Exploring the middle Pleistocene transition

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Main Points:

1. **Introduction: climate across scales**
2. **Methods: Hilbert-Huang Transform (HHT)**
   - empirical mode decomposition (EMD)
   - Hilbert spectral analysis (HSA)
3. **Results:**
   - "41-kyr" vs. "100-kyr" worlds
   - amplitude vs. frequency modulation
   - single- vs. multiple-state dynamics
4. **Conclusions & Perspectives**

the main problem...

"Although the 23-kyr and 41-kyr periodicities found in the palaeoclimate records seem to be almost linearly related to the insolation forcing, the largest climate variations of the past million years occur approximately every 100 kyr though the corresponding eccentricity changes are far too small to force the changes."

[Paillard, 1998]

Earth's climate

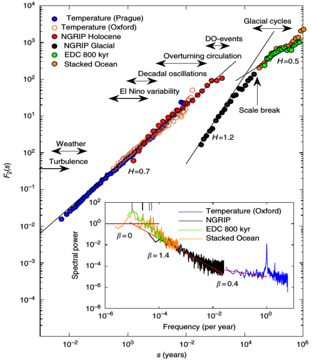
- nonlinear complex system
- variability from daily to multi-millennial timescales, with different correlation times [Schmitt et al., 1995]
- non-trivial persistent structures, internal/external physical processes, stochastic processes, self-similar structures [Schmitt et al., 1995, Marsh & Ditlevsen, 1997, Lovejoy & Schertzer, 2013]

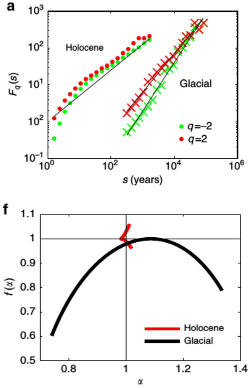
Scaling properties

- hemispheric temperatures: scale invariance observed over the range 5 yr to 40 kyr [Lovejoy & Schertzer, 1986]
- proxy temperatures: scale invariance observed over the range 400 yr to 40 kyr [Schulz et al., 1997, Ditlevsen & Svensmark, 1995]
- "spectral plateau": spectral break in the range 100 - 400 yrs [Ditlevsen & Svensmark, 1995]

Glacial vs. Interglacial periods

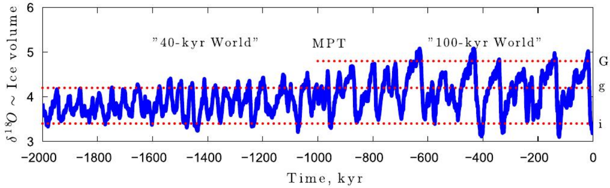
- temperatures are characterized by switches between glacial and interglacial periods, showing signatures of both monofractality and multifractality
- last glacial period (20-120 kyr BP, inside the Pleistocene) → multifractal features
- the last interglacial period (0-10 kyr BP, Holocene) → monofractal structure
- scale break at ∼41 kyr → obliquity variations → glacial cycles





from [Shao & Ditlevsen, 2016]

about the MPT

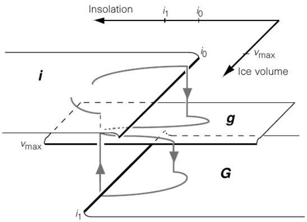


- The astronomical theory of climate, in which the orbital variations are taken to drive the climate changes, has been very successful in explaining many features of the paleoclimate records
- the climatic response to the orbital forcing changed dramatically around 1000 kyr BP
- prior to the MPT, the glacial cycles lasted approximately 40 kyr (the 40 kyr world)
- after the MPT the glacial periods became colder and lasted approximately 100 kyr (the 100 kyr world)
- transitions into the glacial state are gradual → slow buildup of ice sheets
- transitions into the interglacial states (terminations) are much more rapid → breakdown of ice sheets

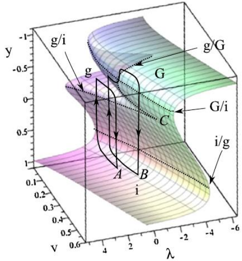
a conceptual model

- the main glacial-interglacial switches occur approximately every 100 kyr, but the changes in insolation forcing are very small in this frequency band
- multiple equilibria in the climate system can provide a solution
- prior to the MPT the 41 kyr cycles oscillator between two equilibrium states, a mild glacial g and an interglacial i
- at the MPT a third deep glacial state G becomes accessible due to the cooling, such that the glacial cycle becomes

$$\boxed{i \rightarrow g \rightarrow G \rightarrow i}$$



from [Paillard, 1998]



from [Ashwin & Ditlevsen, 2015]

