# A chain of processes - from past climate variations to paleoclimate reconstructions

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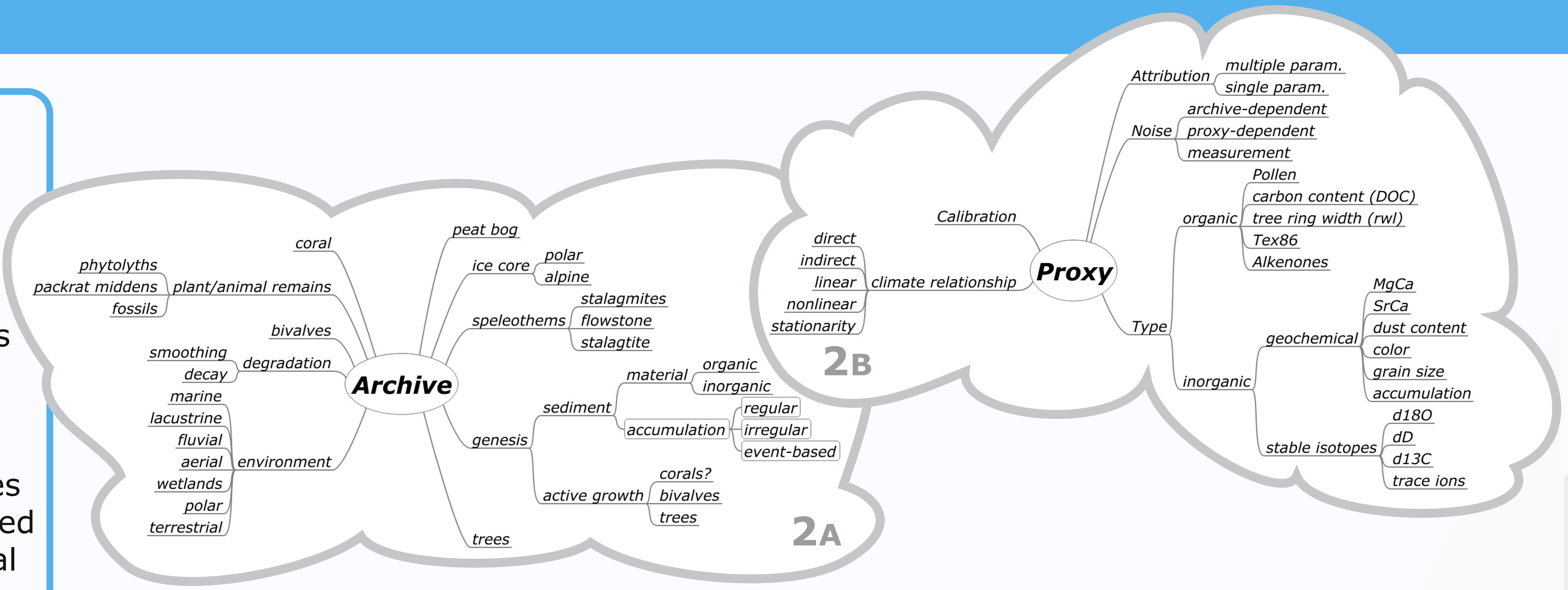
## 1 Past climate variations


are recorded, through nature's sampling, in paleoclimate archives. It is essential to quantify estimation uncertainties, to which each step along the way contributes. Integrating techniques and information across archives and proxies, allows to identify complimentary archive-proxy combinations which can improve past climate estimates across timescales. We find common challenges for many archives, where techniques developed in different communities could reduce the final uncertainy of **paleoclimate reconstructions.**




## 2

**The structure of the archive and proxy landscape** is complex. Which processes affect archives (2A) - and which are proxy-dependent (2B)? Which proxies can be measured on the same archive sample?

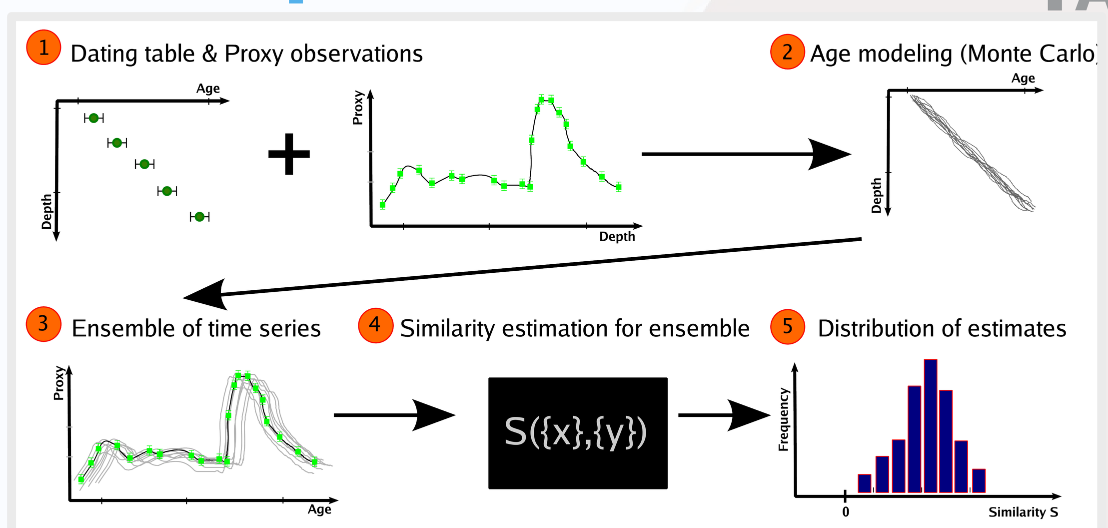
## 3 Common challenges across archives and proxies

