

**Nonlinear regime shifts in Holocene Asian monsoon variability**

J. F. Donges et al.

This discussion paper is/has been under review for the journal Climate of the Past (CP).  
Please refer to the corresponding final paper in CP if available.

# Nonlinear regime shifts in Holocene Asian monsoon variability: potential impacts on cultural change and migratory patterns

J. F. Donges<sup>1,2</sup>, R. V. Donner<sup>1,3</sup>, N. Marwan<sup>1</sup>, S. F. M. Breitenbach<sup>4</sup>, K. Rehfeld<sup>1,5</sup>,  
and J. Kurths<sup>1,6,7</sup>

<sup>1</sup>Potsdam Institute for Climate Impact Research, Telegrafenberg A31,  
14473 Potsdam, Germany

<sup>2</sup>Stockholm Resilience Centre, Stockholm University, Kräftriket 2B, 114 19 Stockholm, Sweden

<sup>3</sup>Department of Biogeochemical Integration, Max Planck Institute for Biogeochemistry,  
Hans-Knöll-Straße 10, 07745 Jena, Germany

<sup>4</sup>Geological Institute, Department of Earth Sciences, ETH Zurich, 8092 Zurich, Switzerland

<sup>5</sup>Alfred Wegener Institute for Polar and Marine Research, Telegrafenberg A43,  
14473 Potsdam, Germany

<sup>6</sup>Department of Physics, Humboldt University, Newtonstr. 15, 12489 Berlin, Germany

<sup>7</sup>Institute for Complex Systems and Mathematical Biology, University of Aberdeen,  
Aberdeen, AB24 3FX, UK

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

⏪

⏩

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

Received: 10 February 2014 – Accepted: 10 February 2014 – Published: 6 March 2014

Correspondence to: J. F. Donges (donges@pik-potsdam.de)

Published by Copernicus Publications on behalf of the European Geosciences Union.

**CPD**

10, 895–975, 2014

**Nonlinear regime shifts in Holocene Asian monsoon variability**

J. F. Donges et al.

[Title Page](#)

[Abstract](#)

[Introduction](#)

[Conclusions](#)

[References](#)

[Tables](#)

[Figures](#)



[Back](#)

[Close](#)

[Full Screen / Esc](#)

[Printer-friendly Version](#)

[Interactive Discussion](#)



## Abstract

The Asian monsoon system has been recognised as an important tipping element in Earth's climate. In this work, we apply recurrence networks, a recently developed technique for nonlinear time series analysis of palaeoclimate data, for detecting episodes with pronounced changes in Asian monsoon dynamics during the last 10 ka in speleothem records from 10 caves covering the major branches of the Asian monsoon system. Our methodology includes multiple archives, explicit consideration of dating uncertainties with the COPRA approach and rigorous significance testing for the coexistence of monsoonal regime shifts at multiple locations to ensure a robust detection of continental-scale changes in monsoonal dynamics. This approach enables us to identify several epochs characterised by nonlinear regime shifts in Asian monsoon variability (8.5–8.0, 5.7–5.4, 4.1–3.6 and 2.8–2.2 ka BP), the timing of which suggests a connection to high-latitude Bond events and other episodes of Holocene rapid climate change (RCC). Interestingly, we also observe a previously unnoticed episode of significantly increased regularity of monsoonal variations around 7.3 ka BP, a timing that is consistent with the typical 1.0–1.5 ka return intervals of Bond events. A possible solar forcing of the detected nonlinear regime shifts in Asian monsoon dynamics is suggested by their co-occurrence with pronounced minima and strong variability in solar activity. Drawing on a comprehensive review of the Holocene archeological record in the Asian monsoon realm, we find that these regime shifts partly coincide with known major periods of migration, pronounced cultural changes, and the collapse of ancient human societies. These findings indicate that also future transitions in monsoonal dynamics could induce potentially severe socio-economic impacts of climate change.

### Nonlinear regime shifts in Holocene Asian monsoon variability

J. F. Donges et al.

[Title Page](#)

[Abstract](#)

[Introduction](#)

[Conclusions](#)

[References](#)

[Tables](#)

[Figures](#)

[⏪](#)

[⏩](#)

[◀](#)

[▶](#)

[Back](#)

[Close](#)

[Full Screen / Esc](#)

[Printer-friendly Version](#)

[Interactive Discussion](#)



# 1 Introduction

Relationships between past climate change and societal responses in the historical and archeological record have frequently been reported, e.g. increased war frequencies (Zhang et al., 2007), societal conflicts and crises (Hsiang et al., 2011, 2013; Zhang et al., 2011), migrations (Büntgen et al., 2011), and collapse of complex societies such as the Akkadian empire (Gibbons, 1993; Cullen et al., 2000), the Egyptian Old Kingdom (Stanley et al., 2003), Mayan urban centres (Haug et al., 2003; Kennett et al., 2012) and Chinese dynasties (Yancheva et al., 2007). While those societal responses are generally acknowledged to be driven by multiple factors and societies differ in their vulnerability to changing environmental conditions (Tainter, 1990), investigating climate as one possible key driver is of large interest in the face of recent anthropogenic climate change (Stocker et al., 2014).

In this contribution, we focus on regime shifts in Asian Summer Monsoon dynamics during the last 10 ka and discuss their potential societal impacts such as cultural change or migratory patterns. Investigating the Asian monsoon domain is relevant for three reasons: (i) the Asian monsoon is a highly dynamic, vulnerable and multistable system (Zickfeld et al., 2005; Levermann et al., 2009) that has been identified as a potential climatic tipping element (Lenton et al., 2008). (ii) Ca. 60 % of the world's population are directly affected by the Asian monsoon with monsoon failures having large potential consequences for food supply in these regions (Wu et al., 2012). (iii) There are multiple known examples for the collapse of early complex societies in the Asian monsoon realm such as the Harappan culture in the Indus valley (Staubwasser and Weiss, 2006), as well as for the impact of climate change on socio-political developments, e.g. war frequencies or dynastic changes in China (Zhang et al., 2007; Yancheva et al., 2007). Thus, a deeper understanding of past changes in Asian monsoon dynamics and their impact on societies will contribute to being able to better anticipate potential consequences of future climate change in the region.

### Nonlinear regime shifts in Holocene Asian monsoon variability

J. F. Donges et al.

[Title Page](#)

[Abstract](#)

[Introduction](#)

[Conclusions](#)

[References](#)

[Tables](#)

[Figures](#)



[Back](#)

[Close](#)

[Full Screen / Esc](#)

[Printer-friendly Version](#)

[Interactive Discussion](#)



## Nonlinear regime shifts in Holocene Asian monsoon variability

J. F. Donges et al.

[Title Page](#)

[Abstract](#)

[Introduction](#)

[Conclusions](#)

[References](#)

[Tables](#)

[Figures](#)

[⏪](#)

[⏩](#)

[◀](#)

[▶](#)

[Back](#)

[Close](#)

[Full Screen / Esc](#)

[Printer-friendly Version](#)

[Interactive Discussion](#)



The Asian Summer Monsoon system is a seasonally recurring wind pattern related to the migration of the Intertropical Convergence Zone and is active from June to October. It is nominally separated into the Indian Summer Monsoon (ISM) and the East Asian Summer Monsoon (EASM). The ISM is divided into the Arabian Sea (AS) branch and the Bay of Bengal (BB) branch, which transport moisture from the Indian Ocean towards Arabia and the Indian Peninsula during the summer wet season (Fig. 1). The AS branch reaches NE Africa and the Arabian Peninsula before turning east towards the west coast of India. The BB branch of the ISM receives much of its moisture from the Arabian Sea, crosses India and reloads over the Bay of Bengal before moving northward until it reaches the Himalaya mountain range. Unable to cross this barrier, it splits into two branches, one moving NW-ward along the Himalaya, the other extending NE-ward into Tibet and China, where it contributes greatly to the summer rainfall. The EASM transports moisture from the adjacent seas into China and also onto the Tibetan Plateau. Complex and time-varying interdependencies have been demonstrated to exist between the different branches of the Asian Summer Monsoon system during the late Holocene (Feldhoff et al., 2012; Rehfeld et al., 2013) as well as at present (Baker et al., 2014).

Our approach is to integrate information on decadal to centennial Asian palaeomonsoonal variability during the Holocene from high-resolution oxygen isotope records from multiple caves, since speleothems are recognised as high-quality palaeoclimate archives for the considered time scales and geographical region. Of special importance for the present study is a robust chronology of the included archives, a requirement that is met by speleothem records. Focussing on one type of archive and proxy, this work extends upon and complements several related re-assessment studies (Morrill et al., 2003; Hu et al., 2008; Maher, 2008; Rehfeld et al., 2013). In contrast to earlier work, we focus not only on the intensity of monsoonal rainfall per se, but aim at identifying changes in the complexity of monsoonal variations as important higher-order information contained in the available records. The rationale behind this approach is that regular and, thus, predictable monsoonal variations are crucial for sustained

socio-economic development, while irregular variations of seasonal rainfall and climatic instabilities have been shown to have acted as triggers for social unrest and drivers of societal changes (Hsiang et al., 2013). Therefore, identifying epochs of regime shifts in the stability of palaeoclimatic variability is of high interest for investigating the role of Asian Summer Monsoon dynamics as a driver of cultural change or migratory patterns in the human realm.

From a methodological point of view, this work introduces several new aspects to the study of palaeoclimate variability: (i) we focus on nonlinear dynamics using recurrence network (RN) analysis of time series. This method is particularly useful for detecting qualitative changes in the dynamics of complex systems (Marwan et al., 2009; Donner et al., 2010b) and has been successfully applied in fields ranging from fluid dynamic over electrochemistry to physiology (Donner et al., 2014). RN analysis is specifically suitable for studying palaeoclimate records – unlike for other time series analysis methods there are only implicit effects of non-uniform sampling in the time domain and minor dating uncertainties (Donges et al., 2011a, b). (ii) We study of continental-scale climatic changes through the integration of information from proxy records from multiple sites distributed over South Asia (Rehfeld et al., 2013). (iii) We explicitly consider and propagate dating uncertainties in the available cave records using the COPRA framework (Breitenbach et al., 2012b), and (iv) we employ rigorous statistical tests for the coexistence of the signatures of monsoonal regime shifts at different sites.

Applying this methodology, we find that previously reported high-latitude Bond events (Bond et al., 1997, 2001) and rapid climate change (RCC) episodes (Mayewski et al., 2004; Fleitmann et al., 2008; Wanner et al., 2008, 2011) were often accompanied by epochs of large-scale nonlinear regime shifts in monsoonal dynamics. Furthermore, we are able to robustly identify at least one previously unnoticed regime shift in Asian Summer Monsoon dynamics during the Holocene, which manifests itself as an epoch of significantly increased regularity of monsoonal variations around 7.3 kaBP. Putting our findings into context with the archeological record, we find that the detected epochs of nonlinear regime shifts in Asian Summer Monsoon dynamics partly coincide with

## Nonlinear regime shifts in Holocene Asian monsoon variability

J. F. Donges et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

⏪

⏩

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



known major periods of migration, pronounced cultural changes, and the collapse of ancient human societies in Asia.

This article is structured as follows: after introducing the data and methods used (Sect. 2), an overview is provided on Holocene RCC events within the Asian monsoon system (Sect. 3). Our results on qualitative changes in monsoon dynamics as recorded in speleothem records are reported in Sect. 4 and are discussed in the context of Bond events and RCC episodes and potential impacts on cultural change and migratory patterns in Sect. 5. Finally, conclusions are drawn in Sect. 6.

## 2 Data and methods

In this section, we explain the selection of palaeoclimate records that are suitable for studying the stability of Asian monsoon dynamics during the Holocene within the frame of the presented strategy. Specifically, we are interested in shifts in the dynamic regime beyond changes in intensity during the last about 10 ka, which call for high-resolution (i.e. sub-decadal) records spanning as much as possible of the Holocene.

Subsequently, the methodology employed for quantitatively evaluating the effects of irregular sampling and dating uncertainties, both common problems in the time series analysis of palaeoclimate records, is introduced. Recurrence analysis is then presented as our statistical technique of choice for detecting epochs of regular (stable or periodic) and more erratic (and, hence, less predictable) dynamics as well as transitions between such episodes in palaeomonsoon variability.

### 2.1 Speleothem records of the Asian palaeomonsoon

Temporally well-resolved, precisely and accurately dated proxy records of palaeoclimate variability are indispensable for the study of spatially and temporally disperse decadal- to centennial-scale climatic episodes. Speleothems (secondary cave deposits, such as stalagmites) constitute terrestrial archives potentially covering several

CPD

10, 895–975, 2014

## Nonlinear regime shifts in Holocene Asian monsoon variability

J. F. Donges et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

⏪

⏩

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



## Nonlinear regime shifts in Holocene Asian monsoon variability

J. F. Donges et al.

[Title Page](#)

[Abstract](#)

[Introduction](#)

[Conclusions](#)

[References](#)

[Tables](#)

[Figures](#)

[⏪](#)

[⏩](#)

[◀](#)

[▶](#)

[Back](#)

[Close](#)

[Full Screen / Esc](#)

[Printer-friendly Version](#)

[Interactive Discussion](#)

hundred thousand years of environmental variability. Current U-Th dating techniques allow establishing robust age models back to < 800 000 years (Cheng et al., 2013). They frequently allow for high-resolution sampling at sub-decadal to even sub-annual scale (Johnson et al., 2006). Stalagmite records offer a multitude of geochemical and petrographic proxies (e.g. oxygen and carbon stable isotope ratios, major and minor element ratios and concentrations, or fluid inclusion water isotopes; Fairchild and Baker, 2012), though often only stable isotope ratios are used to infer changes in rainfall amount, source or intensity.

Available lacustrine (e.g. Kudrass et al., 2001; Ponton et al., 2012) and marine (von Rad et al., 1999; Staubwasser and Weiss, 2006) sediment records from the South Asian domain – although valuable for the study of long-term trends and millennial- to centennial-scale climate episodes – often lack both, sufficiently high sampling rates and chronological control to allow statistically significant comparison of multiple reconstructions at decadal time scale. Available ice core records from the Himalaya and Tibet (Thompson et al., 1997, 2000, 2003) are unfortunately either too short (covering only the past few thousand years) or lack also temporal resolution. Tree rings can generally add valuable information for reconstructing moisture and/or temperature dynamics (Cook et al., 2010; Borgaonkar et al., 2010; Treydte et al., 2006, 2009). However, very few records from Asia extend beyond the last 1000 years and, thus, these cannot be used to study qualitative changes of monsoon dynamics over the course of the Holocene, which are the focus of this study.

Given the considerable number and reasonable spatial distribution of available high-resolution speleothem records from the Asian monsoon domain, and for permitting a better comparability of the results to be obtained, in this study we restrict our attention to such cave archives. Specifically, we select published speleothem oxygen isotope ( $\delta^{18}\text{O}$ ) proxy records from the Asian monsoon domain that fulfil the following criteria: (i) coverage of a significant part of the Holocene (at least several thousand years), (ii) at least decadal resolution (i.e. a resolution of 10 years would result in 100 data points per millennium – a reasonable number for obtaining reliable statistics – which is about the



**Nonlinear regime shifts in Holocene Asian monsoon variability**

J. F. Donges et al.

[Title Page](#)[Abstract](#)[Introduction](#)[Conclusions](#)[References](#)[Tables](#)[Figures](#)[Back](#)[Close](#)[Full Screen / Esc](#)[Printer-friendly Version](#)[Interactive Discussion](#)

coarsest scale on which we expect the dynamical regime shifts studied in this work to be detectable) and (iii) with age uncertainties not larger than a few 100 years (Rehfeld and Kurths, 2014). These requirements are necessary to reliably detect shifts in the dynamical regimes (i.e. the nonlinear variability) of the Asian summer monsoon beyond simple changes in amplitude or variance. In case of multiple records from the same site (i.e. multiple speleothems from the same cave), we choose the dataset with the highest temporal resolution and longest time interval covered. Furthermore, we discard other types of proxies such as  $\delta^{13}\text{C}$ , grey-scale values, etc. available for some records, to obtain a consistent data base including only one variable (which may, however, be interpreted differently in different regions, see below). Other types of records are considered for comparison in the discussion of our results wherever appropriate.

The record database includes speleothem data from Asia, including the Arabian peninsula (influenced by the AS), India and Tibet (mainly under the influence of the BB), and China (with governing EASM) (Fig. 1). One additional record (Liang-Luar cave) from Indonesia has also been included, as this record indicates that the climatic episodes and transitions discussed below are found also in the AISM domain. The selected proxy records are listed in Table 1 together with information on sampling location, the number of samples, temporal resolution, and their interpretation and corresponding references.

Especially from China, many speleothem records have been reported over the last decade giving deep insights into the history of the EASM for the past ca. 300 000 years (Wang et al., 2005, 2008; Cheng et al., 2009; Dong et al., 2010). Unfortunately, only few terrestrial records are available so far from the Indian peninsula that meet our criteria (Sinha et al., 2005, 2007, 2011a, b; Berkelhammer et al., 2010, 2012). The available proxy reconstructions from Indian stalagmites reflect changes in the strength of the ISM, but they also show regional variability in ISM dynamics. Such differences reflect the complexity of the ISM over India, rather than contradicting the general understanding of ISM dynamics (Breitenbach et al., 2012a). The influence of the ISM on different regions in India has been noted by meteorological as well as

## Nonlinear regime shifts in Holocene Asian monsoon variability

J. F. Donges et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

⏪

⏩

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

palaeoclimatic studies (Hoyos and Webster, 2007; Sinha et al., 2011b; Rehfeld et al., 2013). Monitoring of rainwater in NE India reveals that its isotopic composition ( $\delta^{18}\text{O}_{\text{rw}}$ ) depends not simply on the amount of rainfall, but also on moisture source changes such as increased melt water flux, the pathway length an air mass moves from the source to the sampling site and related Rayleigh fractionation, and changes of the isotopic composition of the source (Breitenbach et al., 2010). Still, a clear ISM signal is detected, which allows us to use oxygen isotope ratios as tracers for ISM intensity.

Several records are available from the Arabian Sea realm (Qunf, Hoti and Dimarshim Caves, Table 1, Fig. 1). These are interpreted as reconstructions of the Arabian Sea branch of the ISM (Neff et al., 2001; Fleitmann et al., 2003, 2007). However, these records might not be representative for the dynamics of the ISM over the Indian Peninsula, and additional records must be recovered for a better spatial coverage in the heart of the ISM domain. The stalagmite from Indonesia (Griffiths et al., 2009) represents the tropical Asian monsoon domain and is used for comparison to put our results in a broader climatological context.

## 2.2 Treatment of uncertain depth-age models

Chronologies for the palaeoclimate proxy records used in this study have been established by means of U-series dating. The associated depth-age models are usually obtained by interpolation between the dating points. However, radiometric datings come with uncertainties suggesting that different chronologies might be valid for the proxy record in question (Telford et al., 2004; Buck and Millard, 2004; Blaauw, 2010). Moreover, intercomparison between proxy records with different dating strategies (and hence, time-scale uncertainties) and different non-uniform samplings demonstrates that considering a single depth-age model limits the reliability of all results. Therefore, we use the recently introduced COPRA (CONstructing Proxy Records from Age models) framework for the calculation of ensembles of consistent chronologies (depth-age models) for the used proxy records (Breitenbach et al., 2012b). This strategy allows

error propagation through subsequent statistical treatments and comparisons of multiple records.

Within COPRA, dating uncertainties are considered by a Monte Carlo (MC) simulation. To obtain an ensemble of age models, first, a random number drawn from a normal distribution of the standard deviation as given by the  $1\sigma$  error of the dating is added at each individual dating point. A piece-wise interpolation is then applied on these modified dating points to obtain ages for all proxy data points. This procedure is repeated 100 times (MC simulation) producing an ensemble of 100 possible age models (Fig. 3), where inconsistent realisations violating the stratigraphic constraint are rejected beforehand. In a next step, these age models are used to interpolate the measured proxy values to an equidistant time axis (regular sampling), resulting in a distribution of possible proxy values at each given (or required) time point. Now the time axis is a truly absolute and comparable reference system for all different proxy records, because the uncertainties within the time domain are transferred to uncertainties in the proxy domain (Breitenbach et al., 2012b).

Note, that interpolating the proxy signal to an absolute time axis is a post-processing step particular to this study that is not by default included in the COPRA framework. It is introduced here to additionally test the robustness of the results of recurrence analysis obtained below with respect to the effects of irregular sampling displayed by the available proxy records. Hence, in Sect. 4 we will compare the results obtained from the original irregularly sampled records with those computed from the COPRA ensemble signals that have been interpolated to a regularly sampled reference frame.

### 2.3 Recurrence analysis

Recurrence analysis comprises a class of nonlinear methods of time series analysis that are sensitive to dynamical features beyond what can be captured by commonly used linear statistics, such as power spectra and auto- or cross-correlation functions (Marwan et al., 2007). It is based on the fundamental observation that dynamical systems in Nature tend to recur close to their previously assumed states after a finite

CPD

10, 895–975, 2014

## Nonlinear regime shifts in Holocene Asian monsoon variability

J. F. Donges et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

⏪

⏩

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



## Nonlinear regime shifts in Holocene Asian monsoon variability

J. F. Donges et al.

[Title Page](#)

[Abstract](#)

[Introduction](#)

[Conclusions](#)

[References](#)

[Tables](#)

[Figures](#)

[⏪](#)

[⏩](#)

[◀](#)

[▶](#)

[Back](#)

[Close](#)

[Full Screen / Esc](#)

[Printer-friendly Version](#)

[Interactive Discussion](#)

time (Poincaré, 1890). For example, the weather observations (temperature, precipitation, pressure etc.) made at some meteorological station on a given day may be very similar, but not the same, as those recorded a few years earlier. The temporal structure of these recurrences contains a wealth of information on the dynamical system under study and can be mathematically represented and quantified by recurrence plots (Marwan et al., 2007) or recurrence networks (Marwan et al., 2009; Donner et al., 2010b, 2011; Donges et al., 2012) (see Fig. 4).

Recurrence analysis has been successfully applied to analyse climatological and palaeoclimatological data, e.g. for aligning the time scales of rock magnetic data from sediment cores (Marwan et al., 2002) and searching for relationships between the El-Niño Southern Oscillation (ENSO) and South American palaeoprecipitation (Marwan et al., 2003; Trauth et al., 2003). Recently and importantly for this study, it has been shown that recurrence network analysis (Marwan et al., 2009; Donges et al., 2011a, b; Marwan et al., 2013) and related techniques (Malik et al., 2012) are particularly well-suited for detecting subtle qualitative changes in the dynamics recorded by palaeoclimate proxy series with relatively few data points (compared to typical experimental and modern observational time series). In this study, we are interested in transitions in climate variability that are characterised by significant changes in dynamical complexity, i.e. changes between regular and rather erratic climate variations (Donges et al., 2011b). We argue that these transitions are subtle in the sense that they cannot always be easily and unambiguously identified by eye, in contrast to differing claims (Wunsch, 2007).

