Supplemental Material for the manuscript: What we talk about when we talk about seasonality – A cross-disciplinary review

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This supplemental document is to accompany our article submitted for publication in Earth Science Reviews. We add here the material that is to be type-set in the Boxes 1 to 5 used in the introduction of the main text, as requested by the editor.

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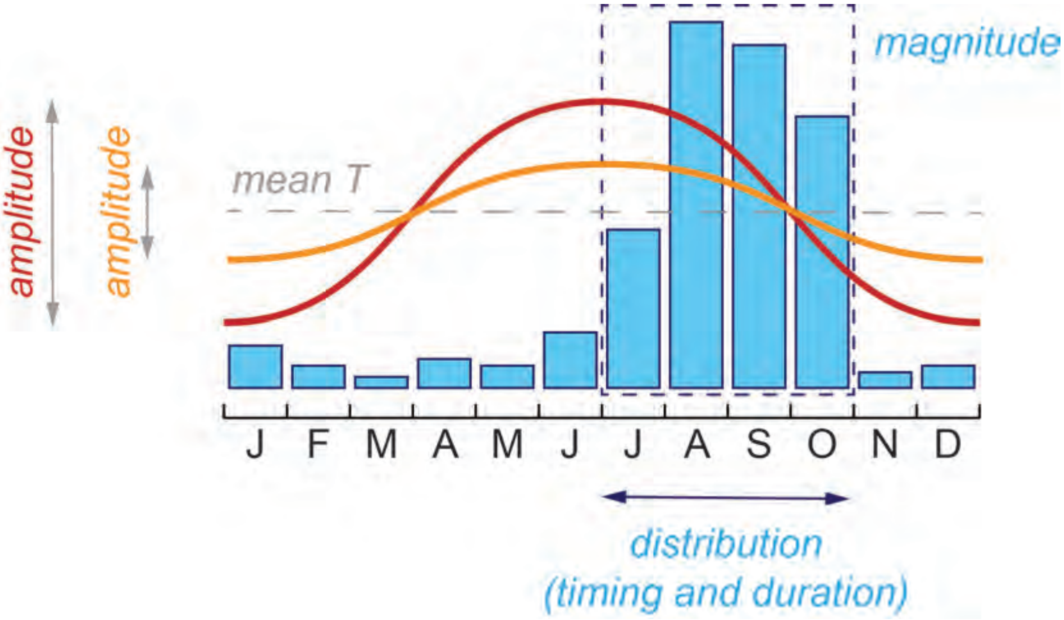