| Challenge | Problematic aspect | Effect on the reconstruction | Approaches (additions & feedback welcome) | Comments (examples/ suggested references) |
|---|---|---|---|---|
| **Attribution & fidelity** | Nonstationarity of proxy ↔ climate response | False trends & nonstationarities | Multi-proxy reconstructions | |
| | Control by multiple climate parameters | Non-independent reconstructions, false trends & covariances | a) forward modeling (req.: good proxy understanding) | |
| | | | b) test against modeled/observed parameter combinations | |
| | | | c) use multiple proxies to find common response | |
| **Recorder sampling → affects mean/ variance** | Snapshot/Intermittent/Event-based | Intra-annual variance > inter-annual variance → snapshot-sampling increases the proxy variance | Simulate & test the effect of aliasing and intermittency (e.g. Persson et al., 2009). With known seasonality: Correct in spectral domain (Kirchner, 2009; Laepple & Huybers, 2013) | |
| | Quasi-continuous | Growth rate changes → time series irregularity | E.g. adapted time series estimators (e.g. Rehfeld & Kurths, 2014) | |
| | Organic growth | Bias effects? | **?**, Monitoring & sensitivity studies | |
| | Spatial vs. temporal signal integration? | Residence/mixing times, changing sources | Monitoring & sensitivity studies | |
| **Seasonality** | Seasonal recorder sampling | If unaccounted for: Biased annual mean, also potentially false trends over millennial timescales (insolation) | Test sensitivity on seasonal recording (Laepple et al., 2011) | |
| **Smoothing/Filtering** | Damping of the signal | Variance reduction – can be accounted for if smoothing depth is known | At low noise levels: Unfolding (Berger, Johnson & Killingley, 1977; Johnsen et al., 2000) | |
| | | | Variability estimates: Correction of the variability spectrum (Laepple & Huybers, 2013) | |
| **Chronologies** | Age modeling | Age tracer ≠ Proxy → time uncertainty leads to bias/variance & problem of cause vs. effect – difficult comparison | Transfer time uncertainty to proxy uncertainty (COPRA, Breitenbach et al., 2012) using age modeling with point-based uncertain (e.g. U/Th, $C^{14}$) and fixed dates (e.g. Volcanoes, Dust layers, known core top). | |
| | Layered archives | Missing layers, combination of layer counts with point-age estimates → time uncertainty | Layered archives: Cross-dating for multiple cores, combination of laminated sections with point-wise age estimates (COPRA) to reduce age uncertainty. | |
| **Calibration** | Spatial and temporal climate/proxy variance can be different | Under-/Overestimation of Low-/High-frequency components | Monitoring & sensitivity studies for proxy understanding; Multi-Proxy reconstructions. | |
| **Time series properties** | 1) irregularity | biases/ variance increase in time series analyses and reconstructions | Adapted time series estimators (Rehfeld & Kurths, 2014) | |
| | 2) age uncertainty | increasing uncertainty & variance | Quantification of uncertainties by using time series ensembles from age modeling (e.g., Rehfeld & Kurths, 2014); variability / spectral estimates are less sensitive to time uncertainty (Rhines & Huybers, 2011). | |

## 4 Cross-pollination potential

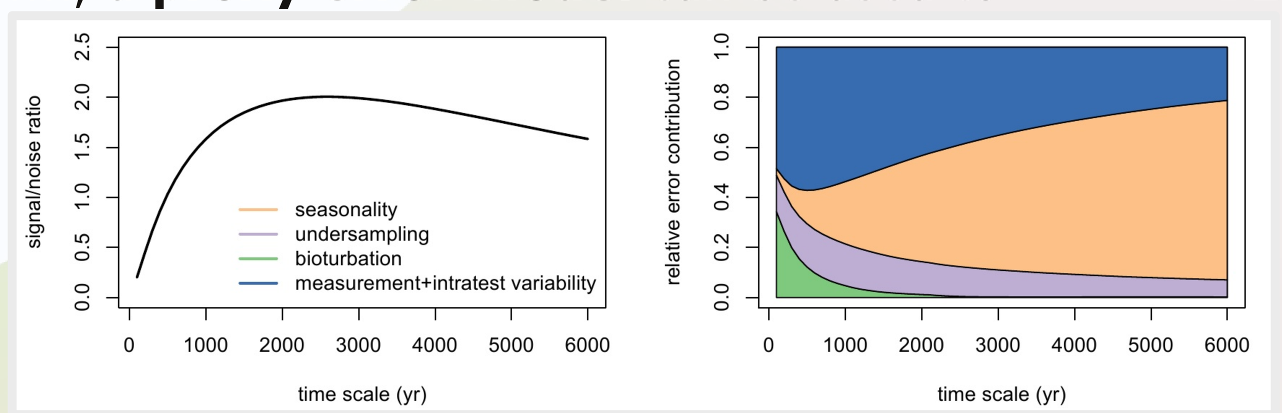
**Age-uncertainty** can be evaluated in time series analyses using Monte-Carlo techniques (Fig. 4A, Rehfeld & Kurths, 2014). Some age-modeling approaches allow for the combination of layer counting and point-based ages. This, along with cross-dating as for tree-ring chronologies, could reduce age uncertainties.

4A




When the fundamental processes affecting the proxy signal are known, a **proxy error model** can be used to quantify the uncertainties if the essential parameters can be estimated. As an example, Fig. 4B shows a synthetic marine core resembling tropical MD03-2707, with proxy modelling as in Laepple & Huybers, 2013.

4B




## 5 References

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**ECUS** – Estimating climate variability by quantifying proxy uncertainty and synthesizing information across archives

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