Potsdam Institute for Climate Impact Research

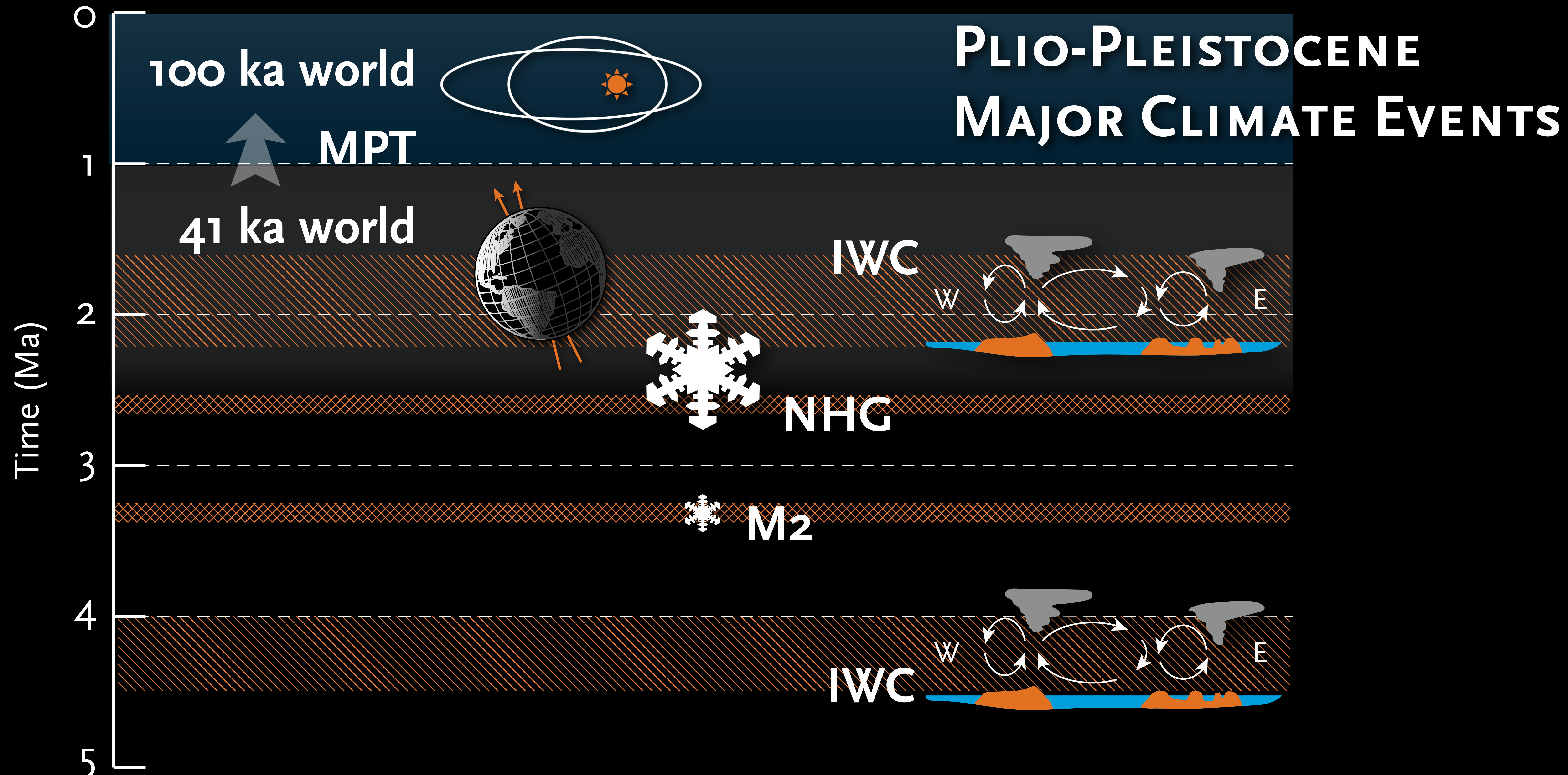
PIK

Norbert Marwan, Jonathan F. Donges,
Reik V. Donner, Deniz Eroglu

Integrative Multivariate Study of Past African Climate Variability

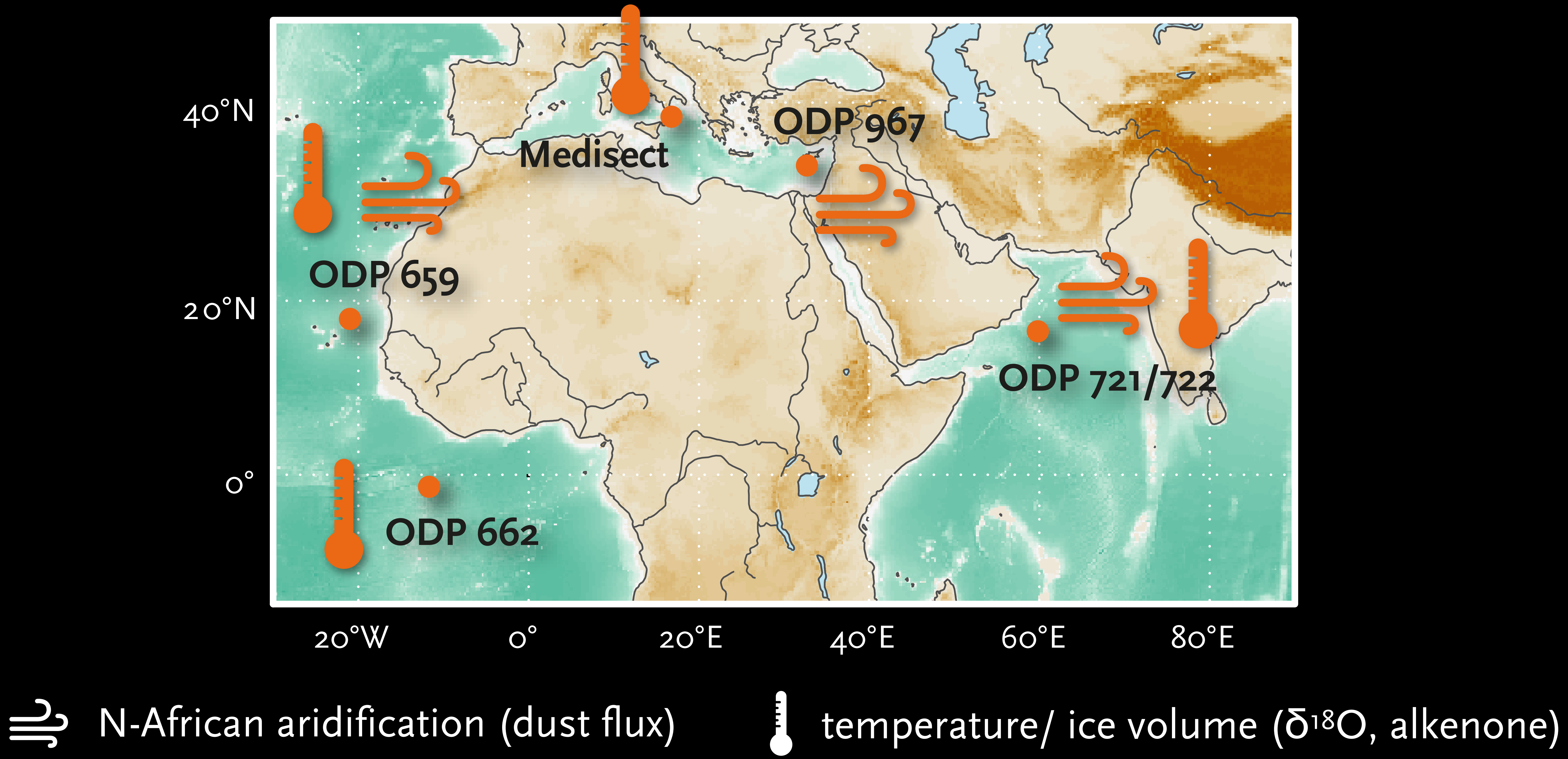
Leibniz-Gemeinschaft

Source: Kalima/Wikipedia

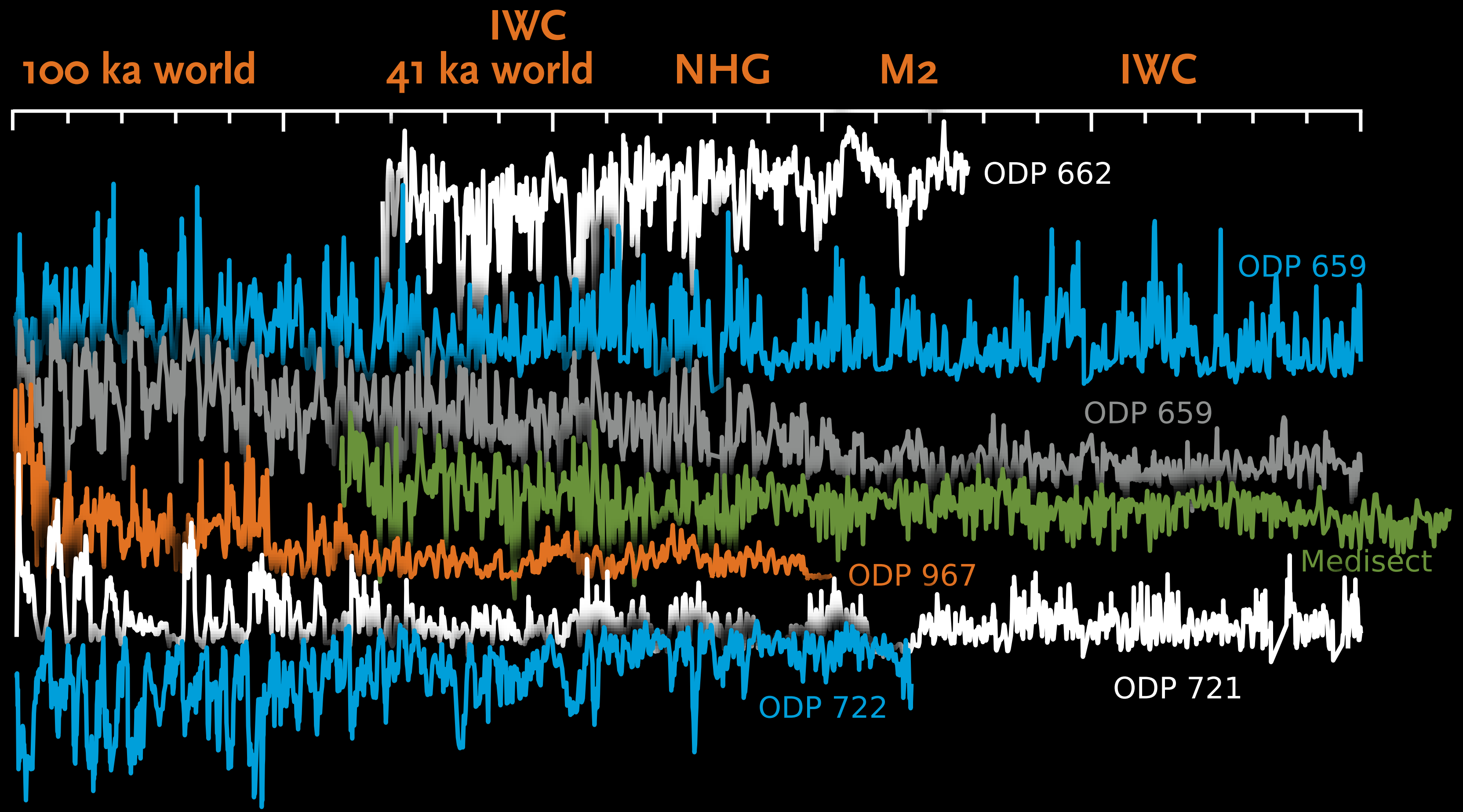


IWC – intensified Walker circulation; M2 – marine isoptope stage M2; NHG – Northern hemisphere glaciation; MPT – Mid-Pleistocene transition

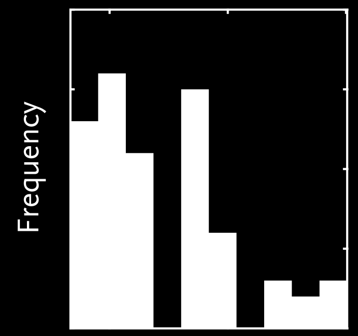
Proxy Records of N-African Climate Variability

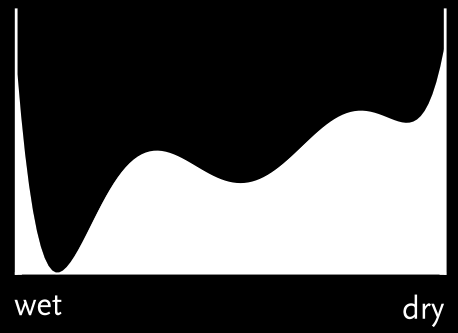


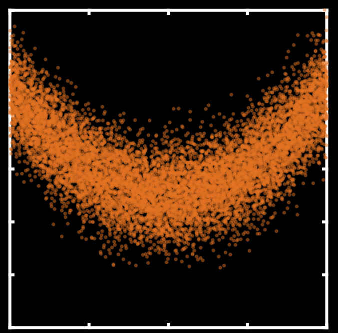
Time Series Variability

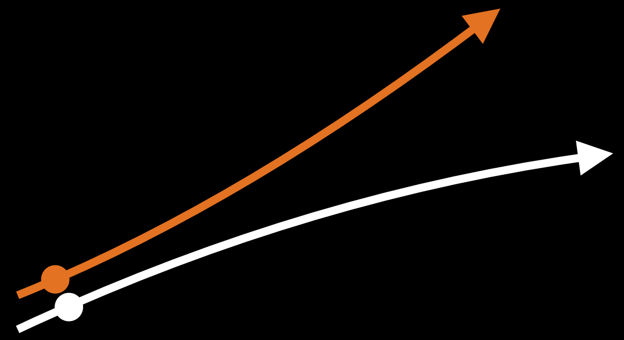


- Data distribution
- Complexity
- Multi-stability
- Nonlinear or linear
- Deterministic or stochastic (or chaotic)

