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Invited Review

Piecing together the past: statistical insights into paleoclimatic reconstructions

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ABSTRACT

Reconstructing a climate process in both space and time from incomplete instrumental and climate proxy time series is a problem with clear societal relevance that poses both scientific and statistical challenges. These challenges, along with the interdisciplinary nature of the reconstruction problem, point to the need for greater cooperation between the earth science and statistics communities – a sentiment echoed in recent parliamentary reports.

As a step in this direction, it is prudent to formalize what is meant by the paleoclimate reconstruction problem using the language and tools of modern statistics. This article considers the challenge of inferring, with uncertainties, a climate process through space and time from overlapping instrumental and climate sensitive proxy time series that are assumed to be well dated – an assumption that is likely only reasonable for certain proxies over at most the last few millennia. Within a unifying, hierarchical space–time modeling framework for this problem, the modeling assumptions made by a number of published methods can be understood as special cases, and the distinction between *modeling assumptions* and *analysis* or *inference* choices becomes more transparent.

The key aims of this article are to 1) establish a unifying modeling and notational framework for the paleoclimate reconstruction problem that is transparent to both the climate science and statistics communities; 2) describe how currently favored methods fit within this framework; 3) outline and distinguish between *scientific* and *statistical* challenges; 4) indicate how recent advances in the statistical modeling of large space–time data sets, as well as advances in statistical computation, can be brought to bear upon the problem; 5) offer, in broad strokes, some suggestions for model construction and how to perform the required statistical inference; and 6) identify issues that are important to both the climate science and applied statistics communities, and encourage greater collaboration between the two.

1. Introduction

This paper is a product of our participation in the 2009–2010 program on "Space–Time Analysis for Environmental Mapping, Epidemiology and Climate Change",[1] organized by the Statistical and Applied Mathematical Sciences Institute (SAMSI), an NSF sponsored research center in North Carolina. Our focus at SAMSI was on the statistical challenges surrounding the reconstruction of past climate from incomplete instrumental and proxy data sets, and part of the motivation for writing this piece stems from the various controversies surrounding the interpretation and assimilation of instrumental and proxy-temperature time series. Much of the controversy points to the potential benefits of greater collaboration between statisticians and paleoclimatologists in the analysis and interpretation of climate data, a sentiment that is echoed in the recent United Kingdom parliamentary report on the University of East Anglia's Climate Research Unit (CRU):

"*We cannot help remarking that it is very surprising that research in an area that depends so heavily on statistical methods has not*

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[1] For more information, see www.samsi.info/programs/research-programs/past.

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been carried out in close collaboration with professional statisticians. Indeed there would be mutual benefit if there were closer collaboration and interaction between CRU and a much wider scientific group outside the relatively small international circle of temperature specialists. "[2]

It seems pertinent that a group of statisticians interested in the climate reconstruction problem, in collaboration with a climate scientist, present both a formal description of the reconstruction problem and offer suggestions for how this field can be advanced via a reasoned use of modern statistics. We will not present a new reconstruction, or propose, test, or apply a specific analysis model. Instead, we provide a detailed presentation of hierarchical statistical models and describe how the different levels should be specified in the context of paleoclimatic reconstructions. More general reviews of climate reconstructions of the last few millennia can be found, for example, in the 2006 National Research Council report on the subject (NRC, 2006), or the Jones et al. (2009) review in *The Holocene*. Hughes and Ammann (2009) provide a broad overview of the state of paleoclimate reconstruction methods, and, as we do, offer suggestions on how to move forward. This article builds upon and provides the necessary background to implement the hierarchical models mentioned in Hughes and Ammann (2009).

Inferring past climate from raw observations of the natural world is a grand challenge. We focus on one particular aspect of the problem: given climate sensitive proxy time series that are assumed to be well dated, how should they be combined along with the instrumental record to arrive at estimates, with uncertainties, of a climate process through space and time? We consider the challenges involved in modeling a space–time process such as annual mean surface temperature anomalies, as well as the difficulties involved in inferring such a process from a number of different data sources, all of which are noisy and incomplete. It is our aim to clearly define the scope of the problem and the nature of the challenges, identify and describe the relevant statistical tools and techniques, and indicate how they can be used in particular applications. In addition, we describe how numerous published methods fit within the proposed hierarchical framework. Posing the paleoclimatic reconstruction problem in the language of modern statistics will help elucidate those areas in which statisticians have expertise that can be brought to bear upon this problem, and will encourage greater collaboration between the climate science and statistics communities.

