Integrative Multivariate Study of Past African Climate Variability

Norbert Marwan, Jonathan F. Donges, Reik V. Donner, Deniz Eroglu
IWC – intensified Walker circulation; M2 – marine isotope stage M2; NHG – Northern hemisphere glaciation; MPT – Mid-Pleistocene transition
Proxy Records of N-African Climate Variability

- N-African aridification (dust flux)
- Temperature/ice volume ($\delta^{18}O$, alkenone)
**Time Series Variability**

- Data distribution
- Complexity
- Multi-stability
- Nonlinear or linear
- Deterministic or stochastic (or chaotic)

Frequency

\[
\begin{array}{c|c|c|c}
& \text{100 ka world} & \text{41 ka world} & \text{NHG} & \text{M2} & \text{IWC} \\
\hline
\text{ODP 662} & & & & & \\
\text{ODP 659} & & & & & \\
\text{ODP 967} & & & & & \\
\text{ODP 722} & & & & & \\
\text{ODP 721} & & & & & \\
\end{array}
\]
**Complexity**

\[ H(n) = -\frac{1}{n-1} \sum p(\pi) \log p(\pi) \]

permutation entropy

Bandt & Pompe, Phys Rev Lett 88, 2002
Multistability (Number of Climate States)

stochastic modelling

\[ U(x) = -\frac{\sigma^2}{2} \log \rho(x) \]

Kwasniok & Lohmann, Phys Rev E 80, 2009
Nonlinearity (Time Irreversibility)

• Reversibility: joint probability of retarded and advanced degree is equal to the one of the reverse sequence

\[ p(x_i, x_{i+1}, \ldots, x_{i+m-1}, x_{i+m}) = p(x_{i+m}, x_{i+m-1}, \ldots, x_{i+1}, x_i) \]

Donges et al., EPL 102, 2013
Deterministic vs. Random Dynamics

\[ R_{i,j} = \begin{cases} 
1 & : \bar{x}_i \approx \bar{x}_j \\
0 & : \bar{x}_i \not\approx \bar{x}_j 
\end{cases} \]

- Determinism: (fraction of points forming diagonal lines)

\[ \text{DET} = \frac{\sum_{l=l_{\text{min}}}^{N} l P(l)}{\sum_{l=1}^{N} l P(l)} \]

recurrence analysis

\[ x_i, x_{i+1}, x_{i+…}, x_j, x_{j+1}, x_{j+…} \]

Increase of stable states

Marwan et al., Quat Sc Rev 274, 2021
Increase of persistent/more regular dynamics

Marwan et al., Quat Sc Rev 274, 2021
Shift to linear behaviour

Marwan et al., Quat Sc Rev 274, 2021
Linear vs. nonlinear dynamics

Marwan et al., Quat Sc Rev 274, 2021
### Very Condensed Summary

<table>
<thead>
<tr>
<th></th>
<th>African hydro-climate</th>
<th>subtropical Atlantic</th>
<th>Arabian sea</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>IWC</strong></td>
<td>2-state dynamics,</td>
<td>increasing states,</td>
<td>decreasing states,</td>
</tr>
<tr>
<td></td>
<td>less predictable,</td>
<td>less predictable</td>
<td>less predictable</td>
</tr>
<tr>
<td></td>
<td>nonlinear behaviour</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>M2</strong></td>
<td>more persistent and</td>
<td>more complex,</td>
<td>(no data)</td>
</tr>
<tr>
<td></td>
<td>periodic dynamics</td>
<td>less predictable</td>
<td></td>
</tr>
<tr>
<td><strong>NHG</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>more persistent,</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>predictable/periodic</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>dynamics</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>MPT</strong></td>
<td>(increase in system</td>
<td>change to more</td>
<td></td>
</tr>
<tr>
<td></td>
<td>states during</td>
<td>regular dynamics</td>
<td></td>
</tr>
<tr>
<td></td>
<td>transition),</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>change to</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>nonlinear</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>behaviour</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Nonlinear time series analysis of palaeoclimate proxy records

Norbert Marwan a, b, *, Jonathan F. Donges a, c, Reik V. Donner a, d, Deniz Ergul e

a Potsdam Institute for Climate Impact Research (PIK), Member of the Leibniz Association, Telegraphenberg A31, 14473, Potsdam, Germany
b Institute of Geosciences, University of Potsdam, Karl-Liebknecht-Straße 24-25, 14476, Potsdam-Golm, Germany
c Stockholm Resilience Centre, Stockholm University, Kräftestr. 28, 11419, Stockholm, Sweden
d Department of Water, Environment, Construction and Safety, Magdeburg-Stendal University of Applied Sciences, Breitscheidstraße 2, 39114, Magdeburg, Germany
e Faculty of Engineering and Natural Sciences, Kadir Has University, 34083, Istanbul, Turkey

Article history:
Received 9 September 2021
Accepted 6 October 2021
Available online 11 November 2021
Handling editor: Martin Trauth

Abstract

Identifying and characterising dynamical regime shifts, critical transitions or potential tipping points in palaeoclimate time series is relevant for improving the understanding of often highly nonlinear Earth system dynamics. Beyond linear changes in time series properties such as mean, variance, or trend, these nonlinear regime shifts can manifest as changes in signal predictability, regularity, complexity, or higher-order stochastic properties such as multi-stability. In recent years, several classes of methods have been put forward to study these critical transitions in time series data that are based on concepts from nonlinear dynamics, complex systems science, information theory, and stochastic analysis. These include approaches such as phase space-based recurrence plots and recurrence networks, visibility graphs, order pattern-based entropies, and stochastic modelling. Here, we review and compare in detail several prominent methods from these fields by applying them to the same set of marine palaeoclimate proxy records of African climate variations during the past 5 million years. Applying these methods, we observe notable nonlinear transitions in palaeoclimate dynamics in these marine proxy records and discuss them in the context of important climate events and regimes such as phases of intensified Walker circulation, marine isotope stage M2, the onset of northern hemisphere glaciation and the mid-Pleistocene transition. We find that the studied approaches complement each other by allowing us to point out distinct aspects of dynamical regime shifts in palaeoclimate time series. We also detect significant correlations of these nonlinear regime shift indicators with variations of Earth’s orbit, suggesting the latter as potential triggers of nonlinear transitions in palaeoclimate. Overall, the presented study underlines the potentials of nonlinear time series analysis approaches to provide complementary information on dynamical regime shifts in palaeoclimate and their driving processes that cannot be revealed by linear statistics or eyeball inspection of the data alone.

© 2021 The Authors. Published by Elsevier Ltd. This is an open access article under the CC BY-NC-ND license.