Since we are interested in the complexity of monsoonal fluctuations during the Holocene on decadal to centennial scales, rather than in millennial and longer-term trends, we detrend the proxy records using a 1000 year running window (Donges et al., 2011a) and study the residual oxygen isotope signals  $\Delta\delta^{18}\text{O}$  as a time series  $\{x_i\}_{i=1}^N$  (Fig. 2). In the remainder of this section, we describe the analytical techniques used for detecting and quantifying qualitative changes in Holocene monsoon dynamics recorded by speleothems, namely, time-delay embedding and recurrence network



## Nonlinear regime shifts in Holocene Asian monsoon variability

J. F. Donges et al.

[Title Page](#)

[Abstract](#)

[Introduction](#)

[Conclusions](#)

[References](#)

[Tables](#)

[Figures](#)

[⏪](#)

[⏩](#)

[◀](#)

[▶](#)

[Back](#)

[Close](#)

[Full Screen / Esc](#)

[Printer-friendly Version](#)

[Interactive Discussion](#)



the average sampling time  $\langle \Delta T \rangle$ , i.e.  $\tau = \lfloor \tau_d / \langle \Delta T \rangle \rfloor$  (Donges et al., 2011a). One technical problem in properly determining this value is that proxy records, like the original speleothem records discussed here are generally characterised by irregular sampling. This either requires an interpolation of the data (possibly leading to biased results, cf. Rehfeld et al., 2011) or specific methods which are able to cope with such irregular sampling for estimating correlation functions (Scargle, 1989; Babu and Stoica, 2009). In this study, we use a Gaussian-kernel based estimator for the auto-correlation functions (Rehfeld et al., 2011; Rehfeld and Kurths, 2014) to determine the typical values for  $\tau_d$ . Although these values can vary when chronological uncertainties are taken into account using the COPRA framework (Fig. 5, cf. Sect. 2.2), we use the decorrelation time obtained from the original record for reference.

### 2.3.2 Recurrence network analysis

Our aim is to detect qualitative changes in palaeomonsoon dynamics reflected in temporal variations of complexity measures computed from the proxy records. For this purpose, we slide a window over the reconstructed climate trajectory containing  $W$  state vectors  $\mathbf{y}_i$  with a step size of  $\Delta W$  state vectors. For rendering the results of the analysis comparable between records with differing average sampling intervals  $\langle \Delta T \rangle$  (this is only an issue for the original records, but not concerning COPRA ensembles), both parameters are chosen such that the corresponding time scales  $W^*$  and  $\Delta W^*$  are approximately the same for all records, i.e.  $W = \lfloor W^* / \langle \Delta T \rangle \rfloor$  and  $\Delta W = \lfloor \Delta W^* / \langle \Delta T \rangle \rfloor$  (where  $\lfloor x \rfloor$  denotes the largest integer not larger than  $x$ ). We select the window size  $W^* = 750$  a for all records. The step size is chosen as  $\Delta W^* = 50$  a for all records. It has been shown in earlier work that the results of recurrence network analysis (RNA) are robust with respect to variations in both window and step size (Donges et al., 2011a).

For each window, we build a recurrence network (RN) from the corresponding set of state vectors (Marwan et al., 2009; Donner et al., 2010b; Donges et al., 2012) (steps 4 and 5 in Fig. 4). Nodes of this network (Boccaletti et al., 2006; Newman, 2010; Cohen and Havlin, 2010) represent state vectors  $\mathbf{y}_i$  from the reconstructed climate trajectory,

while links are established between state vectors that are recurrent, i.e. closer to each other in the phase space of the reconstructed variables than a prescribed threshold distance  $\varepsilon$ . Formally, the RN is represented by its adjacency matrix (which can be alternatively visualised as a recurrence plot, cf. Fig. 4)

$$A_{ij} = \Theta(\varepsilon - \|\mathbf{y}_i - \mathbf{y}_j\|) - \delta_{ij}. \quad (2)$$

Here,  $\Theta(\cdot)$  is the Heaviside function,  $\|\cdot\|$  denotes the supremum norm, and  $\delta_{ij}$  is Kronecker's delta ensuring that state vectors are not connected to themselves forming self-loops in the RN (Donner et al., 2010b). Following generally suggested good practice for recurrence network analysis (Donner et al., 2010a; Marwan, 2011; Donges et al., 2012), the threshold distance  $\varepsilon$  is adaptively chosen for each window to ensure that approximately 5% of all theoretically possible links are present in the network.

The RN's structure contains information on climate dynamics during the time interval covered by the corresponding window. We use the statistical network quantifiers *transitivity*  $\mathcal{T}$  and *average path length*  $\mathcal{L}$  to capture this information, which can be interpreted as measures of climate regularity and abrupt dynamical change, respectively (Donges et al., 2011a, b). High  $\mathcal{T}$  values indicate epochs with regularly varying climate on decadal and centennial scales, e.g. a dominating periodic component in the proxy signal or time intervals with stationary or slowly changing climate, while low  $\mathcal{T}$  values imply epochs with more erratic (i.e. less predictable) climate fluctuations. In contrast, large  $\mathcal{L}$  values highlight time intervals including rapid shifts between different climatic regimes, while low  $\mathcal{L}$  values point to a more stationary climate during the corresponding epoch.

To robustly detect episodes of stability, as well as qualitative changes in monsoonal dynamics that are unlikely to arise from statistical fluctuations alone, we apply the stationarity test proposed in Donges et al. (2011a, b) for each proxy record. From this test we obtain 90% confidence bounds for both quantifiers  $\mathcal{T}$  and  $\mathcal{L}$  indicating which range of values are typical when information from the whole record is taken into account. Thus, for the original irregularly sampled records we are able to identify statistically

**Nonlinear regime shifts in Holocene Asian monsoon variability**

J. F. Donges et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

⏪

⏩

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion







events exhibit a typical return period of about 1000 to 1500 years, which is close to that of the Dansgaard–Oeschger cycles during the last glacial period (Hemming, 2004). The mechanisms leading to this quite regular appearance of both phenomena, as well as their possible relationship are a subject of ongoing discussions and not conclusively resolved yet.

Some, but not all Bond events appear to sharply coincide with periods of marked high-latitude cooling and/or low-latitude aridification and possibly associated cultural changes and large-scale migration patterns (Gupta et al., 2003; Wang et al., 2005; Parker et al., 2006). More specifically, most of these events did not result in a coherent cooling over the entire globe, but had at least partly global effects manifested in distinct local responses such as droughts, increasing storminess, or seasonality changes.

A particularly remarkable example is the 8.2 ka event, which is widely recognised as the most pronounced large-scale Northern Hemisphere cooling episode during the Mid-Holocene (Alley et al., 1997). Regional climate changes associated with this episode are diverse (Alley and Ágústsdóttir, 2005) and include a strengthened atmospheric circulation over the North Atlantic and Siberia, resulting in more frequent winter outbreaks of polar air masses (Mayewski et al., 2004). In the lower northern latitudes, there is palaeoclimatic evidence for widespread aridity, for example, in terms of an intermittent interruption of the African Humid Period (deMenocal et al., 2000), dramatically weakened summer monsoons over the Arabian Sea and tropical Africa (Fleitmann et al., 2003; Alley and Ágústsdóttir, 2005; Morrill and Jacobsen, 2005), and persistent drought in Pakistan (Mayewski et al., 2004). In turn, precipitation in the Near and Middle East increased during the 8.2 ka event (Bar-Matthews et al., 2000; Arz et al., 2003), which indicates a possible southward displacement and intensification of westerlies, associated with changes of the North Atlantic Oscillation. Moreover, regarding the regional focus of this study we note that in comparison with the ISM and EASM domains, available indications for rapid climate change around the 8.2 ka event are somewhat weaker in the AISM domain (Partin et al., 2007; Griffiths et al., 2009).

## Nonlinear regime shifts in Holocene Asian monsoon variability

J. F. Donges et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

⏪

⏩

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



### 3.2 Rapid climate change (RCC) episodes

While the notion of Bond events refers primarily to North Atlantic climate variability, Mayewski et al. (2004) compiled information on global Holocene climate variability and identified six periods of significant large-scale fluctuations based on ca. 50 globally distributed climate records from different kinds of archives (glacier fluctuations, ice cores, marine sediments), for which they coined the term rapid climate change (RCC) episodes. We note again that the associated Holocene climate shifts are much smaller in amplitude and rapidity than those occurring during the last glacial. However, as Mayewski et al. (2004) emphasise, these changes appeared globally in a coherent way and were sufficiently abrupt to affect early human societies (deMenocal, 2001; Haberle and David, 2004). In fact, several of the identified RCC episodes can be attributed to the timing of major disruptions of civilisation (Cullen et al., 2000; Drysdale et al., 2006; Fleitmann et al., 2008; Baldini et al., 2002; Berkelhammer et al., 2012).

The six major Holocene RCC episodes identified by Mayewski et al. (2004) are listed in Table 4. Notably, these episodes coincide with the Bond events B0–B6. However, in some cases (B1, B6) the Bond events appear close to the beginning of the respective RCC episode, whereas in other cases the observed climatic changes appear to set in before the Bond event. However, the palaeoclimate records used by Mayewski et al. (2004) exhibit dating uncertainties of up to 500 years, which does not allow identifying a clear causal relationship between RCC and Bond events. Nevertheless, in what follows we use the RCC episodes as additional benchmarks for our results described below.

The earliest Holocene RCC episode has been termed “Glacial Aftermath” by Mayewski et al. (2004) and has been originally attributed to a time interval between about 9.0 and 8.0 kaBP. Notably, this corresponds to a period characterised by still substantial Northern Hemisphere ice sheets. Consistently with the latter fact, this episode includes the strongest short-lived Holocene cooling episode in the North Atlantic region, the 8.2 ka event (Bond event B5) (Alley et al., 1997), which has probably

## Nonlinear regime shifts in Holocene Asian monsoon variability

J. F. Donges et al.

[Title Page](#)

[Abstract](#)

[Introduction](#)

[Conclusions](#)

[References](#)

[Tables](#)

[Figures](#)



[Back](#)

[Close](#)

[Full Screen / Esc](#)

[Printer-friendly Version](#)

[Interactive Discussion](#)



## Nonlinear regime shifts in Holocene Asian monsoon variability

J. F. Donges et al.

[Title Page](#)

[Abstract](#)

[Introduction](#)

[Conclusions](#)

[References](#)

[Tables](#)

[Figures](#)

[⏪](#)

[⏩](#)

[◀](#)

[▶](#)

[Back](#)

[Close](#)

[Full Screen / Esc](#)

[Printer-friendly Version](#)

[Interactive Discussion](#)



been initiated by a large meltwater pulse reducing the Atlantic thermohaline circulation (Broecker et al., 2010). Moreover, there is recent evidence for additional meltwater pulses preceding the 8.2 ka event, one of which possibly triggered another widespread climate anomaly at about 9.2 kaBP (Fleitmann et al., 2008) given its temporal proximity to the original dating of the Bond event B6. In both cases, the corresponding large-scale temperature drop in mid to high northern latitudes has been accompanied by a significant drying in the northern tropics reflected in several records from the Asian monsoon domain (Mayewski et al., 2004; Fleitmann et al., 2008). In this spirit, this period (RCC5) cannot be unambiguously attributed to a single event, but more likely expressed the global climate response to a series of individual climatic events.

The following four RCC episodes (RCC4 to RCC1) varied in strength and geographical extension, but share the same common pattern of high-latitude cooling and low-latitude aridity. The most extensive episode lasted from about 6.0 to 5.0 kaBP (RCC4) and featured North Atlantic ice rafting (5.9 ka or B4 event), alpine glacier advances, strengthened westerlies, and pronounced aridity in Arabia (Parker et al., 2006). In the low latitudes, it coincided with the beginning decline of the African Humid Period (deMenocal et al., 2000; Francus et al., 2013), but possibly displayed sustained moist conditions in northwestern India and Pakistan (Enzel et al., 1999). The 4.2 to 3.8 kaBP period (RCC3, falling together with the 4.2 ka or B3 event) is commonly weaker and less well expressed in its global-scale characteristics and displayed weaker winds over the North Atlantic and Siberia and generally dryer conditions in the low latitudes (for the ISM see Berkelhammer et al., 2012). Between 3.5 and 2.5 kaBP, another RCC episode (RCC2) with North Atlantic ice rafting (Bond event B2) and strengthened westerlies is found, whereas the signature of the 1.2 to 1.0 kaBP episode (RCC1) again widely resembles that of RCC3. In contrast to the other five Holocene RCC episodes, the last one between 0.6 and 0.15 kaBP (RCC0, corresponding to the Little Ice Age in Europe) has been characterised by high latitude cooling, but wide-spread wet conditions in the low latitudes including an intensified Indian summer monsoon (Mayewski et al., 2004).

A notable exception from this low-latitude pattern is a pronounced drought in Central America (Kennett et al., 2012).

In general, with the exception of the glacial aftermath episode, most RCC intervals show indications of an episodic weakening of solar activity as a possible triggering mechanism in combination with less favourable orbital parameters after the Mid-Holocene optimum (Mayewski et al., 2004). Specifically, during RCC4 and RCC2, there are pronounced maxima of  $^{10}\text{Be}$  and  $\delta^{14}\text{C}$  indicating a decline of solar irradiation. A maximum of  $^{10}\text{Be}$  is also found during RCC3. However, there is little change in  $\delta^{14}\text{C}$  during that period, possibly pointing to an intensified coastal upwelling in the presence of stronger westerlies (Mayewski et al., 2004). In addition to long-term variations of solar forcing, volcanic activity could have acted as an additional relevant factor in some RCC episodes, particularly for the most recent period commonly known as the Little Ice Age (Miller et al., 2012; Schleussner and Feulner, 2013), but also for Bond event B7 (Amigo et al., 2013)

While the existence of episodes of Holocene rapid climate changes is meanwhile widely accepted, there is an ongoing debate about the timing and spatial coherency of these patterns. For example, Wanner et al. (2008) used a different set of paleoclimate time series and “did not find any time period for which a rapid or dramatic climatic transition appears even in a majority of the time series” with the exception of two large-scale shifts at about 5.2 kaBP and between 3.1 and 2.5 kaBP, which partly coincide with the RCC3 and RCC2 episodes reported by Mayewski et al. (2004). Another recent study came to a similar result reporting that the spatio-temporal patterns of temperature and humidity/precipitation exhibited very strong variability during some of the most pronounced Holocene cold episodes (Wanner et al., 2011). In our opinion, these differences among recent studies do not necessarily contradict the existence of consistent large-scale responses of the climate system, but rather highlight the complexity and possible regional variety of such changes. While recent studies have almost exclusively focussed on changes in the amplitudes of palaeoclimate proxies, this work

**Nonlinear regime shifts in Holocene Asian monsoon variability**

J. F. Donges et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

⏪

⏩

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



examines more subtle changes in the nonlinear dynamics of palaeoclimate variability and searches for consistent patterns related to this specific aspect.

Notably, the Holocene RCC episodes (although relatively small in magnitude, Mayewski et al., 2004) coincide with periods of dramatic changes in some ecosystems and human civilisations. For example, the short-lived RCC1 episode appears synchronously with the collapse of the Maya civilisation, which has probably been substantially aggravated by multiple prolonged droughts (Haug et al., 2003; Kennett et al., 2012). The RCC3 episode saw the demise of some of the World's first highly developed complex societies such as the Akkadian Empire, Egypt's Old Kingdom, or the Indus Valley (Harappan) civilisation (Gibbons, 1993; Weiss et al., 1993; Cullen et al., 2000; Stanley et al., 2003; Drysdale et al., 2006). The time period around the 8.2 ka event was characterised by an abrupt abandonment of flourishing settlements in Anatolia and a subsequent spread of early farmers into Southern Europe, which was possibly triggered by increased aridity in the Near and Middle East (Weninger et al., 2006). We will further elaborate on some important examples and their signatures within the Asian monsoon system in Sects. 4 and 5.

## 4 Results

In this section, we report our results of RN analysis for the chosen set of Asian speleothem records, which reveal several epochs of significant nonlinear climatic change during the Holocene. First, the results obtained by using original age models are evaluated for their robustness with respect to dating uncertainties. For this purpose, the well-studied record from the Dongge cave is used as an illustrative example (Sect. 4.1). In the next step, we present our findings on the long-term variability of nonlinear Asian palaeomonsoon dynamics based on the analysis of all 10 speleothem records by means of a summary statistics (Sect. 4.2). Based on these results, the nonlinear signatures of global RCC episodes and their regional fingerprints in the Asian monsoon domain are discussed (Sect. 4.3). The findings are corroborated

CPD

10, 895–975, 2014

### Nonlinear regime shifts in Holocene Asian monsoon variability

J. F. Donges et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

⏪

⏩

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

and confirmed by a comprehensive analysis of the COPRA ensembles for all records, taking full account of the effects of dating uncertainties (Sect. 4.4).

#### 4.1 Nonlinear climatic variability at Dongge cave

For illustrating our methodology in detail, in this section we present and discuss the results of applying RN analysis for detecting episodes of nonlinear change in the EASM strength during the Holocene as captured by the Dongge DA residual oxygen isotope record (Wang et al., 2005) (Fig. 6a). Analysing the time series using the original depth-age model (in the following identified as RAW), epochs of statistically significant deviations from typical EASM variability are identified at 8.5–8.0, 7.4–6.7, 6.6–6.2, 5.7–5.2, 5.2–4.8, 4.9–3.9, ca. 2.6, ca. 2.2 and 0.7–0.5 kaBP based on the quantifiers average path length  $\mathcal{L}$  and transitivity  $\mathcal{T}$  (Fig. 6b and c). Note that while both measures agree on some of the identified epochs, they provide partly complementary information on nonlinear fluctuations in the considered time series (see Sect. 2.3) and, hence, are not expected to yield fully overlapping epochs of significant nonstationarities.

A similar study of the COPRA ensemble of time series generated to include effects of dating uncertainties reveals epochs of atypical nonlinear monsoonal variability at 8.2–6.7, 4.8–3.9 and ca. 3.0 kaBP (Fig. 6b and c). The major episodes of climatic change identified by the measure  $\mathcal{L}$  at 8.2–8.0, 7.4–6.7 and 4.9–3.9 kaBP in the original record are confirmed by analysing the associated COPRA ensemble (Fig. 6b). While this is not as clearly the case for the measure  $\mathcal{T}$  (Fig. 6c), some common features can still be identified. In particular, the epoch of significantly increased climate regularity between 4.5 and 4.2 kaBP is present in the COPRA results as a distinguishable peak (note the scale of typical variations in  $\mathcal{T}$ ), albeit not a significant one.

These results illustrate that while dating uncertainties can have an effect on the results of RN analysis, major epochs of nonlinear change in monsoonal variability are robust features. Hence, in the following we first present the results for the original records and then proceed to evaluate their reliability based on a comprehensive analysis of the full COPRA ensemble associated to each record. In the remainder of this work, we

### Nonlinear regime shifts in Holocene Asian monsoon variability

J. F. Donges et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



## Nonlinear regime shifts in Holocene Asian monsoon variability

J. F. Donges et al.

[Title Page](#)

[Abstract](#)

[Introduction](#)

[Conclusions](#)

[References](#)

[Tables](#)

[Figures](#)

[⏪](#)

[⏩](#)

[◀](#)

[▶](#)

[Back](#)

[Close](#)

[Full Screen / Esc](#)

[Printer-friendly Version](#)

[Interactive Discussion](#)

focus our discussion on epochs that can be identified in both the original records and the COPRA ensembles. In other words, we search for a compromise between studying the original isotopic signal while ignoring dating uncertainties and analysing an ensemble of interpolated isotopic signals under consideration of dating uncertainties, acknowledging that interpolation can introduce artefacts into RN analysis, as it does to any method of time series analysis (Rehfeld et al., 2011).

As a general observation, there is a notable decreasing trend of both measures  $\mathcal{L}$  and  $\mathcal{T}$  towards the present in the COPRA ensemble pointing, e.g. towards a decrease in the regularity of monsoonal variability throughout the Holocene, that is less obvious in the results derived from the original Dongge DA record (Fig. 6b and c). These enhanced trends in the RN characteristics obtained from the COPRA ensemble could be related to a heterogeneous sampling density of the record, due to which interpolation to a common regular temporal reference frame would introduce a degree of smoothness that varies with age.

The epochs of atypical variability of EASM strength identified in the Dongge DA record notably coincide with several RCC episodes (and their associated Bond events), namely the 8.2 ka event (RCC5), RCC2–4 as well as RCC0 (Fig. 6 and Tables 3 and 4). Below we discuss these findings in detail by taking into account a larger set of palaeoclimate records that capture the dynamics of all relevant branches of the Asian Summer Monsoon system.

### 4.2 Multi-record analysis of palaeomonsoon dynamics

RN analysis of the considered 10 speleothem records reveals distinct time intervals which display very unusual dynamics (regarding the stationarity test described in Sect. 2.3.2 and Donges et al., 2011a, b). Figures 7 and 8 show the full variability of transitivity  $\mathcal{T}$  and average path length  $\mathcal{L}$  for all considered records (raw data) that will be discussed in detail below. Figure 9 gives the fractions  $n_{\mathcal{T}}$  and  $n_{\mathcal{L}}$  of all available records  $N_r$  exhibiting unusual dynamics as revealed by RNA as a function of time. Note that before about 10 kaBP and after about 1 kaBP, the number of available records

in this study is strongly reduced, so that we cannot draw any statistically substantiated conclusions about nonlinear climate variability during these intervals. Even more, since age control of all records is clearly limited in the older part of all records, we do not further discuss events found before 10 kaBP (i.e. in the Early Holocene) at this point.

5 The same applies to the results of the corresponding COPRA ensembles displayed in Fig. 10.

In order to interpret the obtained results, we devise a significance test to evaluate the robustness and validity of these results summarised in the statistics  $n_{\mathcal{J}}$  and  $n_{\mathcal{L}}$ . We start with observing that the fraction of records  $n$  showing atypical climatic variability  
10 in a certain time interval depends on the total number of records  $N_r$  available at that time (Fig. 9a), as well as on the probability distribution of the length  $l$  of such episodes  $p(l)$ . For example, if  $N_r$  is small, it is more likely that  $n$  is large because a single record possibly randomly contributing an episode of atypical climatic variability at that time suffices to strongly increase  $n$ . To control for this effect, we randomly generate 1000  
15 binary surrogates for each record and both measures  $\mathcal{L}$  and  $\mathcal{J}$ . These surrogates are constrained to have the same temporal coverage and length distribution of episodes of atypical climate variability  $p(l)$  as obtained from the original record. From these surrogates, a probability distribution  $p(n)$  is computed at each time step. This distribution of the fraction of records showing atypical climate variability that is expected to occur  
20 by chance alone allows us to judge during which epochs the overall climate dynamics as reflected in all records was indeed extraordinary. We consider those epochs as significant large-scale deviations from “typical” climate variability (marked by dark blue and dark green fillings in panels b and c of Figs. 9 and 10, respectively), for which the probability to observe the  $n$  obtained from the observed records (based on original  
25 depth-age models or COPRA ensembles) by chance is smaller than 10 %, corresponding to a confidence level of 90 % (grey lines in panels b and c of Figs. 9 and 10). Note that due to the discrete nature of the observable  $n$ , it is reasonable to consider also epochs with marginally significant epochs, where the probability to observe the  $n$  obtained from the original records by chance is equal to 10 %.

## Nonlinear regime shifts in Holocene Asian monsoon variability

J. F. Donges et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

⏪

⏩

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion





### 4.3 Nonlinear variability changes and RCC episodes

Between about 10 ka and 1 kaBP, we observe that especially  $n_{\mathcal{L}}$  (but to a smaller extent also  $n_{\mathcal{T}}$ , cf. Fig. 9b and c) displays marked cycles with an average return period of ca. 1 to 1.5 ka, which resembles the known cyclicity of Bond events. However, we emphasise that although there are some coincidences between the corresponding timings, the overall synchronicity is not perfect, suggesting that strong episodic high-latitude forcing alone is not a good predictor for the emergence of these time intervals. Alternatively, long-term solar cycles could be a factor triggering the observed cyclicity of monsoon dynamics via direct insolation forcing. However, comparison with a recent reconstruction of Holocene total solar irradiance (TSI) (Steinhilber et al., 2012) fails to provide convincing evidence for such cycles in the TSI data (Fig. 9d).

