Lake sediments as climate archives: strategies for quantifying and reducing uncertainty

Background

Lake ecosystems respond to climate change in many ways, and lake sediments contain a wide range of physical, chemical and biological proxies that can be used to reconstruct palaeoclimates at a range of resolutions and temporal scales. The complexity of the direct and indirect linkages between climate, limnological processes and the preservation of their record in the sediments is recognised but remains a major source of uncertainty. In closed basins changes in effective moisture may be reconstructed from fluctuations in lake level and/or salinity inferred from physical and biological proxies. Similarly, changes in ice cover or temperature-driven changes in pH or DOC may be reconstructed from biological proxies. These ***indirect*** approaches can yield records of high temporal resolution but often only provide qualitative estimates of climate variables. Here we focus on ***direct*** approaches using biological proxies that have the potential to yield high-resolution quantitative estimates of climate change, and on the uncertainties in their interpretation.

Chronological uncertainties

Meromictic lakes with strong seasonal differentiation in sediment input often contain banded or laminated sediments and can allow annually-resolved chronologies to be developed. The variance between replicate lamination counts of the same core typically indicates uncertainties of 3-5%. Errors can be reduced by correlating and cross-dating multiple cores form the same lake. Where laminae are clear and well-resolved chronological uncertainty of < 1% is possible, although where this is not the case the errors may be appreciably higher.

Dating of non-laminated sediments for the last 2000 years usually relies on ^{14}C, supplemented by ^{210}Pb and other short-lived radioisotope dating of the upper-most sediments and additional markers where available (e.g. tephra, key pollen taxa). Despite its importance, age-depth modelling has remained one of the weakest areas of palaeolimnology although recent developments of Bayesian models that allow information on the depositional process to refine the chronology show great promise. Bayesian approaches also have the advantage of combining the modelling and uncertainty estimation in a single, robust, mathematical framework. The urgent need is for training and the dissemination of best practise and software.

Uncertainty in climate reconstructions from biological proxies

Climate reconstructions from biological proxies such as diatoms and chironomids are based on the so-called transfer function approach, in which a mathematical model of species-climate responses derived from a modern training or calibration dataset is applied to fossil assemblages. The approach yields quantitative reconstructions of climate parameters (usually summer temperature for limnological proxies, or temperature and precipitation for pollen). Uncertainties (expressed as standard errors of prediction) are usually estimated from an internal cross-validation of the training set and are typically of the order of 1-2 ºC. However, these are very naive estimates of uncertainty and the true values are likely to be substantially greater.

First, we have very limited knowledge of the physiology of most aquatic biological proxies and, although some may have a direct response to climate, for many the response is mediated through other physical and chemical limnological variables. In many training sets the climate signal is often secondary and usually confounded with water chemistry variables (e.g. higher temperatures correlated with high nutrients, high DOC etc.). An implicit assumption of the transfer function methodology is that the relationships between climate and these "nuisance" variables is invariant through time. This assumption is violated for many regions and is questionable even for remote systems (e.g. those impacted by increases in atmospheric N deposition). Variance partitioning of the training set data can be used to quantify the "independence " of the climate signal and the strength of confounding variables. The latter can account for up to 50% of the climate reconstruction. We currently have, albeit crude, methods to detect no-analogue assemblages based on biological dissimilarity measures but we lack methodologies to identify and quantify the effect of confounding variables.

A second source of additional uncertainty is the choice of numerical calibration method. Palaeolimnologists are prone to tinkering and choose the numerical technique, model complexity (e.g. number of analogues in MAT or components in WAPLS), and delete outliers, to reduce the overall training set error. Cited uncertainties rarely include uncertainties associated with model choice. The behaviour of different numerical methods under no-analogue or other conditions is also poorly known, although recent work has shown that some commonly used techniques are subject to overfitting in the face of spatially autocorrelated calibration data or the presence of strong confounding gradients. Such overfitting yields optimistically low uncertainty estimates and, in some cases, reconstructions prone to extrapolation.

Often several different calibration models yield similar internal uncertainties but yield reconstructions that differ in magnitude, shape (trend) or both. Better methodologies and numerical tools are needed to evaluate reconstructions and in some cases we just have to accept that, at present, it may be impossible to identify the "best" reconstruction.

Strategies to reduce uncertainty

Collaborative efforts have led to an increase in the quality (e.g. taxonomic consistency) of the biological data but there is often considerable error in the climate data used in the calibration models. The use of mean air temperature data instead of spot water temperature measurements is an improvement but the complexity of the relationship between air and lake water temperature means that substantial portions of the apparent uncertainty in the training set is due to unmodelled error in the climate data. The use of in-situ temperature data is the obvious solution but is usually prohibitively expensive. Improved air-water temperature models that take account of lake aspect and catchment conditions are desirable.

Even with more accurate climate data the production of accurate biologically-inferred climate estimates for the late Holocene is a major challenge. First, the uncertainty in the reconstruction is often similar to the expected temperature changes, and second, non-climatic variables such as soil development, vegetation change and human impact may have had a greater effect on the biological proxies than climate. Individual climate reconstructions may contain both climate and spurious non-climate signals and it is currently very difficult to disentangle the two.

An obvious strategy to reduce uncertainty is to compare and combine reconstructions from multiple sites. Current approaches involve the use of a loess local smooth to derive a consensus reconstruction. A similar approach using smoothing splines in 4 dimensions (3 space and time) has been used to derive gridded climate reconstructions for Europe from pollen data. More sophisticated approaches using dynamic factor analysis to identify common and unique trends also have great potential here. Finally, Bayesian methods may again provide the most elegant solution because they can potentially perform reconstructions of entire site networks, combining the reconstruction and inter-site comparison steps in a single modelling framework that accounts for uncertainty in the training set, fossil data and chronologies. Bayesian methodologies have been applied to single-site reconstructions but there are major computational barriers to its routine use. Increased collaboration between palaeoecologists, statisticians and computer scientists is needed to make significant progress.

Requirements for data archiving

Climate reconstructions derived from biological proxies, and their chronologies, are transient. Any database must store the raw data from which the reconstruction and chronology was derived, along with a detailed description of the calibration and age-depth model, and preferably the training set data to enable recalibration using different reconstruction models.