"Many hypotheses have been formulated to explain this 100 kyr problem, sometimes even involving other astronomical parameters. Most of the suggested mechanisms are based on a nonlinear response of the ice-sheet dynamics to the forcing or internal oscillations of the climate system. Although some of these models compare well with the geological record in the spectral domain, all of them fail to reproduce the correct amplitude and phase of each glacial-interglacial cycle. In particular, one of the most prominent interglacial events, isotope stage 11, occurs at a time when the insolation variations are the smallest (around 400 kyr before present, BP) and therefore poses a strong challenge."

[Paillard, 1998]

Is it a "phase-" or "amplitude-"changing phenomenon?

Is it a (non-)linear and/or (non-)stationary phenomenon?

How to analyze paleclimate time series...

- Time series analysis is usually based on traditional approaches (Fourier Transform (FT), Lomb-Scargle analysis (LS), Wavelet Transform (WT)) requiring
  - *a priori* fixed (and usually orthogonal) decomposition basis
  - formed by linearly independent functions/eigenvectors
  - most of them also requiring stationarity

- Paleoclimate time series are not linear and/or stationary, showing multi-scale features, self-similarity, mono-(multi-)fractal features

Hilbert-Huang Transform (HHT)

- Time series analysis method completely removing stationarity and linearity assumptions by using two successive steps
  1. empirical mode decomposition (EMD)
  2. Hilbert spectral analysis (HSA)

HHT application to paleoclimate time series...

Alberti T., Lepreti F., Vecchio A., Bevacqua E., Capparelli V., Carbone V., Natural periodicities and Northern Hemisphere-Southern Hemisphere connection of fast temperature changes during the last glacial period: EPICA and NGRIP revisited, *Climate of the Past*, **10**, 1751, 2014.

1. empirical mode decomposition (EMD)

- a multi-scale analysis can be performed by using the empirical mode decomposition (EMD)
- it allows us to decompose a time series into a finite number of modes and a residue

$$X(t) = \sum_{k=1}^{N} C_k(t) + r(t) \tag{1}$$

- each mode $C_k(t)$ represents a zero-mean intrinsic oscillatory component modulated both in amplitude and in phase

$$C_k(t) = A_k(t) \cos\left[\phi_k(t)\right] \tag{2}$$

- main advantages of EMD
  1. nonlinearity, nonstationarity and adaptive basis functions ($C_k(t)$)
  2. finite number of time-dependent oscillatory components
  3. local and global properties on different timescales
- C_1 is generally associated with noise inside time series

2. Hilbert spectral analysis (HSA)

- traditional approaches fail to investigate frequency contribution of non-stationary signal (so-called instantaneous frequencies)
- assuming a non-stationary time series $s(t) = A(t) \cos \left[2\pi \int_0^t f(t')dt' \right]$
- FFT or WT are not able to extract local information of f(t), while Hilbert Transform can extract it

$$s_H(t) = \frac{1}{\pi} P \int_0^\infty \frac{s(t')}{t - t'} dt' \rightarrow z(t) = s(t) + i s_H(t) = A(t) e^{i\Phi(t)} \rightarrow f(t) = \frac{1}{2\pi} \frac{d\Phi(t)}{dt}$$

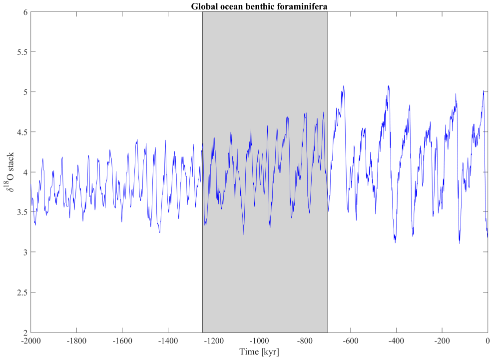
- from instantaneous frequency we can derive instantaneous timescale

$$T(t) = f(t)^{-1}$$

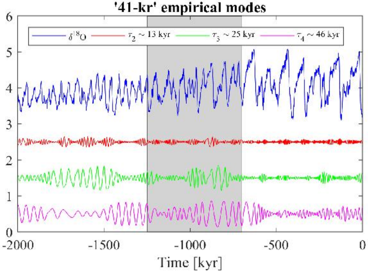
Why to use Hilbert-Huang Transform (HHT)?

