Diatom flickering prior to regime shift

ARISING FROM R. Wang et al. Nature 492, 419–422 (2012)

Potential early warning signals for regime shifts are studied intensively in the field of ecology[1–4]. Wang and colleagues[1] investigated changes in the sediment diatom composition of Lake Erhai, China, and concluded that a regime shift in diatom assemblages that occurred around 2001 was preceded by flickering behaviour for 10 to 30 years. We propose that their results may be more reflective of their data processing than of the diatom data. Although flickering behaviour before regime shifts may be observed in some palaeoenvironmental records, we question whether this behaviour applies to diatoms in Lake Erhai. There is a Reply to this Brief Communication Arising by Wang, R. *et al* . *Nature* **498,** http://dx.doi.org/10.1038/nature12273 (2013).

Wang *et al.*[1] base their conclusions on changes in standard deviation, skewness and lag1 autocorrelation of the diatom assemblage composition (detrended correspondence analysis; DCA) and its diversity (Hill's diversity index N2; HDI) in a sediment core. The statistics were calculated with a 59-year sliding window on the residuals from a linearly interpolated time series, detrended by subtracting a smooth exponential moving average.

We were intrigued by these results, and while investigating the underlying statistical analyses, we noticed three points. First, decreasing time resolution with depth implies that samples represent approximately 1 year in the upper part and approximately 4 years in the deeper part of the sediment profile (Supplementary Fig. 2 in ref. 1). Greater temporal aggregation in the deeper profile reduces the temporal variation in diatom composition, giving a reduced standard deviation for the oldest data. Second, linear interpolation to produce an annual time series alters the statistical properties of the time series by reducing the standard deviation, increasing autocorrelation and broadening the expected distribution of skewness[5]. Coarser resolution in the older sediment results in more interpolated values and thus lower standard deviation and higher autocorrelation. Third, their detrending does not subtract a smooth curve, but a phase-shifted version of the original data with a tendency to overshoot when the original curve changes direction. This results in large residuals when there are abrupt changes in the data. These are expected in the highest resolution part of the core, where there is least averaging and interpolation. The sensitivity tests applied[1] do not seem to address fully the fundamental problems of unevenly spaced temporal data[5].

To assess the null expectation of their methods, we used a simulated time series with mean characteristics similar to those of the DCA[1] and added uncorrelated noise (Fig. 1a). Random variation of the underlying simulated time series is reduced unevenly by aggregation that mimics the sediment sampling from Lake Erhai and interpolation (Fig. 1b). Standard deviation is reduced by factors of approximately 6 in the older data and approximately 3 in the more recent data (Fig. 1c). The increase in standard deviation over time reported in the paper by Wang *et al.*[1] has a similar magnitude to that expected from a purely random process analysed with their methods. The skewness broadens when the sliding window spans data with varying standard deviations, and there is a slight shift towards negative values (Fig. 1d). The skewness reported also display a shift towards negative values within the bounds of expected values. Data processing introduces strong autocorrelation in the older data that is reduced gradually with improved temporal resolution (Fig. 1e), consistent with the pattern that they described.

We reanalysed the data from the paper by Wang *et al.*[1] without interpolation, using a more robust detrending approach and accounting for differences in temporal aggregation by implicitly assuming variance heterogeneity (Fig. 2a, b). There is a gradual increase of approximately 50% in the DCA standard deviation, much smaller than the increase they reported, and the HDI standard deviation does not change (Fig. 2c, d). Skewness in DCA and HDI displays quite different patterns to those reported in their paper, and remains within the approximate 95% confidence bounds ($\pm$ 1.0) expected from a random normal process. Autocorrelation does not decrease over time and is generally low.

The trends in standard deviation, skewness and autocorrelation reported as potential early warning signals of a "regime shift in the trophic state of Lake Erhai" by Wang *et al*.[1] are consistent with the null expectation of their methods and are not reproduced with more robust methods. We therefore suggest that these may be an artefact of the numerical methods used and the inherent problems in time-series analysis of samples with uneven temporal spacing from sediment cores.