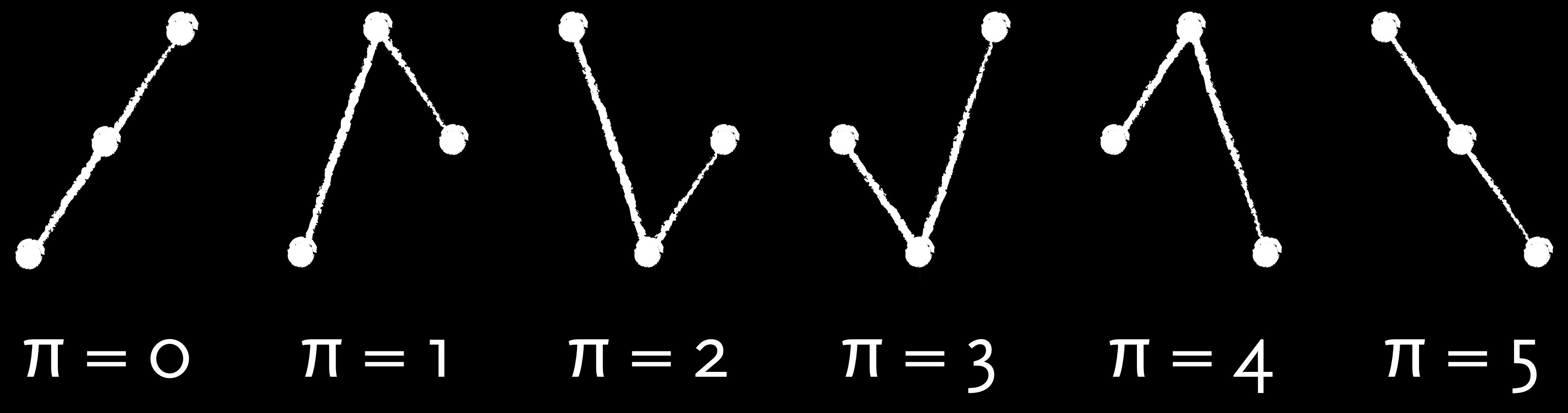








Complexity

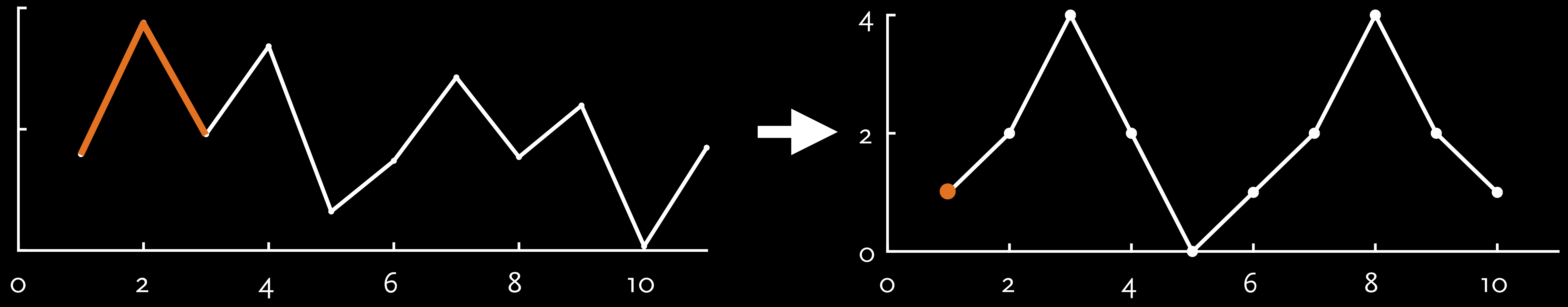


$$H(n) = -\frac{1}{n-1}\sum p(\pi)\log p(\pi)$$

permutation entropy

time series

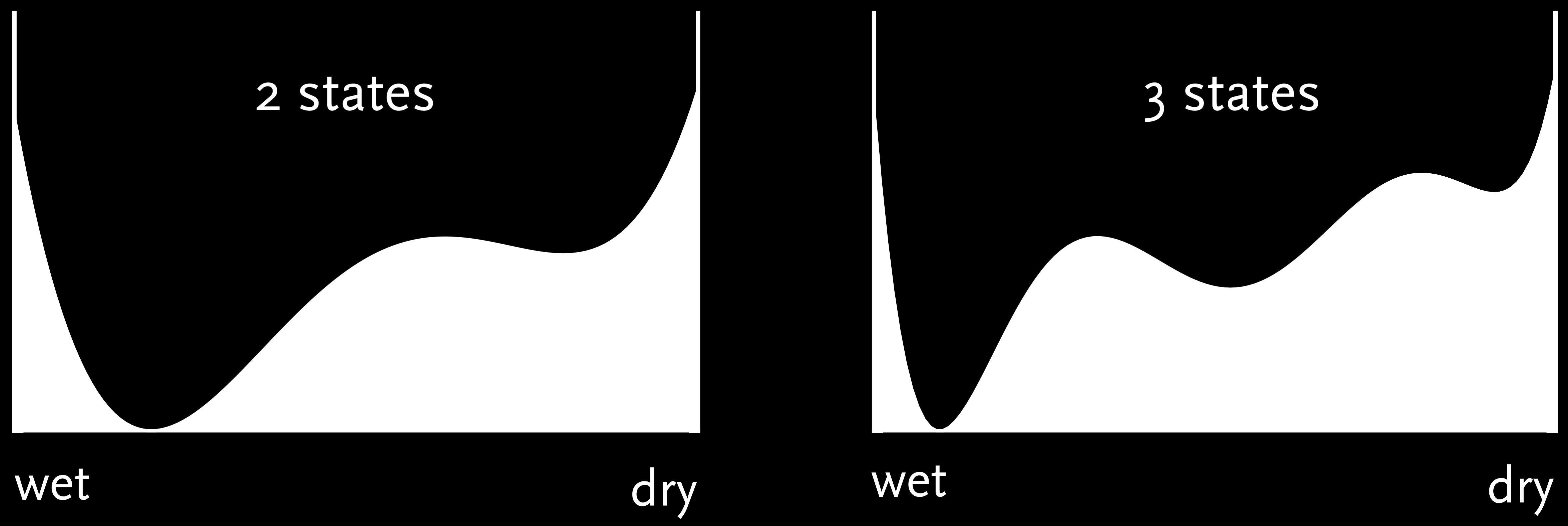
order pattern series



Bandt & Pompe, Phys Rev Lett 88, 2002

Multistability (Number of Climate States)

stochastic modelling

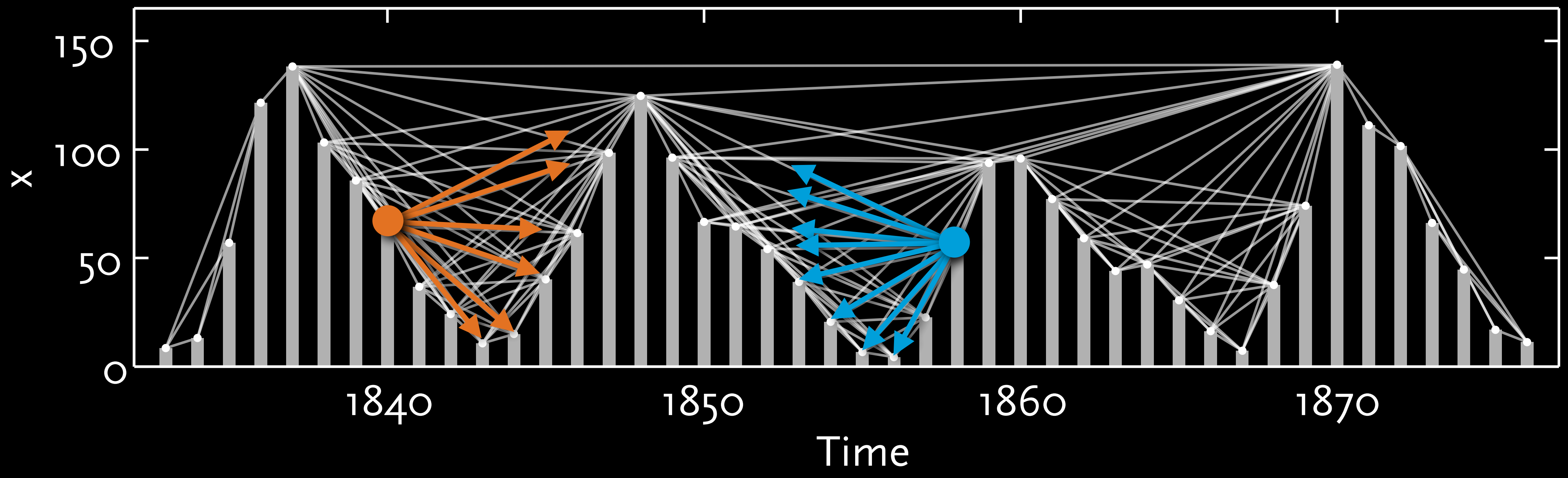


$$U(x) = -\frac{\sigma^2}{2} \log \rho(x)$$

Kwasniok & Lohmann, Phys Rev E 80, 2009

Nonlinearity (Time Irreversibility)