#### 4.3.1 Indications for nonlinear regime shifts

Regarding the fraction  $n_{\mathcal{L}}$  of significant values of  $\mathcal{L}$  in the considered records (Fig. 9b), we observe that the periods with a significant fraction of records displaying unusual  $\mathcal{L}$  values agree remarkably well with the RCC episodes listed by Mayewski et al. (2004). Specifically, significant epochs identified by our test are found at 8.5–7.9, 7.5–7.2, 5.7–5.0, 4.1–3.9 and 3.0–2.4 kaBP. We note that only in one case (B2), these periods coincide with the timing of high-latitude Bond events, whereas four out of five are contained within RCC episodes. The only notable exception is the time interval between 7.5 and 7.2 kaBP identified by our approach.

From the RN analysis of the individual records (cf. Fig. 7), we can draw some preliminary conclusions about the significance and possible spatial extent of the observed nonlinear regime shifts:

- the time period from 8.5–7.9 kaBP is significant in the Liang Luar (before about 8.2 kaBP), Dongge (8.5–7.9 kaBP), Mawmluh (8.3–7.9 kaBP), Hoti (8.0 kaBP) and Qunf records (8.3–7.9 kaBP). This suggests that the AISM and EASM

CPD

10, 895–975, 2014

## Nonlinear regime shifts in Holocene Asian monsoon variability

J. F. Donges et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

⏪

⏩

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



## Nonlinear regime shifts in Holocene Asian monsoon variability

J. F. Donges et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

⏪

⏩

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



does not display marked dynamical changes, the underlying regime shift seems to be concentrated at lower latitudes.

- Finally, the time interval 3.0–2.4 kaBP shows indications for nonlinear regime shifts in most records, with the strongest effects observed in the northernmost caves. This finding suggests a relationship with the progressive weakening of the ISM and EASM over the Holocene, which led to a marked decrease of precipitation in Northern Central China especially over the last 4 ka (Cai et al., 2010).

Comparing our results with the TSI reconstruction from Steinhilber et al. (2012) (Fig. 9d), it is evident that with the exception of the time window 4.1–3.9 kaBP, most periods indicated by unusual  $\mathcal{L}$  coincide with (or are at least temporally close to) strong negative anomalies of solar irradiation. This finding points to direct insolation forcing as likely triggering factors for most observed transition phases. We note that the RCC3 episode containing the 4.1–3.9 kaBP period is generally weaker and less well expressed globally (Mayewski et al., 2004), which might point to a delayed response to a high-latitude feedback (e.g. associated with Bond event B3) indirectly affecting the Asian monsoon system via weakened atmospheric circulation over Central to Northern Asia as well as weaker westerlies.

### 4.3.2 Changes in climate regularity

Compared with  $\mathcal{L}$ , RN transitivity  $\mathcal{T}$  exhibits a similar, yet less clear cyclic variability (Fig. 9c). In particular,  $n_{\mathcal{T}}$  displays periods with a significant fraction of records showing a non-typical degree of dynamic regularity at 9.7–9.0, ca. 8.5, 8.0–7.9, 5.7–5.6, ca. 5.0, 3.9–3.7, 2.9–2.4 and 1.7–1.3 kaBP. Most of these periods overlap partially with RCC episodes, with the exception of the first and last ones, which are, however, only marginally significant. Notably, several of the periods highlighted by  $n_{\mathcal{T}}$  are also very close to TSI minima (Steinhilber et al., 2012). Since weaker insolation reduces global temperature and, hence, evaporation over tropical oceans, a general weakening of monsoon strength is expected during such time intervals. Lower insolation also reduces

## Nonlinear regime shifts in Holocene Asian monsoon variability

J. F. Donges et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



temperature gradients between low and high latitudes, further hampering northward migration of the ITCZ. In turn, this could result in generally more regular interannual variations of summer monsoon strength, which would be reflected in higher values of  $\mathcal{T}$ . Figure 8 shows that almost all “significant” values of  $\mathcal{T}$  are found above the range of “normal” values, indicating that unusually regular variability conditions occur more frequently than unusually irregular ones (Donges et al., 2011b).

Regarding the spatial extent of these “regular phases”, the obtained picture is more ambiguous than that for  $\mathcal{L}$  as an indicator of general dynamical regime shifts. The 8.5 kaBP window only displays significant transitivity at Liang-Luar. For the period of 8.0–7.9 kaBP, we find significant values of  $\mathcal{T}$  only for the Mawmluh and Hoti caves, but not in the Qunf record, which is located in between both. At 5.7–5.6 kaBP, significant RN transivities arise in the Tianmen, Dongge and Liang-Luar records, not allowing a reasonable speculation about possible underlying causes. The same applies to the 3.9–3.7 kaBP interval with significant results only at Qunf, Liang-Luar and Jiuxian. Around 2.9 kaBP and between 2.6 and 2.4 kaBP, we find significantly increased values of  $\mathcal{T}$  at Dimarshim, Heshang and Jiuxian caves, in the latter case also at Lianhua.

As a general limitation for the interpretation of the reported results, we emphasise that RN transitivity is related to the dynamic regularity of a time series. Since the periods of reduced or “regularised” monsoonal dynamics can be expected to be relatively short in comparison with the applied window size (restricted by the temporal resolution of the available records), it is very likely that some possibly relevant features are masked by “normal” conditions prior to and after these periods. Hence, only the most pronounced of such signatures can be detected at all. This limitation calls for future records with an even higher temporal resolution and also more precise age control compared to the records used here.

#### 4.4 Consideration of dating uncertainties

The results obtained using the COPRA framework applied to all considered speleothem records differ to some extent from those for the original time series (Fig. 10). One main

## Nonlinear regime shifts in Holocene Asian monsoon variability

J. F. Donges et al.

[Title Page](#)

[Abstract](#)

[Introduction](#)

[Conclusions](#)

[References](#)

[Tables](#)

[Figures](#)

[⏪](#)

[⏩](#)

[◀](#)

[▶](#)

[Back](#)

[Close](#)

[Full Screen / Esc](#)

[Printer-friendly Version](#)

[Interactive Discussion](#)

reason for this is the definition of a significant episode, which is based on the distributions of RN characteristics obtained for each record. Visual intercomparison between Figs. 9 and 10 shows that the observed fractions of significant records based on  $n_{\mathcal{L}}$  and  $n_{\mathcal{T}}$  are considerably higher in case of the COPRA ensembles. We note that this larger number is partly related to the rather conservative assumption for defining significance levels for each individual dataset used in our computations. The resulting difference is particularly strong for  $n_{\mathcal{L}}$ , where the previously observed cyclicity is almost completely lost, and values are above 0.6 for almost the entire time period under investigation.

In accordance with the limitations arising from the aforementioned observation, we again find periods with a significant fraction of records showing significant deviations of the RN statistics from “normal” values. With respect to  $n_{\mathcal{L}}$  we detect epochs of unusual change in monsoonal variability at 9.9–9.7, 9.3–6.7, 6.0–5.0, 4.2–3.4, 3.2–3.0 (Fig. 10b). Considering  $n_{\mathcal{T}}$ , episodes of extraordinary (ir)regularity of monsoonal dynamics are identified at 9.2–6.5, 5.7–4.9, 4.0–3.8, 3.3–2.5 and 2.4–2.3 ka BP (Fig. 10c). Importantly, most of these epochs obtained under systematic consideration of dating uncertainties overlap with the corresponding episodes of unusual monsoonal dynamics that were revealed based on the original depth-age models (Sect. 4.3). This indicates, that our results can be considered as robust with respect to dating uncertainties. The detailed curves for all records are provided in the Supplementary Information.

As a particular feature, both  $n_{\mathcal{L}}$  and  $n_{\mathcal{T}}$  show “perfect” values of 1 indicating the presence of nonlinear regime shifts and extraordinary levels of regularity throughout the entire time interval between 9.0 and 8.2 ka BP. As already discussed for the Dongge record (Sect. 4.1), this effect is at least partly due to the larger age uncertainty in the older parts of the studied speleothem sequences ranging back to this period of time. It increases the effect of interpolation within the COPRA ensembles and, hence, induces a greater degree of regularity. However, since we have already observed corresponding episodes using the original depth-age models, we conclude that this result should not be discarded as solely artificially induced by COPRA.

## Nonlinear regime shifts in Holocene Asian monsoon variability

J. F. Donges et al.

[Title Page](#)

[Abstract](#)

[Introduction](#)

[Conclusions](#)

[References](#)

[Tables](#)

[Figures](#)

[⏪](#)

[⏩](#)

[◀](#)

[▶](#)

[Back](#)

[Close](#)

[Full Screen / Esc](#)

[Printer-friendly Version](#)

[Interactive Discussion](#)

In general, we conclude that using COPRA ensembles holds a great potential for refining the results of our analysis, as well as other types of time series analysis techniques that could be applied to palaeoclimate proxy data. However, the corresponding strategy for defining significant periods for individual records needs to be carefully chosen, probably in a more rigorous way than in the present work. A disadvantage of the proposed framework is that generating ensembles of COPRA realisations and determining the significance of the results of RN analysis for each ensemble member by means of bootstrapping techniques is computationally expensive. Moreover, as our results indicate, a heterogeneous density of sampling points along the considered sequence can lead to a varying strength of interpolation-induced artefacts due to the COPRA method, which calls for more sophisticated statistical tests taking this fact explicitly into account. To this end, we leave this as an open problem to be addressed in future work.

## 5 Effects on human societies

Utilising the long-term variations and dynamical transitions within the Holocene Asian monsoon domain, we can now relate not just the general mean environmental conditions (e.g. arid vs. humid climate), but also their temporal variability to possible consequences for the development of early cultures in the region of interest. In this section, we elaborate on such potential linkages between the spatio-temporal pattern of different RCC episodes, their respective environmental impacts and known transitions in the archeological record. We particularly focus on the spatial component, i.e. the signature of climatic changes and dynamics in different regions. Beyond previous studies focussing on the mean climatic conditions and changes thereof, we explicitly consider the role of regularity in the inter-annual monsoon dynamics. This novel aspect provides an important additional factor determining the environmental basis for population growth, migration, and cultural developments that have allowed early human societies coping with their natural resources in a sustainable way. See Fig. 11 for a regionally

resolved overview on the timing of inferred nonlinear monsoonal regime shifts relative to societal events.

Our results suggest relatively strong impacts of past climatic changes on the state and early cultural development in the Asian monsoon domain. Most of these impacts were closely related to rainfall amount and seasonality, determining the water availability for agricultural purposes in vast parts of the considered region. Temperature drops possibly have additionally fostered societal changes and migration in regions where minimum temperatures pose a crucial limit to crop cultivation (e.g. in northern central to western China). Beyond the mean climatic conditions, monsoon dynamics plays a key role for the development and persistence of prehistoric human cultures. On the one hand, very strong intra-annual variability of precipitation could relate to pronounced extremes limiting the habitability of fertile river valleys. On the other hand, erratic inter-annual changes of monsoon strength relate to frequent drought periods limiting the amount of population that could subsist in the affected region.

## 5.1 Arabian Peninsula

The cultural phases in the southern Arabian peninsula display a striking synchronicity with changes in environmental conditions. As we will detail below, the results of our RN analysis of the Qunf and Dimarshim records support the picture of transitions of prehistoric societies following climatic changes, which is consistent with earlier findings (Parker et al., 2006).

The first known fully established prehistoric cultures on the Arabian peninsula developed in the fertile northeastern plains of Mesopotamia (Ubaid period, 8.5–5.8 ka BP, see Carter and Philip, 2010), but did not reach far enough South to be directly influenced by changes of the Asian monsoon until ca. 6.5 ka BP. This observation is in line with the fact that the period between ca. 7.5 and 7.0 ka BP was characterised by marked changes in the dynamical IOM patterns (see Sect. 4.3), which could have provided an environmental obstacle for the early southward expansion of the Ubaid culture. Notably, the timing of the latter period coincides well with a known sharp break in the number of

## Nonlinear regime shifts in Holocene Asian monsoon variability

J. F. Donges et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

⏪

⏩

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



## Nonlinear regime shifts in Holocene Asian monsoon variability

J. F. Donges et al.

[Title Page](#)

[Abstract](#)

[Introduction](#)

[Conclusions](#)

[References](#)

[Tables](#)

[Figures](#)

[⏪](#)

[⏩](#)

[◀](#)

[▶](#)

[Back](#)

[Close](#)

[Full Screen / Esc](#)

[Printer-friendly Version](#)

[Interactive Discussion](#)

settlements in the Egyptian Sahara around 7.3 kaBP, while Neolithic and predynastic farming communities began flourishing in the Nile Valley at about the same time (Kuper and Kröpelin, 2006). Taken together, the cultural developments at the Arabian peninsula and the adjacent part of Northeast Africa indicate that environmental conditions outside the fertile banks and flood plains of great rivers may have been insufficient for a sustained and developed human population – likely due to low (and less regular) rainfalls.

Only in its later stages (after about 6.5 kaBP) characterised by intense and rapid urbanisation in Mesopotamia, Ubaid artifacts could be traced along the Persian Gulf through to Oman. The available archaeological record indicates an abrupt end of this period in eastern Arabia and the Oman peninsula at ca. 5.8 kaBP. From the IOM perspective, the values of our RN statistics  $\mathcal{L}$  (Fig. 7) reveal more unstable ISM conditions and, hence, environmental conditions between 5.7 and 5.0 kaBP, which were less favourable for agriculture, although the corresponding indications are only weakly seen in the Qunf record. Indeed, this time interval was characterised by a general climatic drying trend expressed by lowering lake levels and dune reactivation (Parker et al., 2006), possibly related with the 5.9 ka high latitude cooling event (Mayewski et al., 2004). The sustained aridity led to the development of a semi-desert nomadic culture, with very few indications of human inhabitation in vast parts of the southeastern Arabian peninsula for about one millenium (Uerpmann, 2003).

After the demise of the Ubaid culture and the subsequent “Dark Millenium”, the copper age Hafit culture flourished between about 5.4/5.2 and 4.5 kaBP in the southeastern part of the Arabian peninsula (Potts, 1993; Parker et al., 2006). There is evidence for another century-scale drying/cooling event at around 5.2 kaBP (Bar-Matthews et al., 1997; Lemcke and Sturm, 1997; Cullen et al., 2000; Staubwasser and Weiss, 2006), which might have played a key role for cultural changes associated with urbanisation and colonisation in the late Mesopotamian Uruk civilisation (Weiss, 2000, and references therein).



## Nonlinear regime shifts in Holocene Asian monsoon variability

J. F. Donges et al.

[Title Page](#)

[Abstract](#)

[Introduction](#)

[Conclusions](#)

[References](#)

[Tables](#)

[Figures](#)

[⏪](#)

[⏩](#)

[◀](#)

[▶](#)

[Back](#)

[Close](#)

[Full Screen / Esc](#)

[Printer-friendly Version](#)

[Interactive Discussion](#)

According to our RN analysis, the subsequent centuries (ca. 5.0 to 4.5 kaBP) do not display any significant indications for regime shifts in monsoonal dynamics (Fig. 11). This situation may have provided sufficiently stable humid conditions for establishing developed cultures in southeastern Arabia. From the archaeological perspective, this climatic period partially overlaps with the beginning bronze age in southern Arabia, where the Hafit culture was successively replaced by the Umm an-Nar culture (about 4.7–4.0 kaBP). The latter developed intense trade with Sumer and the Indus valley civilisation (Boivin et al., 2010), especially based on intense copper mining.

The results of our RN analysis demonstrate that the known large-scale RCC episode after 4.2 kaBP (Mayewski et al., 2004) was followed by a time interval of marked monsoonal instability between 4.1 and 3.9 kaBP visible in the Qunf record. This perfectly coincides with the archaeological finding that around 4.2 kaBP, the Umm an-Nar culture underwent some sudden changes in settlement pattern and pottery style and was finally replaced by the Wadi Suq culture (4.0–3.6 kaBP) (Parker et al., 2006). Available archaeological evidence points to a successive decline, which goes along with the collapse of the Indus valley culture and subsequent loss of direct trade relationships with Mesopotamia around 3.8 kaBP (Boivin et al., 2010). Notably, the cultural decline in the southern Arabian peninsula started at about the same time (ca. 4.2 to 4.1 kaBP) as the collapse of the Akkadian Empire, the abandonment of agricultural plains in northern Mesopotamia and strong migration into southern Mesopotamia (Weiss et al., 1993; Kerr, 1998; Cullen et al., 2000; deMenocal et al., 2000; Berkelhammer et al., 2012), whereas resettlement of the northern plains of Mesopotamia (with smaller population) took place only after about 3.9 kaBP, a period exhibiting wide-spread agricultural change in Near East (Riehl, 2008). The order and extent of these cultural changes and migration in northern Arabia can be explained by a severe weakening of the ISM. In such case, the ISM would propagate far less northward, leading to a dramatic decrease in summer rainfall in northern Arabia. In turn, this region would depend much more on winter precipitation (snow) delivered by the westerlies. As a result, one can expect human settlements to be concentrated along the rivers that transport meltwater

## Nonlinear regime shifts in Holocene Asian monsoon variability

J. F. Donges et al.

[Title Page](#)

[Abstract](#)

[Introduction](#)

[Conclusions](#)

[References](#)

[Tables](#)

[Figures](#)

⏪

⏩

◀

▶

[Back](#)

[Close](#)

[Full Screen / Esc](#)

[Printer-friendly Version](#)

[Interactive Discussion](#)

from the mountains during summertime, which is consistent with the migratory patterns described before. Supporting this explanation, palaeoclimatic data indeed point to dramatic changes in precipitation patterns associated with the AS branch of the ISM, whereas there is no indication of marked temperature changes in the adjacent Arabian Sea (Doose-Rolinski et al., 2001) around 4.2 kaBP. Moreover, this period of weakened ISM is consistent with numerous findings pointing to a centennial-scale drought affecting a large region from North Africa and the Mediterranean over Near and Middle East up to India (Gasse and Campo, 1994; Arz et al., 2006; Bar-Matthews et al., 1997; Bar-Matthews and Ayalon, 2011; Lemcke and Sturm, 1997; Staubwasser et al., 2003).

After the end of the middle Wadi Suq culture around 3.6 kaBP, late bronze age cultures were established (3.6–3.3 kaBP, see Parker et al., 2006), with only few settlements being identified by archaeologists so far. The period 3.3–2.3 kaBP corresponds to the iron age in the region (Parker et al., 2006). Up to ca. 2.6 kaBP, this epoch is characterised by a renewed growth of population fostered by new inventions such as underground irrigation systems (Magee, 1998; Parker et al., 2006) and the domestication of dromedaries (Peters, 1997). This suggests that the dominating culture was able to adapt to generally arid conditions during this period. Specifically, the use of dromedaries allowed an intensification of land trade across Arabia, contributing to the rise of civilisation in southern Arabia (Parker et al., 2006). Around 2.8 kaBP, the kingdoms of Saba, Ma'in, Qataban, Ausan, Hadramaut and others emerged, performing sea trade with India and East Africa and spreading the Arab culture far towards the North. The Dimarshim record reveals a sequence of further regime shifts between 3.0 and 2.5 kaBP corresponding to intermittent periods with relatively regular variability of the monsoon (as shown by  $\mathcal{J}$ , cf. Fig. 8), which could have additionally fostered the cultural developments within this period.

In summary, there have been ample factors affecting the cultural development in southern Arabia (such as the availability of developed trade partners and the relevance of different trade “modes”). However, the variability of environmental conditions – in terms of both the mean climate state and the dynamics on inter-annual to possibly

intra-annual scales – has played a key role for the rise and fall of different cultures on the Arabian peninsula within the last 10 ka. In particular, water availability (and, hence, amount, seasonality and regularity of monsoonal precipitation) has been identified as a crucial factor controlling the stability of early human societies in this region.

## 5.2 India

Present-day knowledge about Indian prehistory demonstrates that varying environmental conditions associated with the strength and stability of the ISM have played a vital role in fostering cultural growth and development. More specifically, regime shifts in ISM variability, and particularly ISM failures, triggered periods of large-scale migration. In the following, we discuss the synchronicity between the climatic changes as identified in this work and cultural development in detail.

Stone age human population in Southern Asia is documented by a large body of archaeological evidence (Kulke and Rothermund, 2004). Early indications of Neolithic settlements practicing farming and herding can be found in Western Pakistan, especially at the Mehrgarh site, since at least ca. 9.0 ka BP (Possehl, 2002; Brooks, 2006). Around 7.5 ka BP, first ceramics appear, later accompanied by increasing use of copper. However, the currently available archaeological record is too sparse to draw any specific conclusions about possible climatically triggered changes in the Early to Mid Holocene. While persistent inhabitation of Western Pakistan is documented for several millennia, first developed farming communities appeared after 6.3 ka BP (Brooks, 2006). The period between 5.5 and 5.0 ka BP experienced a sequence of different relatively short-living cultural periods, followed by the transition to bronze age (Kulke and Rothermund, 2004). This sequence of cultural epochs between 6.0 and 5.0 ka BP appears to be affected by relatively unstable ISM dynamics revealed by our RN analysis (Fig. 7), requiring a step-wise development for adapting to ongoing changes of environmental conditions.

After 5.0 ka BP, first cities associated with the Indus valley (Harappan) civilisation appeared (Possehl, 2002; Singh, 2008), taking the cultural and economic leadership in the

## Nonlinear regime shifts in Holocene Asian monsoon variability

J. F. Donges et al.

[Title Page](#)

[Abstract](#)

[Introduction](#)

[Conclusions](#)

[References](#)

[Tables](#)

[Figures](#)

[⏪](#)

[⏩](#)

[◀](#)

[▶](#)

[Back](#)

[Close](#)

[Full Screen / Esc](#)

[Printer-friendly Version](#)

[Interactive Discussion](#)



**Nonlinear regime shifts in Holocene Asian monsoon variability**

J. F. Donges et al.

[Title Page](#)[Abstract](#)[Introduction](#)[Conclusions](#)[References](#)[Tables](#)[Figures](#)[Back](#)[Close](#)[Full Screen / Esc](#)[Printer-friendly Version](#)[Interactive Discussion](#)

entire region. Regarding our RN analysis, the absence of significant periods in our RN statistics  $\mathcal{L}$  between about 5.0 and 4.1 kaBP (Fig. 7) indicates a period of environmental conditions lacking strong abrupt changes. This relatively stable climate dynamics allowed adaptation of the culture followed by sustained growth. With the emergence of the new central cities in the Indus valley, other former cultural centres like Mehrgarh or Kalibangan lost their societal importance and were abandoned after about 4.6 kaBP, marking the beginning of the mature Harappan phase (Kulke and Rothermund, 2004). Around 4.5 kaBP, planned cities like Harappa and Mohenjo Daro testified a comparably high level of civilisation, including sewage systems, bath houses and harbours. One main aspect of this fast innovation was the use of the Indus river for inundation-based farming and transportation, making the Harappan culture the first in South Asia to develop sustained trade relationships over a large region (Singh, 2008).

