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Was the drought really responsible? Assessing statistical relationships between climate extremes and cultural transitions

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ABSTRACT

It is commonplace to assert causal relationships between episodes of extreme climate with dramatic cultural shifts. We explore the problem of statistically assessing the correspondence between episodes of extreme climate (such as droughts) and cultural events (such as depopulation) they are purported to explain. In order to do this: 1) We describe a method that permits the objective identification of climate extremes in a way that is independent of their supposed causal outcomes; 2) We discuss how we identify and date cultural transitions of interest; 3) We explore a variety of decision rules for determining whether or not there is a match between a given extreme climate interval and the interval during which a transition began; and 4) We propose an intuitive Monte Carlo approach to statistically assess the observed correspondence between the climate extremes and the cultural transitions. Our application does not indicate statistical support for a linkage between intervals of extreme climate and major transitions in any of the seven cultural traditions in the Southwest US that we examined.

1. Introduction

When one of us (Kintigh) toured Betatakin, a cliff dwelling in northern Arizona in the early 1970s, the Park ranger confidently explained that its abandonment, sometime between 1286 and 1300 (all dates C.E.), was a consequence of the northern Southwest's great drought from about 1275 to 1300. Both the abandonment and the drought are well documented (Van West and Dean, 2000; Douglass, 1929). While intuitively plausible, the validity of the causal argument is much less apparent.

Indeed, more critical analyses have cast doubt on drought as a single-cause explanation of many settlement abandonments (e.g., Kohler et al., 2010; Varien, 1999). Critiques commonly note that earlier climatic episodes in the same locations that were demonstrably more severe did not lead to abandonments. This article takes a complementary tack and attempts to address this question statistically. The problem is *to determine whether there is a relationship that is statistically unlikely to have occurred by chance between a set of multi-year extreme climate events and a set of cultural transitions they are purported to explain.*

Recent papers have statistically addressed the relationship between longer term *trends* in climate change with trends in human population and other social variables (Zhang et al., 2011; Kelly et al., 2013). However, to our knowledge, the question of correspondence between extreme climatic *events* and discrete cultural transitions has not previously been satisfactorily addressed.[1] There are four methodological problems that must be solved if we are to answer a question of this sort for any specific case: 1) We must have a way to identify and date the episodes of extreme climate; 2) We must identify and date the cultural transitions of interest; 3) We must define what it means for there to be a meaningful match between a given climate extreme and an interval during which a transition began; and 4) We must have a method that will statistically assess the observed correspondence between the climate extremes and the cultural transitions.

At the outset, we want to emphasize this paper describes a

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[1] In their study, Plog and his colleagues declined to perform statistical testing arguing it is inappropriate “given incomplete understanding of the archaeological record and the imprecise dating (1988:251).” However, they propose and apply what amounts to a binomial model (although it is not identified as such) to derive expectations for how often particular kinds of cultural events (e.g. the onset of colonization/expansion) should be associated with specified environmental conditions (e.g. periods of high spatial variability in precipitation; 1988:250–256).

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method for statistically assessing the *association* between extreme climate events and major cultural transitions. While a strong statistical association can be important evidence linking the two, it is neither a necessary nor a sufficient condition for a causal argument. Multiple lines of evidence are needed to support any argument for *causation* and a persuasive argument for causation can sometimes be made in the absence of a demonstrable statistical association. Our goal is to articulate what is needed in order to make a purely statistical assessment of observed temporal associations, so the statistical evidence can be appropriately used to support or argue against environmental explanations of cultural processes.

2. Materials and methods

2.1. Statistical assessment of the correspondence

We begin with a proposed solution to the last of the problems identified above, a method to statistically assess a temporal correspondence. We temporarily set aside the first three questions: how we identify and date the cultural transitions and the climate extremes, and how we decide whether or not there is a match between a cultural transition and an interval of extreme climate. For the moment, we will simply assume that, for the period of interest (the analytical interval), we have identified and dated both the intervals that constitute the extreme climate events and timing of the cultural transitions. And, we will use, again temporarily, a decision rule that accepts any temporal overlap between the period during which the cultural transition occurred and an interval of extreme climate as constituting a relationship between these periods.

