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Introduction

Time Series Analysis for Earth, Climate and Life Interactions

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A reliable prediction of future climate change and its consequences for life on earth requires a deep understanding of the driving forces and internal interactions in the Earth's climate-biosphere system (Fig. 1). To this end, quantitative indicators of past climate conditions have been measured since the 1950s, first on marine sediments and soon after on other climate archives such as lake sediments, glaciers, speleothems and other archives. The use of time series analysis methods helps to establish quantitative relationships between forcing and climate change as well as internal interactions in the Earth's climate system. Knowledge of the complex system Earth with its components is a prerequisite for the calibration of models that allow predictions for the climate of the future. New methodological developments help to address typical challenges in paleoclimate investigations, such as irregular sampling, dating uncertainties, or hidden couplings and transitions.

The virtual special issue of *Quaternary Science Reviews* invited scientists from paleoclimate research and related disciplines to share their views on the development of time series analysis with the readers, to present new developments in the methods to detect trends, rhythms and events in paleoclimate time series and to show applications of the use of time series analysis. Manuscripts included in the special volume are reviews, research papers, and short methods papers. The special Issue offered the possibility to provide extensive data sets (real data or synthetic data), computer code for the evaluation of the data as well as multimedia material of any kind in an electronic supplement.

This special issue contains a mix mix of review articles, methodological papers, and original work by early career scientists. As guest editors, we first attempt to provide an overview of the most popular linear methods of spectral analysis (Trauth, 2021) and nonlinear methods of time-series analysis (Marwan et al., 2021). The first paper by Trauth (2021) provides a comprehensive review of spectral analysis methods in Quaternary sciences including the prerequisites for their application as well as advantages and disadvantages. It then continues with an analysis of the history of the use of spectral analysis methods and their application in paleoclimate reconstructions. It also includes the author's advice on the use of linear spectral analysis methods. The paper by Marwan et al. (2021) provides a review and comparison of a selection of nonlinear methods of climate time-series analysis including phase space-based recurrence plots and recurrence networks, visibility graphs, order pattern-based entropies, and stochastic modeling. The considered methods give deeper insights into the paleoclimate dynamics, in particular the number of climate states (multi-stability), nonlinear vs. linear behavior, and changing predictability due to more cyclical dynamics. The authors demonstrate how a synthesis of such different methods can give insights into the spatial differences in the impact of global climate drivers such as orbital variations and on the changes of large-scale atmospheric patterns.

The virtual special issue continues with the paper by Grove (2021) introducing an algorithm that objectively decomposes an empirical climatic signal into change and variability components. This algorithm helps to study paleoclimatic effects on prehistoric human societies as well as those studying the nature and effects of contemporary climate change. The paper by Chase (2021) reviews the influence of orbital forcing on southern African paleo-records. It uses wavelet and semblance analysis to explore the nature of this forcing and finds that orbital eccentricity has a significant influence across inter-tropical Africa. Furthermore, ice-volume changes seem to alter the character of orbitally-induced climate variations.

The following papers by Duesing et al. (2021), Trauth et al. (2021a) and Ulfers et al. (2022b) address methods and applications to classify types of climate variability and discuss possible differential impacts on the evolution of Homo sapiens and its ancestors. The paper by Duesing et al. (2021) uses wavelet-based methods to detect episodes of increased variability in a ~620 kyr long record from southern Ethiopia, corresponding to changes in the eccentricity of the earth's orbit, and tries to link these highly variable episodes to the Acheulean to Middle Stone Age technologies in Africa. Trauth et al. (2021a) uses recurrence plots/recurrence quantification analysis to distinguish two types of variability in the same record, (1) slow variations with ~20 kyr cyclicity and rather gradual wet-dry-wet transitions and (2) millennium-scale variations with rapid (decadal) transition. The different types of variability and the transitions between those types may have had important implications for the shaping of the habitat of *H. sapiens* and the direct ancestors of this species. The work of Ulfers et al. (2022b) examines possible half-precession cycles in a long core from Lake Ohrid using wavelet power spectral and cross correlation analysis. The authors find that paleoclimate in this part of Mediterranean and southern Europe is directly influenced by the African monsoons.

The special issue also contains papers dealing with different methods and their application to detect more or less rapid climate transitions that may have been associated with key events in the evolution of humans and animals. The paper by Trauth et al. (2021b) tries to falsify the hypothesis of a connection between Northern Hemisphere Glaciation, African climate and human evolution. The authors first provide a comprehensive review of the emergence of a scientific hypothesis, which has been persistently popular despite mounting evidence against it. They use two independent techniques to map the duration and amplitude of this transition in key records of environmental change in Africa, which leads to the conclusion that a consistent transition at ~2.5 Ma does not exist and therefore there is no link between the intensification of the Northern Hemisphere Glaciation, a stepwise transition towards a more arid climate in Africa and an important species turnover in the area. Berner et al. (2022) uses a Bayesian inference approach to unravel multiple changes in marine records of terrestrial dust flux around Africa to detect a conjoint stepwise transition in climate at (2.35–2.10) Ma and (1.70–1.50) Ma, that may be associated with the reorganization of the Hadley-Walker Circulation.