It has to be noted that the Harappan agriculture ultimately relied on inundation/rain-based farming and did probably not perform large-scale canal irrigation (Giosan et al., 2012). Hence, the Harappan cities exhibited an intimate link with the ISM and depended on seasonal water supply of the Indus. Only few perennial glacier-fed rivers contributed significantly to the overall discharge (Giosan et al., 2012). From a climatic perspective, the rise of the Indus valley civilisation is closely related with the gradual decrease of monsoonal precipitation starting already about 5.0 kaBP (Enzel et al., 1999), reaching its temporary minimum only after 4.0 kaBP. The reduction of seasonal rainfall was probably a key factor fostering the successive increase of inundation-based farming and a dense population of the fertile river banks (Giosan et al., 2012).

At about 4.2 kaBP (i.e. at about the same time as in vast parts of the northern hemispheric subtropics), geological records reveal a strong reduction of Indus river discharge (Staubwasser et al., 2003) together with increased dust flux from northern Arabia (Enzel et al., 1999). Recent results based on speleothem records suggest that the corresponding changes were rapid (i.e. on decadal time-scales) (Berkelhammer et al., 2012). Staubwasser et al. (2003) suggests a weakening of westerlies as a key component of observed environmental change, leading to a modification in the seasonality of

## Nonlinear regime shifts in Holocene Asian monsoon variability

J. F. Donges et al.

[Title Page](#)

[Abstract](#)

[Introduction](#)

[Conclusions](#)

[References](#)

[Tables](#)

[Figures](#)

[⏪](#)

[⏩](#)

[◀](#)

[▶](#)

[Back](#)

[Close](#)

[Full Screen / Esc](#)

[Printer-friendly Version](#)

[Interactive Discussion](#)

the ISM and, taken together, a significant reduction in annual rainfall. Such a complex ISM-westerlies teleconnection is also reflected in present-day meteorological conditions as revealed by non-linear climate network analyses (Malik et al., 2010, 2012). However, a strong reduction of the ISM (penetrating far less northwards over the Arabian peninsula) independent of the westerlies would possibly be sufficient for explaining the pattern associated with this RCC episode between Arabia and India.

The intense aridity after 4.2 kaBP lead to southeastward habitat shifts within the Harappan cultural domain and culminated in the full collapse of the culture and its transformation from a highly organised urban to a post-urban phase around 3.9 kaBP (Possehl, 1997). Former cultural centres like Harappa and Mohenjo Daro were abandoned and shifted eastward towards the Himalayan foothills in northern India, where smaller settlements emerged at different places (Possehl, 1997; Giosan et al., 2012). Our RN analysis confirms changes in the IOM dynamical regime as seen in the Qunf record between ca. 4.1 and 3.9 kaBP, suggesting that the sudden decrease of rainfall in northwestern India triggering the collapse of the Harappan culture was accompanied by a dynamic instability of interannual precipitation variability.

Around 3.9 kaBP, the archaeological record provides first evidence for the beginning of the copper hoard culture in northern India and a gradual transition towards iron age in northwestern India (Kulke and Rothermund, 2004). Subsequently, there were several waves of migration of Indo-Aryan peoples to northwest India and the northern Indus valley, resulting in violent clashes with the original inhabitants (Kulke and Rothermund, 2004; Singh, 2008). Several centuries passed until a new highly developed culture emerged on the Indian subcontinent. The Vedic epoch (3.5–2.5 kaBP) has been characterised by an outstanding religion and philosophy (Singh, 2008). The results of our RN analysis again allow putting these archaeological findings into some climatic context: After 3.9 kaBP, our complementary RN statistics  $\mathcal{T}$  (Fig. 8) reveals a period of relatively stable IOM variability (note that there is no comparably well preserved published speleothem record from India so far covering this time interval), which could have promoted stable and fertile conditions in northwestern India fostering the development

of the Vedic culture. After 3.2 kaBP, this culture spread from northwest India into the subcontinent and the Ganges plain, supported by the aforementioned migratory patterns of Indo-Aryan peoples. At about 2.5 kaBP, there has been a consolidation into 16 major oligarchies and monarchies (mahajanapadas), which were united in the Mauryan Empire at about 2.4 kaBP forming the first kingdom spanning vast parts of the subcontinent. It has to be noted, however, that this kingdom did not exist for very long time and collapsed already after ca. 2.3 kaBP (Kulke and Rothermund, 2004; Singh, 2008).

### 5.3 South-East Asia

Compared to southern Arabia and India, relatively little is known about human prehistory of South-East Asia. Archaeological records tracing human population during the Early to Mid Holocene are sparse, which is also due to the high humidity in the region being unfavourable for the preservation of artefacts.

In northern Vietnam, some archaeological data give evidence for the Nusantara maritime trading network, which was formed by several groups of Malayo-Polynesian origin and connected this region with the Philippines, southern China and Taiwan (later also coastal areas through to South Korea and southern Japan). The existence of this network has been confirmed for some time interval between at least about 7.0 and 2.0 kaBP (Solheim, 2000). By exchanging knowledge on various types of economic activity (hunting, gathering, rice farming, horticulture, etc.), the Nusantara network contributed significantly to early cultural development in the region. Since about 4.5 kaBP, there are indications for several waves of migration from southern China, northeast India and eastern Tibet into South-East Asia, with the immigrants bringing their further developed cultures with them (Tarling, 1993). In the Mekong delta, there is evidence for sustained inhabitation since ca. 2.4 kaBP, whereas the first kingdoms in the region have been founded only after 2.0 kaBP (Meyer, 1997). These early kingdoms were based on agriculture and maritime trade, both of them contributed to the centralisation of authorities and, hence, population.

## Nonlinear regime shifts in Holocene Asian monsoon variability

J. F. Donges et al.

[Title Page](#)

[Abstract](#)

[Introduction](#)

[Conclusions](#)

[References](#)

[Tables](#)

[Figures](#)

[⏪](#)

[⏩](#)

[◀](#)

[▶](#)

[Back](#)

[Close](#)

[Full Screen / Esc](#)

[Printer-friendly Version](#)

[Interactive Discussion](#)



## Nonlinear regime shifts in Holocene Asian monsoon variability

J. F. Donges et al.

[Title Page](#)

[Abstract](#)

[Introduction](#)

[Conclusions](#)

[References](#)

[Tables](#)

[Figures](#)

[⏪](#)

[⏩](#)

[◀](#)

[▶](#)

[Back](#)

[Close](#)

[Full Screen / Esc](#)

[Printer-friendly Version](#)

[Interactive Discussion](#)



Given the lack of data, convincing links between cultural developments in South-East Asia and Asian monsoon variability are much harder to establish than for southern and southwestern Asia. The situation is further aggravated by the fact that water availability is typically no limiting environmental factor in this region. Specifically, rainfall variability may have played a role only for civilisations in the northern part of South-East Asia, but would have hardly any effect on human societies in the tropics. In turn, other types of natural hazards (such as volcanic eruptions) could have a greater influence here (Lavigne et al., 2013). To this end, we note that the Liang-Luar record displays two marked periods of very low values of our RN statistics  $\mathcal{L}$ , possibly indicating rapid changes in the dynamical precipitation regime, around about 8.5 and 5.7 kaBP, both of which coincide with known large-scale Holocene RCC episodes (Mayewski et al., 2004). Notably, we observe that both periods are characterised by particularly regular variability (Fig. 8), which could have fostered cultural developments (Donges et al., 2011b). In turn, for the period of fast societal change after 2.4 kaBP, the single record of Liang-Luar considered in this work is insufficient to draw any substantiated conclusions on possible cultural responses to marked environmental changes.

### 5.4 China

The development of prehistoric cultures and complex societies in China is one of the best studied examples providing multiple examples for the impact of climatic changes on human populations. Earliest records of rain-fed agriculture in northern China trace back to about 7.8 kaBP (An et al., 2005). Between 7.8 and 4.0 kaBP, there is a steady increase in the number of archaeological sites (An et al., 2005) pointing to a continuous cultural development in large parts of China. The absence of evidence for irrigation-based farming indicates that rain-fed agriculture was sufficient to supply Neolithic and early Chalcolithic peoples, which successively spread over regions with less favourable climatic conditions, e.g. the western loess plateau (An et al., 2005).

Detailed inspection of the presently available archaeological records reveals a first large expansion of prehistoric sites in the Guanzhong and Xiliao river basins between

## Nonlinear regime shifts in Holocene Asian monsoon variability

J. F. Donges et al.

[Title Page](#)

[Abstract](#)

[Introduction](#)

[Conclusions](#)

[References](#)

[Tables](#)

[Figures](#)

[⏪](#)

[⏩](#)

[◀](#)

[▶](#)

[Back](#)

[Close](#)

[Full Screen / Esc](#)

[Printer-friendly Version](#)

[Interactive Discussion](#)

6.0 and 5.0 kaBP (Wagner et al., 2013). Yasuda et al. (2004) examined the cultures at the middle reaches of the Yangtze river and found evidence of four cultural transitions at the beginnings of the early Daxi (6.4–6.1 kaBP), middle Daxi (5.8 kaBP), Qujialing (5.3 kaBP) and Shijiahe (4.5 kaBP) cultures. All four transitions can be related with climate deterioration associated with a weakened EASM.

The climax of prehistoric agriculture was reached during the Majiayao period (5.3–4.2 kaBP). Favourable and stable climatic conditions fostered the expansion of the Qijia culture (4.3–3.9 kaBP) (An et al., 2005). A similar statement can be made for the Majiayao culture: Wet conditions from 5.8 to 4.9 kaBP fostered the population growth. Dry conditions between 4.9 and 4.7 kaBP resulted in a decline and eastward migration of this culture. Subsequent wetter climate from 4.7–3.9 kaBP supported an accelerated spread of the Qijia culture (Dong et al., 2012). In general, the Majiayao and Qijia periods are characterised by key agricultural developments (Jia et al., 2013). For the Henan and Shanxi provinces, Liu (1996) revealed that the third millennium BC displayed a transition from more egalitarian to stratified societies, with settlement patterns indicating mainly simple chiefdoms.

Widespread collapse of Neolithic cultures characterises the end of the third millennium BC in vast parts of China (Wu and Liu, 2004; Liu and Feng, 2012). In the Yishu river basin, the Longshan culture suffered from a shortfall in harvests, resulting in resource scarcity and decrease in population revealed by a sudden drop in the number of archaeological sites (Gao et al., 2007). Consequently, it was replaced at ca. 4.0 kaBP by the underdeveloped Yueshi culture. In the lower Yangtze river valley (Jiangsu and Zhejiang provinces), the Liangzhu culture (5.3–4.2 kaBP) collapsed after about 4.3 kaBP (Stanley et al., 1999; Yu et al., 2000; Li et al., 2010). In a similar way, the Shijiahe culture (4.6–4.2 kaBP) in the middle Yangtze river valley (Lianghu area of Hubei and Hunan provinces) declined and finally vanished between about 4.2 and 4.0 kaBP (Wu and Liu, 2004; Li et al., 2010; Yasuda et al., 2004). The same holds for the Shangdong Longshan culture (4.6–4.2 kaBP) in the lower Yellow river valley (Liu, 1996, 2000). Moreover, there is evidence for a collapse of the rain-fed agriculture of



the Qijia period (4.4–3.9 kaBP) in the upper Yellow river valley in the Gansu and Qinghai provinces around 4.0 kaBP (see Wu and Liu, 2004; An et al., 2005 and references therein).

The reconstruction of the nature of the climatic transitions that possibly triggered the aforementioned large-scale cultural changes has remained somewhat ambiguous so far. Huang et al. (2010, 2011) report strong indications of a series of extraordinary floods in the middle realm of the Yellow river, which might have contributed to the demise of existing cultures and their replacement by others, including the abandonment of settlements along the Yellow river. In turn, Gao et al. (2007) attribute their findings to some exceptionally cool period. In the light of results obtained in other parts of the Asian monsoon domain indicating a general weakening of the monsoon and, hence, decreases in summer rainfalls, combined evidences for cooling, drying and flooding point to a period of marked instability of the EASM between about 4.5 and 4.0 kaBP. This hypothesis is consistent with the results of our RN analysis for the Dongge and Tianmen records (significantly high values of  $\mathcal{L}$ , see Fig. 7). Our RN statistics  $\mathcal{T}$  (Fig. 8) points to short periods with relatively regular monsoon dynamics, which could be interpreted as an indicator for intervals of generally weakened EASM. These epochs might have been followed by more erratic monsoon dynamics, which eventually gave rise to the floods observed by Huang et al. (2010, 2011). Notably, we do not find comparable signatures in the other three Chinese speleothem records analysed in this work, although they are much closer to the regions with reported evidence for almost synchronous cultural changes. There are different possible reasons for this lack of additional evidence, including localised climatic conditions. Specifically, due to the complex migration pattern of the EASM front it is possible that for the same year, monsoonal rainfall is strong in one region, but weak in another one. With the spatial distribution and temporal resolution of available speleothem data, we are not able to further address this point here.

Following the period of cultural changes discussed above, our RN analysis does not indicate any period of particularly regular monsoon dynamics (high  $\mathcal{T}$ ) between 4.0

## Nonlinear regime shifts in Holocene Asian monsoon variability

J. F. Donges et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

**Nonlinear regime shifts in Holocene Asian monsoon variability**

J. F. Donges et al.

[Title Page](#)[Abstract](#)[Introduction](#)[Conclusions](#)[References](#)[Tables](#)[Figures](#)[⏪](#)[⏩](#)[◀](#)[▶](#)[Back](#)[Close](#)[Full Screen / Esc](#)[Printer-friendly Version](#)[Interactive Discussion](#)

and 3.0 kaBP (Fig. 8). In turn, we observe an end of the rather persistent dynamical changes (high  $\mathcal{L}$ ) in southern China (Dongge cave) around 3.9 kaBP (Fig. 7). The archaeological record provides evidence for the emergence of first state-level societies developing from the Neolithic societies (Longshan cultures) in the central plains of northern China around 4.0 kaBP (Liu, 1996; Lee, 2004). The corresponding urbanisation tendencies are supported by a substantial decrease in the number of archaeological sites during the early bronze age (4.0–3.5 kaBP), e.g. the almost full abandonment of the Guanzhong basin (Wagner et al., 2013). At about the same time (4.0–3.6 kaBP), the earliest documented kingdoms associated with the Xia dynasty emerged, which were later replaced by the Shang dynasty (3.6–3.0 kaBP). The ongoing cultural developments were accompanied by widespread changes in the agricultural strategies. For example, for the western loess plateau, a transition from long-established rain-fed farming communities to pastoralism has been found after about 3.6 kaBP, further concentrating settlements (An et al., 2005). In summary, it is likely that the period between 4.0 and 3.0 kaBP did not experience any marked large-scale changes in EASM dynamics, which can be related to stable (though not necessarily very humid) climatic conditions. One exception found in our analysis is a time interval of exceptionally low values of  $\mathcal{L}$  between 3.5 and 3.0 kaBP, which is present in the Lianhua record but not in the three other caves. The latter disagreement could again originate from local climatic conditions, but also other changes to the archive at Lianhua cave acting on time-scales not resolved by our analysis.

Around 3.1 kaBP, palaeoclimatic records indicate a strong shift to more arid conditions around the Chinese loess plateau (Huang et al., 2002). Consequently, bronze age cultures experienced a shortfall of livestock and crop affecting the northern nomadic tribes and southern urban Han Chinese, respectively. Food scarcity culminated in widespread southward migration, including re-location of the political capital as well as other major cities of the rising pre-dynastic Zhou culture on the southern loess plateau (Huang et al., 2002). Arable farming was replaced by pastoral farming. In summary, severe droughts and great famines in the loess plateau region can be considered



**Nonlinear regime shifts in Holocene Asian monsoon variability**

J. F. Donges et al.

[Title Page](#)[Abstract](#)[Introduction](#)[Conclusions](#)[References](#)[Tables](#)[Figures](#)[⏪](#)[⏩](#)[◀](#)[▶](#)[Back](#)[Close](#)[Full Screen / Esc](#)[Printer-friendly Version](#)[Interactive Discussion](#)

domain. Analysing these sediments, Xiao et al. (2009) report several episodes of weak EASM at 8.0–7.85, 6.4–6.05, 5.15–4.9, 4.5–3.8, 3.05–2.8, 1.65–1.4, 1.15–0.9, 0.7–0.6 and 0.4–0.35 kaBP. In turn, Hu et al. (2008) studied the speleothem records from Heshang and Dongge caves and report marked periods of EASM weakening at 4.8–4.1, 3.7–3.1 and 1.4–1.0 kaBP, which is only partially in line with the lacustrine archive. Note that both results do not match the distinct Holocene RCC episodes reported by Mayewski et al. (2004). Despite these ambiguities, climatic and archaeological record again exhibit strong linkages: The first marked increase in the number of prehistoric sites in China is associated with a period of relatively humid conditions after 6.0 kaBP. In turn, as discussed above, the arid periods 4.2–4.0, around 3.6 and 3.0–2.8 kaBP correspond to epochs of strong cultural changes and migration, possibly triggered by famines and resource scarcity. In general, the second and first millennium BC were characterised by relatively low rainfall. This is consistent with the archaeological observation that up to ca. 2.0 kaBP, most settlements in northern China were located along river courses (Lee, 2004): human cultures were depending on water from the river because of insufficient monsoonal precipitation.

Notably, aridity shifts and cultural responses appear not fully synchronous in different parts of China. This is consistent with the fact that the peak monsoon intensity (most humid period) during the Holocene was reached at different periods in distinct parts of China (An et al., 2000; Cai et al., 2010). The associated spatial pattern reveals a sustained southward EASM shift related to the successive weakening of solar irradiation over the mid Holocene and accompanied by seasonality changes of monsoonal precipitation.

## 6 Conclusions

In this work, we have presented the first application of a novel technique of nonlinear time series analysis, recurrence network (RN) analysis, to a consistent set of spatially distributed palaeoclimatic archives from the Asian monsoon domain. Specifically, we

**Nonlinear regime shifts in Holocene Asian monsoon variability**

J. F. Donges et al.

[Title Page](#)[Abstract](#)[Introduction](#)[Conclusions](#)[References](#)[Tables](#)[Figures](#)[⏪](#)[⏩](#)[◀](#)[▶](#)[Back](#)[Close](#)[Full Screen / Esc](#)[Printer-friendly Version](#)[Interactive Discussion](#)

have reanalysed 10 available high-resolution speleothem-based oxygen isotope proxy records for Holocene Asian summer monsoon intensity with this new approach. We find previously reported extra-tropical Bond events and rapid climate change episodes to often be accompanied by epochs of spatially extensive nonlinear regime shifts in monsoonal dynamics, e.g. towards extraordinary regular (stable) or erratic (unstable) variability and low or high rainfall of the different monsoon branches. Particularly pronounced epochs of monsoonal regime shifts have been detected around 8.5–8.0, 5.7–5.4, 4.1–3.6 and 2.8–2.2 kaBP. Additionally, we observe an epoch of significantly increased regularity of monsoonal variations around 7.3 kaBP. The timing of this event is consistent with the typical 1.0–1.5 ka return intervals of Bond events and glacial Dansgaard–Oeschger events but has been rarely reported in the literature so far. This result calls for an in-depth investigation of additional palaeoclimate records from the Asian Monsoon domain for identifying the underlying mechanisms. Notably, most of the detected epochs of monsoonal regime shifts occur temporally close to pronounced minima and/or strong fluctuations in reconstructed solar activity, indicating that changes in solar forcing play an important role in driving nonlinear transitions in monsoonal dynamics.

Furthermore, we have shown that the detected nonlinear regime shifts in Asian Monsoon dynamics partly coincide with known major periods of migration, pronounced cultural changes, and the collapse of ancient human societies from the archaeological record in Arabia, India, South-East Asia and China: Sustained epochs of regular monsoonal variations have fostered the development of complex societies, while episodes of unusually irregular seasonal rainfall patterns had a detrimental effect on agriculture and led to cultural decline and societal collapse. These observations indicate that future changes in monsoonal dynamics might lead to potentially severe socio-economic repercussions in the Asian Monsoon domain, where ca. 60% of today's world human population is located. In the future, a more rigorous statistical analysis of coincidences (Donges et al., 2011b) and potential causal relationships between monsoonal

regime shifts and societal responses from the archeological records is desirable, posing, however, considerable challenges in terms of data quality and availability.

We developed a framework for performing an integrative nonlinear time series analysis of palaeoclimate records under explicit consideration of dating uncertainties. We have chosen RN analysis as a technique that is well-suited for investigating palaeoclimate data. RN analysis has been demonstrated before to be able to detect relevant nonlinear dynamic changes such as shifts from regular (e.g. periodic) to more erratic (e.g. chaotic) variability that cannot be readily revealed by linear statistics such as windowed mean or variance (Donges et al., 2011a, b). After combining the results from multiple proxy records, rigorous statistical significance testing helps identification of epochs where an unexpected fraction of all considered sites displays unusual dynamics, pointing towards pronounced nonlinear regime shifts in monsoonal dynamics. Importantly, the results obtained from the original published records have been confirmed by a detailed ensemble analysis evaluating effects of dating uncertainties via the COPRA framework. Further development of recurrence network analysis and related techniques is needed for more consistently accounting for irregular sampling and uncertain dating of observations at an earlier stage in the analysis chain, e.g. by following a Bayesian approach.

To further improve and spatio-temporally refine the presented analysis, a larger number of high-quality proxy records with smaller dating errors and a higher temporal resolution is needed. Particularly India promises a great potential for such proxy records spanning the entire Holocene, but too few have become available so far. For capturing the detailed nonlinear dynamics of monsoonal variations, annually or even sub-annually resolved records with dating uncertainties on the order of one to five years are required, features which are already attainable for speleothem isotope proxies by state-of-the-art measurement equipment today. Finally, other available types of archives such as tree rings or marine and lacustrine sediments should be included in the data base processed by the proposed analysis framework, requiring, however, a methodology for ensuring the consistent comparison and integration of this diverse set of data sources.

**Nonlinear regime shifts in Holocene Asian monsoon variability**

J. F. Donges et al.

[Title Page](#)

[Abstract](#)

[Introduction](#)

[Conclusions](#)

[References](#)

[Tables](#)

[Figures](#)



[Back](#)

[Close](#)

[Full Screen / Esc](#)

[Printer-friendly Version](#)

[Interactive Discussion](#)



Supplementary material related to this article is available online at <http://www.clim-past-discuss.net/10/895/2014/cpd-10-895-2014-supplement.pdf>.

*Acknowledgements.* This work has been financially supported by the Leibniz association (project ECONS), the German National Academic Foundation, the Federal Ministry for Education and Research (BMBF) via the Potsdam Research Cluster for Georisk Analysis, Environmental Change and Sustainability (PROGRESS) and project GLUES, IRTG 1740 (DFG), the Stordalen Foundation via the PB.net initiative, and the Max Planck Society. S. F. M. Breitenbach acknowledges financial support from SNF Project CRSI22\_132646. We thank Franziska Lechleitner (ETH Zurich) for valuable comments and discussions. Recurrence network analysis has been performed using the Python package `pyunicorn` (Donges et al., 2013). A Matlab implementation of the COPRA framework developed by some of the authors of this paper is available within the TOCSY toolbox (`tocsy.pik-potsdam.de`).