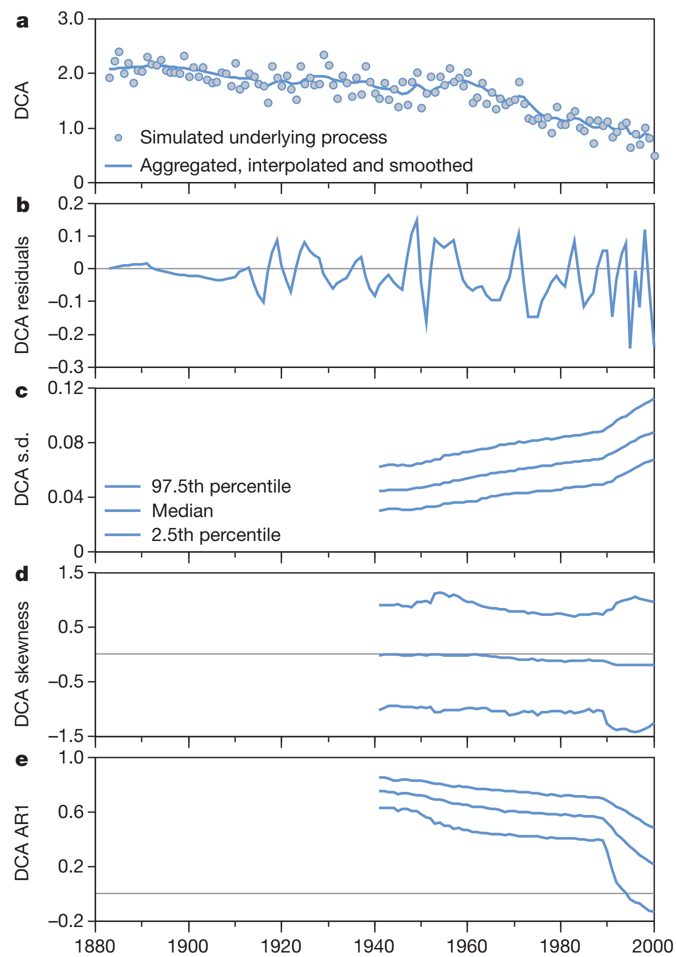

Figure 1 | **Simulated data processing and early warning signals. a**, One simulation of the underlying data-generating process and the time series resulting from temporal aggregation, interpolation and smoothing. **b**, Residuals from the simulated process in **a** and from the data processing in ref. 1. **c**–**e**, Distributions of standard deviation, skewness and lag1 autocorrelation (AR1) from 1,000 simulations using a 59-year sliding window during the period between 1883 to 2000. This figure is for comparison with Fig. 3 of ref. 1. Grey horizontal lines mark 0 on the *y* axis.