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1. S1: Box 1 – Definitions

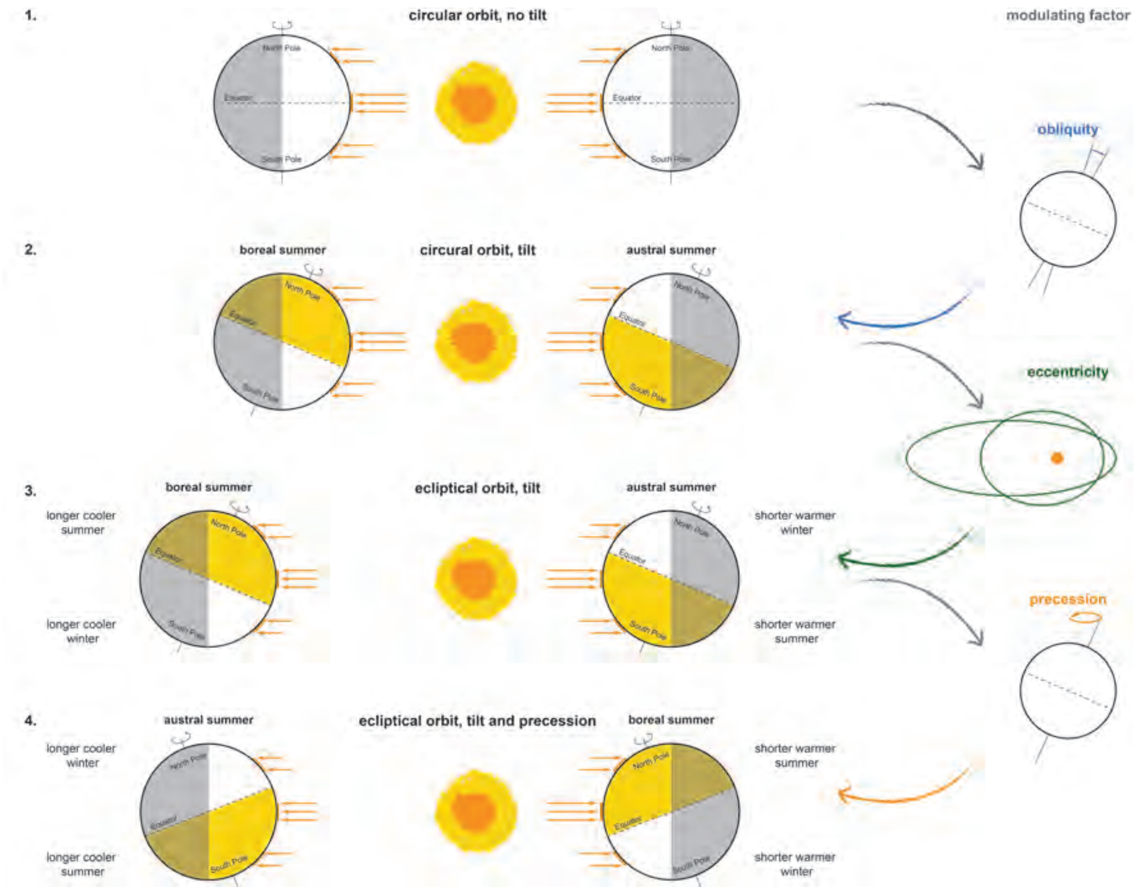
‘Seasonality’ is widely used in many disciplines of palaeo-research, yet it is lacking a clear definition. In the scientific literature, references to changes in seasonality are as frequent as they are ambiguous. A survey of this literature raises many questions: what does *‘increased’* or *‘decreased seasonality’* actually mean? Can we quantify this change? And is the amplitude all that matters? What about temporal distribution? Does temperature and precipitation always respond symmetrically and harmonically? [7] highlighted that one should refer to the annual cycle rather than the seasonal cycle since the period is one year, not one season, and we endorse this approach. Here we define key concepts related to seasonality and how they will be used throughout this review.

Annual cycle of temperature – can be symmetric, sinusoidal, and is defined by maxima and minima. **Seasonality of temperature** refers to an amplitude between maxima and minima. In theory, the annual budget reaches zero, meaning that colder winters are counterbalanced by warmer summers.

Annual cycle of precipitation – is defined by magnitude (amount) and temporal distribution (timing – when: duration – for how long). **Seasonality of rainfall** should take all three of these components into consideration, which, in case of palaeoenvironmental archives and their limitations in resolution, is rarely feasible. In modern climatology the beginning of the hydrological year differs from the beginning of the calendar year.

Seasonality of temperature and seasonality of rainfall together make **climate seasonality**.

Annual cycle of human activities (e.g., foraging, farming, migration) – strongly related to natural temperature and precipitation cycles, which influence the growing season and availability of static resources and the movement patterns of mobile resources (see box 5). The availability and sustainability of these resources influence human subsistence strategies, which in turn inform other types of cultural behavior. **Seasonality of an activity** refers to its timing and duration.



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2. S2: Box 2 – Orbital influences on annual and diurnal cycles

The diurnal (Earth rotation around its axis, 24 h) and annual (Earth rotation around the Sun, 1 year) cycles can be observed and experienced during a human lifetime. On longer, multi-millennial time scales, these cycles are influenced by changes in Earth's orbital parameters, obliquity, eccentricity, and precession. Changes in orbital parameters have been calculated theoretically [6] and their persistence on Earth climate has been documented in geological record ([4] and more). Fundamentally, seasonal variability is controlled by the amount of incoming solar radiation (**insolation**), arriving at different latitudes at different angles as Earth orbits the sun. Below we consider four different scenarios to illustrate how changes in orbital parameters influence the annual insolation distribution and the length of day.