visibility graph



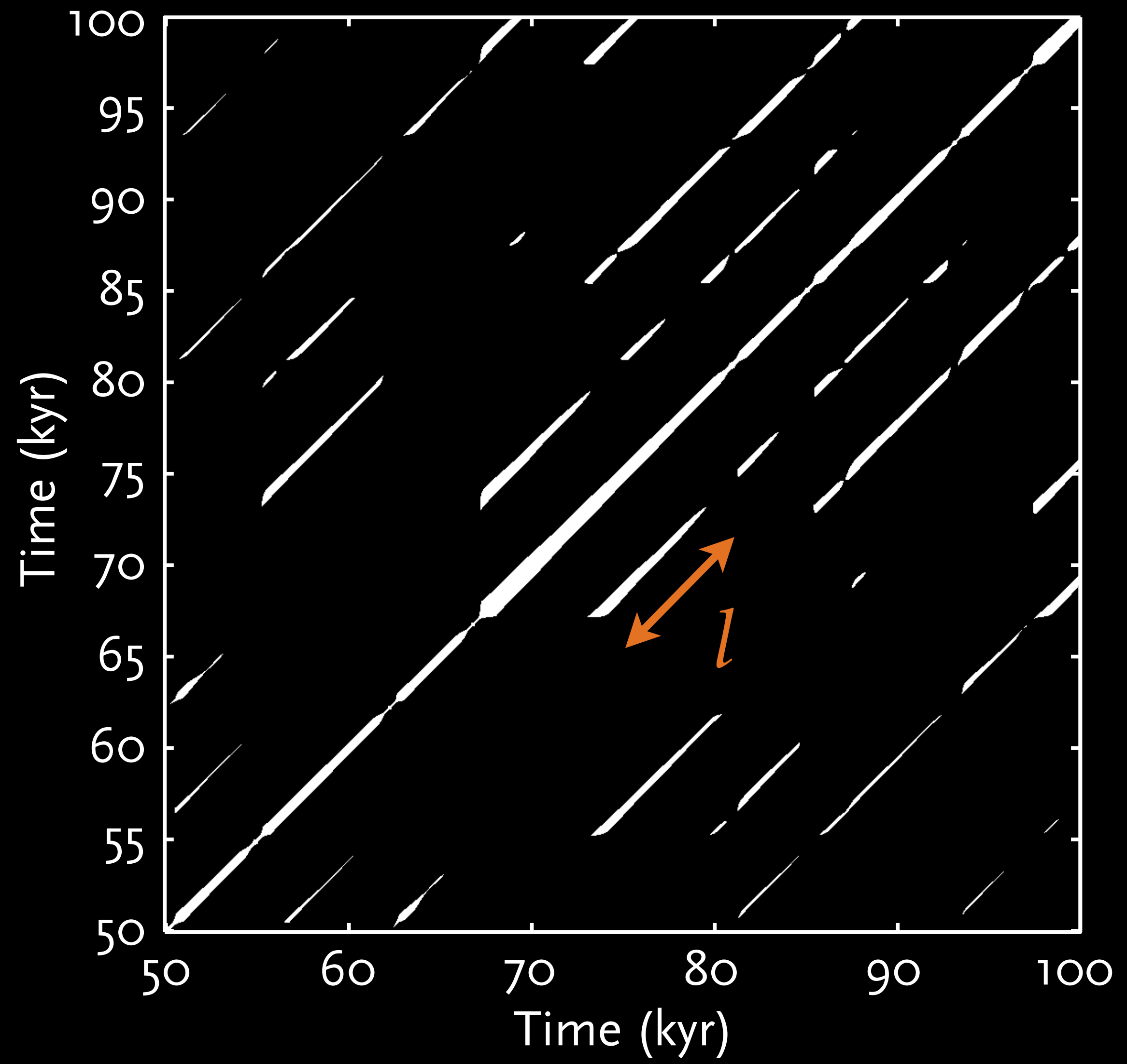
- Reversibility: joint probability of retarded and advanced degree is equal to the one of the reverse sequence

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

Donges et al., EPL 102, 2013

Deterministic vs. Random Dynamics

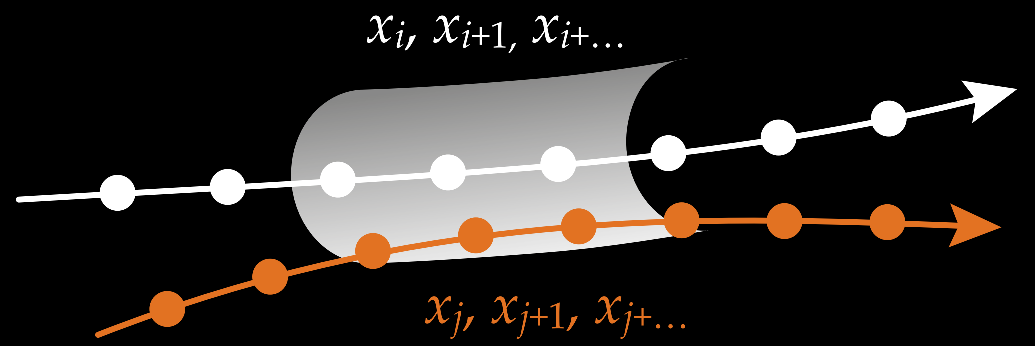
$$R_{i,j} = \begin{cases} 1 : \vec{x}_i \approx \vec{x}_j \\ 0 : \vec{x}_i \not\approx \vec{x}_j \end{cases}$$