## References

- Alley, R. B. and Ágústssdóttir, A. M.: The 8k event: cause and consequences of a major Holocene abrupt climate change, *Quaternary Sci. Rev.*, 24, 1123–1149, doi:10.1016/j.quascirev.2004.12.004, 2005. 911
- Alley, R. B., Mayewski, P. A., Sowers, T., Stuiver, M., Taylor, K. C., and Clark, P. U.: Holocene climatic instability: A prominent, widespread event 8200 yr ago, *Geology*, 25, 483–486, doi:10.1130/0091-7613(1997)025<0483:HCIAPW>2.3.CO;2, 1997. 911, 912, 962
- Amigo, Á., Lara, L. E., and Smith, V. C.: Holocene record of large explosive eruptions from Chaitén and Michinmahuida Volcanoes, Chile, *Andean Geol.*, 40, 227–248, doi:10.5027/andgeoV40n2-a03, 2013. 914, 962
- An, C.-B., Tang, L., Barton, L., and Chen, F.-H.: Climate change and cultural response around 4000 cal yr BP in the western part of Chinese Loess Plateau, *Quaternary Res.*, 63, 347–352, doi:10.1016/j.yqres.2005.02.004, 2005. 933, 934, 935, 936

CPD

10, 895–975, 2014

## Nonlinear regime shifts in Holocene Asian monsoon variability

J. F. Donges et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



## Nonlinear regime shifts in Holocene Asian monsoon variability

J. F. Donges et al.

[Title Page](#)

[Abstract](#)

[Introduction](#)

[Conclusions](#)

[References](#)

[Tables](#)

[Figures](#)

[⏪](#)

[⏩](#)

[◀](#)

[▶](#)

[Back](#)

[Close](#)

[Full Screen / Esc](#)

[Printer-friendly Version](#)

[Interactive Discussion](#)



- An, Z., Porter, S. C., Kutzbach, J. E., Xihao, W., Suming, W., Xiaodong, L., Xiaoqiang, L., and Weijian, Z.: Asynchronous Holocene optimum of the East Asian monsoon, *Quaternary Sci. Rev.*, 19, 743–762, doi:10.1016/S0277-3791(99)00031-1, 2000. 938
- Arz, H. W., Lamy, F., Pätzold, J., Müller, P. J., and Prins, M.: Mediterranean moisture source for an Early-Holocene humid period in the Northern Red Sea, *Science*, 300, 118–121, doi:10.1126/science.1080325, 2003. 911
- Arz, H. W., Lamy, F., and Pätzold, J.: A pronounced dry event recorded around 4.2 ka in brine sediments from the northern Red Sea, *Quaternary Res.*, 66, 432–441, doi:10.1016/j.yqres.2006.05.006, 2006. 928
- Babu, P. and Stoica, P.: Spectral analysis of nonuniformly sampled data – a review, *Digit. Signal Process.*, 20, 359–378, doi:10.1016/j.dsp.2009.06.019, 2009. 908
- Baker, A. J., Sodemann, H., Baldini, J. U. L., Breitenbach, S. F. M., Johnson, K. R., van Hunen, J., and Zhang, P.: Indian Ocean source for East Asian Summer Monsoon rainfall, *Geophys. Res. Lett.*, in review, 2014. 899
- Baldini, J. U. L., McDermott, F., and Fairchild, I. J.: Structure of the 8200-year cold event revealed by a speleothem trace element record, *Science*, 296, 2203–2206, doi:10.1126/science.1071776, 2002. 912, 962
- Bar-Matthews, M. and Ayalon, A.: Mid-Holocene climate variations revealed by high-resolution speleothem records from Soreq Cave, Israel and their correlation with cultural changes, *Holocene*, 21, 163–171, doi:10.1177/0959683610384165, 2011. 928
- Bar-Matthews, M., Ayalon, A., and Kaufman, A.: Late quaternary paleoclimate in the eastern Mediterranean region from stable isotope analysis of speleothems at Soreq Cave, Israel, *Quaternary Res.*, 47, 155–168, doi:10.1006/qres.1997.1883, 1997. 926, 928
- Bar-Matthews, M., Ayalon, A., and Kaufman, A.: Timing and hydrological conditions of Saproel events in the eastern Mediterranean, as evident from speleothems, Soreq cave, Israel, *Chem. Geol.*, 169, 145–156, doi:10.1016/S0009-2541(99)00232-6, 2000. 911
- Berkehamer, M., Sinha, A., Mudelsee, M., Cheng, H., Edwards, R. L., and Cannariato, K.: Persistent multidecadal power of the Indian Summer Monsoon, *Earth Planet. Sc. Lett.*, 290, 166–172, doi:10.1016/j.epsl.2009.12.017, 2010. 903
- Berkehamer, M., Sinha, A., Stott, L., Cheng, H., Pausata, F. S. R., and Yoshimura, K.: An abrupt shift in the Indian monsoon 4000 years ago, in: *Climates, Landscapes, and Civilizations*, edited by: Giosan, L., Fuller, D. Q., Nicoll, K., Flad, R. K., and Clift, P. D.,



## Nonlinear regime shifts in Holocene Asian monsoon variability

J. F. Donges et al.

[Title Page](#)

[Abstract](#)

[Introduction](#)

[Conclusions](#)

[References](#)

[Tables](#)

[Figures](#)

[⏪](#)

[⏩](#)

[◀](#)

[▶](#)

[Back](#)

[Close](#)

[Full Screen / Esc](#)

[Printer-friendly Version](#)

[Interactive Discussion](#)



vol. 198 of Geophys. Monogr. Ser., American Geophysical Union, Washington, D.C., 75–87, doi:10.1029/2012GM001207, 2012. 903, 912, 913, 927, 930, 960

Blaauw, M.: Methods and code for “classical” age-modelling of radiocarbon sequences, *Quat. Geochronol.*, 5, 512–518, doi:10.1016/j.quageo.2010.01.002, 2010. 904

Boccaletti, S., Latora, V., Moreno, Y., Chavez, M., and Hwang, D. U.: Complex networks: structure and dynamics, *Phys. Rep.*, 424, 175–308, doi:10.1016/j.physrep.2005.10.009, 2006. 908

Boivin, N., Blench, R., and Fuller, D. Q.: Archaeological, linguistic and historical sources on ancient seafaring: a multidisciplinary approach to the study of early maritime contact and exchange in the Arabian peninsula, in: *The Evolution of Human Populations in Arabia*, edited by: Petraglia, M. D. and Rose, J. I., *Vertebrate Paleobiology and Paleoanthropology*, Springer, Dordrecht, the Netherlands, 251–278, doi:10.1007/978-90-481-2719-1\_18, 2010. 927

Bond, G., Showers, W., Cheseby, M., Lotti, R., Almasi, P., deMenocal, P., Priore, P., Cullen, H., Hajdas, I., and Bonani, G.: A pervasive millennial-scale cycle in North Atlantic Holocene and glacial climates, *Science*, 278, 1257–1266, doi:10.1126/science.278.5341.1257, 1997. 900, 910, 965

Bond, G., Kromer, B., Beer, J., Muscheler, R., Evans, M. N., Showers, W., Hoffmann, S., Lotti-Bond, R., Hajdas, I., and Bonani, G.: Persistent solar influence on North Atlantic climate during the Holocene, *Science*, 294, 2130–2136, doi:10.1126/science.1065680, 2001. 900, 910

Borgaonkar, H., Sikder, A., Ram, S., and Pant, G.: El Niño and related monsoon drought signals in 523-year-long ring width records of teak (*Tectona grandis* L. F.) trees from south India, *Palaeogeogr. Palaeoclimatol.*, 285, 74–84, doi:10.1016/j.palaeo.2009.10.026, 2010. 902

Breitenbach, S. F. M., Adkins, J. F., Meyer, H., Marwan, N., Kumar, K. K., and Haug, G. H.: Strong influence of water vapor source dynamics on stable isotopes in precipitation observed in Southern Meghalaya, NE India, *Earth Planet. Sc. Lett.*, 292, 212–220, doi:10.1016/j.epsl.2010.01.038, 2010. 904

Breitenbach, S. F. M., Lechleitner, F., Plessen, B., Marwan, N., Cheng, H., Adkins, J. F., and Haug, G. H.: Reconstructing monsoon variations in India – evidence from speleothems, abstract PP13D-02, in: *2012 Fall Meeting, AGU*, 3–7 December 2012, San Francisco, Calif., 2012a. 903

## Nonlinear regime shifts in Holocene Asian monsoon variability

J. F. Donges et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

⏪

⏩

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

- Breitenbach, S. F. M., Rehfeld, K., Goswami, B., Baldini, J. U. L., Ridley, H. E., Kennett, D. J., Prufer, K. M., Aquino, V. V., Asmerom, Y., Polyak, V. J., Cheng, H., Kurths, J., and Marwan, N.: COntstructing Proxy Records from Age models (COPRA), *Clim. Past*, 8, 1765–1779, doi:10.5194/cp-8-1765-2012, 2012b. 900, 904, 905
- 5 Brockwell, P. J. and Davis, R. A.: *Time Series: Theory and methods*, 2nd Edn., Springer, New York, 2006. 969
- Broecker, W. S., Denton, G. H., Edwards, R. L., Cheng, H., Alley, R. B., and Putnam, A. E.: Putting the Younger Dryas cold event into context, *Quaternary Sci. Rev.*, 29, 1078–1081, doi:10.1016/j.quascirev.2010.02.019, 2010. 913
- 10 Brooks, N.: Cultural responses to aridity in the Middle Holocene and increased social complexity, *Quatern. Int.*, 151, 29–49, doi:10.1016/j.quaint.2006.01.013, 2006. 929
- Buck, C. E. and Millard, A. R. (Eds.): *Tools for Constructing Chronologies*, Lecture Notes in Statistics, vol. 177, Springer, London, 2004. 904
- Büntgen, U., Tegel, W., Nicolussi, K., McCormick, M., Frank, D., Trouet, V., Kaplan, J. O., Herzog, F., Heussner, K.-U., Wanner, H., Luterbacher, J., and Esper, J.: 2500 years of European climate variability and human susceptibility, *Science*, 331, 578–582, doi:10.1126/science.1197175, 2011. 898, 962
- 15 Cai, Y., Tan, L., Cheng, H., An, Z., Edwards, R. L., Kelly, M. J., Kong, X., and Wang, X.: The variation of summer monsoon precipitation in central China since the last deglaciation, *Earth Planet. Sc. Lett.*, 291, 21–31, doi:10.1016/j.epsl.2009.12.039, 2010. 921, 938, 960
- 20 Cai, Y., Zhang, H., Cheng, H., An, Z., Edwards, R. L., Wang, X., Tan, L., Liang, F., Wang, J., and Kelly, M.: The Holocene Indian monsoon variability over the southern Tibetan Plateau and its teleconnections, *Earth Planet. Sc. Lett.*, 335–336, 135–144, doi:10.1016/j.epsl.2012.04.035, 2012. 960
- 25 Carter, R. A. and Philip, G.: *Beyond the Ubaid: Transformation and Integration in the Late Prehistoric Societies of the Middle East*, vol. 63 of *Studies in Ancient Oriental Civilization*, The Oriental Institute of the University of Chicago, Chicago, 2010. 925
- Cheng, H., Edwards, R. L., Broecker, W. S., Denton, G. H., Kong, X., Wang, Y., Zhang, R., and Wang, X.: Ice age terminations, *Science*, 326, 248–252, doi:10.1126/science.1177840, 30 2009. 903

## Nonlinear regime shifts in Holocene Asian monsoon variability

J. F. Donges et al.

[Title Page](#)

[Abstract](#)

[Introduction](#)

[Conclusions](#)

[References](#)

[Tables](#)

[Figures](#)

[⏪](#)

[⏩](#)

[◀](#)

[▶](#)

[Back](#)

[Close](#)

[Full Screen / Esc](#)

[Printer-friendly Version](#)

[Interactive Discussion](#)



- Cheng, H., Lawrence Edwards, R., Shen, C.-C., Polyak, V. J., Asmerom, Y., Woodhead, J., Hellstrom, J., Wang, Y., Kong, X., Spötl, C., Wang, X., and Alexander Jr., E. C.: Improvements in  $^{230}\text{Th}$  dating,  $^{230}\text{Th}$  and  $^{234}\text{U}$  half-life values, and U-Th isotopic measurements by multi-collector inductively coupled plasma mass spectrometry, *Earth Planet. Sc. Lett.*, 371, 82–91, doi:10.1016/j.epsl.2013.04.006, 2013. 902
- Cohen, R. and Havlin, S.: *Complex Networks: Structure, Robustness and Function*, Cambridge University Press, Cambridge, 2010. 908
- Cook, E. R., Anchukaitis, K. J., Buckley, B. M., D'Arrigo, R. D., Jacoby, G. C., and Wright, W. E.: Asian Monsoon failure and megadrought during the last millennium, *Science*, 328, 486–489, doi:10.1126/science.1185188, 2010. 902
- Cosford, J., Qing, H., Eglington, B., Matthey, D., Yuan, D., Zhang, M., and Cheng, H.: East Asian monsoon variability since the Mid-Holocene recorded in a high-resolution, absolute-dated aragonite speleothem from eastern China, *Earth Planet. Sc. Lett.*, 275, 296–307, doi:10.1016/j.epsl.2008.08.018, 2008. 960
- Cullen, H. M., deMenocal, P. B., Hemming, S., Hemming, G., Brown, F. H., Guilderson, T., and Sirocko, F.: Climate change and the collapse of the Akkadian empire: evidence from the deep sea, *Geology*, 28, 379–382, doi:10.1130/0091-7613(2000)28<379:CCATCO>2.0.CO;2, 2000. 898, 912, 915, 926, 927, 962
- Dahl, S. O., Nesje, A., Lie, Ø., Fjordheim, K., and Matthews, J. A.: Timing, equilibrium-line altitudes and climatic implications of two early-Holocene glacier readvances during the Erdalen Event at Jostedalsbreen, western Norway, *Holocene*, 12, 17–25, doi:10.1191/0959683602hl516rp, 2002. 962
- deMenocal, P. B.: Cultural responses to climate change during the late Holocene, *Science*, 292, 667–673, doi:10.1126/science.1059827, 2001. 910, 912
- deMenocal, P. B., Ortiz, J., Guilderson, T., Adkins, J., Sarnthein, M., Baker, L., and Yarusinsky, M.: Abrupt onset and termination of the African Humid Period: rapid climate responses to gradual insolation forcing, *Quaternary Sci. Rev.*, 19, 347–361, doi:10.1016/S0277-3791(99)00081-5, 2000. 911, 913, 927
- Dong, G., Jia, X., An, C., Chen, F., Zhao, Y., Tao, S., and Ma, M.: Mid-Holocene climate change and its effect on prehistoric cultural evolution in eastern Qinghai Province, China, *Quaternary Res.*, 77, 23–30, doi:10.1016/j.yqres.2011.10.004, 2012. 934

**Nonlinear regime shifts in Holocene Asian monsoon variability**

J. F. Donges et al.

[Title Page](#)[Abstract](#)[Introduction](#)[Conclusions](#)[References](#)[Tables](#)[Figures](#)[⏪](#)[⏩](#)[◀](#)[▶](#)[Back](#)[Close](#)[Full Screen / Esc](#)[Printer-friendly Version](#)[Interactive Discussion](#)

Dong, J., Wang, Y., Cheng, H., Hardt, B., Edwards, R. L., Kong, X., Wu, J., Chen, S., Liu, D., Jiang, X., and Zhao, K.: A high-resolution stalagmite record of the Holocene East Asian monsoon from Mt Shennongjia, central China, Holocene, 20, 257–264, doi:10.1177/0959683609350393, 2010. 903

5 Donges, J. F., Donner, R. V., Rehfeld, K., Marwan, N., Trauth, M. H., and Kurths, J.: Identification of dynamical transitions in marine palaeoclimate records by recurrence network analysis, Nonlinear Proc. Geophys., 18, 545–562, doi:10.5194/npg-18-545-2011, 2011a. 900, 906, 907, 908, 909, 917, 940, 965, 970

10 Donges, J. F., Donner, R. V., Trauth, M. H., Marwan, N., Schellnhuber, H. J., and Kurths, J.: Non-linear detection of paleoclimate-variability transitions possibly related to human evolution, P. Natl. Acad. Sci. USA, 108, 20422–20427, doi:10.1073/pnas.1117052108, 2011b. 900, 906, 909, 917, 922, 933, 939, 940

15 Donges, J. F., Heitzig, J., Donner, R. V., and Kurths, J.: Analytical framework for recurrence network analysis of time series, Phys. Rev. E, 85, 046105, doi:10.1103/PhysRevE.85.046105, 2012. 906, 908, 909

Donges, J. F., Heitzig, J., Runge, J., Schultz, H. C., Wiedermann, M., Zech, A., Feldhoff, J. H., Rheinwalt, A., Kutza, H., Radebach, A., Marwan, N., and Kurths, J.: Advanced functional network analysis in the geosciences: the pyunicorn package, Geophys. Res. Abstr., 15, 3558, 2013. 941

20 Donner, R. V., Zou, Y., Donges, J. F., Marwan, N., and Kurths, J.: Ambiguities in recurrence-based complex network representations of time series, Phys. Rev. E, 81, 015101, doi:10.1103/PhysRevE.81.015101, 2010a. 909

25 Donner, R. V., Zou, Y., Donges, J. F., Marwan, N., and Kurths, J.: Recurrence networks – a novel paradigm for nonlinear time series analysis, New J. Phys., 12, 033205, doi:10.1088/1367-2630/12/3/033205, 2010b. 900, 906, 908, 909

Donner, R. V., Small, M., Donges, J. F., Marwan, N., Zou, Y., Xiang, R., and Kurths, J.: Recurrence-based time series analysis by means of complex network methods, Int. J. Bifurcat. Chaos, 21, 1019–1046, doi:10.1142/S0218127411029021, 2011. 906

30 Donner, R. V., Donges, J. F., Zou, Y., and Feldhoff, J. H.: Recurrence Quantification Analysis: Theory and Best Practices, chap.: Complex network analysis of recurrences, Springer, Berlin, Heidelberg, in press, 2014. 900

## Nonlinear regime shifts in Holocene Asian monsoon variability

J. F. Donges et al.

[Title Page](#)

[Abstract](#)

[Introduction](#)

[Conclusions](#)

[References](#)

[Tables](#)

[Figures](#)

[⏪](#)

[⏩](#)

[◀](#)

[▶](#)

[Back](#)

[Close](#)

[Full Screen / Esc](#)

[Printer-friendly Version](#)

[Interactive Discussion](#)



- Doose-Rolinski, H., Rogalla, U., Scheeder, G., Lückge, A., and von Rad, U.: High-resolution temperature and evaporation changes during the Late Holocene in the northeastern Arabian Sea, *Paleoceanography*, 16, 358–367, doi:10.1029/2000PA000511, 2001. 928
- Drysdale, R., Zanchetta, G., Hellstrom, J., Maas, R., Fallick, A., Pickett, M., Cartwright, I., and Piccini, L.: Late Holocene drought responsible for the collapse of Old World civilizations is recorded in an Italian cave flowstone, *Geology*, 34, 101–104, doi:10.1130/G22103.1, 2006. 912, 915, 962
- Enzel, Y., Ely, L. L., Mishra, S., Ramesh, R., Amit, R., Lazar, B., Rajaguru, S. N., Baker, V. R., and Sandler, A.: High-resolution Holocene environmental changes in the Thar Desert, North-western India, *Science*, 284, 125–128, doi:10.1126/science.284.5411.125, 1999. 913, 930
- Esper, J., Shiyatov, S. G., Mazepa, V. S., Wilson, R. J. S., Graybill, D. A., and Funkhouser, G.: Temperature-sensitive Tien Shan tree ring chronologies show multi-centennial growth trends, *Clim. Dynam.*, 21, 699–706, doi:10.1007/s00382-003-0356-y, 2003. 962
- Esper, J., Frank, D., Büntgen, U., Verstege, A., Luterbacher, J., and Xoplaki, E.: Long-term drought severity variations in Morocco, *Geophys. Res. Lett.*, 34, L17702, doi:10.1029/2007GL030844, 2007. 962
- Fairchild, I. J. and Baker, A.: *Speleothem Science: From Process to Past Environments*, Wiley-Blackwell, Chichester, 2012. 902
- Feldhoff, J. H., Donner, R. V., Donges, J. F., Marwan, N., and Kurths, J.: Geometric detection of coupling directions by means of inter-system recurrence networks, *Phys. Lett. A*, 376, 3504–3513, doi:10.1016/j.physleta.2012.10.008, 2012. 899
- Fleitmann, D., Burns, S. J., Mudelsee, M., Neff, U., Kramers, J., Mangini, A., and Matter, A.: Holocene forcing of the Indian monsoon recorded in a stalagmite from southern Oman, *Science*, 300, 1737–1739, doi:10.1126/science.1083130, 2003. 904, 911, 960
- Fleitmann, D., Burns, S. J., Mangini, A., Mudelsee, M., Kramers, J., Villa, I., Neff, U., Al-Subbary, A. A., Buettner, A., Hippler, D., and Matter, A.: Holocene ITCZ and Indian monsoon dynamics recorded in stalagmites from Oman and Yemen (Socotra), *Quaternary Sci. Rev.*, 26, 170–188, doi:10.1016/j.quascirev.2006.04.012, 2007. 904, 960
- Fleitmann, D., Mudelsee, M., Burns, S. J., Bradley, R. S., Kramers, J., and Matter, A.: Evidence for a widespread climatic anomaly at around 9.2 ka before present, *Paleoceanography*, 23, PA1102, doi:10.1029/2007PA001519, 2008. 900, 912, 913, 962

## Nonlinear regime shifts in Holocene Asian monsoon variability

J. F. Donges et al.

[Title Page](#)

[Abstract](#)

[Introduction](#)

[Conclusions](#)

[References](#)

[Tables](#)

[Figures](#)

[⏪](#)

[⏩](#)

[◀](#)

[▶](#)

[Back](#)

[Close](#)

[Full Screen / Esc](#)

[Printer-friendly Version](#)

[Interactive Discussion](#)



- Francus, P., von Suchodoletz, H., Dietze, M., Donner, R. V., Bouchard, F., Roy, A.-J., Fagot, M., Verschuren, D., and Kröpelin, S.: Varved sediments of Lake Yoa (Ounianga Kebir, Chad) reveal progressive drying of the Sahara during the last 6100 years, *Sedimentology*, 60, 911–934, doi:10.1111/j.1365-3091.2012.01370.x, 2013. 913
- 5 Gao, H., Zhu, C., and Xu, W.: Environmental change and cultural response around 4200 calyrBP in the Yishu River Basin, Shandong, *J. Geogr. Sci.*, 17, 285–292, doi:10.1007/s11442-007-0285-5, 2007. 934, 935
- Gasse, F. and Campo, E. V.: Abrupt post-glacial climate events in West Asia and North Africa monsoon domains, *Earth Planet. Sc. Lett.*, 126, 435–456, doi:10.1016/0012-821X(94)90123-6, 1994. 928
- 10 Gibbons, A.: How the Akkadian Empire was hung out to dry, *Science*, 261, 985, doi:10.1126/science.261.5124.985, 1993. 898, 915, 962
- Giosan, L., Clift, P. D., Macklin, M. G., Fuller, D. Q., Constantinescu, S., Durcan, J. A., Stevens, T., Duller, G. A. T., Tabrez, A. R., Gangal, K., Adhikari, R., Alizai, A., Filip, F., Van Laningham, S., and Syvitski, J. P. M.: Fluvial landscapes of the Harappan civilization, *P. Natl. Acad. Sci. USA*, 109, 1688–1694, doi:10.1073/pnas.1112743109, 2012. 930, 931
- 15 Griffiths, M. L., Drysdale, R. N., Gagan, M. K., Zhao, J., Ayliffe, L. K., Hellstrom, J. C., Hantoro, W. S., Frisia, S., Feng, Y., Cartwright, I., St. Pierre, E., Fischer, M. J., and Suwargadi, B. W.: Increasing Australian–Indonesian monsoon rainfall linked to early Holocene sea-level rise, *Nat. Geosci.*, 2, 636–639, doi:10.1038/ngeo605, 2009. 904, 911, 960
- 20 Gupta, A., Anderson, D., and Overpeck, J.: Abrupt changes in the Asian southwest monsoon during the Holocene and their links to the North Atlantic Ocean, *Nature*, 421, 354–357, doi:10.1038/nature01340, 2003. 911
- Haberle, S. G. and David, B.: Climates of change: human dimensions of Holocene environmental change in low latitudes of the PEP-II transect, *Quatern. Int.*, 118, 165–179, doi:10.1016/S1040-6182(03)00136-8, 2004. 912
- 25 Haug, G. H., Günther, D., Peterson, L. C., Sigman, D. M., Hughen, K. A., and Aeschlimann, B.: Climate and the collapse of Maya civilization, *Science*, 299, 1731–1735, doi:10.1126/science.1080444, 2003. 898, 915
- 30 Hemming, S. R.: Heinrich events: massive late Pleistocene detritus layers of the North Atlantic and their global climate imprint, *Rev. Geophys.*, 42, RG1005, doi:10.1029/2003RG000128, 2004. 911