How then do we determine the likelihood that a correspondence as strong or stronger than the correspondence observed in the actual record would occur by chance if there were no relationship between them? Classical statistics allows us to address many similar problems with statistical tests in which one uses a relevant theoretical distribution (such as the χ^2 distribution) to determine the probability of obtaining, by chance, a test statistic (such as the χ^2 statistic) greater than or equal to the one that was observed. However, in this case, we lack a relevant theoretical distribution, so we instead use a Monte Carlo approach, which has the additional benefit of being intuitively understandable without recourse to higher mathematics.

The actual data consist of a set of dated, multi-year intervals of climate extremes and a set of one or more dated cultural transitions whose correspondence with the climate extremes we wish to assess. These intervals reside within a longer *analytical interval* (e.g., 900 to 1500) over which we have knowledge of observed climatic and cultural events. To apply a Monte Carlo approach, we need to conceptualize and to generate a great number of random, or chance, occurrences that we can sensibly compare with the actual, observed data.

The Monte Carlo procedure we propose takes the cultural transition intervals as fixed in time and then creates a very large number of randomized climatic sequences. For each random trial we use our decision rule to determine the number of matches between the *randomized* intervals of climate extremes and the actual times of cultural transition. The probability we seek is simply the proportion of the random trials in which there are as many or more matches between the actual transition intervals and the randomized intervals of climate extremes as are observed in the actual data. If our analytical interval has three transitions, two of which are matched with actual climate extremes, then the probability of doing as well or better by chance is the proportion of all random runs that had two or more matches to the three transitions (i.e., a match to any two transitions or matches to all three transitions).

Loosely speaking, if randomized climate regimes only rarely produce as many or more matches than we actually observe, then we are encouraged to believe that the relationships we have observed may be meaningful. If the randomized climate intervals frequently produce at least as many matches as we observed in the actual data, then we have no statistical support for the relationship.

The question then is what exactly do we mean by a randomized climate regime? We view the analytical interval (the period of interest) as comprised of a series of intervals of extreme climate separated from each other with non-extreme intervals that we will call "gaps." In creating the randomized climate regime for the analytical interval, the fundamental idea is to randomly shuffle the *order* of the climate extreme intervals, and separately, to randomly shuffle the *order* of the gaps, leaving all the interval and gap lengths the same. Having established the new random orders of the extreme intervals and gaps, we interleave them to create a randomized climate for a hypothetical analytical interval. Every randomized climate regime will have the same number of climate extremes of the same length, and the same number of the gaps of the same length. However, by shuffling their orders, we eliminate any meaningful correspondence between the climate extremes and the fixed cultural transition intervals.[2]

To recap, we first determine how many cultural transitions match climate extreme intervals observed in the actual data. We then generate a large number of randomized climate regimes covering the analytical interval and for each we count the number of matches with the cultural transition intervals. If that number is as large or larger than the observed number of matches, then we increment a counter. Once the trials have been run, we divide that counter by the number of random trials to obtain the proportion of random trials in which a correspondence equal to or greater than the observed was found. That is the probability we are seeking: the likelihood that a correspondence as strong or stronger than the observed correspondence would occur by chance.[3]

This can be illustrated with a simple example. Let's say that we are considering the analytical interval from 1001 to 1500 and there is a single transition dated from 1201–1220. Let's also say that we have five extreme climate intervals from 1011–1030, from 1136–1140, from 1196–1205, 1361–1370, and 1441–1445. In this 500-year interval, there are 50 years of extreme climate events and a single cultural transition dated to a 20-year period (see Fig. 1).

Using a decision rule that considers any overlap between a given cultural transition interval and an extreme climate interval as a match, the single cultural transition is matched with a climate extreme in the "actual" data of our example. Using that same decision rule with randomized climate regimes, a match is found in about 23% of 1,000,000 random runs (five randomized runs, two of which have matches, are shown in Fig. 1). Thus, while we had a match in the actual data, it is also common to find a match in the randomized climate regimes. If there were no relationship between

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[2] It is possible that there is some temporal autocorrelation in the lengths of the gaps and extreme climate intervals that would affect the probabilities calculated under our randomization procedure that samples gaps and extreme climate intervals "without replacement." As alternatives, not explored here, one could sample the gaps and extreme intervals with replacement, or—using a Fourier analysis or ARIMA—generate climatic data that could be converted into gaps and extreme intervals that could be compared with the empirical data. In all these cases, however, the number of gaps and extreme intervals would frequently be different from the observed.