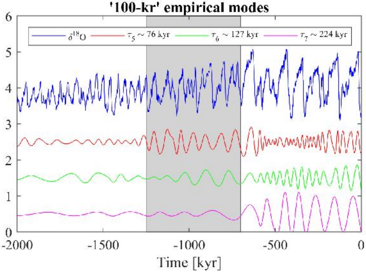
1. the EMD allows to extract local properties of oscillating modes and embedded structures without any *a priori* selected basis $\rightarrow$ useful for nonlinear signals
2. the HSA can be used, after EMD, to investigate non-stationary features of each oscillating mode and/or embedded structure
3. instantaneous amplitudes $\{A_i(t)\}$ and instantaneous frequencies $\{f_i(t)\}$ of IMFs allows to obtain local time-dependent features of the analyzed signal $s(t)$

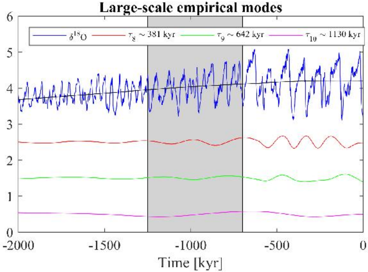
middle Pleistocene transition (MPT)



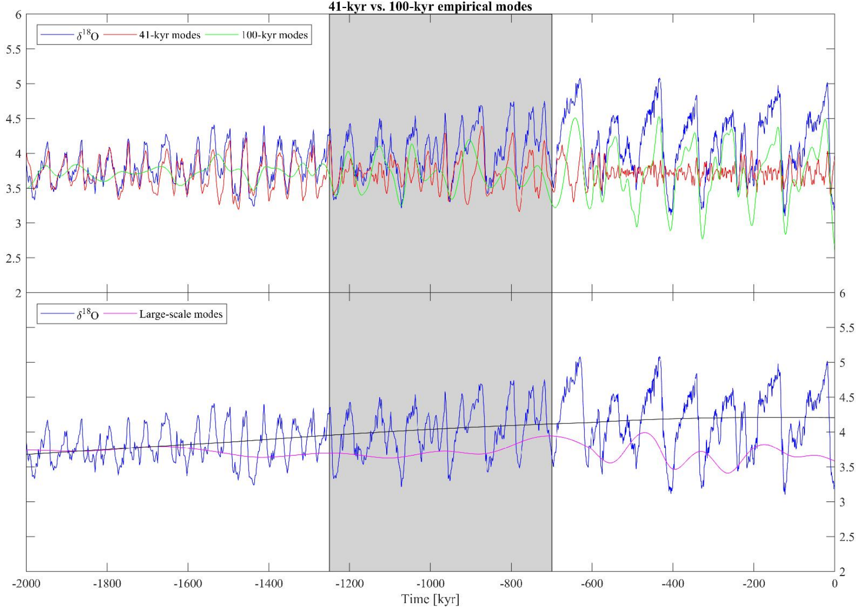
- a proxy for the global ice volume [Lisiecki & Raymo, 2005]
- increases in volume $\rightarrow$ decreases in temperatures
- oscillatory behavior on timescales of 41-kyr and 100-kyr $\rightarrow$ Milankovitch cycles
- what about between 1200-700 kyr BP?



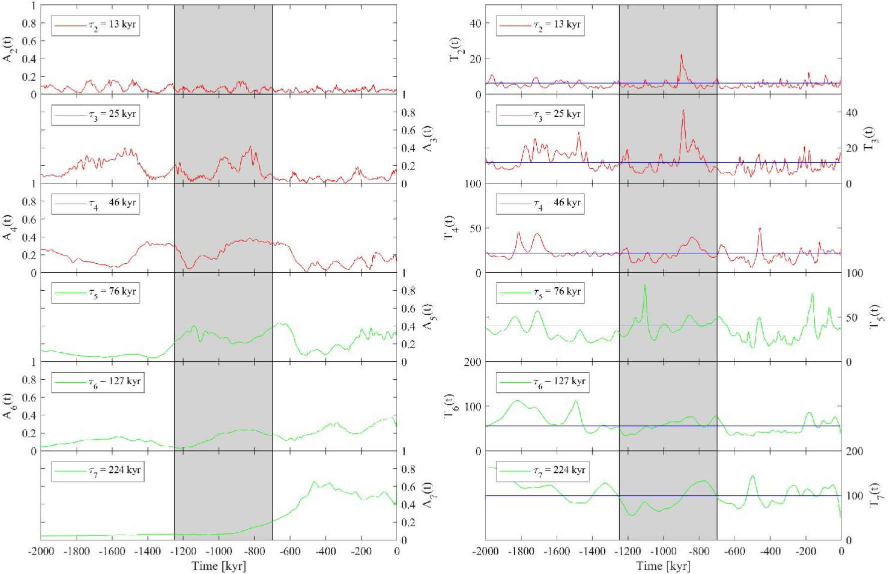




- EMD analysis revealed multi-scale variability
- three different dynamical components: “41-kyr”, “100-kyr”, “large-scale” dynamics



