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Identifying coherent patterns of environmental change between multiple, multivariate records: an application to four 1000-year diatom records from Victoria, Australia

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ABSTRACT

Empirical orthogonal functions (EOFs) of indirect archives of environmental change are increasingly used to identify coherent trends between palaeoclimate records, to separate externally forced patterns from locally driven idiosyncrasies. Lake sediments are particularly suited to such syntheses: they are abundant in most landscapes and record a wide array of information, yet local complexities often conceal or confuse the climate signal recorded at individual sites. Lake sediment parameters usually exhibit non-linear, multivariate and indirect responses to climate, therefore identifying coherent patterns between two or more lake records presents a complex challenge. Ideally, the selection of representative variables should be non-subjective and inclusive of as many different variables as possible, allowing for unexpected correlations between sites. In order to meet such demands, we propose a two-tier ordination procedure whereby site-specific (local) ordinations, obtained using Detrended Correspondence Analysis (DCA), are nested within a second, regional EOF. Using the local DCAs as representative variables allows the retention of a larger fraction of variance from each site, removes any subjectivity from variable selection and retains the potential for observing multiple, coherent signals from within and between each dataset. We explore this potential using four decadally resolved diatom records from volcanic lakes in Western Victoria, Australia. The records span the 1000 years prior to European settlement in CE 1803. Our analyses reveal at least two coherent patterns of ecological change that are manifest in each of the four datasets, patterns which may have been overlooked by a single-variable, empirical orthogonal function approach. This intra-site coherency provides a valuable step towards understanding multi-decadal hydroclimate variability in southeastern Australia.

1. Introduction

Our understanding of Southern Hemispheric climate variability on multi-decadal to multi-centennial timescales is limited by a scarcity of quantitative, sub-decadally resolved climate records, a problem which is particularly manifest in Australia. To date the only annually resolved palaeoclimate records from Australia which extend further back in time than the most recent c. 350 years, are located in the latitudinal extremes of Tasmania and the northern tropics (Cook et al., 2000; Neukom and Gergis, 2012; PAGES 2k Consortium, 2013; Haig et al., 2014). By contrast, a number of sedimentary records exist, from shallow coastal/marine areas, lakes, peat bogs and speleothems, some of which span multiple millennia at sub-decadal resolution, but are limited by some degree of chronological uncertainty (Dodson et al., 1994; Mooney, 1997; Saunders et al., 2012, 2013; Mills et al., 2013; Wilkins et al., in press; Barr et al., 2014). In most cases, these archives offer

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indirect records of climate change, via geochemical, sedimentological and palaeoecological properties, limiting the potential for deriving quantitative climate records. However, identification of coherent patterns amongst multiple datasets can provide convincing evidence for regional scale climate or hydrological change. Importantly, by combining datasets, it is possible to separate patterns of externally forced climate variability from the idiosyncrasies which may exist within stand-alone records. Such potential has been highlighted by the use of empirical orthogonal functions (EOFs), derived using principal components analysis (PCA), in order to identify the coherent patterns between multiple records within regional and global palaeoclimate datasets (Clark et al., 2007, 2009; Shakun and Carlson, 2010; Anchukaitis and Tierney, 2012; Clark et al., 2012; Shakun et al., 2012; Tierney et al., 2013).

The use of EOFs is well grounded in climate and palaeoclimate research, but the majority of studies have applied the technique to either instrumental data or annually resolved palaeoclimate records such as tree ring or coral datasets (Weare et al., 1976; Smith et al., 1996; Mann et al., 1998). The extraction of EOFs from sedimentary archives represents a particular challenge due to the uncertainties associated with both dating and climatic interpretation. Recent implementation of Monte Carlo iterative age modelling within EOF analyses represents a valuable step towards dealing with age uncertainty in sediment records (Shakun and Carlson, 2010; Anchukaitis and Tierney, 2012). However, an ongoing issue with sediment based EOFs relates to the multivariate nature of many sedimentary records. Most sedimentary archives contain multiple lines of information, including geochemical parameters, microfossil remains or sedimentological properties. In the usual absence of quantitative palaeoclimate reconstructions (e.g. temperature, rainfall; Saunders et al., 2012, 2013), the selection of representative variables from each site remains a source of ambiguity. It is impossible to include all of these variables within a regional ordination: doing so would fail the criterion of data independence and potentially bias the analysis to the site which contributes the most variables. However, selecting a single representative timeseries from each site can be subjective and can undermine the explorative element of the analysis. In addition, reducing a detailed matrix to a single variable leads to the loss of potentially relevant information and discards the considerable effort and time invested in collecting the data in the first place.