The assumption that the proxy series are well dated is likely only reasonable for certain types of proxy over at most the last few millennia. The treatment of time-uncertain proxy time series is an active field of research (Haslett et al., 2006a; Auestad et al., 2008; Haam and Huybers, 2010), and becomes particularly important when considering proxy archives such as pollen and sea floor sediment cores that, in contrast with tree rings and ice cores, do not form laminations with a known frequency. Likewise, raw observations of proxy archives frequently undergo considerable processing before being put forth as a climate sensitive time series. For example, raw pollen counts or percentages are transformed via comparison with modern analogues (e.g., Haslett et al., 2006b), and some estimate of the biological growth effect must be removed from individual tree ring series before they are combined into a climate sensitive site chronology (e.g., Briffa et al., 1992; Melvin and Briffa, 2008; Schofield, in preparation). Recent work (e.g., Haslett et al., 2006b), has focused on forward-model based approaches to processing raw observations into climate sensitive series. This article will not focus on either time uncertainty or this processing of raw proxy observations into climate sensitive series, but we will provide brief comments on how progress on those problems can be incorporated into the framework outlined below.

It is important to recognize that we are not the first group of statisticians to become interested in this problem, and hopefully we are not the last. There have been numerous time series analyses of paleorecords in the statistics literature, such as Visser and Molenaar (1988); West (1997); Harvill and Ray (2006); and Haslett et al. (2006b). More recently, Li et al. (2010) present a hierarchical model and apply it to pseudoproxies derived from climate models, while Brynjarsdóttir and Berliner (2011) reconstruct surface temperatures using borehole temperature profiles. Likewise, several recent papers from the climate literature have proposed hierarchical models in the context of reconstructing past climate. Lee et al. (2008) propose a state-space or Kalman filter model for inferring large-scale spatial average temperatures, which we interpret as a hierarchical model (see Section 8.3). Lee et al. (2008) include estimates of climate forcing series in the inference model, and the specification of separate models for the target process and the data. In contrast, Tingley and Huybers (2010a,b) propose a simple hierarchical statistical model without forcings to infer a climate field in both space and time. While there are examples in the published literature of hierarchical models and Bayesian analysis applied to paleoclimate data (e.g., Haslett et al., 2006b; Li et al., 2010; Tingley and Huybers, 2010a), what has been lacking, until know, is a more general argument for and exposition of Bayesian hierarchical modeling for inferring past climate.

In Section 2, we introduce a representative subset of the data from Mann et al. (2008a) in order to illustrate the challenges posed by paleoclimatic and instrumental data, and to motivate the modeling approach we favor. We then present a general, hierarchical statistical space–time modeling framework appropriate for the reconstruction problem in Section 3. The key specifications of this class of models are the space–time structure of the target climate process, which we discuss in Section 4, and the relationships between the statistical processes characterizing the data sources and the target process, which we describe in Section 5. We then discuss issues regarding the observations in Section 6, including the influence of observational errors and the treatment of missing data. Performing inference on this class of space–time models is non-trivial and can be computationally intensive, and we provide suggestions on how to overcome these difficulties in Section 7. Within the hierarchical modeling framework, a number of published reconstructions methods can be interpreted as special cases, and thus our approach yields a unifying framework for paleoclimatic reconstructions. We discuss several commonly used methods in Section 8, and then close with some general remarks and discussion in Section 9.

2. A motivating data set

Mann et al. (2008a) present a reconstruction of hemispheric and global surface temperatures over the last two millenia using 1209 proxy time series (described in the supplement, Mann et al., 2008b) and the $5^\circ \times 5^\circ$ gridded surface temperature data product from the University of East Anglia's Climatic Research Unit (Brohan et al., 2006).[3] We illustrate a number of challenges posed by paleoclimate data by considering a subset of this data, geographically restricted to Northern North America and Greenland, and consisting of only the instrumental, tree ring density, tree ring width, ice core $\delta^{18}O$, and annual lake sediment varve thickness time series (Figs. 1 and 2).

There are a number of climate quantities that a researcher might wish to reconstruct from a data set of this sort, including time series of

[2] Taken from www.uea.ac.uk/mac/comm/media/press/CRUstatements/SAP.

[3] The proxy data is available at www.meteo.psu.edu/mann/supplements/MultiproxyMeans07/, and the instrumental data set at www.cru.uea.ac.uk/cru/data/temperature/.