[3] For numbers of gaps and extreme events under 7 or 8, it is both possible and statistically preferable to examine all the possible orderings (permutations) of gaps and extreme events, count the outcomes, and derive an exact probability. If n is the larger of the number of gaps or extreme intervals, then the number of permutations is $n!(n-1)!$ For n's of 7, 8, and 9 this number is 3,628,800, 203,212,800, and about 1.46×10^{10}.

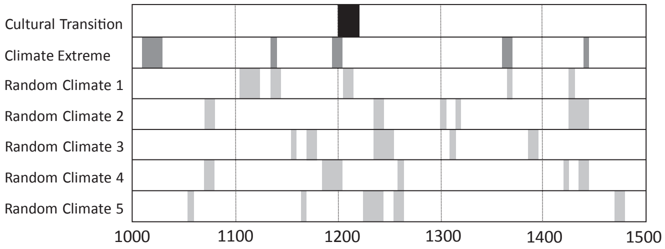

Fig. 1. Hypothetical example showing observed cultural transitions and extreme climate intervals along with five randomized climate sequences. Matches are found in the actual climate data and random sequence 1 and 4.

the transitions and the climate extremes, about a fourth of the time we would find a correspondence this strong by chance.

However, if we instead apply a more realistic matching rule that requires that the cultural transition start no less than 5 years after, and no more than 10 years after the beginning of an extreme climate event (which we stipulate must last at least 5 years), the probability drops from 0.23 to 0.07. Using this rule, we get a match by chance (with the randomized climate intervals) only about 7% of the time. Because the match observed with the actual climate data is rarely observed in the randomized climate regimes, is relatively unlikely that a correspondence would be found if there were no relationship.

The general procedure described above produces probabilities based on all cultural transitions and empirical matches that occur within a given analytical interval. If one wished to separately evaluate the statistical evidence with respect to each transition, one would simply include only the single transition in the input data and adjust the analytical interval accordingly.

2.2. *Identifying climate extremes*

While an immense literature is devoted to reconstructing past climate and a number of ways of presenting these data have been utilized, there is no agreed upon methodology to actually define the beginning and end of extreme climate intervals. The selection of a threshold value (below which drought is identified) and the method of smoothing annual precipitation data for highly variable climate regimes are the key decisions (Ingram, 2010:100–103). For example, Van West and Dean (2000) have identified dry conditions with a 10-year weighted running mean and a one standard deviation threshold. Other thresholds (e.g., quartiles, deciles), smoothing methods (e.g., cubic splines, low-pass filters), and methods of identification (e.g., PDSI) may also be applied.

Ingram (2010) and colleagues (Ingram and Streeter, Supplementary Information in Nelson et al., 2016) have recently proposed an alternative procedure and applied it to a variety of contexts using tree-ring retrodicted precipitation and streamflow data developed by others[4]. We briefly summarize that method here and use it to identify the intervals of extreme climate in the analyses presented below. First, annual variations in precipitation levels reconstructed from tree-rings are smoothed with a centered nine-year moving average. Smoothing the precipitation in this way accommodates but does not ignore anomalous years (e.g., wet) within an extreme period (e.g., drought) that likely are not sufficient to end an extreme period (one rainy year is not normally considered to end a sustained drought). Next, the smoothed precipitation values for all years are divided into quartiles. Years with smoothed values in the first quartile are considered to be of sufficient rarity to have substantially and negatively influenced resource productivity or human perceptions of productivity relative to typical conditions. Extreme intervals in this analysis are defined as five or more sequential years of extreme climate, based on the smoothed values. We expect that shorter deleterious periods were likely addressed by existing buffering strategies (e.g., storage, exchange, or diet modification).

2.3. *Identifying cultural transitions*

In this study we are examining the statistical relationship between climate extremes and cultural transitions. The transitions were periods of substantial social change, including both major shifts in settlement patterns or lifeways and dramatic transformations such as depopulations of entire regions. However, other kinds of cultural events putatively linked to climate could be similarly examined.