One particular consequence of reducing multivariate palaeoecological data to single variables prior to EOF analysis is that it undermines the possibility of observing correlations between secondary modes of variability at two or more sites, despite the intuitive likelihood of such correlations existing. Lake ecosystems are subjected to a variety of external and internal forces, which ultimately determine the expression of their sedimentary record (Battarbee, 2000; Smol et al., 2005; Mills et al., 2014; Wigdahl et al., 2014). Neighbouring lake systems exhibit different sensitivities to external forcing: a hypothetical 'Site A' might respond dramatically to changes in rainfall, through changes in lake level, whilst the effect of rainfall upon 'Site B' might manifest in a more muted physical/ecological response, e.g. through changing nutrient balance or lake water stratification. In such a scenario, even though rainfall changes do affect 'Site B', a comparison of the major patterns of ecological change at both sites would reveal limited coherency. Existing approaches to regional data syntheses do not allow for such variable climate–lake interactions. We therefore propose an alternative approach to exploring regional coherency between sedimentary archives using two-tiered nested ordinations. This involves reducing each site-specific multivariate dataset to a series of orthogonal variables using established methods of ecological data dimension reduction (in this case, Detrended Correspondence Analysis; DCA). The DCA sample scores of all site specific ordinations (hitherto termed 'local DCAs') are then combined within a 'regional' (multiple site) EOF analysis, which is performed using PCA following previous studies. The approach is applied to a suite of four diatom records from volcanic lakes in Western Victoria, Australia, which span the millennium prior to European colonisation (CE 800–1800). Coupled with iterative age modelling to account for age uncertainty similar to Anchukaitis and Tierney (2012), our approach provides a flexible, multi-layered means of exploring coherency between multivariate sediment records which allows for the detection of multiple patterns of change.

2. Sites and methods

Four sedimentary diatom records were selected from lakes within the western Victorian Volcanic Plains, Australia. Those sites were Lake Purrumbete, Lake Elingamite, Lake Surprise and Tower Hill Main Lake (Fig. 1). Each of the lakes is situated in a late Pleistocene volcanic crater, located within 50 km of the western coastline of Victoria. The climate of this region is Mediterranean in character, with cool, wet winters and mild, dry summers. The four study sites were selected based on their proximity to each other, similarities in lake and catchment morphology and size and because for each site there is a recently derived diatom record which spans the last >1200 years at decadal or sub-decadal temporal resolution. Given the sparse distribution of high-resolution records for the entire Australian continent, let alone the Southern Hemisphere, this collection of similar datasets from western Victoria represents a significant palaeoclimate resource.

All datasets used in this study have been published, and therefore collection of sediment cores and subsequent diatom analyses are discussed in those papers and reports (Barr, 2010; Mills et al., 2013; Barr et al., 2014). All raw diatom data are available via the NOAA Palaeoclimatology Database (http://www.ncdc.noaa.gov/data-access/paleoclimatology-data). The previous papers and reports describe the dating techniques employed, using a combination of radiocarbon analysis (of plant macrofossils, pollen extracts and acid resistant organic material), ^{210}Pb dating of recent sediments and the use of exotic pollen horizons in comparison with the known age of local European colonisation. In some cases, the original authors were led to reject certain anomalous radiocarbon ages, and those decisions are mirrored here. For Lake Elingamite and Lake Surprise, a radiocarbon age offset was estimated based on differences between ^{14}C and ^{210}Pb dates in the upper sediments (480 $\pm$ 44 years and 424 $\pm$ 74 years respectively; Barr et al., 2014). These offsets, which are interpreted to reflect the influence of radiometrically old groundwater derived carbon, are also used here for consistency.

Age-depth models were derived using the CLAM program in R (Blaauw, 2010). In order to maintain a consistent approach throughout, each of the four age models was constructed using smoothed spline interpolation, with a relatively rigid smoothing factor of 0.6 chosen as one which adequately captures the distribution of age constraints for all sites. ^{14}C ages were calibrated against the Southern Hemisphere ^{14}C master chronology (Hogg et al., 2013), with age uncertainties based on 10,000 Monte Carlo iterations (Blaauw, 2010).

In an approach which largely follows Anchukaitis and Tierney (2012), palaeoenvironmental timeseries were generated and analysed within an iterative age modelling framework to address the imprecision of radiocarbon-based chronologies. For each of the 10,000 CLAM derived site-specific age models, each dataset was linearly interpolated, resampled at 5 year intervals and truncated to