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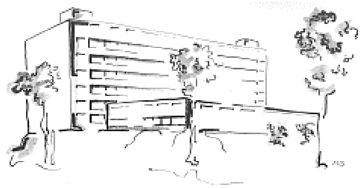

Long-term correlations in climate

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25.1.2007, 14:00
Levich Institute
City College of New York

Outline

1. **Basics of long-term correlations**
   a) Definition
   b) Quantification
   c) Effects
   d) Occurrence

2. **Long-term correlations in climate**
   a) Overview
   b) in temperature records
      (climate model)
   c) Detection problem
      (temperature reconstructions)

Part 1 – Basics of long-term correlations

Time series

- sequence of values
- stochastic
- measured record

Statistical properties

- probability densities
- auto-correlations

Long-term correlations

auto-correlation function: $C(s) = \frac{\langle \tau_i \tau_{i+s} \rangle}{\langle \tau_i^2 \rangle} = \frac{1}{(N-s)\langle \tau_i^2 \rangle} \sum_{i=1}^{N-s} \tau_i \tau_{i+s}$
(average zero)

correlation-time: $s_\times = \int_0^\infty C(s) \mathrm{d}s$

- finite (short-term), e.g. exp. decay: $C(s) = \mathrm{e}^{-s/s_\times}$
- infinite (long-term), e.g. power-law: $C(s) \sim s^{-\gamma} \quad 0 < \gamma < 1$

Quantification

Methods:

direct estimation of $C(s) \sim s^{-\gamma}$ correlation exponent

power spectrum: $P(f) \sim f^{-\beta}$ spectral exponent

fluctuation analysis: $F^{(n)}(s) \sim s^{\alpha}$ fluctuation exponent

Relations:

$$\boxed{\begin{array}{ll} \gamma = 1 - \beta & \\ & \beta = 2\alpha - 1 \\ \gamma = 2 - 2\alpha & \end{array}}$$

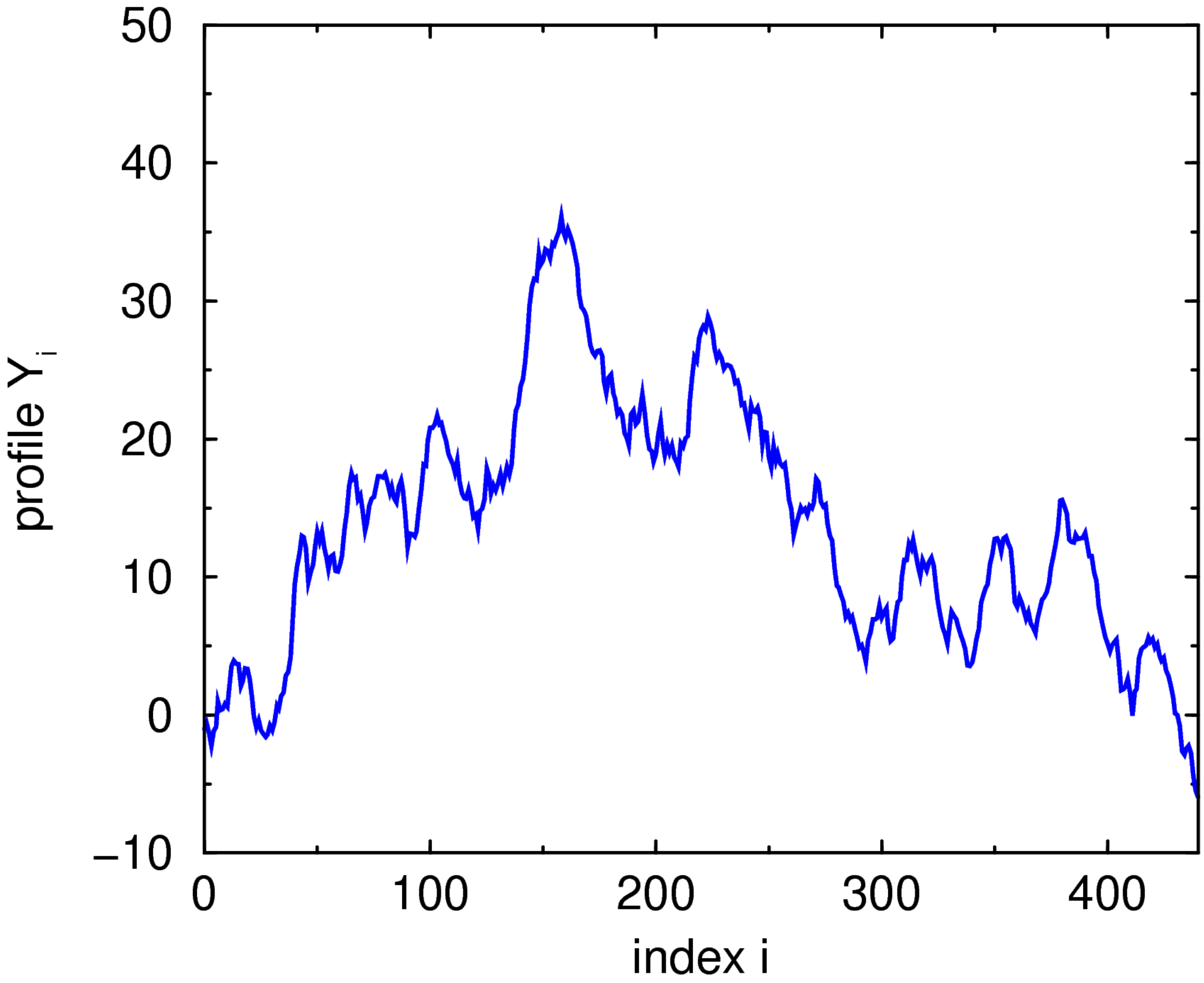
Different cases:

$\alpha \simeq 0{,}5$	uncorrelated
$0{,}5 < \alpha < 1{,}0$	long-term correlated
$1{,}0 < \alpha$	non-stationary

Detrended Fluctuation Analysis

1. cumulative sum $$Y_n = \sum_{i=1}^{n} \tau_i$$

Detrended Fluctuation Analysis

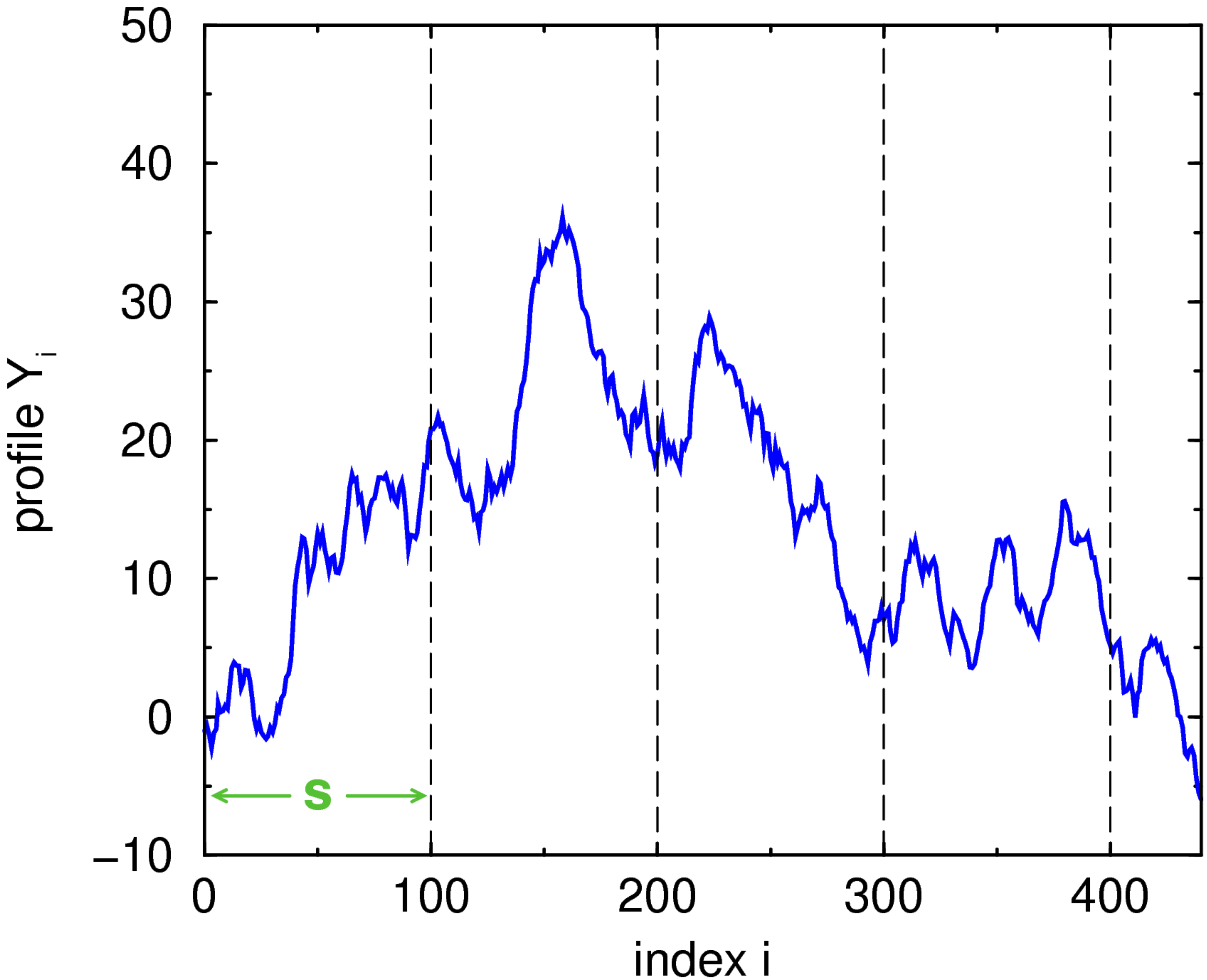