Sadly, we cannot identify or date cultural transitions using a well-defined procedure analogous to that proposed for identifying climate extremes. Instead, we rely on expert judgments by a group of Southwest U.S. archaeologists with whom we are collaborating on comparative studies of cultural vulnerability and transformation (Nelson et al., 2010, 2012, 2016; Hegmon et al., 2016; Torvinen et al., 2015). For their individual cases, researchers identified and dated major episodes of cultural transition. We summarize the transitions used here in Table 1. Not surprisingly, many of these transitions are recognized at the boundaries between traditionally defined archaeological periods or phases (Bocinsky et al., 2016), however we do not see all phase changes as associated with dramatic cultural transitions.

2.4. *Correspondence between a climate extreme and a transition*

The hypothetical example presented above (Fig. 1) highlights the importance of the choice of a decision rule regarding what counts as a match between an interval of extreme climate and a cultural transition. *If* there is a causal relationship, we expect that the *beginning* of the cultural transition should *follow* a substantial felt or perceived impact of a climatic episode or event.

Thus, we need to know both when the extreme climate interval begins, and the time lag from the start of the interval to the time that an archaeologically observable *impact* of the climate event would be expected. The climate events for the Southwest US examples we explore in this paper are droughts, or (for the Hohokam) periods of low stream flow (smoothed, using the procedure described above for precipitation). Ethnographic data from Pueblo Indian farmers suggests that droughts of up to four years are sufficiently common that an effort is made to maintain two to four years' supply of stored corn. As stream flow is highly variable, a similar situation would have obtained for Hohokam irrigation farmers. With the use of storage and other buffering strategies as well as the time required for the archaeologically detectable signal of a transition to appear, it seems reasonable to assume that a transformative *impact* of the drought is not strongly seen until about five years after it began. (Recall also that for our purposes, droughts are defined to be five or more years in length.) Thus, if there is a relationship between a climate extreme and a cultural transition, we would expect the archaeologically-detectable transition to begin no *sooner* than five years after the beginning of an

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[4] The Chaco, Mesa Verde, Zuni (Cibola), and Salinas (Santa Fe) precipitation reconstructions were developed at the Laboratory of Tree-ring Research, University of Arizona, by Dean and Robinson (1978). The Mimbres (Central Rio Grande) precipitation reconstruction was developed by Grissino-Mayer et al. (1997). The Central Arizona (San Francisco Peaks) precipitation reconstruction was developed by Salzer and Kipfmueller (2005). The Hohokam streamflow reconstruction (Lower Salt, Tonto, and Verde Rivers) was developed by Graybill (1989). The droughts used in this analysis were identified by Ingram.

Table 1
Cultural transitions.

Cultural tradition	Transition[a]	Nature of transition[b]	Computational interval[c]	P (Number of observed matches by chance)[d]		
				Strong match	Moderate match	Weak match
Zuni	1250–1300	Nucleation	882–1518	0.51 (1)	0.29 (2)	0.71 (2)
	1350–1400	Settlement Shift				
Salinas	1250–1325	Jacal/Masonry	895–1518	0.42 (1)	0.21 (2)	0.60 (2)
	1400–1450	Aggregation				
Mimbres	950–1000	Pithouse/Pueblo	889–1518	0.36 (1)	0.56 (1)	0.82 (1)
	1130–1150	Reorganization				
Mesa Verde	1250–1300	Depopulation	845–1340	1.0 (0)	1.0 (0)	1.0 (0)
Hohokam	1070–1100	Reorganization	796–1503	0.43 (1)	0.71 (1)	0.57 (2)
	1375–1450	Depopulation				
Central Arizona	1350–1450	Depopulation	884–1541	1.0 (0)	0.45 (1)	0.77 (1)
Chaco	1125–1150	Reorganization/Population Decline	761–1211	1.0 (0)	1.0 (0)	0.43 (1)

[a] Transitions were identified by Keith Kintigh and Matthew Peeples for Zuni, Katherine Spielmann for Salinas, Margaret Nelson and Michelle Hegmon for Mimbres, Donna Glowacki and Michelle Hegmon for Mesa Verde, David Abbott and Scott Ingram for Hohokam and Central Arizona, and by group consensus for Chaco.

