A New Framework for Inferring Earth's Past Climate

Bayesian Hierarchical Models for Climate Field Reconstruction; Palisades, New York, 8–11 February 2011

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Inferring Earth's past climate from noisy, incomplete proxy time series remains an important challenge in the geosciences. Bayesian hierarchical models (BHMs), which have theoretical advantages over established regression methods based on empirical orthogonal functions (EOFs), are a powerful new method for spatially explicit climate field reconstruction. Whereas EOF-based approaches involve projecting the proxy and instrumental data sets onto reduced subspaces and then assuming a linear relationship between these transformed variables, BHMs allow for scientific knowledge about the target climate field to be included at the process level of the hierarchy and for each data type to have a different functional relationship with that target field.

A workshop held at the Lamont-Doherty Earth Observatory of Columbia University provided in-depth exposure to BHMs for climate reconstructions to researchers who currently use EOF-based multivariate regression models for inferring past climate. In addition, the workshop explored how other established methods perform in relation to BHMs and examined the ability of each approach to characterize reconstruction uncertainties in practice.

One topic discussed at the meeting was the distinction between model construction and the inference technique used to fit the model and infer past climate. The key shift in thinking is not to Bayesian methods but to a focus on model construction. Inference can then be conducted using a range of tools, but as models become more involved, Bayesian inference strategies may be the simplest option and additionally allow for a full treatment of uncertainty. Hierarchical modeling provides a flexible paradigm in which to encode scientific knowledge and a framework that leads naturally to debates over what science should be included rather than a focus on the details of the inference.

Uncertainty quantification was also discussed at the workshop. Bayesian inference allows for direct sampling from the posterior distribution of all unknowns, and the resulting uncertainty estimates for the reconstructed climate encapsulate the uncertainties involved in the estimation of all model parameters. Such results are not readily obtainable using standard, frequentist inference for regression models.

Participants also noted the advantages of methods, such as Bayesian inference, that produce ensembles of possible reconstructions. An ensemble can be used, for example, to estimate the distribution of extreme values or the uncertainty in a temporally smoothed time series. Such results cannot readily be obtained from traditional, frequentist confidence intervals.

In addition, workshop attendees agreed that it is important to consider both bias and variance when assessing a reconstruction of past climate. Traditional validation methods have developed tools appropriate for evaluating bias, while Bayesian posterior ensembles are especially useful in evaluating variance.

The question of how to model spatial covariance within the BHM framework was also discussed in detail, with a focus on how to incorporate information about specific spatial patterns such as empirical EOFs and teleconnection patterns. The important modeling choice in this regard is whether such information should be included in the mean structure or the covariance structure, while technical issues such as the number of EOFs to retain should rightly be secondary to the development of reasonable and scientifically informed models.

As with the adoption of any tool or technology into a new situation, there is necessarily a learning curve, and it will take considerable collaborative effort between statisticians and paleoclimatologists to fully exploit hierarchical models in the context of paleoclimatic reconstructions. This workshop took significant steps toward enabling such collaborations, the results of which will be a welcome addition to the growing literature on the inference of past climate.

The online supplement to this meeting report (http://www.agu.org/eos_elec) provides additional details on the topics discussed at the meeting.

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