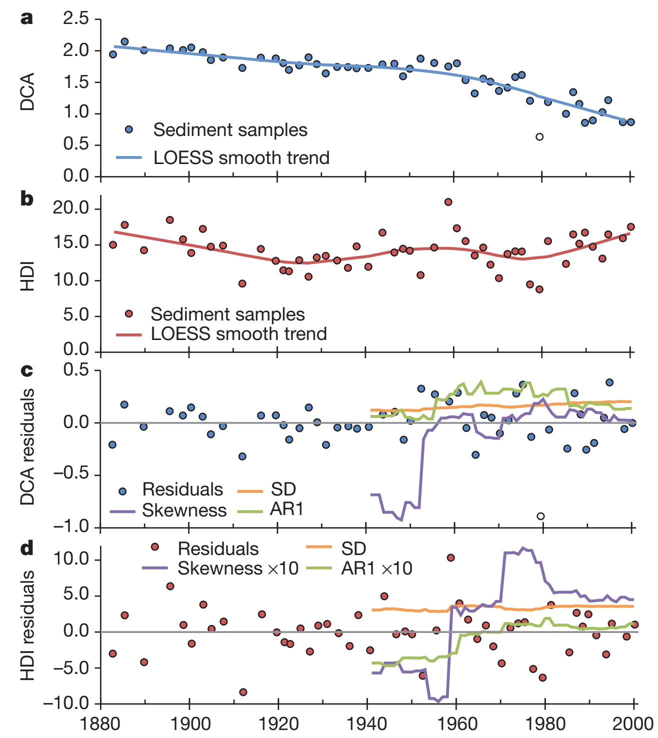

Figure 2 | Re-analysis of potential early warning signals compiled from the diatom community in Lake Erhai. a, **b**, Trends in diatom composition and diversity based on detrended correspondence analysis (DCA) of diatom composition (**a**) and Hill's diversity index N2 (HDI) (**b**) with LOESS smoothing functions used for detrending. **c**, **d**, Residuals from **a** and **b**, with s.d., skewness, and autocorrelation (AR1) calculated using a 59-year sliding window during the period between 1883 and 2000. Skewness and autocorrelation are scaled by factor 10 in **d**. One DCA observation deviated substantially from other observations (open symbol in **a** and **c**) and was not included in this re-analysis.

Methods

We simulated time series ($n = 1{,}000$) with an annual resolution of a process that resembles the characteristics of DCA[1]: the mean decreases slowly before 1960 and faster thereafter, and the standard deviation of the uncorrelated noise is 0.25. The time series were aggregated to mimic the observed sample spacing. The remaining analysis follows ref. 1.

To repeat the analysis of early warning signals with more robust methods, we detrended the non-interpolated DCA and HDI values before 2001 (Fig. 1 in ref. 1) with a LOESS smoothing function. Residuals from detrending were standardized by the square root of the period that the values represent to account for differences in temporal aggregation. Autocorrelation is calculated from the data with missing values, calculation of early warning signals otherwise follow ref. 1.

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Wang *et al.* reply

REPLYING TO J. Carstensen, R. J. Telford & H. J. B. Birks

Some issues have been raised with regard to our paper[1], by Carstensen *et al.*[2]. In terms of our data processing, we were aware from the outset of the problems of unevenly spaced temporal data and sediment dating errors. We also wanted to duplicate, as far as possible, the methods published previously that had been used to identify early warning signals in palaeoenvironmental data (for example, ref. 3). Thus, we applied two standard smoothing functions (exponential and Gaussian kernel) to interpolated and non-interpolated (original) diatom data, expressed as three statistical indices (detrended correspondence analysis (DCA), Hill's diversity index N2 (HDI) and correspondence analysis), using different sliding-window sizes and the two-standard-deviation range of dates for each sample.

Despite their criticisms, the LOESS approach used by Carstensen *et al.*[1] also does not capture explicitly the unequal time increments in the sediment data and does not confront the dating error problem. However, the results described (Fig. 2 in ref. 1) still confirm increasing variance for DCA, albeit with reduced and possibly non-significant trends, and increased skewness if one 'outlier' is retained. We also note that their results do not replicate the full range of our tests. They do not seem to address the issue of window size, the sensitivity to the full range of dating errors, or cover the full range of indices (there is no correspondence analysis). Their assumption that "Greater temporal aggregation in the deeper profile reduces the temporal variation in diatom composition" has to be countered by the observation that among the samples dating back to 1885 ($n = 49$), two of the seven larger temporal aggregations ($\geq$3.4 years per sample compared to the mean of 2.4 $\pm$ 0.9 years per sample) are in fact recent samples, dated to 1986 and 1998 (Supplementary Fig. 2a in ref. 1).

The new simulation method proposed by Carstensen *et al.*[1] to test the null hypothesis is interesting, but again does not fully account for the temporal aggregation in the actual DCA data; instead, it 'resembles' our DCA data. The model does not use the real time periods in the sediment data derived from the dating model and it does not take into account the real errors in the dating model. Therefore, the simulation demonstrates a general principle for testing a null model but does not in itself overturn the findings from the analyses of our paper.

In conclusion, given the sensitivity of residuals to different smoothing functions and the choice of parameters (for example, window size and span value), the main implication of the work by Carstensen *et al.*[1] is that future studies of sediment data should evaluate the results from a wide range of smoothing-function options. In any case, we do not advocate the use of time-series analyses of sediment data alone to infer early warning signals. At Lake Erhai, China, our context included a wealth of real-time observations (for example, algal blooms) that amounted to prima facie evidence for increased ecosystem instability before a critical transition. In our view, the new results do not make a case for overturning the main findings of the paper.

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