[b] Zuni transitions are population aggregation and nucleation into fewer and larger settlements (1250–1300) and a widespread shift in settlement locations (1350–1400). Salinas transitions are a change in architectural styles (1250–1325) and settlement aggregation (1400–1450). Mimbres transitions are a shift in settlement location and architectural style (950–1000) and reorganization, reduction in population, and expansion of settlement locations (1130–1150). The Mesa Verde transition is a complete regional depopulation (1250–1300). Hohokam transitions are a major reorganization, contraction in settled area, and shift in architectural style (1070–1100) and a regional depopulation of large settlements (1375–1450). The Central Arizona transition is a complete regional depopulation (1350–1450). The Chaco transition is a reorganization and major decline in population of Chaco Canyon (1125–1150).

[c] The analytical interval is 900–1500, except for Mesa Verde it is 900–1300 and for Chaco it is 900–1200 (due to earlier depopulations in these regions). These intervals were selected to include all the cultural transitions on which our related comparative research (cited above) has focused. The start date for the computational interval is set at the beginning of the extreme climate interval or gap (period without a climate extreme) that includes the start date of the analytical interval. The computational interval end date is set at the end of the extreme climate interval or gap that includes the end date of the period of interest. Thus, all moving intervals and gaps considered represent real periods in the randomized climate regimes.

[d] Probability that we would see a relationship as strong or stronger than was observed in the actual data (as many or more matches) if there were no relationship between the climatic and cultural events (i.e., that they were independent). Strong Match, start of impact (5 years after start of climate extreme interval) is ±5 years of start of transition; Moderate Match, start of impact is ±10 years of start of transition; Weak Match, start of impact is ±20 years of start of transition. The number of observed matches for each decision rule is shown in parentheses.

extreme drought interval.

We also need to date the beginning of the cultural transitions. The beginning dates for archaeologically documented transitions are often hard to pin down with precision, even for the generally well-dated cultural traditions represented here. The beginning date an archaeologist assigns to a transition is the earliest date for which archaeological evidence for the transition is *detected*. That date could easily be some time after the true start of the social changes leading to the transition. And, of course, there is often uncertainty associated with the dating of the evidence that indicates the start of the transition. For present purposes we simply assume that there is some uncertainty associated with each transition's start date, which can be positive, negative, or both. The precise specification of the decision rule used ought to depend on the nature of the climatic events and the consequent lag in their impacts and on the degree of uncertainty about the dating of the transition or of the extreme climate intervals. This uncertainty frequently manifests itself (including in our application) with the rounding of transitions to dates, such as 1275 to 1300 or 1350 to 1400.

For our cases, we suggest a decision rule that says that a match is observed if the start of the impact of an extreme climate interval (the climate event start date plus the impact lag) falls within the range of possible transformation start dates including their uncertainty. Referring to Fig. 2, a match is observed with the earlier—but not the later drought. In our analyses, we choose to apply strong, moderate, and weak matching criteria to test the correspondence between climate extremes and transitions. For the reasons presented above, in our Southwest U.S. cases, we will use an impact lag of 5 years and a range of uncertainties of plus or minus 5 (strong), 10 (moderate), and 20 (weak) years around the transformation start date.

On a more technical note, we must set the computational start date for each analytical interval so that the extreme intervals and the "gaps" in each randomized climate regime are real, which is to say that they exist in the actual reconstructed climate time-series of each cultural tradition. Thus, the computational start date for each analytical interval is set at the beginning of the extreme interval or gap in which the analytical interval start date lies, and the computational end date is set at the end of the extreme interval or gap in which the end date of the analytical interval lies.

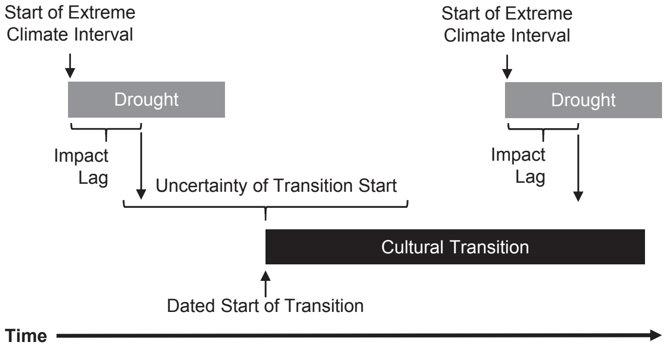

Fig. 2. Illustration showing a match between the drought shown on the left and the cultural transition. In this case, the initiation of the drought impact overlaps with the beginning of the period of uncertainty around the dated start of the cultural transition. There is no match with the drought on the right.