1. If the Earth's rotational axis was perpendicular to the orbital plane, the insolation angle for each latitude would be constant throughout the year. Insolation gradients would exist between the latitudes, but there would be no seasonal changes. Daytime would have the same length at each latitude.

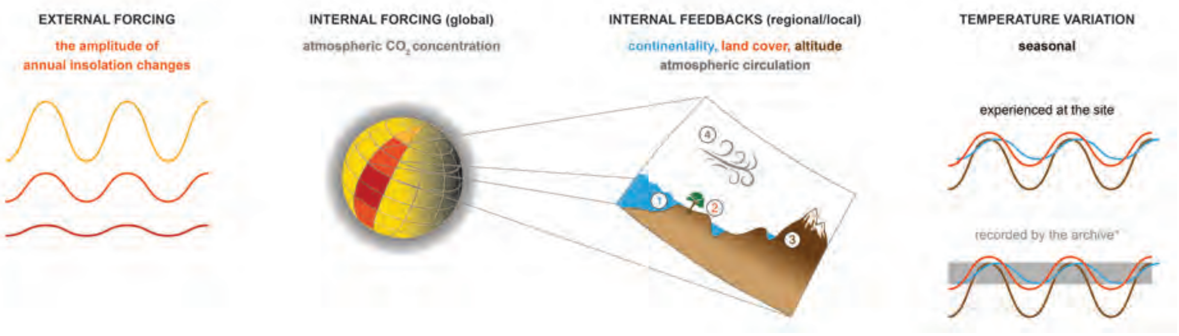
2. Increasing the tilt (**obliquity**) changes the insolation angle during Earth's rotation around the sun. The hemisphere tilted towards the sun experiences warmer temperatures (summer), and longer days. The amplitude of seasonal differences increases with the tilt. The length of the obliquity cycle is ca 42 ka. At the equator, the length of the daytime is roughly constant throughout the year, it gets longer (24 h) towards the 'summer' pole and shorter (0 h) towards 'winter' pole. Summer and winter are of equal length in both hemispheres.

3. Changing the shape of the orbit (**eccentricity**) influences the distance of the Earth to the sun and the length of the seasons. **Eccentricity of the orbit modulates the effect of the obliquity.** The seasons at aphelion are colder (the Earth is further away from the sun) and longer (further away from the sun it's gravitational pull is weaker, so the Earth moves slower) than at perihelion. Eccentricity has two cycles, a short one, ca. 100 ka, and a long one, ca. 400 ka. In the presented scenario (corresponding to modern day conditions) the gradient between summer and winter insolation

(here, translated into temperature) is steeper in the southern hemisphere (SH) compared to the northern hemisphere (NH).

4. The wobble of Earth's rotational axis (**precession**) changes the direction of the tilt and determines which hemisphere is tilted towards the sun at perihelion (summer). The same hemisphere will be tilted away from the sun at aphelion (winter). **Precession thus determines on which hemisphere the amplitude of annual change in insolation is larger.** The overall length of the precessional cycle is ca 23 ka.

While systematic changes in insolation are, next to atmospheric CO_2 concentration, the most important driver for seasonal temperature variations, other factors can modify temperature variations (see box 3).



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3. S3: Box 3 – External and internal forcing, and internal feedbacks

The energy received from the sun per unit area (insolation) is kept in check by Earth's atmospheric CO_2 concentration. Insolation changes (**external forcing**) are periodic and fixed for a given season and latitude (see box 2) and as such are predictable. In pre-industrial times CO_2 concentration (internal forcing) varied little between the hemispheres, following the respective vegetation season, and large variations in CO_2 level were global [8, 1].

At the low latitudes the total amount of the insolation received is larger than that received at the high latitudes and the poles, but the amplitude of annual change is very small. Hence in low latitudes annual cycle is expressed in precipitation changes (wet and dry season). The amplitude of annual insolation change increases with distance from the equator and manifests itself in temperature and daylight duration changes.

Still, the Earth unit area receiving insolation is rarely homogeneous and the surface properties can modulate (dampen, amplify, or delay) the local response. **Internal feedbacks** are semi-stochastic.

A novel (in a geological sense) element of internal feedback, referred to as anthropogenic climate variability, combines greenhouse gas emission, deforestation and land use change. The sensitivity of a given archive can further influence the palaeoenvironmental record.