- EMD reconstructions are able to capture the different observed dynamics



- amplitude changes are observed before/after MPT
- Milankovitch scales are present before/after the MPT

Climate potential

- A minimal non-linear stochastic model is described through an SDE:

$$dz = -\frac{\partial U(z)}{\partial z} dt + F(t)dt + \sigma dW \tag{3}$$

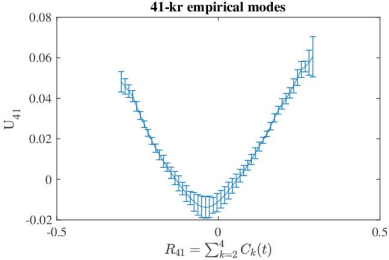
  where a "climate potential" can have multiple minima, corresponding to different climate states.

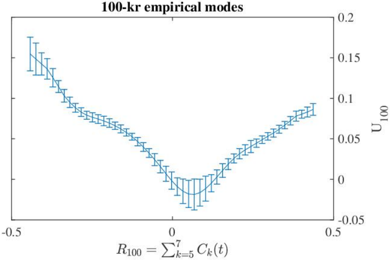
- Through the Fokker-Planck equation the probability density function $\rho(z,t)$ can be related to $U(z)$

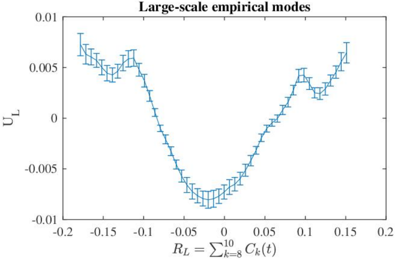
$$\frac{\partial \rho(z,t)}{\partial t} = \frac{\partial}{\partial z}\left[U'(z)\rho(z,t)\right] + \frac{\partial}{\partial z}\left[F(t)\rho(z,t)\right] + \frac{1}{2}\sigma^2 \frac{\partial^2}{\partial z^2}\rho(z,t) \tag{4}$$

- Stationary solution of F-P equation allows to obtain

$$\boxed{U(z) = -\frac{\sigma^2}{2}\ln\rho}$$



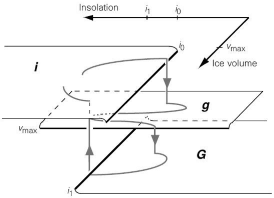




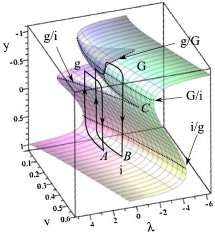
- Milankovitch scales, i.e., "41-kyr world" (IMFs 2-4) and "100-kyr world" (IMFs 5-7), are characterized by a single-well climate potential (U_{41}, U_{100})
- large-scale dynamics (IMFs 8-10) $\rightarrow$ three-well climate potential (U_L)

What we found?

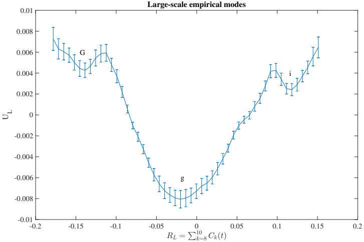
- We found that both 41-kyr and 100-kyr periodicities are present during the last 2 Ma although amplitudes changes in time producing the well-known separation between “100-kyr world” and “41-kyr world” → This suggests that the observed behavior is not related to changes in frequency
- Moreover, we also found a larger timescales component and a monotonic non-decreasing trend
- Finally, from a dynamical system point of view we found that both 41-kyr and 100-kyr components can be seen as a single-state forcing, while smooth transitions between three different climate states can be obtained by using larger timescales component, in agreement with previous works



[Paillard, Nature, 1998]



[Ashwin & Ditlevsen, Clim Dyn, 2015]



[Alberti et al., Geophys. Res. Abs., 2018]

Thanks for the attention