3. Results and discussion

We examined seven cultural traditions that experienced a combined total of eleven transitions over the period of interest (900–1500 CE in most cases). We ran all Monte Carlo analyses 3,000,000 times, producing probabilities that are stable to three decimal places.

The first row in Table 1 shows that in the Zuni case using the strong match criterion, only one of the two real-world transitions in the 900–1500 interval has a matching climate extreme, i.e., an extreme having an impact date within five years of the transition start date (this is indicated by the “(1)” next to the probability). For the moderate and weak matching criteria, however, both observed cultural transitions match an extreme climate interval whose impact date is within 10 (or 20) years of the transition start date (indicated by the “(2)”). For the strong criterion, 51% of the 3,000,000 randomized climate regimes had as many matches (one) as observed in the actual data. For the moderate criterion, the results are not much more encouraging. In that case, 29% of the randomized climates had the observed, two or more matches. (The probability is lower than for the strong matching criterion because it is less likely to randomly find *two* matches associated with the weak criterion than it is to randomly see a single empirical match associated with the strong criterion.)

In interpreting the results of this analysis, we want to emphasize that what we have done is to calculate the probability that we would see a relationship as strong or stronger than was observed in the actual data *if there were no relationship between the climatic and the cultural events* (i.e., that they were independent). In statistical terms, this is the familiar probability of making a Type 1 Error. This is *not* the probability that the relationship is non-coincidental (i.e., that there is a functional relationship between the climatic and cultural events).

In practical terms, a low calculated probability (if we had found any) would mean that an observed result (or an even stronger relationship) would be unlikely if climate and culture (as we have measured them) were independent. That would suggest either that there is a real relationship or that we have an unusual coincidence despite truly independent variables. A high probability means that the observed result could easily have occurred by chance even if there were no relationship.

In fact, looking across the seven cultural traditions examined in Table 1, there is not a single case in which the analysis strongly suggests a statistical relationship. Matches in the real world between actual droughts and cultural transitions as we have identified them are no more common than we would expect, by chance, if there were no relationship between them.

The Mesa Verde case warrants an additional comment. The abandonment of the Mesa Verde area of southwestern Colorado in the late 1200s CE would seem to be the poster child for an environmentally caused transformation, in this case the “Great Drought” often dated to 1276-1299 CE.[5] While this belief is firmly entrenched in popular and professional consciousness, it has become clear that the abandonment process, in fact, began more than 20 years or so prior to the onset of the Great Drought (Glowacki, 2015). Because zero matches were observed empirically, we don't need to run the Monte Carlo Analysis to realize that with randomized climates we would *always* find as many or more than zero matches, yielding the probabilities of 1.0 in Table 1. (In fact, with the strong match criterion, 20% of the randomized climates had matches compared with zero matches in the empirical data.)

Schwindt et al. (2016) recently provided a close examination of the relationship between climate and population history in the Mesa Verde region. Their reconstructed population, graphed at 25-year intervals, declines substantially between 1250 CE and 1275. Rather than rely on rainfall alone, they use reconstructed rainfall and temperature to model the dry farming “maize growing niche.” A steep decline in the size of the maize growing niche starts shortly after 1200 and bottoms out, across the region, about 1250 CE. They make a compelling argument that climate change does influence the population history in the Mesa Verde region, concluding:

> During the A.D. 1225–1260 period … the study area as a whole reached [its] most unfavorable balance between population size and the size of the area in which maize could be grown.

The Great Drought certainly had a major impact on the people in the Mesa Verde area and probably contributed to a continuing process of depopulation late in the 13th century. However, because it started well after the beginning of the regional population decline and even longer after the start in the decline in the size of the maize growing niche, the drought cannot be argued to have *initiated* that process—which is what we are attempting to assess here.

4. Conclusions

Arguments linking important cultural changes with natural catastrophes are commonplace in archaeology, and these days, perhaps even more so outside archaeology. Indeed, the logic of these arguments sometimes seems so compelling that a critical examination of the question appears unnecessary. The questions are rarely, if ever, well specified and these arguments often share a critical weakness. They focus on the occasions in which a correspondence is observed (e.g. a massive abandonment follows quickly on the heels of a sustained drought), but neglect the times when there is an environmental calamity and no transition, and those in which there is a cultural transition but no accompanying environmental disaster.