- **Continentality**: a measure of the difference in the annual temperature maxima and minima that occurs over land compared to water. The oceans capacity for storing heat (thermal inertia) is greater than that of the continents which means it warms slower but also cools slower than land masses. Further, the upper ocean layer can distribute heat both, vertically and horizontally. By storing heat in summer and releasing it in winter oceans considerably dampen the annual cycle of temperature. In contrast, the continental interiors experience much larger annual temperature differences. The large thermal inertia of the oceans shifts the annual temperature maxima and minima of surface water and coastal regions in relation to temperature over continental interiors. The land-ocean distribution is also important in moderating the insolation-prescribed hemispheric seasonality contrast: under modern day conditions the gradient between summer and winter insolation is steeper in the SH compared to the NH; however, the SH ocean/land ratio counteracts the large temperature gradients. Size and distribution of the continents have also impact on the seasonal precipitation patterns, with continental interior receiving less rainfall than coastal regions.

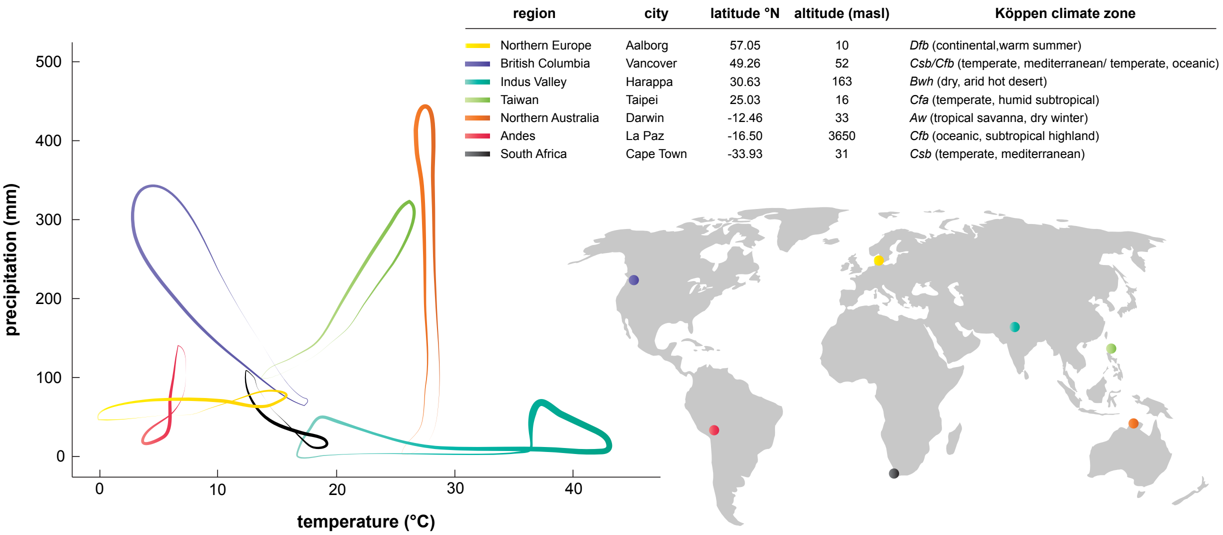
- **Land cover**: differences in surface properties represented by vegetation changes (e.g.: forest vs steppe vs bare rock), snow cover, or surface water distribution affect the albedo and the heat capacity of the surface. The effect of these differences on the overlying atmosphere is analogous to the ocean surface temperature anomalies, but on a much smaller spatial scale.

- **Altitude**: temperature in the troposphere (lowest layer of atmosphere) decreases with increasing altitude. The rate (lapse rate) is approximately 1°C for every 100 m.

- **Atmospheric circulation patterns**: seasonal variability of precipitation and temperature is modulated by the large-scale atmospheric circulation patterns and by the ocean circulation, operating on interannual to multi-decadal time scales (e.g., El Niño-Southern Oscillation (ENSO), the North Atlantic Oscillation (NAO), the

Pacific North American pattern (PNA), the Pacific Decadal Oscillation (PDO) and the Atlantic Multidecadal Oscillation (AMO), among others). These atmospheric and ocean modes of variability can influence the precipitation and temperature in different ways. For example, NAO exerts a strong influence on the hydroclimate variability of Europe, while the PNA strongly influences the hydroclimate of the U.S.

