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Advances in Bayesian time series analysis of palaeoclimate data

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Time series analysis of palaeoclimate data is used to identify quasi-periodic changes attributable to astronomical forcing of insolation by Earth's axial obliquity and precession, and orbital eccentricity, i.e., Milankovitch cycles. Hays et al. (1976) applied time series analysis – including spectral analysis, filtering, tuning and hypothesis testing – on palaeoclimatic data from the most recent 500 Ka of Earth history to demonstrate forcing from these astronomical parameters. The CENOGRID "splice" (Westerhold et al., 2000) has since extended this evidence to 66 Ma. Investigators have also recognised the imprint of Milankovitch cycles in palaeoclimatic records reaching back into the Precambrian.

Palaeoclimate time series present unique challenges: sample spacing is generally not constant; measured data represent combinations of palaeoenvironmental factors; most problematic of all, palaeoclimate time scales are almost never known with adequate certainty. Important time constraints are provided by geochronology from volcanic ash layers, geomagnetic reversals and selected chemostratigraphic events, but only at isolated, widely spaced points along geologic time, and only extremely rarely do they provide a precision sufficient to determine the time-periodicity of palaeoclimate variations at Milankovitch scales. Investigators must also grapple with uncertainties in celestial mechanics, and in the theory of climate change, sedimentation and alteration. From this collective information, one may choose to investigate mechanisms of climate or environmental change (climate modelling); estimate the chronology and duration of stratigraphic series of palaeoclimate data (cyclostratigraphy); and constrain the celestial mechanics of Earth's distant past.

In principle, all of these objectives can be obtained through application of a hierarchical Bayesian model: astronomical forcing -> climate -> environment -> sedimentation -> alteration -> observation. Bayesian theory allows us to reverse all of the arrows and to update information about sedimentation, the environment, climate, and astronomical forcing. However, in Bayesian

statistics, expressing a likelihood function is a fundamental step and requires parameterising stochastic quantities. One needs to be clear and explicit about errors. We present an example that considers an explicit-likelihood route for Quaternary data (Carson et al., 2019). In the more distant geologic past, uncertainties about climate and sedimentation are increasingly challenging. Strategies tend to be based on pattern identification by the investigator, with or without numerical techniques. Examples include recognising orbital eccentricity bundling in paleoclimatic data sequences that exhibit precession cycling, and studying the relationships between frequency and amplitudes (Meyers and Malinverno, 2018). We review examples illustrating the relationship between frequency and amplitude together with the supporting theory.

References: Carson et al., Proc. R. Soc. A (2019), 475, 20180854; Hays et al., Sci. (1976), 194(4270), 1121-1132; Meyers, S.R., Malinverno, A., Proc. Natl. Acad. Sci. U.S.A. (2018), 115(25), 6363-6368; Westerhold et al., Sci. (2020), 369, 1383-1387.