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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

[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 $n!(n\text{-}1)!$ For n's of 7, 8, and 9 this number is 3,628,800, 203,212,800, and about 1.46×10^{10}.