- **Volcanic activity**: volcanic eruptions inject large quantities of aerosols into the atmosphere, and stratospheric circulation distributes them across the planet. In general, aerosols have a cooling effect. However, the scale of this effect depends on where (hemisphere and latitude), when (season), how much (the volume), and for how long (single or multiple eruption events) the material was injected.



	region	city	latitude °N	altitude (masl)	Köppen climate zone
🟨	Northern Europe	Aalborg	57.05	10	*Dfb* (continental,warm summer)
🟪	British Columbia	Vancover	49.26	52	*Csb/Cfb* (temperate, mediterranean/ temperate, oceanic)
🟦	Indus Valley	Harappa	30.63	163	*Bwh* (dry, arid hot desert)
🟩	Taiwan	Taipei	25.03	16	*Cfa* (temperate, humid subtropical)
🟧	Northern Australia	Darwin	-12.46	33	*Aw* (tropical savanna, dry winter)
🟥	Andes	La Paz	-16.50	3650	*Cfb* (oceanic, subtropical highland)
⬛	South Africa	Cape Town	-33.93	31	*Csb* (temperate, mediterranean)

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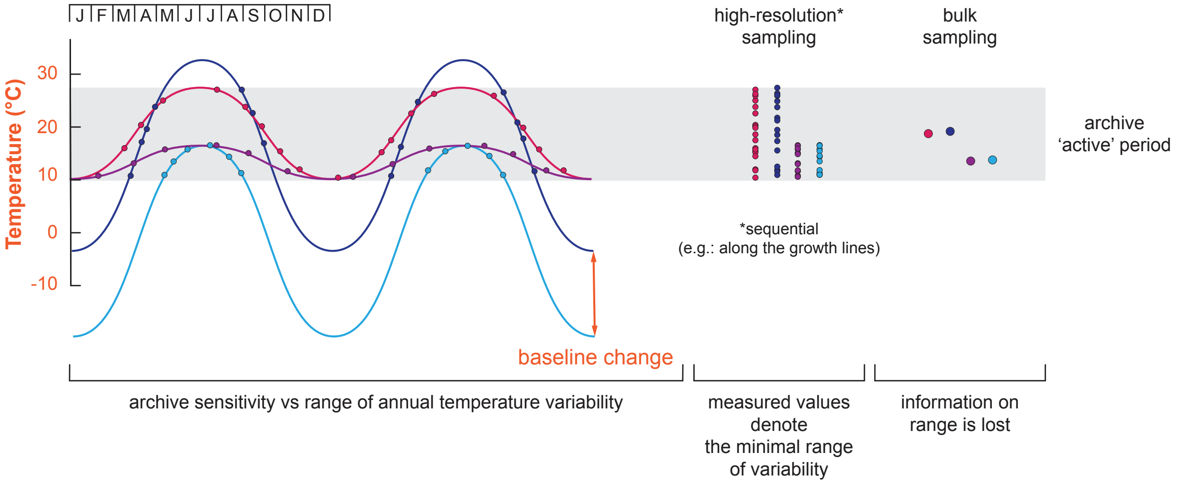
4. S4: Box 4 – Combined influence of latitude, continentality, and altitude

Köppen [5] classification of climate divides climate zones into 5 main groups (tropical - A, dry - B, temperate - C, continental - D and polar - E), based on seasonal temperature and precipitation patterns. This grouping takes into consideration not only latitude but also continentality and altitude. Köppen's climate zones are the best example of differences in amplitude of seasonal change along the same latitude (the theoretical line subjected to the same insolation forcing). We have chosen 7 examples of archaeologically relevant sites from around the globe to illustrate the possible range of local seasonal temperature and precipitation (modern data from `https://en.climate-data.org`). Tropical and temperate climates are characterized by larger amplitude of precipitation changes, dry and continental climate by larger amplitude of temperature. In case of tropical site in the Andes, the altitude is responsible for low temperature values. Note that the plot does not account for potential evapotranspiration.