## Nonlinear regime shifts in Holocene Asian monsoon variability

J. F. Donges et al.

[Title Page](#)

[Abstract](#)

[Introduction](#)

[Conclusions](#)

[References](#)

[Tables](#)

[Figures](#)

[⏪](#)

[⏩](#)

[◀](#)

[▶](#)

[Back](#)

[Close](#)

[Full Screen / Esc](#)

[Printer-friendly Version](#)

[Interactive Discussion](#)



- Hou, J., Huang, Y., Shuman, B. N., Oswald, W. W., and Foster, D. R.: Abrupt cooling repeatedly punctuated early-Holocene climate in eastern North America, *Holocene*, 22, 525–529, doi:10.1177/0959683611427329, 2012. 962
- Hoyos, C. D. and Webster, P. J.: The role of intraseasonal variability in the nature of Asian Monsoon precipitation, *J. Climate*, 20, 4402–4424, doi:10.1175/JCLI4252.1, 2007. 904
- Hsiang, S. M., Meng, K. C., and Cane, M. A.: Civil conflicts are associated with the global climate, *Nature*, 476, 438–441, doi:10.1038/nature10311, 2011. 898
- Hsiang, S. M., Burke, M., and Miguel, E.: Quantifying the influence of climate on human conflict, *Science*, 341, 1235367, doi:10.1126/science.1235367, 2013. 898, 900
- Hu, C., Henderson, G. M., Huang, J., Xie, S., Sun, Y., and Johnson, K. R.: Quantification of Holocene Asian monsoon rainfall from spatially separated cave records, *Earth Planet. Sc. Lett.*, 266, 221–232, doi:10.1016/j.epsl.2007.10.015, 2008. 899, 938, 960
- Huang, C. C., Pang, J., and Li, P.: Abruptly increased climatic aridity and its social impact on the Loess Plateau of China at 3100 aBP, *J. Arid Environ.*, 52, 87–99, doi:10.1006/jare.2002.0981, 2002. 936
- Huang, C. C., Pang, J., Zha, X., Zhou, Y., Su, H., and Li, Y.: Extraordinary floods of 4100–4000 a BP recorded at the Late Neolithic ruins in the Jinghe River Gorges, middle reach of the Yellow River, China, *Palaeogeogr. Palaeoclimatol.*, 289, 1–9, doi:10.1016/j.palaeo.2010.02.003, 2010. 935
- Huang, C. C., Pang, J., Zha, X., Su, H., and Jia, Y.: Extraordinary floods related to the climatic event at 4200 a BP on the Qishuihe River, middle reaches of the Yellow River, China, *Quaternary Sci. Rev.*, 30, 460–468, doi:10.1016/j.quascirev.2010.12.007, 2011. 935
- Jia, X., Dong, G., Li, H., Brunson, K., Chen, F., Ma, M., Wang, H., An, C., and Zhang, K.: The development of agriculture and its impact on cultural expansion during the late Neolithic in the Western Loess Plateau, China, *Holocene*, 23, 85–92, doi:10.1177/0959683612450203, 2013. 934
- Johnson, K. R., Hu, C., Belshaw, N. S., and Henderson, G. M.: Seasonal trace-element and stable-isotope variations in a Chinese speleothem: the potential for high-resolution paleomonsoon reconstruction, *Earth Planet. Sc. Lett.*, 244, 394–407, doi:10.1016/j.epsl.2006.01.064, 2006. 902

**Nonlinear regime shifts in Holocene Asian monsoon variability**

J. F. Donges et al.

[Title Page](#)[Abstract](#)[Introduction](#)[Conclusions](#)[References](#)[Tables](#)[Figures](#)[⏪](#)[⏩](#)[◀](#)[▶](#)[Back](#)[Close](#)[Full Screen / Esc](#)[Printer-friendly Version](#)[Interactive Discussion](#)

- Kaniewski, D., Paulissen, E., Van Campo, E., Al-Maqdissi, M., Bretschneider, J., and Van Lerberghe, K.: Middle East coastal ecosystem response to middle-to-late Holocene abrupt climate changes, *P. Natl. Acad. Sci. USA*, 105, 13941–13946, doi:10.1073/pnas.0803533105, 2008. 962
- 5 Kaniewski, D., Paulissen, E., Campo, E. V., Weiss, H., Otto, T., Bretschneider, J., and Lerberghe, K. V.: Late second–early first millennium BC abrupt climate changes in coastal Syria and their possible significance for the history of the Eastern Mediterranean, *Quaternary Res.*, 74, 207–215, doi:10.1016/j.yqres.2010.07.010, 2010. 962
- 10 Kantz, H. and Schreiber, T.: *Nonlinear Time Series Analysis*, 2nd Edn., Cambridge University Press, Cambridge, 2004. 907
- Kennel, M. B., Brown, R., and Abarbanel, H. D. I.: Determining embedding dimension for phase-space reconstruction using a geometrical construction, *Phys. Rev. A*, 45, 3403–3411, doi:10.1103/PhysRevA.45.3403, 1992. 907
- 15 Kennett, D. J., Breitenbach, S. F. M., Aquino, V. V., Asmerom, Y., Awe, J., Baldini, J. U., Bartlein, P., Culleton, B. J., Ebert, C., Jazwa, C., Macri, M. J., Marwan, N., Polyak, V., Prufer, K. M., Ridley, H. E., Sodemann, H., Winterhalder, B., and Haug, G. H.: Development and disintegration of Maya political systems in response to climate change, *Science*, 338, 788–791, doi:10.1126/science.1226299, 2012. 898, 914, 915
- 20 Kerr, R. A.: Sea-floor dust shows drought felled Akkadian Empire, *Science*, 279, 325–326, doi:10.1126/science.279.5349.325, 1998. 927
- Kudrass, H., Hofmann, A., Doose, H., Emeis, K., and Erlenkeuser, H.: Modulation and amplification of climatic changes in the Northern Hemisphere by the Indian summer monsoon during the past 80 kyr, *Geology*, 29, 63–66, doi:10.1130/0091-7613(2001)029<0063:MAAOCC>2.0.CO;2, 2001. 902
- 25 Kulke, H. and Rothermund, D.: *A History of India*, 4th Edn., Routledge, Abingdon, 2004. 929, 930, 931, 932
- Kuper, R. and Kröpelin, S.: Climate-controlled Holocene occupation in the Sahara: motor of Africa's evolution, *Science*, 313, 803–807, doi:10.1126/science.1130989, 2006. 926
- 30 Lachniet, M. S.: Climatic and environmental controls on speleothem oxygen-isotope values, *Quaternary Sci. Rev.*, 28, 412–432, doi:10.1016/j.quascirev.2008.10.021, 2009. 907



## Nonlinear regime shifts in Holocene Asian monsoon variability

J. F. Donges et al.

[Title Page](#)

[Abstract](#)

[Introduction](#)

[Conclusions](#)

[References](#)

[Tables](#)

[Figures](#)

[⏪](#)

[⏩](#)

[◀](#)

[▶](#)

[Back](#)

[Close](#)

[Full Screen / Esc](#)

[Printer-friendly Version](#)

[Interactive Discussion](#)

- Lavigne, F., Degeai, J.-P., Komorowski, J.-C., Guillet, S., Robert, V., Lahitte, P., Oppenheimer, C., Stoffel, M., Vidal, C. M., Surono, Pratomo, I., Wassmer, P., Hajdas, I., Hadmoko, D. S., and de Belizal, E.: Source of the great A. D. 1257 mystery eruption unveiled, Samalas volcano, Rinjani Volcanic Complex, Indonesia, *P. Natl. Acad. Sci. USA*, 110, 16742–16747, doi:10.1073/pnas.1307520110, 2013. 933
- 5 Lee, Y. K.: Control strategies and polity competition in the lower Yi-Luo Valley, North China, *J. Anthropol. Archaeol.*, 23, 172–195, doi:10.1016/j.jaa.2004.01.002, 2004. 936, 938
- Lemcke, G. and Sturm, M.:  $\delta^{18}\text{O}$  and trace element measurements as proxy for the reconstruction of climate changes at Lake Van (Turkey): preliminary results, in: *Third Millenium BC Climate Change and Old World Collapse*, edited by: Dalfes, H., Kukla, G., and Weiss, H., vol. 49 of NATA ASU Series, Series I: Global Environmental Change, Springer, Berlin, 178–196, 1997. 926, 928
- 10 Lenton, T. M., Held, H., Kriegler, E., Hall, J. W., Lucht, W., Rahmstorf, S., and Schellnhuber, H. J.: Tipping elements in the Earth's climate system, *P. Natl. Acad. Sci. USA*, 105, 1786–1793, doi:10.1073/pnas.0705414105, 2008. 898
- Levermann, A., Schewe, J., Petoukhov, V., and Held, H.: Basic mechanism for abrupt monsoon transitions, *P. Natl. Acad. Sci. USA*, 106, 20572–20577, doi:10.1073/pnas.0901414106, 2009. 898
- 15 Li, Y., Wu, J., Hou, S., Shi, C., Mo, D., Liu, B., and Zhou, L.: Palaeoecological records of environmental change and cultural development from the Liangzhu and Qujialing archaeological sites in the middle and lower reaches of the Yangtze River, *Quatern. Int.*, 227, 29–37, doi:10.1016/j.quaint.2010.05.015, 2010. 934
- Liu, F. and Feng, Z.: A dramatic climatic transition at  $\sim 4000$  cal yr BP and its cultural responses in Chinese cultural domains, *Holocene*, 22, 1181–1197, doi:10.1177/0959683612441839, 2012. 934
- 20 Liu, L.: Settlement patterns, chiefdom variability, and the development of early states in North China, *J. Anthropol. Archaeol.*, 15, 237–288, doi:10.1006/jaar.1996.0010, 1996. 934, 936
- Liu, L.: The development and decline of social complexity in northern China: some environmental and social factors, *Indo-Pacific Prehist. Assoc. Bull.*, 4, 14–34, 2000. 934
- 30 Magee, P.: Settlement patterns, polities and regional complexity in the Southeast Arabian Iron Age, *Paléorient*, 24, 49–60, doi:10.3406/paleo.1998.4676, 1998. 928

## Nonlinear regime shifts in Holocene Asian monsoon variability

J. F. Donges et al.

[Title Page](#)

[Abstract](#)

[Introduction](#)

[Conclusions](#)

[References](#)

[Tables](#)

[Figures](#)

[⏪](#)

[⏩](#)

[◀](#)

[▶](#)

[Back](#)

[Close](#)

[Full Screen / Esc](#)

[Printer-friendly Version](#)

[Interactive Discussion](#)

- 5 Maher, B. A.: Holocene variability of the East Asian summer monsoon from Chinese cave records: a re-assessment, *Holocene*, 18, 861–866, doi:10.1177/0959683608095569, 2008. 899
- 10 Malik, N., Marwan, N., and Kurths, J.: Spatial structures and directionalities in Monsoonal precipitation over South Asia, *Nonlin. Processes Geophys.*, 17, 371–381, doi:10.5194/npg-17-371-2010, 2010. 931
- 15 Malik, N., Zou, Y., Marwan, N., and Kurths, J.: Dynamical regimes and transitions in Plio-Pleistocene Asian monsoon, *Europhys. Lett.*, 97, 40009, doi:10.1209/0295-5075/97/40009, 2012. 906, 931
- 20 Marwan, N.: How to avoid potential pitfalls in recurrence plot based data analysis, *Int. J. Bifurcat. Chaos*, 21, 1003–1017, doi:10.1142/S0218127411029008, 2011. 909
- Marwan, N., Thiel, M., and Nowaczyk, N. R.: Cross recurrence plot based synchronization of time series, *Nonlinear Process. Geophys.*, 9, 325–331, doi:10.5194/npg-9-325-2002, 2002. 906
- 25 Marwan, N., Trauth, M. H., Vuille, M., and Kurths, J.: Comparing modern and Pleistocene ENSO-like influences in NW Argentina using nonlinear time series analysis methods, *Clim. Dynam.*, 21, 317–326, doi:10.1007/s00382-003-0335-3, 2003. 906
- Marwan, N., Romano, M. C., Thiel, M., and Kurths, J.: Recurrence plots for the analysis of complex systems, *Phys. Rep.*, 438, 237–329, doi:10.1016/j.physrep.2006.11.001, 2007. 905, 906, 907
- 30 Marwan, N., Donges, J., Zou, Y., Donner, R., and Kurths, J.: Complex network approach for recurrence analysis of time series, *Phys. Lett. A*, 373, 4246–4254, doi:10.1016/j.physleta.2009.09.042, 2009. 900, 906, 908
- Marwan, N., Schinkel, S., and Kurths, J.: Recurrence plots 25 years later – gaining confidence in dynamical transitions, *Europhys. Lett.*, 101, 20007, doi:10.1209/0295-5075/101/20007, 2013. 906
- Mayewski, P. A., Rohling, E. E., Curt Stager, J., Karlén, W., Maasch, K. A., David Meeker, L., Meyerson, E. A., Gasse, F., van Kreveland, S., Holmgren, K., Lee-Thorpe, J., Rosqvist, G., Racki, F., Staubwasser, M., Schneider, R. R., and Steigl, E. J.: Holocene climate variability, *Quaternary Res.*, 62, 243–255, doi:10.1016/j.yqres.2004.07.001, 2004. 900, 911, 912, 913, 914, 915, 919, 921, 926, 927, 933, 938, 962, 963, 965
- Meyer, M. W.: *Asia: a Concise History*, Rowman & Littlefield, Lanham, 1997. 932

## Nonlinear regime shifts in Holocene Asian monsoon variability

J. F. Donges et al.

[Title Page](#)

[Abstract](#)

[Introduction](#)

[Conclusions](#)

[References](#)

[Tables](#)

[Figures](#)

[⏪](#)

[⏩](#)

[◀](#)

[▶](#)

[Back](#)

[Close](#)

[Full Screen / Esc](#)

[Printer-friendly Version](#)

[Interactive Discussion](#)

Miller, G. H., Geirsdóttir, Á., Zhong, Y., Larsen, D. J., Otto-Bliesner, B. L., Holland, M. M., Bailey, D. A., Refsnider, K. A., Lehman, S. J., Southon, J. R., Anderson, C., Björnsson, H., and Thordarson, T.: Abrupt onset of the Little Ice Age triggered by volcanism and sustained by sea-ice/ocean feedbacks, *Geophys. Res. Lett.*, 39, L02708, doi:10.1029/2011GL050168, 2012. 914

Morrill, C. and Jacobsen, R. M.: How widespread were climate anomalies 8200 years ago?, *Geophys. Res. Lett.*, 32, L19701, doi:10.1029/2005GL023536, 2005. 911

Morrill, C., Overpeck, J. T., and Cole, J. E.: A synthesis of abrupt changes in the Asian summer monsoon since the last deglaciation, *Holocene*, 13, 465–476, doi:10.1191/0959683603hl639ft, 2003. 899

Neff, U., Burns, S. J., Mangini, A., Mudelsee, M., Fleitmann, D., and Matter, A.: Strong coherence between solar variability and the monsoon in Oman between 9 and 6 kyr ago, *Nature*, 411, 290–293, doi:10.1038/35077048, 2001. 904, 960

Newman, M. E. J.: *Networks: an Introduction*, Oxford University Press, Oxford, 2010. 908

Parker, A. G., Goudie, A. S., Stokes, S., White, K., Hodson, M. J., Manning, M., and Kennet, D.: A record of Holocene climate change from lake geochemical analyses in southeastern Arabia, *Quaternary Res.*, 66, 465–476, doi:10.1016/j.yqres.2006.07.001, 2006. 911, 913, 925, 926, 927, 928, 962

Partin, J. W., Cobb, K. M., Adkins, J. F., Clark, B., and Fernandez, D. P.: Millennial-scale trends in west Pacific warm pool hydrology since the Last Glacial Maximum, *Nature*, 449, 452–455, doi:10.1038/nature06164, 2007. 911

Peters, J.: The dromedary: ancestry, history of domestication and medical treatment in early historic times, *Tierarztl. Prax. G N.*, 25, 559–565, 1997. 928

Plunkett, G. and Swindles, G.: Determining the Sun's influence on Lateglacial and Holocene climates: a focus on climate response to centennial-scale solar forcing at 2800 cal BP, *Quaternary Sci. Rev.*, 27, 175–184, doi:10.1016/j.quascirev.2007.01.015, 2008. 962

Poincaré, H.: Sur la probléme des trois corps et les équations de la dynamique, *Acta Math.-Djursholm*, 13, 3–270, 1890. 906

Ponton, C., Giosan, L., Eglinton, T. I., Fuller, D. Q., Johnson, J. E., Kumar, P., and Collett, T. S.: Holocene aridification of India, *Geophys. Res. Lett.*, 39, L03704, doi:10.1029/2011GL050722, 2012. 902

Possehl, G. L.: The transformation of the Indus Civilization, *J. World Prehist.*, 11, 425–472, doi:10.1007/BF02220556, 1997. 931

**Nonlinear regime shifts in Holocene Asian monsoon variability**

J. F. Donges et al.

[Title Page](#)[Abstract](#)[Introduction](#)[Conclusions](#)[References](#)[Tables](#)[Figures](#)[⏪](#)[⏩](#)[◀](#)[▶](#)[Back](#)[Close](#)[Full Screen / Esc](#)[Printer-friendly Version](#)[Interactive Discussion](#)

- Possehl, G. L.: The Indus Civilization: a Contemporary Perspective, Altamira Press, Oxford, 2002. 929
- Potts, D.: The late prehistoric, protohistoric, and early historic periods in Eastern Arabia (ca. 5000–1200 BC), *J. World Prehist.*, 7, 163–212, doi:10.1007/BF00975450, 1993. 926
- 5 Rehfeld, K. and Kurths, J.: Similarity estimators for irregular and age-uncertain time series, *Clim. Past*, 10, 107–122, doi:10.5194/cp-10-107-2014, 2014. 903, 908, 969
- Rehfeld, K., Marwan, N., Heitzig, J., and Kurths, J.: Comparison of correlation analysis techniques for irregularly sampled time series, *Nonlinear Process. Geophys.*, 18, 389–404, doi:10.5194/npg-18-389-2011, 2011. 908, 917, 961, 969
- 10 Rehfeld, K., Marwan, N., Breitenbach, S. F. M., and Kurths, J.: Late Holocene Asian summer monsoon dynamics from small but complex networks of paleoclimate data, *Clim. Dynam.*, 41, 3–19, doi:10.1007/s00382-012-1448-3, 2013. 899, 900, 904
- Riehl, S.: Climate and agriculture in the ancient Near East: a synthesis of the archaeobotanical and stable carbon isotope evidence, *Veg. Hist. Archaeobot.*, 17, 43–51, doi:10.1007/s00334-008-0156-8, 2008. 927
- 15 Scargle, J. D.: Studies in astronomical time series, III: Fourier transforms, autocorrelation functions, and cross-correlation functions of unevenly spaced data, *Astrophys. J.*, 343, 874–887, doi:10.1086/167757, 1989. 908
- Schleussner, C. F. and Feulner, G.: A volcanically triggered regime shift in the subpolar North Atlantic Ocean as a possible origin of the Little Ice Age, *Clim. Past*, 9, 1321–1330, doi:10.5194/cp-9-1321-2013, 2013. 914
- 20 Singh, U.: A History of Ancient and Early Medieval India: From the Stone Age to the 12th Century, Dorling Kindersley, Delhi, 2008. 929, 930, 931, 932
- Sinha, A., Cannariato, K., Stott, L., Li, H., You, C., Cheng, H., Edwards, R., and Singh, I.: Variability of Southwest Indian summer monsoon precipitation during the Bølling-Ållerød, *Geology*, 33, 813, doi:10.1130/G21498.1, 2005. 903
- 25 Sinha, A., Cannariato, K., Stott, L., Cheng, H., Edwards, R., Yadava, M., Ramesh, R., and Singh, I.: A 900-year (600 to 1500 AD) record of the Indian summer monsoon precipitation from the core monsoon zone of India, *Geophys. Res. Lett.*, 34, 16707, doi:10.1029/2007GL030431, 2007. 903
- 30 Sinha, A., Berkelhammer, M., Stott, L., Mudelsee, M., Cheng, H., and Biswas, J.: The leading mode of Indian Summer Monsoon precipitation variability during the last millennium, *Geophys. Res. Lett.*, 38, L15703, doi:10.1029/2011GL047713, 2011a. 903

## Nonlinear regime shifts in Holocene Asian monsoon variability

J. F. Donges et al.

[Title Page](#)

[Abstract](#)

[Introduction](#)

[Conclusions](#)

[References](#)

[Tables](#)

[Figures](#)

[⏪](#)

[⏩](#)

[◀](#)

[▶](#)

[Back](#)

[Close](#)

[Full Screen / Esc](#)

[Printer-friendly Version](#)

[Interactive Discussion](#)



- Sinha, A., Stott, L., Berkelhammer, M., Cheng, H., Edwards, R., Buckley, B., Aldenderfer, M., and Mudelsee, M.: A global context for megadroughts in monsoon Asia during the past millennium, *Quaternary Sci. Rev.*, 30, 47–62, doi:10.1016/j.quascirev.2010.10.005, 2011b. 903, 904
- 5 Solheim, W.: Taiwan, Coastal South China and Northern Viet Nam and the Nusantara Maritime Trading Network, *J. East Asian Archaeol.*, 2, 273–284, 2000. 932
- Stanley, D. J., Chen, Z., and Song, J.: Inundation, sea-level rise and transition from Neolithic to Bronze Age cultures, Yangtze Delta, China, *Geoarchaeology*, 14, 15–26, doi:10.1002/(SICI)1520-6548(199901)14:1<15::AID-GEA2>3.0.CO;2-N, 1999. 934
- 10 Stanley, J.-D., Krom, M. D., Cliff, R. A., and Woodward, J. C.: Short contribution: Nile flow failure at the end of the Old Kingdom, Egypt: strontium isotopic and petrologic evidence, *Geoarchaeology*, 18, 395–402, doi:10.1002/gea.10065, 2003. 898, 915, 962
- Staubwasser, M. and Weiss, H.: Holocene climate and cultural evolution in late prehistoric–early historic West Asia, *Quaternary Res.*, 66, 372–387, doi:10.1016/j.yqres.2006.09.001, 15 2006. 898, 902, 926
- Staubwasser, M., Sirocko, F., Grootes, P. M., and Segl, M.: Climate change at the 4.2 ka BP termination of the Indus valley civilization and Holocene south Asian monsoon variability, *Geophys. Res. Lett.*, 30, 1425, doi:10.1029/2002GL016822, 2003. 928, 930
- Steinhilber, F., Abreu, J. A., Beer, J., Brunner, I., Christl, M., Fischer, H., Heikkilä, U., Kubik, P. W., Mann, M., McCracken, K. G., Millerf, H., Miyaharag, H., Oerterf, H., and Wilhelms, F.: 9400 years of cosmic radiation and solar activity from ice cores and tree rings, *P. Natl. Acad. Sci. USA*, 109, 5967–5971, 2012. 919, 921, 973
- 20 Stocker, T. F., Qin, D., Plattner, G.-K., Tignor, M., Allen, S. K., Boschung, J., Nauels, A., Xia, Y., Bex, V., and Midgley, P. M. (Eds.): IPCC, 2013: Climate Change 2013: the Physical Science Basis, Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, Cambridge University Press, in press, 2014. 898
- 25 Swindles, G. T., Plunkett, G., and Roe, H. M.: A delayed climatic response to solar forcing at 2800 cal. BP: multiproxy evidence from three Irish peatlands, *Holocene*, 17, 177–182, doi:10.1177/0959683607075830, 2007. 962
- 30 Tainter, J.: The collapse of complex societies, in: *New Studies in Archeology*, Cambridge University Press, 1990. 898