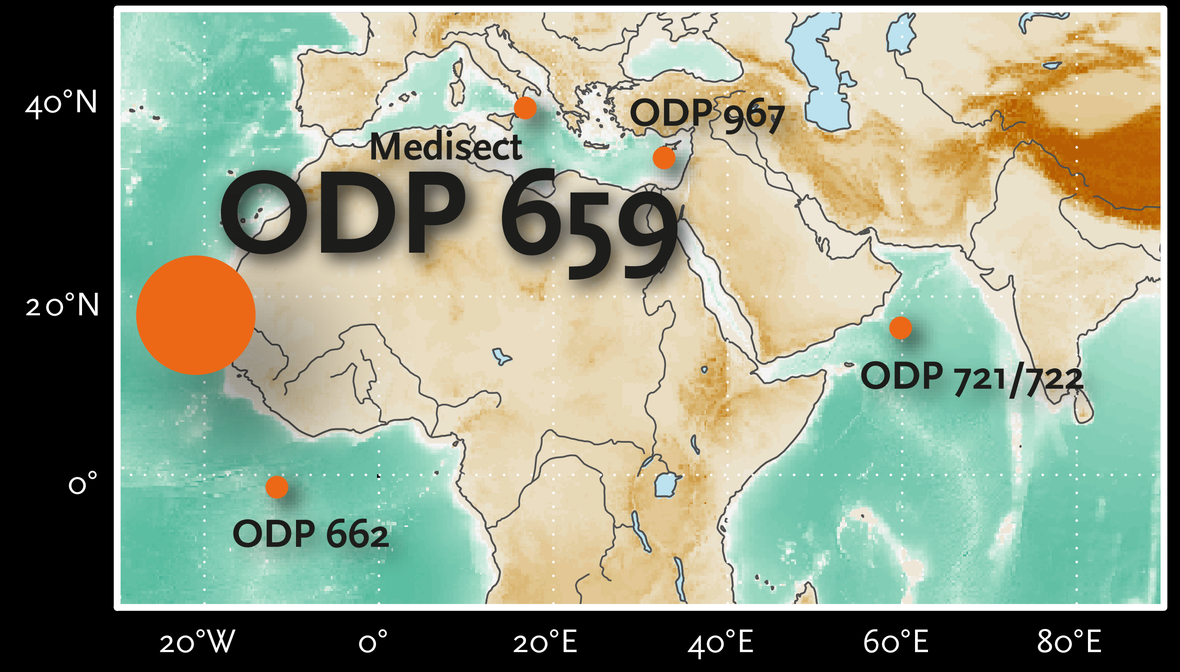
recurrence analysis

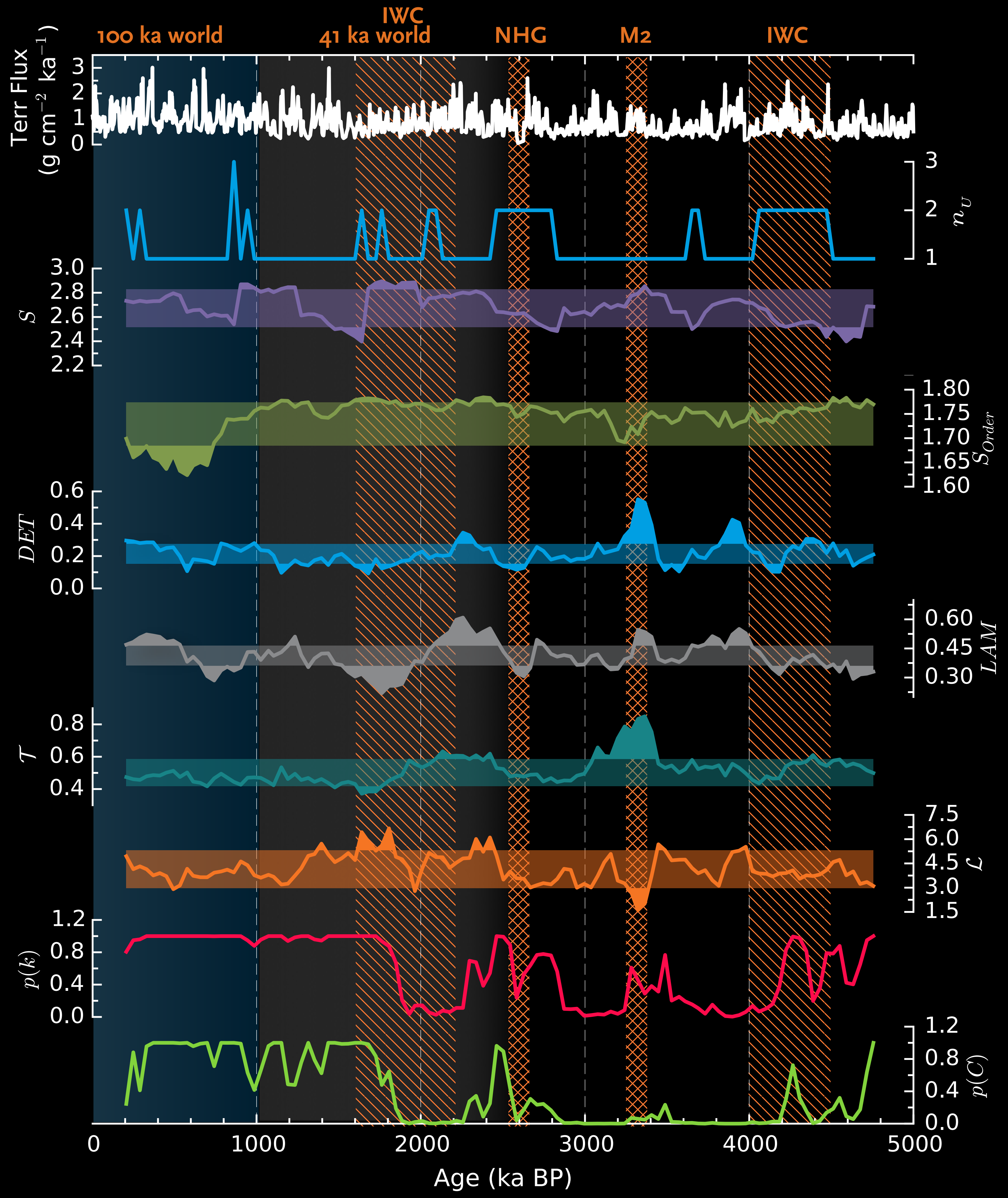
- Determinism: (fraction of points forming diagonal lines)