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5. S5: Box 5 – Relevance of seasonal bias recognition and adapting sampling strategy

Treating seasonally biased records as representing annual means might lead to flawed interpretations. The opposite is also true: records reflecting annual means should be treated with caution when interpreting seasonal changes in temperature or rainfall.

In our conceptual example here, some archives record the full range of annual temperatures, while others only a portion. The correct recognition of the recorded interval is crucial for further interpretation, regional or global synthesis, and comparison [2, 10]. Adequate sampling is an additional challenge, in particular when the sedimentation/growth rate of the archive is low. de Winter et al. [9] discuss in depth how sampling strategy might influence obtained results and propose a schematic guide for choosing the optimal approach. Depending on archive sensitivity and sampling strategy, the shift of the baseline without change in the amplitude might be inaccurately perceived as an increase or decrease in seasonality of respective parameter. Further, comparing the same proxies (e.g., δ^{18}O) from different archives, or the same, but geographically distant, archive does not guarantee that they record the same season.

6. S6: Box 6 – Glossary for archaeological terms

- **Cultural transmission**: related to TEK (see below), the process by which technology, behaviors, and other aspects of culture pass intergenerationally between individuals within a group or between populations.
- **Demic diffusion**: cultural diffusion of ideas, languages, and technologies accompanied by migrations of human populations.
- **Foraging**: collection or hunting of naturally available resources. While it contrasts food production, foraging still might modify landscape.
- **Traditional Ecological Knowledge (TEK)**: knowledge of ecology and human-environmental relationships developed and/or acquired by native of local peoples over long periods of time through direct engagement with their local environments.
- **Pastoral community**: a population in which herd animals influence cultural systems and make up a large proportion of subsistence resources.
- **Qanat**: ancient underground tunnel systems found in the Middle East and North Africa and Central and West Asia that move infiltrated groundwater, surface water, or spring water to the earth's surface using gravity for irrigation and drinking water.
- **Seriation**: the pattern of stylistic and technological change in artifacts for a particular cultural group in a region. Seriation is often used to determine age of archaeological sites.
- **Subak**: a water and irrigation management system for intensification of terraced paddy fields on Bali island, Indonesia which was developed in the 9th century and is closely related to regional political, economic, and religious systems.
- **Subsistence resources**: resources necessary for individuals or a population to survive. Although this term is often synonymous with food resources, it can include clothing, tools, and shelter.
- **Subsistence strategies**: systems within which humans obtain the resources necessary to survive. They can include hunter-gatherer, agriculture, pastoral, etc.
- **Swidden farming**: also known as slash-and-burn farming, a cyclical farming technique of cutting and burning biomass to create a nutrient base for crop production with the longer part of the cycle is devoted to fallowing to allow biomass to regenerate. Practiced primarily in the tropics where farming is rainfall dependent.