## Nonlinear regime shifts in Holocene Asian monsoon variability

J. F. Donges et al.

[Title Page](#)

[Abstract](#)

[Introduction](#)

[Conclusions](#)

[References](#)

[Tables](#)

[Figures](#)

[⏪](#)

[⏩](#)

[◀](#)

[▶](#)

[Back](#)

[Close](#)

[Full Screen / Esc](#)

[Printer-friendly Version](#)

[Interactive Discussion](#)

- Takens, F.: Detecting strange attractors in turbulence, in: Dynamical Systems and Turbulence, Warwick 1980: Proceedings of a symposium held at the University of Warwick 1979–80, edited by: Rand, D. and Young, L.-S., vol. 898 of Lecture Notes in Mathematics, Springer, New York, 366–381, doi:10.1007/BFb0091924, 1981. 907
- 5 Tang, Z., Chen, D., Wu, X., and Mu, G.: Redistribution of prehistoric Tarim people in response to climate change, *Quatern. Int.*, 36–41, doi:10.1016/j.quaint.2013.01.021, 2013. 937
- Tarling, N.: *The Cambridge History of Southeast Asia Volume 1: From Early Times to c.1800*, Cambridge University Press, Cambridge, doi:10.1017/CHOL9780521355056, 1993. 932
- Telford, R., Heegaard, E., and Birks, H.: All age-depth models are wrong: but how badly?, *Quaternary Sci. Rev.*, 23, 1–5, doi:10.1016/j.quascirev.2003.11.003, 2004. 904
- 10 Thompson, L. G., Yao, T., Davis, M. E., Henderson, K. A., Mosley-Thompson, E., Lin, P.-N., Beer, J., Synal, H.-A., Cole-Dai, J., and Bolzan, J. F.: Tropical climate instability: the Last Glacial Cycle from A Qinghai-Tibetan ice core, *Science*, 276, 1821–1825, doi:10.1126/science.276.5320.1821, 1997. 902
- 15 Thompson, L. G., Yao, T., Mosley-Thompson, E., Davis, M. E., Henderson, K. A., and Lin, P.-N.: A high-resolution millennial record of the South Asian Monsoon from Himalayan ice cores, *Science*, 289, 1916–1919, doi:10.1126/science.289.5486.1916, 2000. 902
- Thompson, L. G., Mosley-Thompson, E., Davis, M., Lin, P.-N., Henderson, K., and Mashiotta, T.: Tropical glacier and ice core evidence of climate change on annual to millennial time scales, *Climatic Change*, 59, 137–155, doi:10.1023/A:1024472313775, 2003. 902
- 20 Trauth, M. H., Bookhagen, B., Marwan, N., and Strecker, M. R.: Multiple landslide clusters record Quaternary climate changes in the northwestern Argentine Andes, *Palaeogeogr. Palaeocli.*, 194, 109–121, doi:10.1016/S0031-0182(03)00273-6, 2003. 906
- Treydte, K. S., Schleser, G., Helle, G., Frank, D., Winiger, M., Haug, G., and Esper, J.: The twentieth century was the wettest period in northern Pakistan over the past millennium, *Nature*, 440, 1179–1182, doi:10.1038/nature04743, 2006. 902
- 25 Treydte, K. S., Frank, D. C., Saurer, M., Helle, G., Schleser, G. H., and Esper, J.: Impact of climate and CO<sub>2</sub> on a millennium-long tree-ring carbon isotope record, *Geochim. Cosmochim. Acta*, 73, 4635–4647, doi:10.1016/j.gca.2009.05.057, 2009. 902
- 30 Uerpmann, M.: The dark millennium: remarks on the final Stone Age in the Emirates and Oman, in: *Archaeology of the United Arab Emirates*, edited by: Potts, D. T., Al-Naboodah, H., and Hellyer, P., Trident Press, London, 74–81, 2003. 926

**Nonlinear regime shifts in Holocene Asian monsoon variability**

J. F. Donges et al.

[Title Page](#)[Abstract](#)[Introduction](#)[Conclusions](#)[References](#)[Tables](#)[Figures](#)[⏪](#)[⏩](#)[◀](#)[▶](#)[Back](#)[Close](#)[Full Screen / Esc](#)[Printer-friendly Version](#)[Interactive Discussion](#)

- van Geel, B., Buurman, J., and Waterbolk, H. T.: Archaeological and palaeoecological indications of an abrupt climate change in the Netherlands, and evidence for climatological teleconnections around 2650 BP, *J. Quaternary Sci.*, 11, 451–460, doi:10.1002/(SICI)1099-1417(199611/12)11:6<451::AID-JQS275>3.0.CO;2-9, 1996. 962
- 5 von Rad, U., Schaaf, M., Michels, K. H., Schulz, H., Berger, W. H., and Sirocko, F.: A 5000-yr record of climate change in varved sediments from the oxygen minimum zone off Pakistan, Northeastern Arabian Sea, *Quaternary Res.*, 51, 39–53, 1999. 902
- Wagner, M., Tarasov, P., Hosner, D., Fleck, A., Ehrich, R., Chen, X., and Leipe, C.: Mapping of the spatial and temporal distribution of archaeological sites of northern China during the  
10 Neolithic and Bronze Age, *Quatern. Int.*, 344–357, doi:10.1016/j.quaint.2012.06.039, 2013. 934, 936, 937
- Wang, Y., Cheng, H., Edwards, R. L., He, Y., Kong, X., An, Z., Wu, J., Kelly, M. J., Dykoski, C. A., and Li, X.: The Holocene Asian monsoon: links to solar changes and North Atlantic climate, *Science*, 308, 854–857, doi:10.1126/science.1106296, 2005. 903, 911, 916, 960, 966, 968
- 15 Wang, Y., Cheng, H., Edwards, R. L., Kong, X., Shao, X., Chen, S., Wu, J., Jiang, X., Wang, X., and An, Z.: Millennial-and orbital-scale changes in the East Asian monsoon over the past 224 000 years, *Nature*, 451, 1090–1093, doi:10.1038/nature06692, 2008. 903, 937
- Wanner, H., Beer, J., Bütikofer, J., Crowley, T. J., Cubasch, U., Flückiger, J., Goosse, H., Grosjean, M., Joos, F., Kaplan, J. O., Küttel, M., Müller, S. A., Prentice, I. C.,  
20 Solomina, O., Stocker, T. F., Tarasov, P., Wagner, M., and Widmann, M.: Mid- to Late Holocene climate change: an overview, *Quaternary Sci. Rev.*, 27, 1791–1828, doi:10.1016/j.quascirev.2008.06.013, 2008. 900, 910, 914
- Wanner, H., Solomina, O., Grosjean, M., Ritz, S. P., and Jetel, M.: Structure and origin of Holocene cold events, *Quaternary Sci. Rev.*, 30, 3109–3123,  
25 doi:10.1016/j.quascirev.2011.07.010, 2011. 900, 914
- Weiss, B.: The decline of Late Bronze Age civilization as a possible response to climatic change, *Climatic Change*, 4, 173–198, doi:10.1007/BF00140587, 1982. 962
- Weiss, H.: Beyond the Younger Dryas – collapse as adaptation to abrupt climate change in ancient West Asia and the Eastern Mediterranean, in: *Environmental Disaster and the Archaeology of Human Response*, edited by: Bawden, G. and Rey craft, R., vol. 7 of *Anthropological Papers*, Maxwell Museum of Anthropology, Albuquerque, 75–98, 2000. 926
- 30

## Nonlinear regime shifts in Holocene Asian monsoon variability

J. F. Donges et al.

[Title Page](#)

[Abstract](#)

[Introduction](#)

[Conclusions](#)

[References](#)

[Tables](#)

[Figures](#)

[⏪](#)

[⏩](#)

[◀](#)

[▶](#)

[Back](#)

[Close](#)

[Full Screen / Esc](#)

[Printer-friendly Version](#)

[Interactive Discussion](#)



- Weiss, H., Courty, M. A., Wetterstrom, W., Guichard, F., Senior, L., Meadow, R., and Curnow, A.: The genesis and collapse of third millennium north Mesopotamian civilization, *Science*, 261, 995–1004, doi:10.1126/science.261.5124.995, 1993. 915, 927, 962
- Weninger, B., Alram-Stern, E., Bauer, E., Clare, L., Danzeglocke, U., Jöris, O., Kubatzki, C., Rollefson, G., Todorova, H., and van Andel, T.: Climate forcing due to the 8200 cal yr BP event observed at Early Neolithic sites in the eastern Mediterranean, *Quaternary Res.*, 66, 401–420, doi:10.1016/j.yqres.2006.06.009, 2006. 915
- Wu, G., Liu, Y., He, B., Bao, Q., Duan, A., and Jin, F.-F.: Thermal controls on the Asian summer monsoon, *Scientific Reports*, 2, 404, doi:10.1038/srep00404, 2012. 898
- Wu, W. and Liu, T.: Possible role of the “Holocene Event 3” on the collapse of Neolithic Cultures around the Central Plain of China, *Quatern. Int.*, 117, 153–166, doi:10.1016/S1040-6182(03)00125-3, 2004. 934, 935
- Wunsch, C.: Extremes, patterns, and other structures in oceanographic and climate records, in: Proceedings of the 15th ‘Aha Huliko‘a Hawaiian Winter Workshop on Extreme Events, University of Hawaii, Honolulu, 141–148, 2007. 906
- Xiao, J., Chang, Z., Wen, R., Zhai, D., Itoh, S., and Lomtatidze, Z.: Holocene weak monsoon intervals indicated by low lake levels at Hulun Lake in the monsoonal margin region of north-eastern Inner Mongolia, China, *Holocene*, 19, 899–908, doi:10.1177/0959683609336574, 2009. 938
- Yancheva, G., Nowaczyk, N. R., Mingram, J., Dulski, P., Schettler, G., Negendank, J. F., Liu, J., Sigman, D. M., Peterson, L. C., and Haug, G. H.: Influence of the intertropical convergence zone on the East Asian monsoon, *Nature*, 445, 74–77, doi:10.1038/nature05431, 2007. 898, 937
- Yasuda, Y., Fujiki, T., Nasu, H., Kato, M., Morita, Y., Mori, Y., Kanehara, M., Toyama, S., Yano, A., Okuno, M., Jiejun, H., Ishihara, S., Kitagawa, H., Fukusawa, H., and Naruse, T.: Environmental archaeology at the Chengtoushan site, Hunan Province, China, and implications for environmental change and the rise and fall of the Yangtze River civilization, *Quatern. Int.*, 149–158, doi:10.1016/j.quaint.2004.02.016, 2004. 934
- Yu, S., Zhu, C., Song, J., and Qu, W.: Role of climate in the rise and fall of Neolithic cultures on the Yangtze Delta, *Boreas*, 29, 157–165, doi:10.1111/j.1502-3885.2000.tb01208.x, 2000. 934



## Nonlinear regime shifts in Holocene Asian monsoon variability

J. F. Donges et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

⏪

⏩

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

- Zhang, D. D., Brecke, P., Lee, H. F., He, Y.-Q., and Zhang, J.: Global climate change, war, and population decline in recent human history, *P. Natl. Acad. Sci. USA*, 104, 19214–19219, doi:10.1073/pnas.0703073104, 2007. 898
- 5 Zhang, D. D., Lee, H. F., Wang, C., Li, B., Pei, Q., Zhang, J., and An, Y.: The causality analysis of climate change and large-scale human crisis, *P. Natl. Acad. Sci. USA*, 108, 17296–17301, doi:10.1073/pnas.1104268108, 2011. 898
- Zhou, J., Wang, S., Yang, G., and Xiao, H.: Younger Dryas event and cold events in Early-Mid Holocene: record from the sediment of Erhai Lake, *Adv. Clim. Change Res. Suppl.*, 3, 1673–1719, 2007. 962
- 10 Zickfeld, K., Knopf, B., Petoukhov, V., and Schellnhuber, H.: Is the Indian summer monsoon stable against global change?, *Geophys. Res. Lett.*, 32, L15707, doi:10.1029/2005GL022771, 2005. 898

## Nonlinear regime shifts in Holocene Asian monsoon variability

J. F. Donges et al.

**Table 1.** List of speleothem  $\delta^{18}\text{O}$  oxygen isotope records used in this study including cave name, speleothem ID, cave location, number of data points  $N$ , average sampling time  $\langle\Delta T\rangle$ , and climatological interpretation (IOM: Indian Ocean monsoon, ISM: Indian summer monsoon, EASM: East Asian summer monsoon, AISM: Australian-Indonesian summer monsoon). From the Mawmluh record, all data points prior to 9 kaBP were discarded, since the older part of the record was recently found to be insufficiently dated (M. Berkelhammer, personal communication, 2013).

	Cave name	Speleothem	Latitude	Longitude	$N$	$\langle\Delta T\rangle$ [a]	Interpretation	Reference
1	Dimarshim, Yemen	D1	12°33′ N	53°41′ E	530	8.3	IOM strength	Fleitmann et al. (2007)
2	Qunf, Oman	Q5	17°10′ N	54°18′ E	1412	7.3	IOM strength	Fleitmann et al. (2003, 2007)
3	Hoti, Oman	H5	23°05′ N	57°21′ E	832	4.3	IOM strength	Neff et al. (2001)
4	Mawmluh, India	KM-A	25°16′ N	91°53′ E	889	6.0	ISM strength	Berkelhammer et al. (2012)
5	Tianmen, Tibet	TM-18	30°55′ N	90°40′ E	1005	4.9	ISM strength	Cai et al. (2012)
6	Dongge, China	DA	25°17′ N	108°5′ E	2124	4.2	EASM strength	Wang et al. (2005)
7	Lianhua, China	A1	29°29′ N	109°32′ E	819	8.1	EASM strength	Cosford et al. (2008)
8	Heshang, China	HS4	30°27′ N	110°25′ E	1223	7.8	EASM strength	Hu et al. (2008)
9	Jiuxian, China	C996-1	33°34′ N	109°6′ E	828	10.5	EASM strength	Cai et al. (2010)
10	Liang-Luar, Indonesia	LR06-B1	8°32′ S	120°26′ E	1289	9.7	AISM strength	Griffiths et al. (2009)

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



## Nonlinear regime shifts in Holocene Asian monsoon variability

J. F. Donges et al.

**Table 2.** Decorrelation time  $\tau_d$  of speleothem oxygen isotope records determined as the first zero-crossing of the auto-correlation function (ACF). The ACF was computed from the detrended time series using a Gaussian-kernel estimator applied to the original irregularly sampled records (kernel bandwidth  $h = \langle \Delta T \rangle / 4$  as suggested by Rehfeld et al., 2011). A sliding-window detrending was applied with a 1000 a bandwidth for all records.

	Cave name	Decorrelation time $\tau_d$ [a]
1	Dimarshim, Yemen	100
2	Qunf, Oman	216
3	Hoti, Oman	57
4	Mawmluh, India	146
5	Tianmen, Tibet	90
6	Dongge, China	185
7	Lianhua, China	193
8	Heshang, China	60
9	Jiuxian, China	73
10	Liang-Luar, Indonesia	135

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

⏪

⏩

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

## Nonlinear regime shifts in Holocene Asian monsoon variability

J. F. Donges et al.

[Title Page](#)

[Abstract](#)

[Introduction](#)

[Conclusions](#)

[References](#)

[Tables](#)

[Figures](#)

[⏪](#)

[⏩](#)

[◀](#)

[▶](#)

[Back](#)

[Close](#)

[Full Screen / Esc](#)

[Printer-friendly Version](#)

[Interactive Discussion](#)

**Table 3.** List of Bond events and potentially related cultural changes (selection).

No.	Timing (ka BP)	Notes and related events
B0	≈ 0.5	Little Ice Age (Esper et al., 2003, 2007)
B1	≈ 1.4	Migration Period (Büntgen et al., 2011; Esper et al., 2003, 2007)
B2	≈ 2.8	Initiation of Iron Age Cold Epoch (van Geel et al., 1996; Swindles et al., 2007; Plunkett and Swindles, 2008), early 1st millennium BC drought in the Eastern Mediterranean (Weiss, 1982; Kaniewski et al., 2008, 2010), possibly triggering the collapse of Late Bronze Age cultures
B3	≈ 4.2	4.2 ka event, collapse of the Akkadian Empire (Gibbons, 1993; Weiss et al., 1993; Cullen et al., 2000; Stanley et al., 2003; Drysdale et al., 2006), end of Egyptian Old Kingdom
B4	≈ 5.9	5.9 ka event (Parker et al., 2006)
B5	≈ 8.1	8.2 ka event (Alley et al., 1997; Baldini et al., 2002)
B6	≈ 9.4	Erdalen event of glacier activity in Norway (Dahl et al., 2002; Fleitmann et al., 2008), cold event in China (Zhou et al., 2007; Hou et al., 2012)
B7	≈ 10.3	(Hou et al., 2012; Amigo et al., 2013)
B8	≈ 11.1	Transition from the Younger Dryas to the boreal (Mayewski et al., 2004)

## Nonlinear regime shifts in Holocene Asian monsoon variability

J. F. Donges et al.

**Table 4.** List of Holocene rapid climate change (RCC) episodes (Mayewski et al., 2004) including possible forcing mechanisms and temporally associated Bond events (Table 3).

No.	Timing (ka BP)	Possible mechanisms	Associated Bond events
RCC0	0.6–0.15	Reduced solar forcing, volcanism	B0
RCC1	1.2–1.0	Reduced solar forcing	B1
RCC2	3.5–2.5	Reduced solar forcing	B2
RCC3	4.2–3.8	Reduced solar forcing	B3
RCC4	6.0–5.0	Reduced solar forcing	B4
RCC5	9.0–8.0	Orbital changes, meltwater pulse, volcanism	B5, B6

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

⏪

⏩

◀

▶

Back

Close

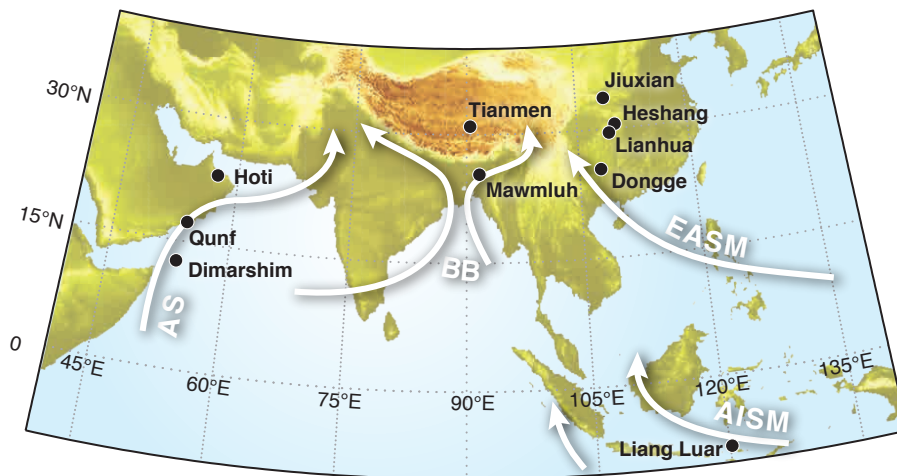
Full Screen / Esc

Printer-friendly Version

Interactive Discussion

## Nonlinear regime shifts in Holocene Asian monsoon variability

J. F. Donges et al.



**Fig. 1.** Map of South Asia showing the main flow directions of moist air masses associated with different monsoon branches: Arabian Sea (AS) and Bay of Bengal (BB) branches of the Indian summer monsoon, East Asian summer monsoon (EASM), and Australian-Indonesian summer monsoon (AISM). Furthermore, the locations of the caves where the speleothem records used in this work have been obtained from are displayed (cf. Table 1).

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

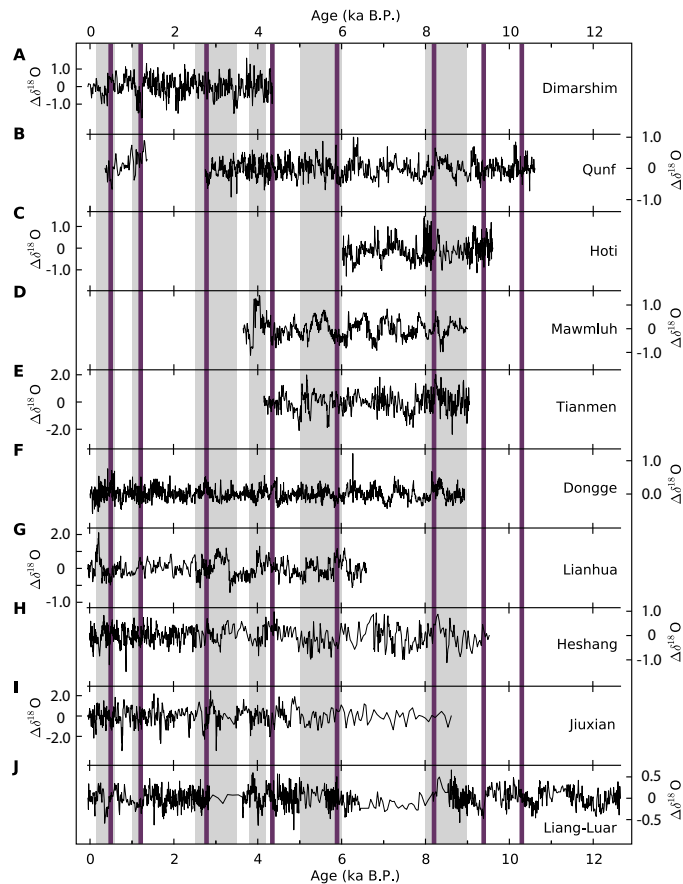
Full Screen / Esc

Printer-friendly Version

Interactive Discussion

## Nonlinear regime shifts in Holocene Asian monsoon variability

J. F. Donges et al.



**Fig. 2.** Residual oxygen isotope records  $\Delta\delta^{18}\text{O}$  analysed in this study (all measured in units of [‰VPDB]). The original records listed in Table 1 have been detrended using a 1000 a moving window (cf. Donges et al., 2011a). Bond events (violet lines, Bond et al., 1997) and RCC episodes (grey bars, Mayewski et al., 2004) are displayed for reference.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

⏪

⏩

◀

▶

Back

Close

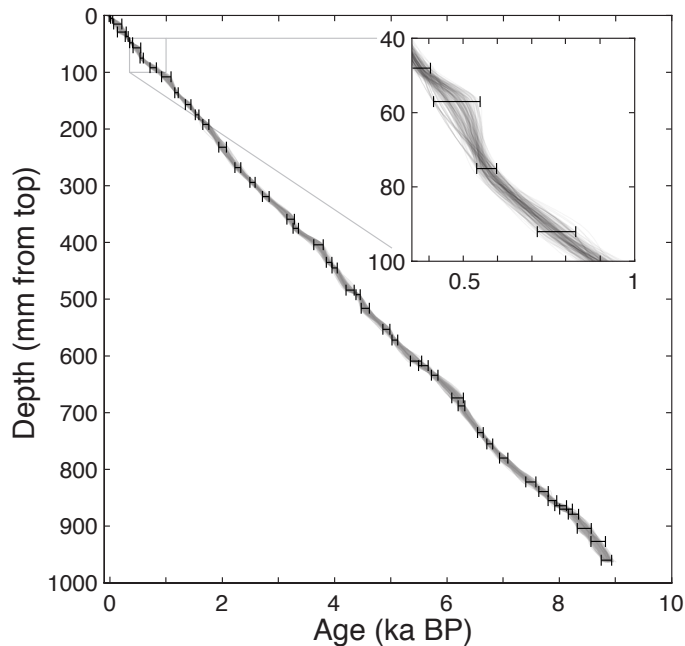
Full Screen / Esc

Printer-friendly Version

Interactive Discussion

**Nonlinear regime shifts in Holocene Asian monsoon variability**

J. F. Donges et al.



**Fig. 3.** Exemplary depth-age model for the Dongge DA record (Wang et al., 2005) represented as an ensemble of 1000 different chronologies. The inset shows an enlarged view of a specific time interval illustrating the spread of depth-age models due to dating uncertainties. Discrete dating points are indicated by black dots, while the associated  $2\sigma$  dating uncertainties are displayed by error bars.