The paper by Kaboth-Bahr and Mudelsee (2022) provides an analysis of low-latitude climate transitions in the Cenozoic using *rampfit* regression and links these transitions to variations in the Walker Circulation (WC). The authors find that the WC experienced a two-phased evolution between the Late Pliocene and the Early Pleistocene with significant transitional steps at 2.75 and 2.1 Ma. Mitsui and Boers (2022) use a machine-learning approach suggesting that the amplitude increase in the earth's obliquity cycle is a requisite for the appearance of the Mid-Bruhnes Transition at ~430 kyr BP. In contrast, the change in the mean eccentricity level across the MBT has a smaller impact on the appearance of the MBT. This result has important implications for the understanding of glacial cycles and the origin of transitions such as the MBT. The paper by Boettner et al. (2021) examines nine climate transitions in the Cenozoic and searches for early-warning signals of bifurcation-induced transitions, an important and rapidly developing new application of time-series analysis. The authors indeed find such early-warning signals for five out of nine transitions, based on critical slowing down, a typical behavior of a physical system approaching a tipping point, indicating potential regime shifts during the last 66 Ma.

The work of Hatvani et al. (2021) aims to test/model whether or not a signal for a given period can be robustly detected from a sedimentary proxy record considering its mean sampling resolution and degree of chronological uncertainty. In doing so, the paper goes a step further than many applications of time-series analysis, namely because it attempts to support the trustworthiness of the results with an error estimate. The authors try to make their method as easily accessible as possible to other authors by providing an online tool called Chronological Uncertainty & Spectral Peaks (CUSP). The paper of Ulfers et al. (2022a) addresses the basis of time series analyses in the sense that it first discusses the generation of seismic data, drill core data and age models, in particular in those situations where core material and hence datable material is no longer available.

We believe that the papers in our virtual special issue on "Time Series Analysis for Earth, Climate and Life Interactions" provide a good overview of the currently available methods of time-series analysis in Quaternary sciences and thus offer a good introduction to all readers, especially young scientists. Most papers have accompanying computer code and data, synthetic and real paleoclimate data, so that readers can quickly become familiar with the methods and modify them for their own applications.

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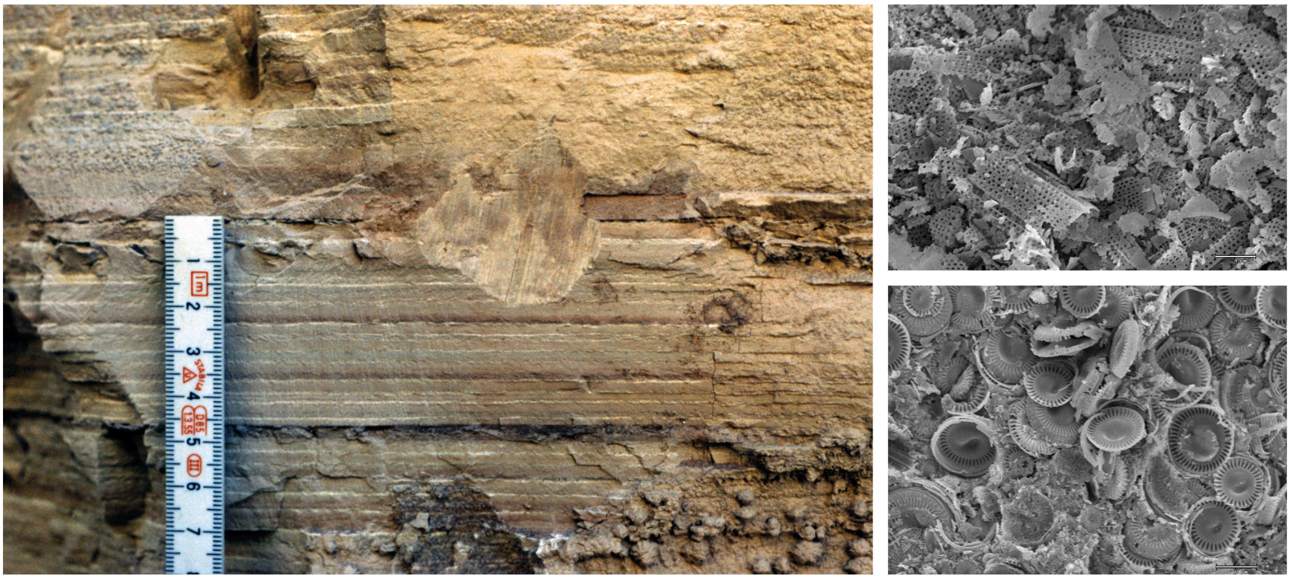

Figure 1 – Example of an earth, climate and life interaction in an ~30 kyr old landslide dammed lake in the Quebrada de Cafayate in the northwestern Argentine Andes as inferred from annually-layed sediments, studied by the guest editors in the late 1990s (Trauth et al., 1999, 2003, Marwan et al., 2003). Each layer begins with iron-rich reddish-brownish clays from Cretaceous sedimentary rocks, followed by greenish clays from Paleozoic rocks, topped by a thin diatomite layer, reflecting the seasonal cycle of summer rains and subsequent algae blooms (photo on the left). Every 3–7 layers the varves are slightly thicker and darker due to more intense rains as the result of the influence of the El Niño/Southern Oscillation. The influx of recurring iron-rich clays leads to a complete turnover in the diatom assemblage from a *Aulacoseira granulata* flora (top right) to a *Cyclotella agassizensis* (bottom right) dominated ecosystem as the analysis of scanning electron micrographs of the corresponding diatomite layers suggests.