7. S7: Box 7 – Glossary for statistical terms

- **Boostrapping** is a nonparametric statistical technique that allows to estimate confidence bounds or prediction errors for a signal through resampling. Based on an empirical estimate of a system's probability distribution, n values from this distribution are randomly drawn with replacement in each of N_b bootstrap runs.
- **Complexity** of a signal comprises a range of features that are typically encountered in the study of nonlinear and nonstationary systems. Measuring the complexity of a signal complements and exceeds characterization of strictly linear signals, e.g. by reflecting their tendency to exponentially deviate from a given value or the degree of irregularity in their variability. Even systems which predominately exhibit regular, periodic behaviour may show episodic bursts of irregular, chaotic dynamics that can be best captured by complexity measures. In seasonal climate signals, this can be expressed as a superposition of variations in periodicity, amplitude, and timing as well as in abrupt shifts from predictable to stochastic or intermittent dynamics (e.g., caused by a changing influence of semi-stochastic large scale atmospheric patterns).
- **Continuous Wavelet Transform (CWT)** is a signal decomposition into small oscillations with specific frequency. Each oscillation is represented by a shifted and scaled version of a *Mother Wavelet*. CWT is a powerful tool to track signal cycle changes through time (e.g., the annual cycle). They are similar to a time series power spectrum but allow for better reconstruction of the signal in time.
- **Dynamic Time Warping** allows matching signals of varying length and with distinct sampling. Its application to proxy records can be interesting for comparing signals with very different temporal resolution. It can inform on optimal signal alignment and provides a (dis)similarity measure.
- **Entropy** is a universal concept in thermodynamics that can be interpreted as the amount of information that is associated with state of a system. In applications to (nonlinear) time series, it is commonly utilized as a complexity measure. Many different definitions are possible (Shannon entropy, permutation entropy, …) while each of them requires the empirical estimation of a probability distribution. It is often also loosely interpreted as an indicator of how 'disordered' a system behaves.
- **Exceedence times** are time instances at which a time series $x(t)$ has a larger than pre-specified value a: $x(t) > a$. For palaeoseasonality, a characteristic value (e.g., mean wet season rainfall, see fig. 15 in main text) can be computed in order to study at which time t_i this value is first exceeded in an given year. Decreasing exceedance times would then indicate a trend towards an earlier wet season onset.
- **Granger causality** is a prediction-based concept of statistical causality. If a signal X_1 causes a signal X_2, then past values of X_1 should allow to predict future X_2 values beyond the information contained in past X_2 values alone. The mathematical formulation of Granger causality is based on linear regression modelling of stochastic processes [3].
- **Hilbert-Huang analysis, Empirical mode decomposition and Singular Spectrum Analysis** are distinct methods that are used to decompose a signal into *intrinsic modes*. If a signal contains significant variability at multiple timescales, each mode may represent this scale-specific variability. In contrast to CWT, decomposition does not rely on a specific type of function.
- **Hilbert-transformation (HT)** is a mathematical transformation of a signal that allows to extract its *instantaneous frequency and phase*. It is related to the Fourier transform. When studying an annual cycle, the instantaneous phase of a signal reflects *how much is cycle is shifted forwards and backwards for different episodes in time*.
- **Independence** of a signal is a common prerequisite for applying statistical analyses and means that the studied signal does not exhibit any serial dependence, implying an absence of trends, cycles or stochastic long-range dependence.
- **Kolmogorov-Smirnov distance** measures similarity between probability distribution functions (PDF). It is used to test whether an empirical PDF is compatible with a known reference distribution (e.g. a normal distribution) or if two empirically estimated PDFs could be generated from the same reference distribution. It may yield spurious results if many extreme values are included in the empirical sample.

- **Least-squares based wavelet approach** allows extraction of cycles through time. Least-squares optimization aims at minimizing the squared deviation between a result and the optimal result. When applied to wavelets, this approach can obtain a near-optimal wavelet representation of a cycle through time, despite uneven sampling.
- **Nonstationarity** in a signal can indicate that an external process affects the studied system such that it, e.g., results in a continuous change of the mean in a time series. Other nonstationary signal variations include shifts in variance, extreme events, or continuous variations in dominant cycles.
- **Non-rectangular, smooth kernel function** apply weights to neighboring observed data in a time series. Often used in sliding-window analyses, e.g. moving averages. A window function is chosen that decays smoothly towards the edges of the time window of specified width h. Smooth kernel windows allow better temporal localization of the covered time series segment, thereby limiting spurious artefacts in spectral analysis compared to sliding window analyses. A popular example are normal-weighed Gaussian kernel windows.
- **Normality** refers to the notion that the empirical estimate of a signal's probability density function can be well approximated by a normal distribution.
- **Quantiles** are statistical values that characterize a PD. For empirical data a quantile is a specific value that splits the sample of all values into one fraction p that is smaller and one fraction $1 - p$ that is larger than the quantile. This value is referred to as the (empirical) p-quantile of the sample. Quantiles are often used to report confidence intervals.
- **Return periods** are periods in which a time series returns to a similar or equivalent magnitude it has visited before. In extreme value analysis, a certain extremely high (low) magnitude is specified as *return level*. The return time corresponding to this return level denotes the time interval typically passed between two events above (below) this return level. It is estimated from a model description of the time series called *generalized extreme value distribution*.
- **Seasonality indicators** are standardized, quantified characterizations of one or more seasonal features. They allow to enhance comparability between different expressions of seasonality in distinct archives and help multi-proxy palaeoseasonality studies. Often focussed on quantifying a single feature of seasonal change.

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