[Title Page](#)[Abstract](#)[Introduction](#)[Conclusions](#)[References](#)[Tables](#)[Figures](#)[⏪](#)[⏩](#)[◀](#)[▶](#)[Back](#)[Close](#)[Full Screen / Esc](#)[Printer-friendly Version](#)[Interactive Discussion](#)



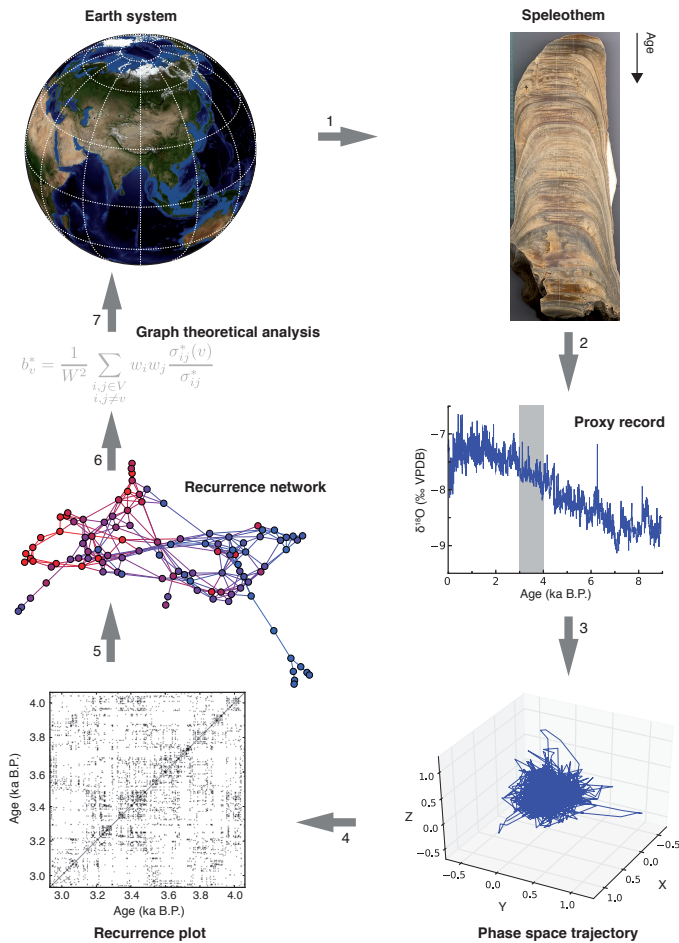


Fig. 4. Caption on next page.

**Nonlinear regime shifts in Holocene Asian monsoon variability**

J. F. Donges et al.

[Title Page](#)

[Abstract](#) | [Introduction](#)

[Conclusions](#) | [References](#)

[Tables](#) | [Figures](#)

[⏪](#) | [⏩](#)

[⏴](#) | [⏵](#)

[Back](#) | [Close](#)

[Full Screen / Esc](#)

[Printer-friendly Version](#)

[Interactive Discussion](#)



## Nonlinear regime shifts in Holocene Asian monsoon variability

J. F. Donges et al.

**Fig. 4.** Workflow of recurrence network analysis of palaeoclimate records (here from speleothems). Step 1 indicates the deposition of chemical or physical information on past climate fluctuations in slowly growing speleothems. In step 2, this information is extracted from the speleothem in form of a proxy record (here, the Dongge DA  $\delta^{18}\text{O}$  record; Wang et al., 2005, is used as an example). Subsequently, in step 3 a section of the obtained proxy record (selected time interval indicated by grey bar) is embedded in phase space to unravel the fluctuations induced by variations of the multiplicity of different relevant climatic parameters. In steps 4 and 5, the structure of recurring palaeoclimate states in the proxy record is represented as a recurrence plot and recurrence network (node colour indicates age of palaeoclimate states increasing from red (younger) to blue (older)), respectively. In step 6, the structure of the recurrence network corresponding to a certain epoch is quantified by graph-theoretical measures such as transitivity  $\mathcal{T}$  or average path length  $\mathcal{L}$ . Finally, this analysis provides insights into nonlinear palaeoclimate variability that can be interpreted taking the underlying Earth system dynamics into account in step 7. The original contribution of this study lies in steps 3–7.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

Printer-friendly Version

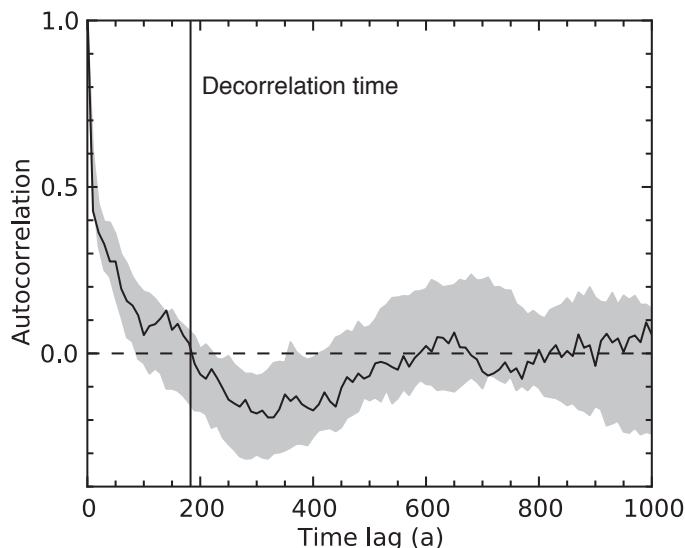
Interactive Discussion



---

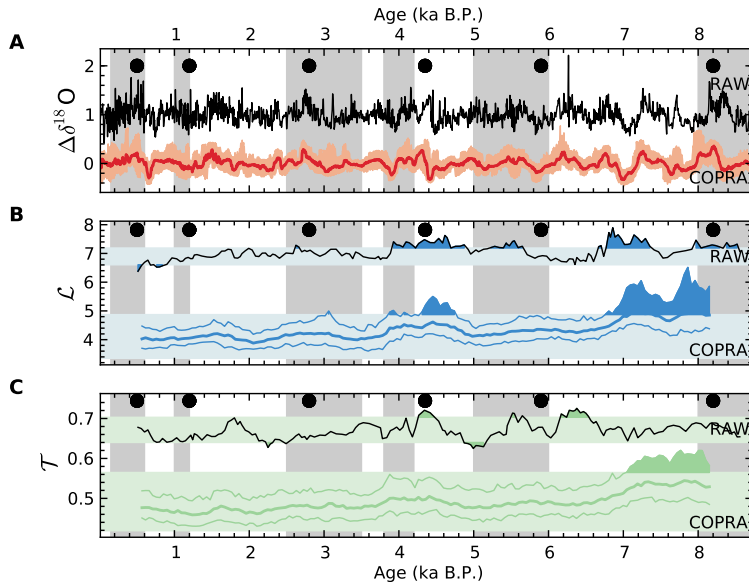
**Nonlinear regime shifts in Holocene Asian monsoon variability**

J. F. Donges et al.

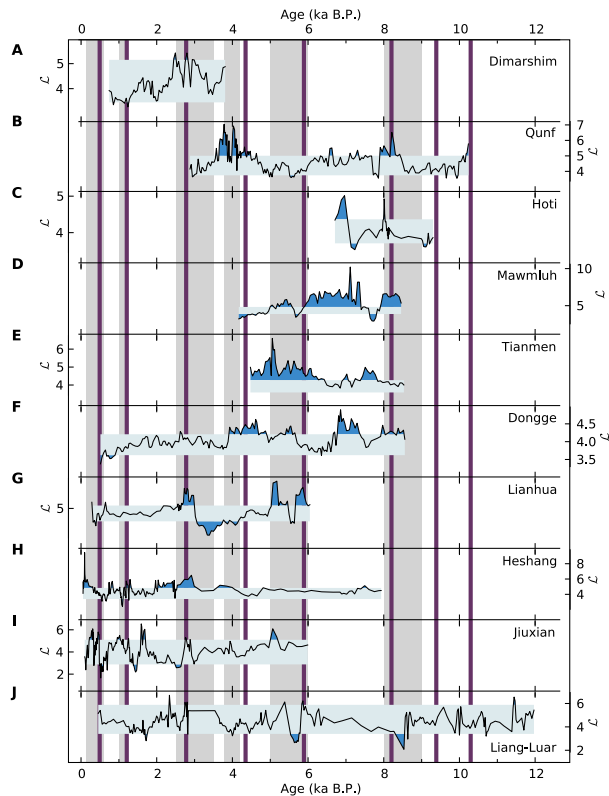


**Fig. 5.** Auto-correlation function (ACF) for the Dongge residual oxygen isotope record (black solid line) computed using the Gaussian-kernel estimator by Rehfeld et al. (2011) and Rehfeld and Kurths (2014) after subtracting millennial-scale trends by means of a sliding-window detrending with a bandwidth of 1000 a. The effect of dating uncertainties is illustrated by the full spread of auto-correlation at each time delay obtained from the regularly sampled Dongge COPRA ensemble (Sect. 2.2) using a standard ACF estimator (grey shading, Brockwell and Davis, 2006). The decorrelation time inferred using the Gaussian-kernel estimator is indicated by a vertical line.

[Title Page](#)[Abstract](#)[Introduction](#)[Conclusions](#)[References](#)[Tables](#)[Figures](#)[⏪](#)[⏩](#)[◀](#)[▶](#)[Back](#)[Close](#)[Full Screen / Esc](#)[Printer-friendly Version](#)[Interactive Discussion](#)



**Fig. 6.** Effects of dating uncertainties on the results of RN analysis for the Dongge DA residual oxygen isotope record (COPRA). Data and results for the original Dongge record are also displayed for reference (RAW, data and results have been shifted vertically to larger values for readability, compare Figs. 7 and 8). **(A)** Residual oxygen isotope ratio after detrending, **(B)** RN average path length  $\mathcal{L}$ , and **(C)** RN transitivity  $\mathcal{T}$ . Median (thick coloured lines) and 90 % confidence intervals (coloured shading and thin coloured lines) from an ensemble of 100 time series realisations of the COPRA algorithm for transferring dating uncertainties to uncertainties in proxy values and, hence, in RN statistics are shown. The values of RN statistics expected for the predominant dynamical regime from all COPRA realisations are indicated by the 90 % confidence bounds from a stationarity test (horizontal coloured bars in panels **B** and **C**, cf. Donges et al., 2011a). Epochs of atypical climatic variability are indicated by dark blue and dark green fillings, respectively. Bond events (bullets) and RCC episodes (grey bars) are displayed for reference.



**Fig. 7.** Time-evolution of an indicator of rapid qualitative dynamical change (RN average path length  $\mathcal{L}$ ) in monsoonal strength fluctuations obtained from a sliding window analysis of the residual oxygen isotope records displayed in Fig. 2 (using the original published age model without taking dating uncertainties into account). The predominant dynamical regime is marked by 90% confidence bounds from a stationarity test (horizontal light blue bars). Deviations from this regime indicate epochs of significant climatic change (dark blue fillings). Bond events (violet lines) and RCC episodes (grey bars) are displayed for reference.

## Nonlinear regime shifts in Holocene Asian monsoon variability

J. F. Donges et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

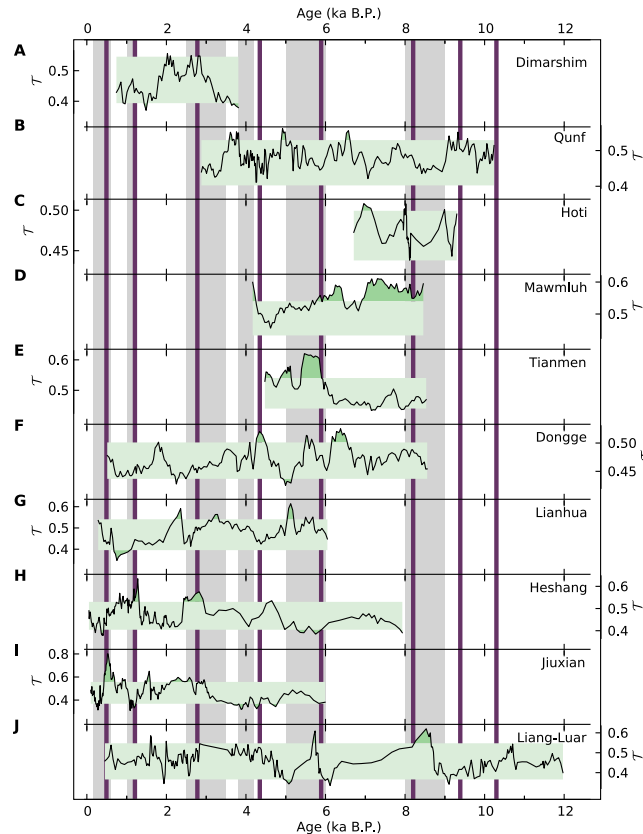
Printer-friendly Version

Interactive Discussion



## Nonlinear regime shifts in Holocene Asian monsoon variability

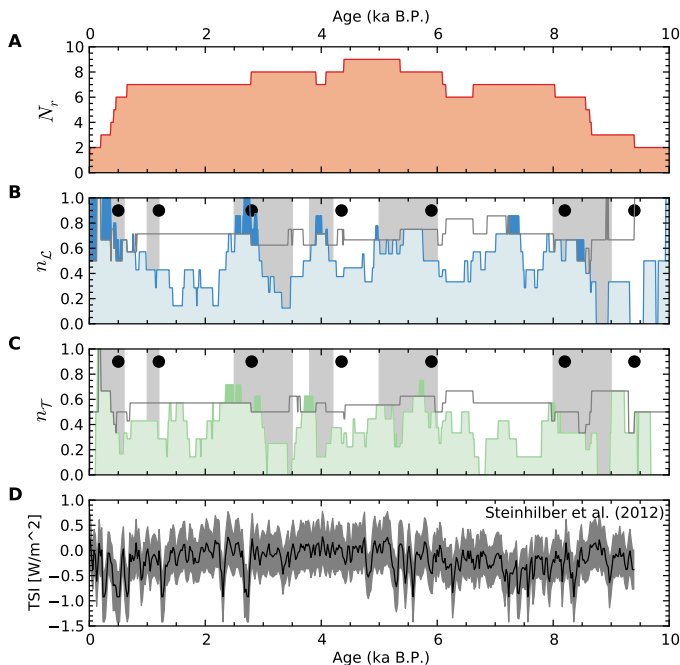
J. F. Donges et al.



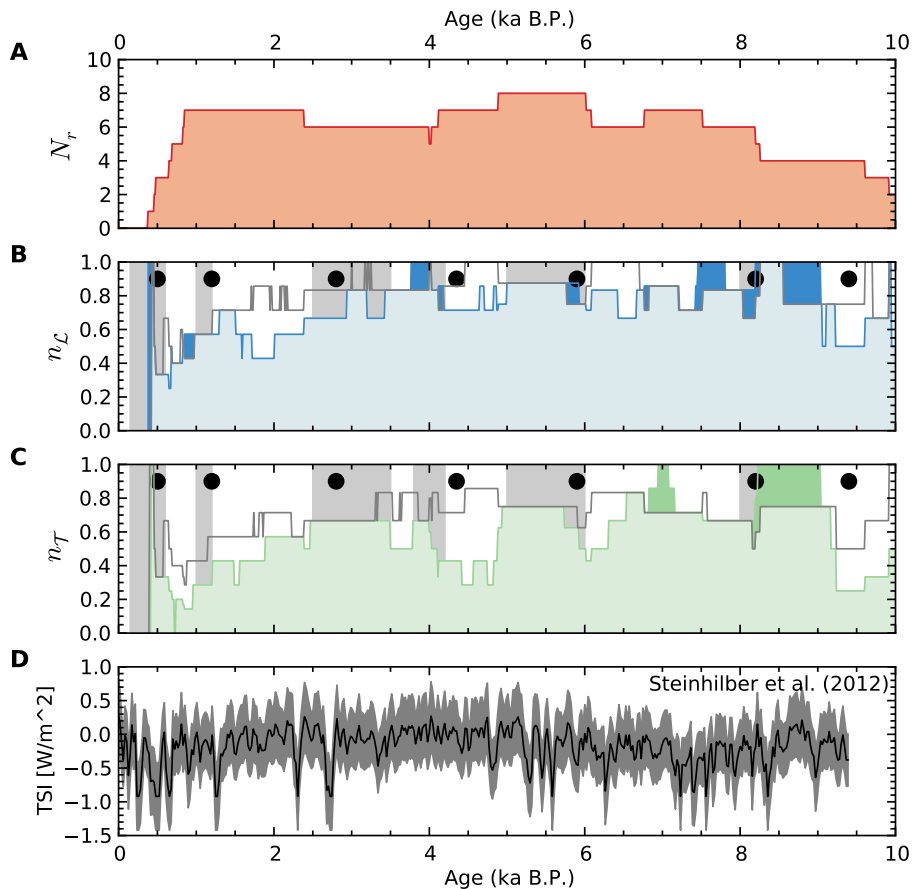
**Fig. 8.** Time-evolution of the regularity (RN transitivity  $\mathcal{T}$ ) of variations in monsoonal strength obtained as in Fig. 7. The predominant dynamical regime is marked by 90 % confidence bounds from a stationarity test (horizontal light green bars). Deviations from this regime indicate epochs of significantly enhanced or diminished climate regularity (dark green fillings). Bond events (violet lines) and RCC episodes (grey bars) are displayed for reference.

## Nonlinear regime shifts in Holocene Asian monsoon variability

J. F. Donges et al.



**Fig. 9.** Summary statistics of results obtained from detrended raw palaeoclimate records (Figs. 2, 7 and 8): **(A)** number of records  $N_r$  in this study giving information on nonlinear palaeoclimate variability in each considered time interval. **(B, C)** Fraction of records  $n_L$  (blue),  $n_T$  (green) exhibiting non-typical dynamics regarding the RN characteristics  $\mathcal{L}$  (**B**, indicating dynamical changes) and  $\mathcal{T}$  (**C**, indicating epochs of particular (in)stability). Epochs of significant climatic change are marked in dark blue and dark green, respectively. Grey lines in panels **(B, C)** indicate the fractions of records with non-typical dynamics that might arise due to chance (90 % confidence level; for a detailed description of our significance test, please see the main text). **(D)** Reconstruction of total solar irradiance according to Steinhilber et al. (2012) (grey shading indicates  $1\sigma$  errors).



**Fig. 10.** As in Fig. 9, but based on the COPRA ensembles of all considered palaeoclimate records.



## Nonlinear regime shifts in Holocene Asian monsoon variability

J. F. Donges et al.

[Title Page](#)

[Abstract](#)

[Introduction](#)

[Conclusions](#)

[References](#)

[Tables](#)

[Figures](#)

[⏪](#)

[⏩](#)

[◀](#)

[▶](#)

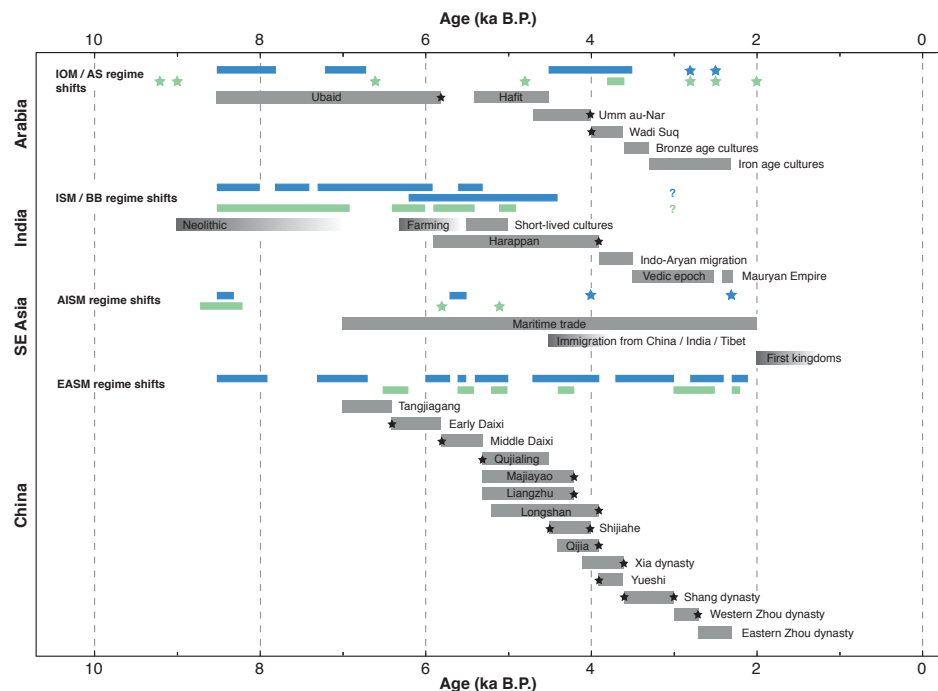
[Back](#)

[Close](#)

[Full Screen / Esc](#)

[Printer-friendly Version](#)

[Interactive Discussion](#)



**Fig. 11.** Regional monsoonal regime shifts relative to cultural change and migratory events in Arabia, India, South-East Asia and China during the Holocene. Nonlinear regime shifts revealed by the RN measures average path length and transitivity are indicated by blue and green bars (extended shifts > 100 a) and stars (short shifts < 100 a), respectively. Cave records are assigned to different monsoon branches as in Table 1. For the region of India, question marks signal a lack of data from suitable published speleothem palaeoclimate records for the time after 4 ka BP. Reportedly abrupt establishments or terminations of human cultures are marked by black stars. Note that the direction of time is reversed with respect to all other figures in this work for consistency with the archeological and historical literature.