". In: *Proceedings of the National Academy of Sciences* 101.12, pp. 4136–4141. arXiv: `2014WR016527 [10.1002]`.

McCabe, Gregory J. and Michael D. Dettinger (1999). "Decadal variations in the strength of ENSO teleconnections with precipitation in the western United States". In: *International Journal of Climatology* 19.13, pp. 1399–1410.

Mesoudi, Alex (2018). "Migration, acculturation, and the maintenance of between-group cultural variation". In: *PLoS ONE* 13.10, pp. 1–23.

Mills, Barbara J, Jeffery J Clark, Matthew a Peeples, W R Haas, John M Roberts, J Brett Hill, Deborah L Huntley, Lewis Borck, Ronald L Breiger, Aaron Clauset, and M Steven Shackley (2013a). "Transformation of social networks in the late pre-Hispanic US Southwest." In: *Proceedings of the National Academy of Sciences of the United States of America* 110.15, pp. 5785–90.

Mills, Barbara J., Matthew A. Peeples, W. Randall Haas, Jr., Lewis Borck, Jeffery J. Clark, and John M. Roberts, Jr. (2015). "Multiscalar Perspectives on Social Networks in the Late Prehispanic Southwest". In: *American Antiquity* 80.1, pp. 3–24.

Mills, Barbara J, John M Roberts Jr, Jeffery J Clark, William R Haas Jr, Deborah Huntley, Matthew A Peeples, Lewis Borck, Susan C Ryan, Meaghan Trowbridge, and Ronald L Breiger (2013b). "The Dynamics of Social Networks in the Late Prehispanic US Southwest". In: *Network analysis in archaeology: New approaches to regional interaction*. Oxford University Press. Chap. 8, pp. 181–202.

Murphy, M. A., R. Dezzani, D. S. Pilliod, and A. Storfer (2010). "Landscape genetics of high mountain frog metapopulations". In: *Molecular Ecology* 19.17, pp. 3634–3649.

Nolin, David A. (2010). "Food-Sharing Networks in Lamalera, Indonesia". In: *Human Nature* 21.3, pp. 243–268.

North, G. R., T. L. Bell, and R. F. Cahalan (1982). *Sampling Errors in the Estimation of Empirical Orthogonal Funtions.*

Paliou, Eleftheria and Andrew Bevan (2016). "Evolving settlement patterns, spatial interaction and the socio-political organisation of late Prepalatial south-central Crete". In: *Journal of Anthropological Archaeology* 42, pp. 184–197.

Peeples, Matthew A. and W. Randall Haas (2013). "Brokerage and Social Capital in the Prehispanic U.S. Southwest". In: *American Anthropologist* 115.2, pp. 232–247.

Pingel, Thomas J. (2010). "Modeling Slope as a Contributor to Route Selection in Mountainous Areas". In: *Cartography and Geographic Information Science* 37.2, pp. 137–148.

Rautman, Alison E (1993). "Resource Variability, Risk, and the Structure of Social Networks: An Example from the Prehistoric Southwest". In: *American Antiquity* 58.3, pp. 403–424.

Richman, Michael B. (1986). "Review Article: Rotation of principal components". In: *Journal of Climatology* 6.March, pp. 293–335.

Routson, Cody C., Connie A. Woodhouse, Jonathan T. Overpeck, Julio L. Betancourt, and Nicholas P. McKay (2016). "Teleconnected ocean forcing of Western North American droughts and pluvials during the last millennium". In: *Quaternary Science Reviews* 146, pp. 238–250.

Ryu, Jae H., Mark D. Svoboda, John D. Lenters, Tsegaye Tadesse, and Cody L. Knutson (2010). "Potential extents for ENSO-driven hydrologic drought forecasts in the United States". In: *Climatic Change* 101.3, pp. 575–597.

Schnegg, Michael (2015). "Reciprocity on Demand: Sharing and Exchanging Food in Northwestern Namibia". In: *Human Nature* 26.3, pp. 313–330.

Seager, Richard and Martin Hoerling (2014). "Atmosphere and ocean origins of North American droughts". In: *Journal of Climate* 27.12, pp. 4581–4606.

Sen, Ashish and Tony E. Smith (1995). *Gravity Models of Spatial Interaction Behavior*. Springer-Verlag, p. 572.

Sheppard, Paul R, Andrew C Comrie, Gregory D Packin, Kurt Angersbach, and Malcolm K Hughes (2002). "The Climate of the US Southwest". In: *Climate Research* 21, pp. 219–238.

Shirk, Andrew J., Erin L. Landguth, and Samuel A. Cushman (2018). "A comparison of regression methods for model selection in individual-based landscape genetic analysis". In: *Molecular Ecology Resources* 18.1, pp. 55–67. arXiv: `0608246v3 [arXiv:physics]`.

Steiger, Nathan J., Jason E. Smerdon, Edward R. Cook, and Benjamin I. Cook (2018). "A reconstruction of global hydroclimate and dynamical variables over the Common Era". In: *Scientific Data* 5, pp. 1–15.

Stillman, Paul E., James D. Wilson, Matthew J. Denny, Bruce A. Desmarais, Shankar Bhamidi, Skyler J. Cranmer, and Zhong Lin Lu (2017). "Statistical Modeling of the Default Mode Brain Network Reveals a Segregated Highway Structure". In: *Scientific Reports* 7.1, pp. 1–14. arXiv: `arXiv:1408.1149`.

Strawhacker, Colleen, Grant Snitker, Katherine A. Spielmann, Maryann Wasiolek, Jonathan Sandor, Ann Kinzig, and Keith Kintigh (2017). "Risk landscapes and domesticated landscapes: Food Security in the Salinas province". In: *Landscapes of Social Transformation in the Salinas Province and the Eastern Pueblo World*. Ed. by Katherine A. Spielmann. University of Arizona Press, pp. 103–118.

Taliaferro, Matthew S., Bernard A. Schriever, and M. Steven Shackley (2010). "Obsidian procurement, least cost path analysis, and social interaction in the Mimbres area of southwestern New Mexico". In: *Journal of Archaeological Science* 37.3, pp. 536–548.

Tobler, W and S Wineburg (1971). "A cappadocian speculation." In: *Nature* 231.5297, pp. 39–41.

Varien, Mark (1999). *Sedentism and mobility in a social landscape: Mesa Verde and beyond*. University of Arizona Press.

Verdery, Ashton M., Barbara Entwisle, Katherine Faust, and Ronald R. Rindfuss (2012). "Social and spatial networks: Kinship distance and dwelling unit proximity in rural Thailand". In: *Social Networks* 34.1, pp. 112–127. arXiv: `NIHMS150003`.

Vicente-Serrano, S. M., S. Beguería, J. I. López-Moreno, M. Angulo, and A. El Kenawy (2010). "A New Global 0.5 Gridded Dataset (1901–2006) of a Multiscalar Drought Index: Comparison with Current Drought Index Datasets Based on the Palmer Drought Severity Index". In: *Journal of Hydrometeorology* 11.4, pp. 1033–1043.

Weiss, Barry (1982). "The decline of Late Bronze Age civilization as a possible response to climatic change". In: *Climatic Change* 4.2, pp. 173–198.

Wilson, Alan (1971). "Family of spatial interaction models, and associated developments". In: *Environment and Planning* 3.1, pp. 1–32.

— (2008). "Boltzmann, Lotka and Volterra and spatial structural evolution: an integrated methodology for some dynamical systems". In: *Journal of the Royal Society, Interface* 5.25, pp. 865–871.

Wood, Simon N (2006). *Generalized Additive Models: An Introduction with R*. Chapman and Hall/CRC press.