We have proposed a statistical methodology that enables critical examination of these associations. Any rigorous test, of course, demands a well-specified question. Our presentation demonstrates that it is actually demanding to fully specify the empirical implications of these arguments and to develop data that are sufficiently refined to test them. In our case, the question is: What is the probability of obtaining, by chance, as many or more matches between climate extremes and cultural transitions as were actually observed? To answer this question, we need to know the dates (and associated uncertainties) for the climatic and cultural events and the expected lag (if any) from onset of the environmental episode to initiation of the transformation. We also need an explicit statement of what does and does not constitute a match. The probability is calculated by applying a Monte Carlo method, with a large number of trials, to a specified temporal interval.

Our analyses of seven cultural traditions experiencing eleven cultural transitions over periods of 400–600 years did not identify a single case with statistical support for a relationship between the major transitions and episodes of climatic extremes, using a range of specific criteria for a match. This is *not* to say that the droughts experienced by these people were unimportant—only that their timing does not strongly suggest that the climate extremes were responsible for initiating the transitions.

It is important to recognize that these results, and others obtained by this method, are sensitive to the match criteria used, to the severity of the events identified as “extreme,” to the dating of the environmental and cultural transitions, and to the selection of the period of interest considered.[6] Nonetheless, we were frankly

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[5] Using our procedure to define extreme climate events, the beginning of the Great Drought is also dated to 1276.

[6] Extending the period of interest by 100 years (starting at 800 rather than 900) for our Zuni, Mimbres, and Central Arizona cases did not substantially change the results. The lowest probability obtained in these three cases remained at 0.29. The individual probabilities had a mean increase of 0.01 and ranged from −0.04 to +0.08. For the Hohokam and Chaco cases, the computed analytical interval extended back before 800 in the analysis already presented. In the Salinas case, the necessary paleoenvironmental data were not readily available to extend the interval back to 800. Because Mesa Verde has no matches with extreme intervals under any of the decision rules considered, the probabilities must remain at 1.0.

surprised that none of these associations was found to be statistically unusual.

The lack of a statistically demonstrable relationship does not necessarily mean there is no functional or causal relationship. It also does not mean that climate did not in any way contribute to the transitions. It does mean, however, that to make an argument for such a relationship, one cannot simply point out the temporal coincidence. Causal arguments must rely on additional lines of evidence (e.g. for dietary stress, conflict) that support a much more strongly contextualized argument linking the climatic and cultural events, and they must consider other climatic episodes of comparable magnitude, and their associated cultural contexts, that did not result in transitions.

The Mesa Verde case, discussed above, provides a useful example. Examining the climatic record over 660 years, and incorporating a maize niche model, population growth rates and population density, Schwindt et al. (2016) convincingly link population declines with climatic variables.

Furthermore, causal arguments cannot ignore the particular characteristics of the individual droughts or periods of low streamflow. And, similar climatic episodes could have very different social impacts because societies' vulnerabilities also change through time (Ingram, 2015). Researchers interested in how climate influences societies should consider both the probability that the observed relationships are statistically likely or unlikely, the characteristics (e.g., duration, magnitude, intensity) of the extreme climate events, and the dynamics of societal vulnerability.

We have presented an analysis of an area in which we have annual-resolution, tree-ring based climatic data and short and relatively well-dated cultural transitions. Our approach is likely to be useful in the many parts of the world that have developed tree-ring records. The method is framed in general terms and could be applied to areas with somewhat less well dated cultural and environmental sequences, as long as there is a reasonable correspondence in the precision of the dating of cultural and environmental events. This is often the case in prehistory where the same dating techniques (e.g. AMS dating) are used to date cultural events and environmental sequences. This correspondence would not obtain, for example, in historic cases in which cultural events are very precisely dated but that have only coarse resolution of the climatic data.

Droughts and periods of low streamflow undoubtedly had substantial impacts on the ancient residents of the Southwest. What we have shown is that seemingly straightforward arguments positing environmental causes of major cultural change cannot be taken at face value. What we have offered is a method to evaluate the statistical relationship between intervals of extreme climate and cultural transitions that might have been stimulated by these extremes that can provide one line of evidence to evaluate arguments for climatically-induced culture change.

The Delphi (Pascal) source code, a Windows executable file implementing this method, and the climate and transition dating files used in this analysis are freely available online at https://github.com/kintigh/MatchInterval.

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