$$DET = \frac{\sum_{l=l_{\min}}^{N} l\,P(l)}{\sum_{l=1}^{N} l\,P(l)}$$

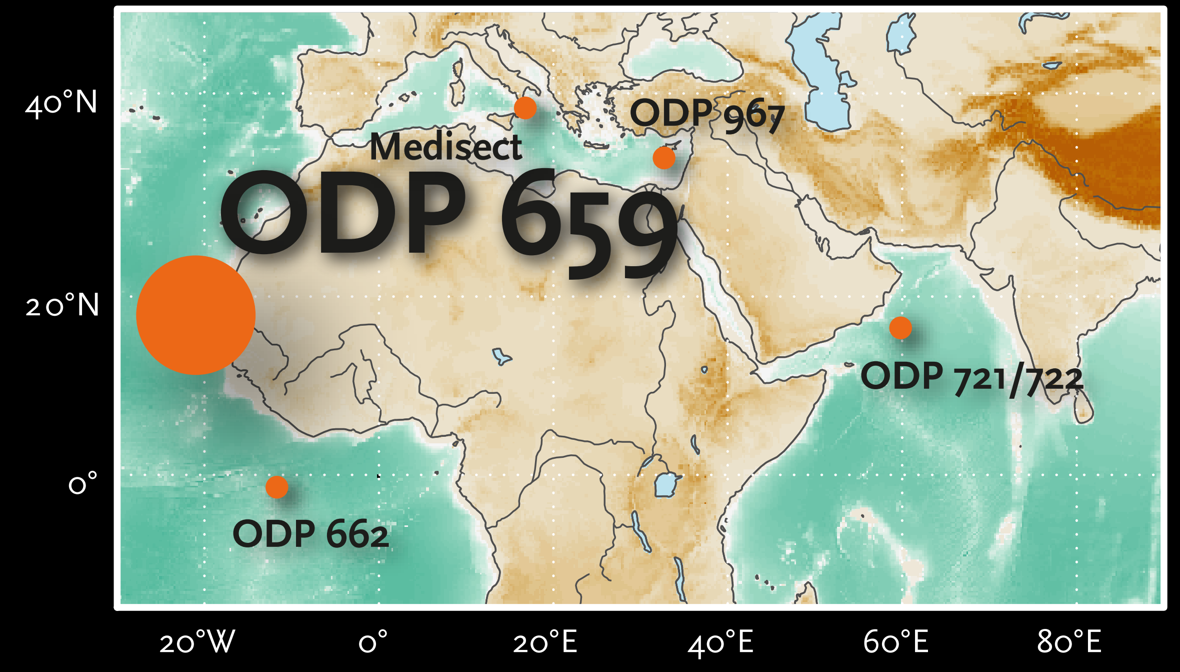


Marwan et al., Phys Rep 438, 2007

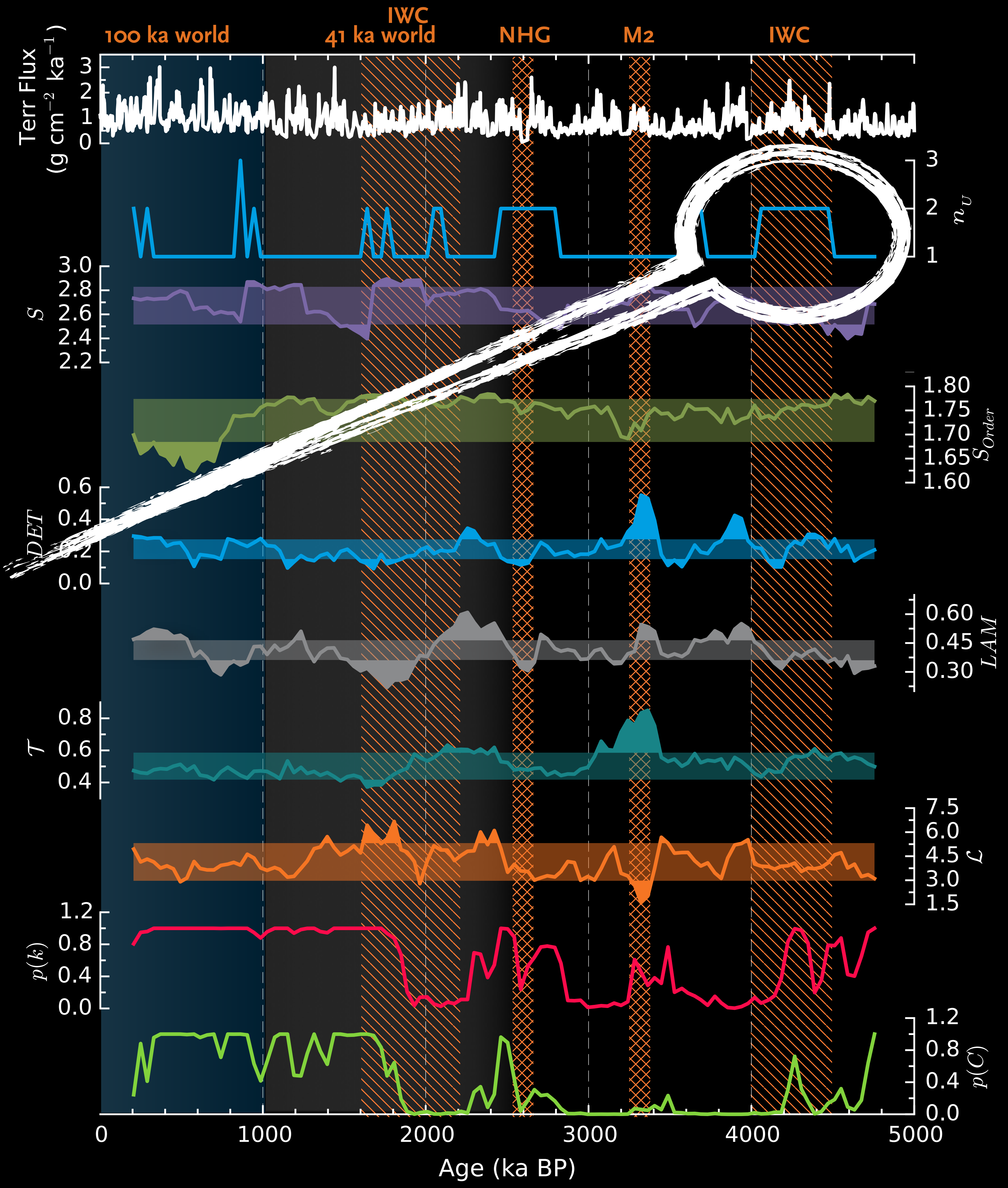




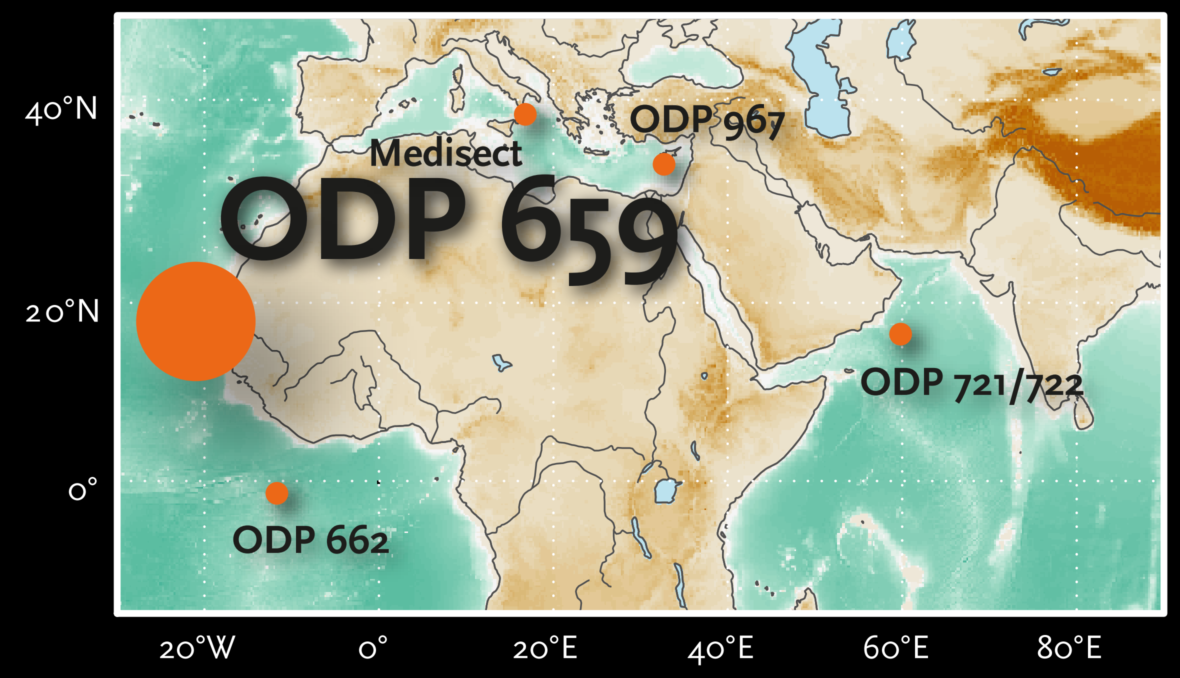
Marwan et al., Quat Sc Rev 274, 2021



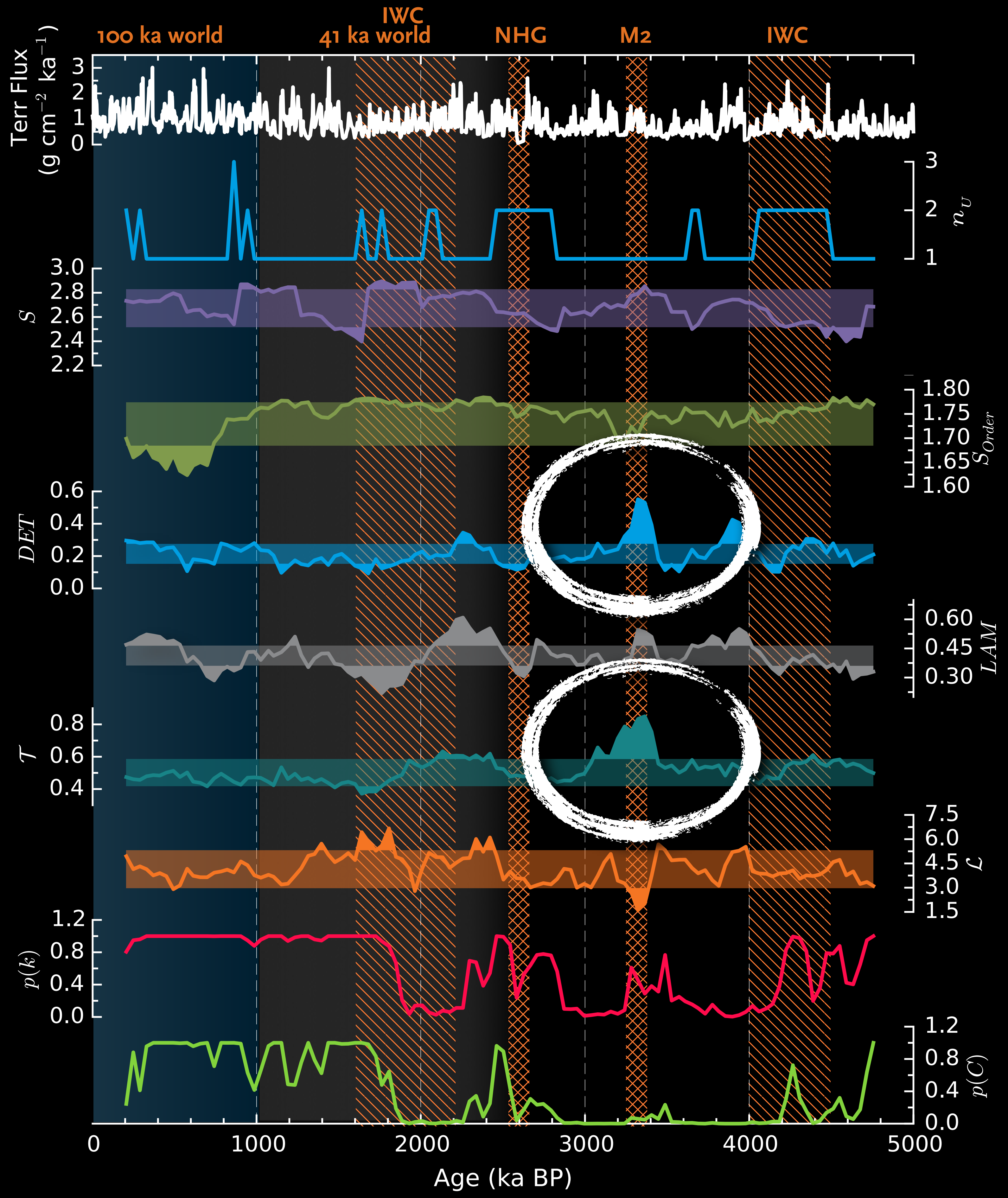
Increase of stable states



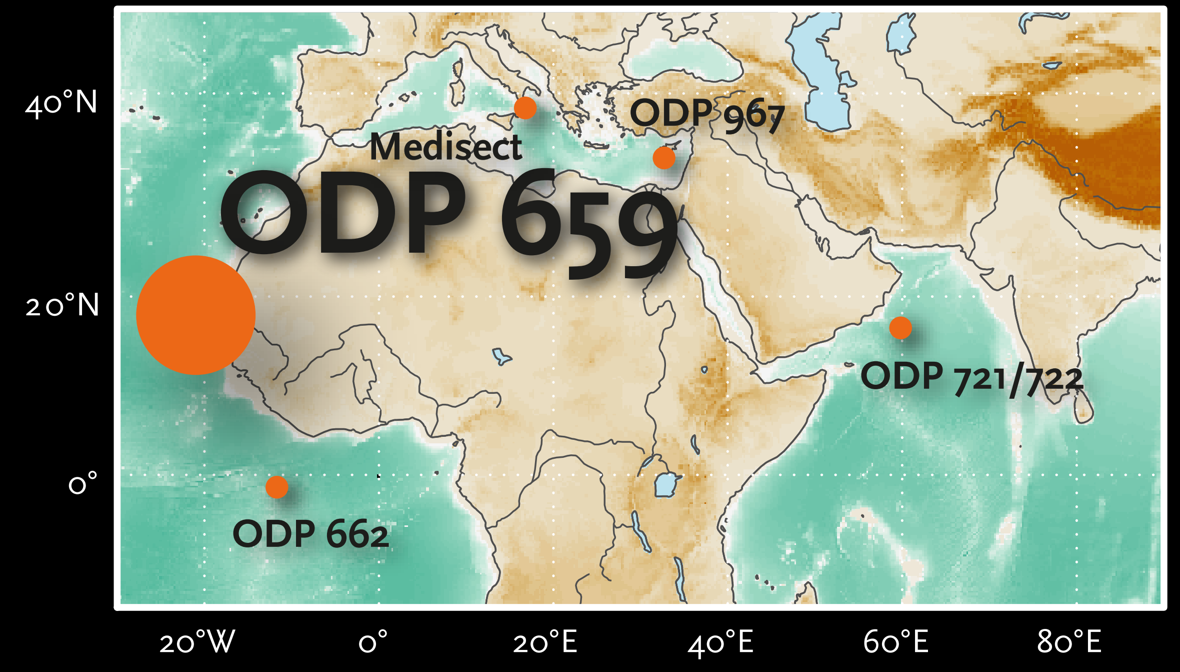
Marwan et al., Quat Sc Rev 274, 2021

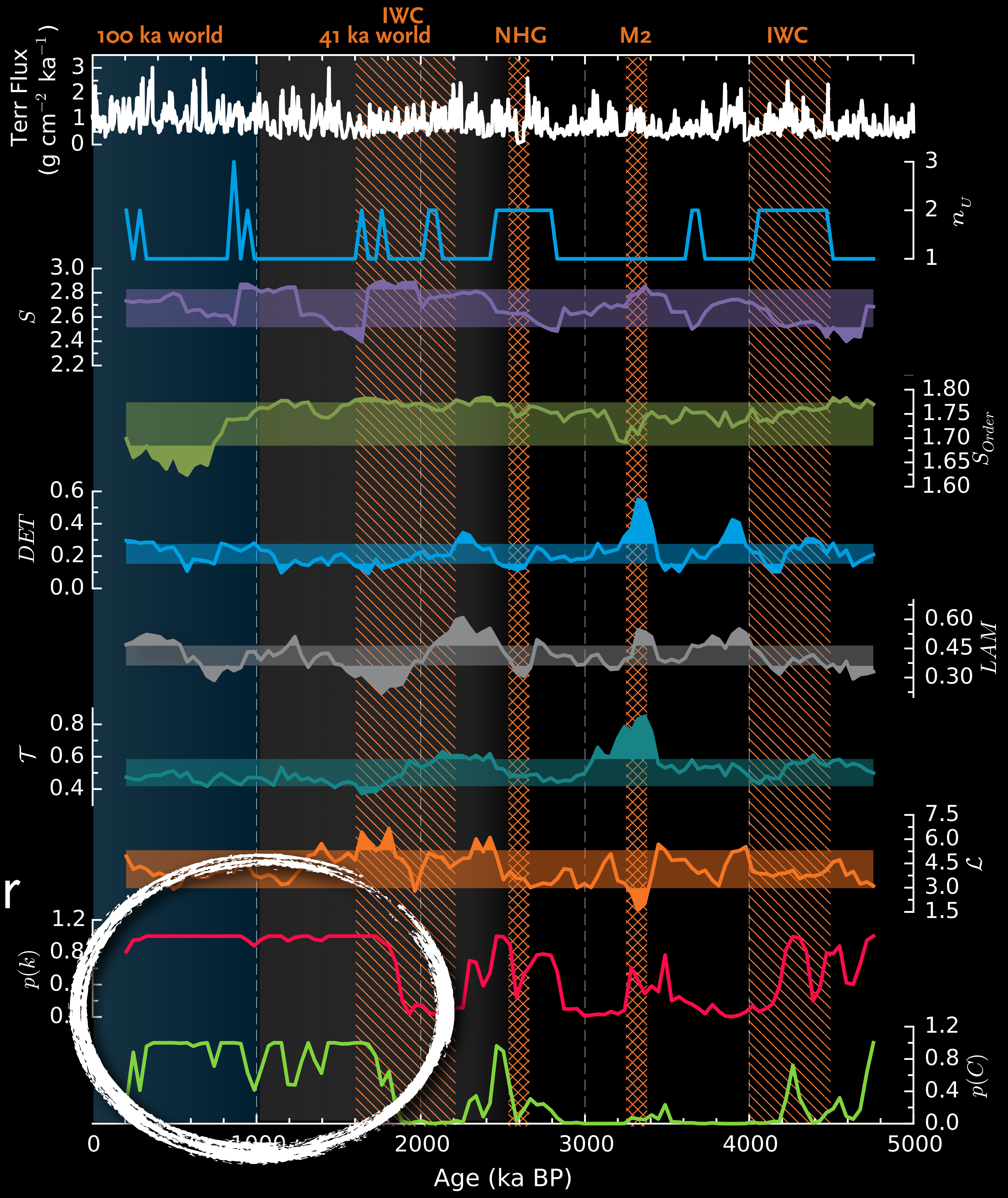


Increase of persistent/
more regular dynamics



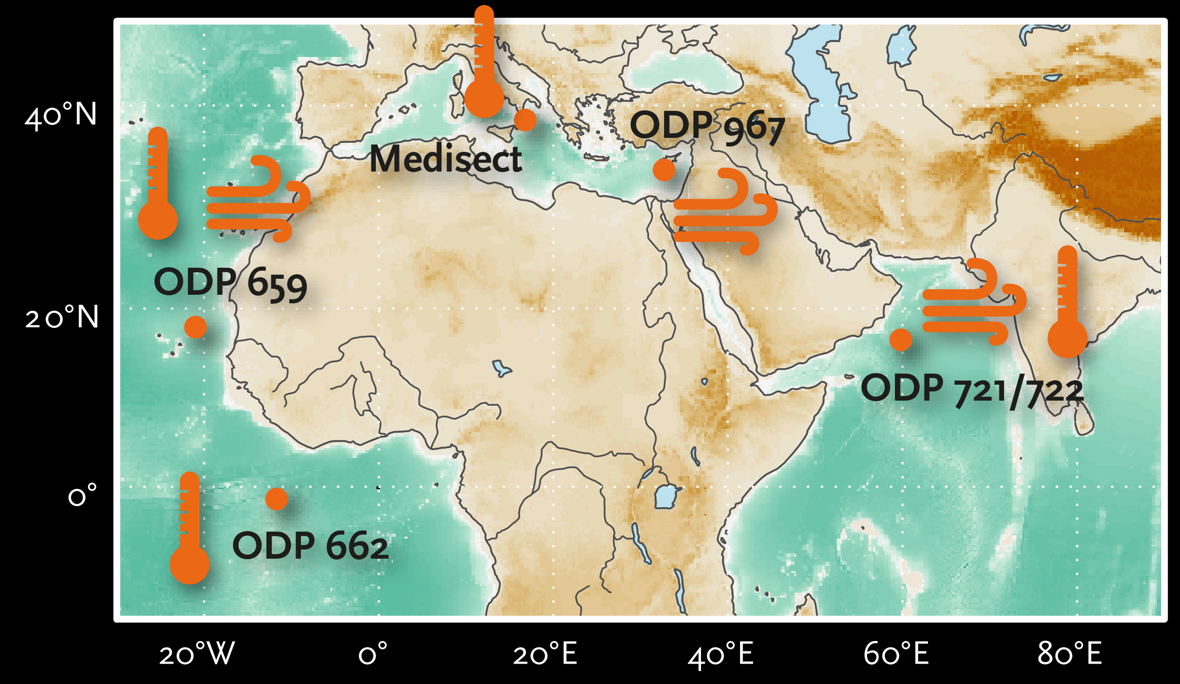
Marwan et al., Quat Sc Rev 274, 2021

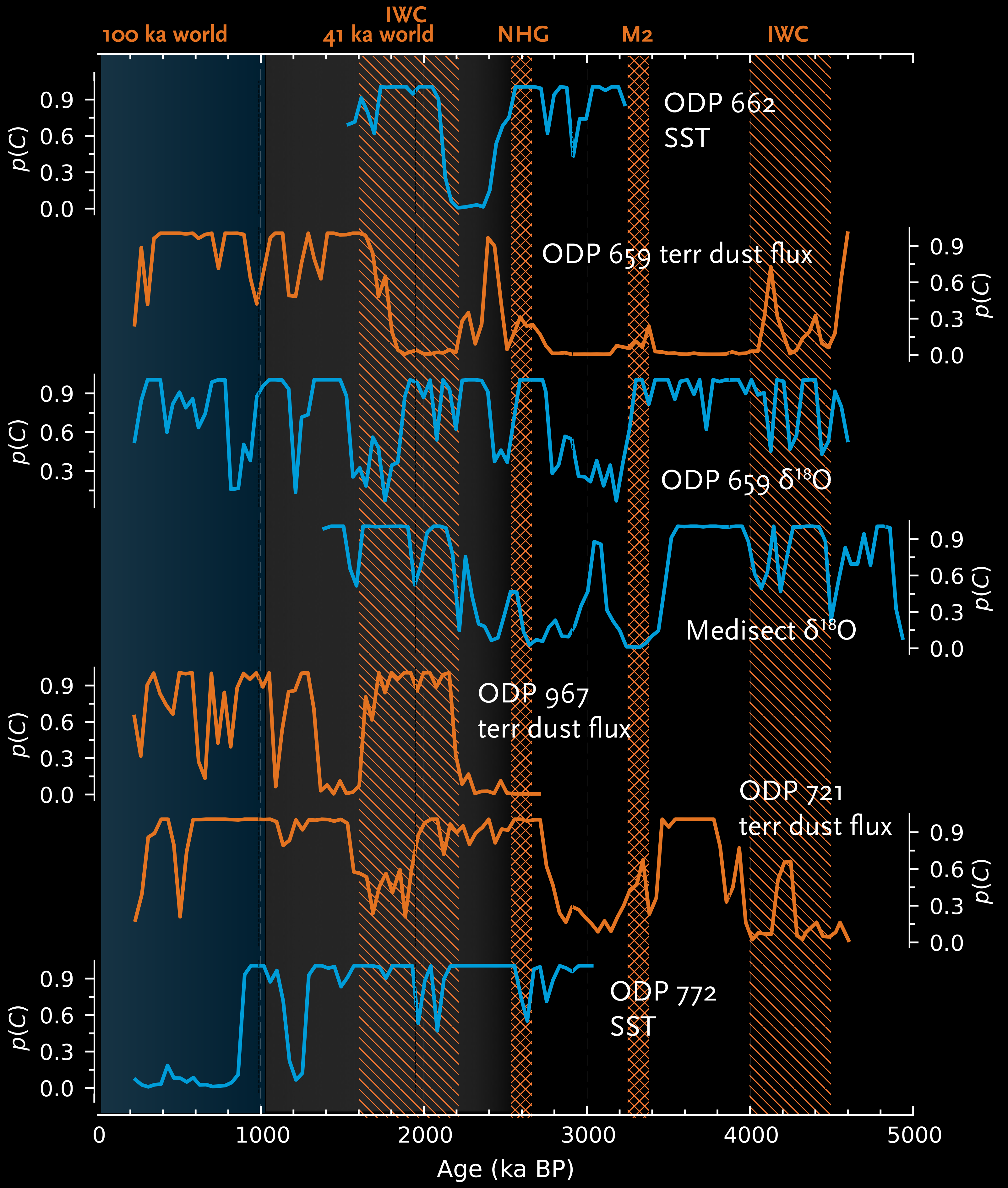




Shift to linear behaviour

Marwan et al., Quat Sc Rev 274, 2021





Linear vs. nonlinear dynamics

Marwan et al., Quat Sc Rev 274, 2021

Very Condensed Summary

	African hydro-climate	subtropical Atlantic	Arabian sea
IWC	2-state dynamics, less predictable, nonlinear behaviour	increasing states, less predictable	decreasing states, less predictable
M2	more persistent and periodic dynamics	more complex, less predictable	(no data)
NHG	more persistent, predictable/periodic dynamics		
MPT	(increase in system states during transition), change to more regular dynamics		change to nonlinear behaviour

Quaternary Science Reviews 274 (2021) 107245

Contents lists available at ScienceDirect

Quaternary Science Reviews

journal homepage: www.elsevier.com/locate/quascirev

Nonlinear time series analysis of palaeoclimate proxy records

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

[a] Potsdam Institute for Climate Impact Research (PIK), Member of the Leibniz Association, Telegrafenberg 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, Kräftriket 2B, 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 INFO

Article history:
Received 9 September 2021
Accepted 6 October 2021
Available online 11 November 2021

Handling editor: Martin Trauth

Keywords:
Nonlinear time series analysis
Palaeoclimate proxy
Pliocene
Pleistocene
Climate transition
Regime shift

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.