Detrended Fluctuation Analysis

1. cumulative sum $$Y_n = \sum_{i=1}^{n} \tau_i$$

2. separate into windows

Detrended Fluctuation Analysis



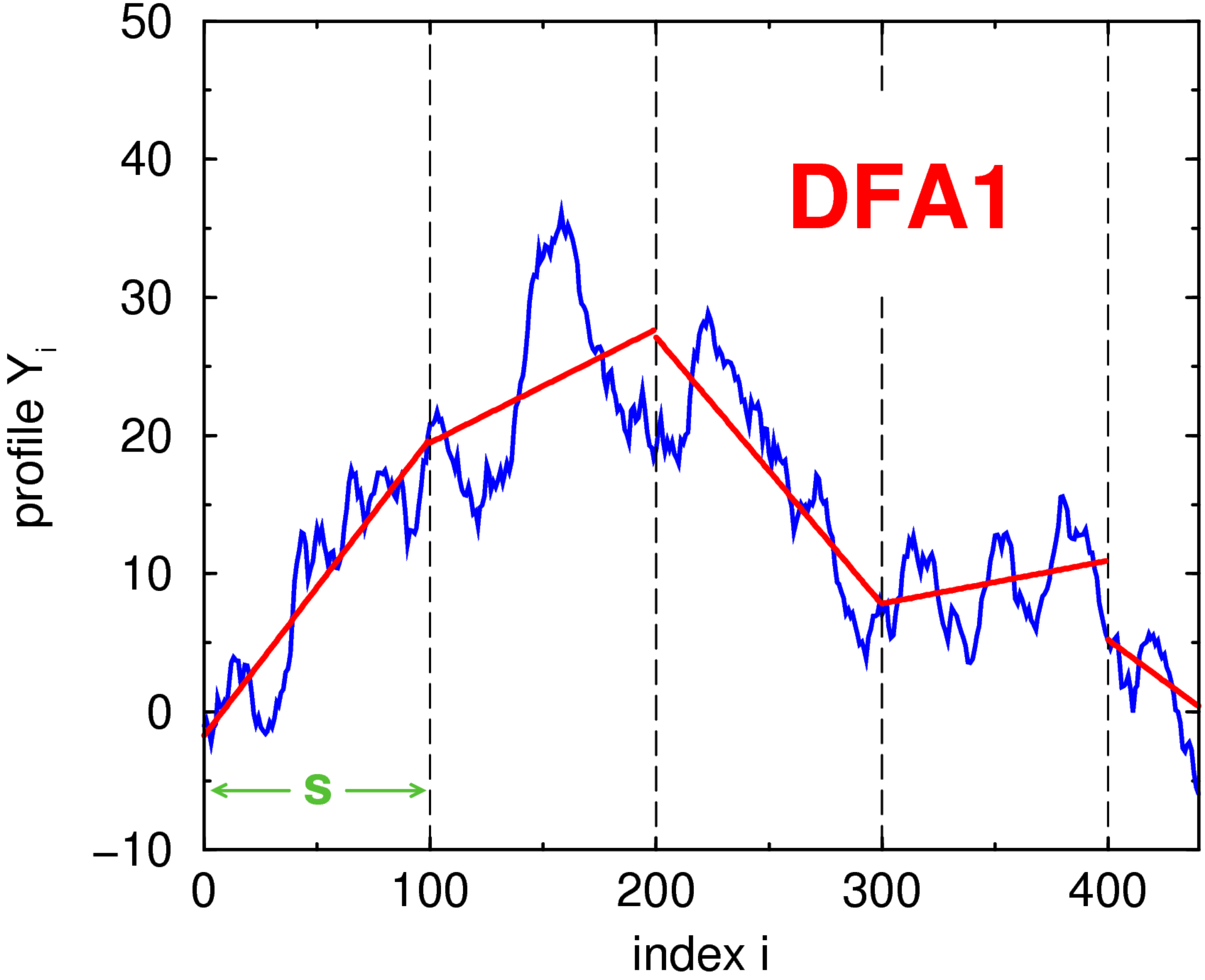
Detrended Fluctuation Analysis

1. cumulative sum $$Y_n = \sum_{i=1}^{n} \tau_i$$

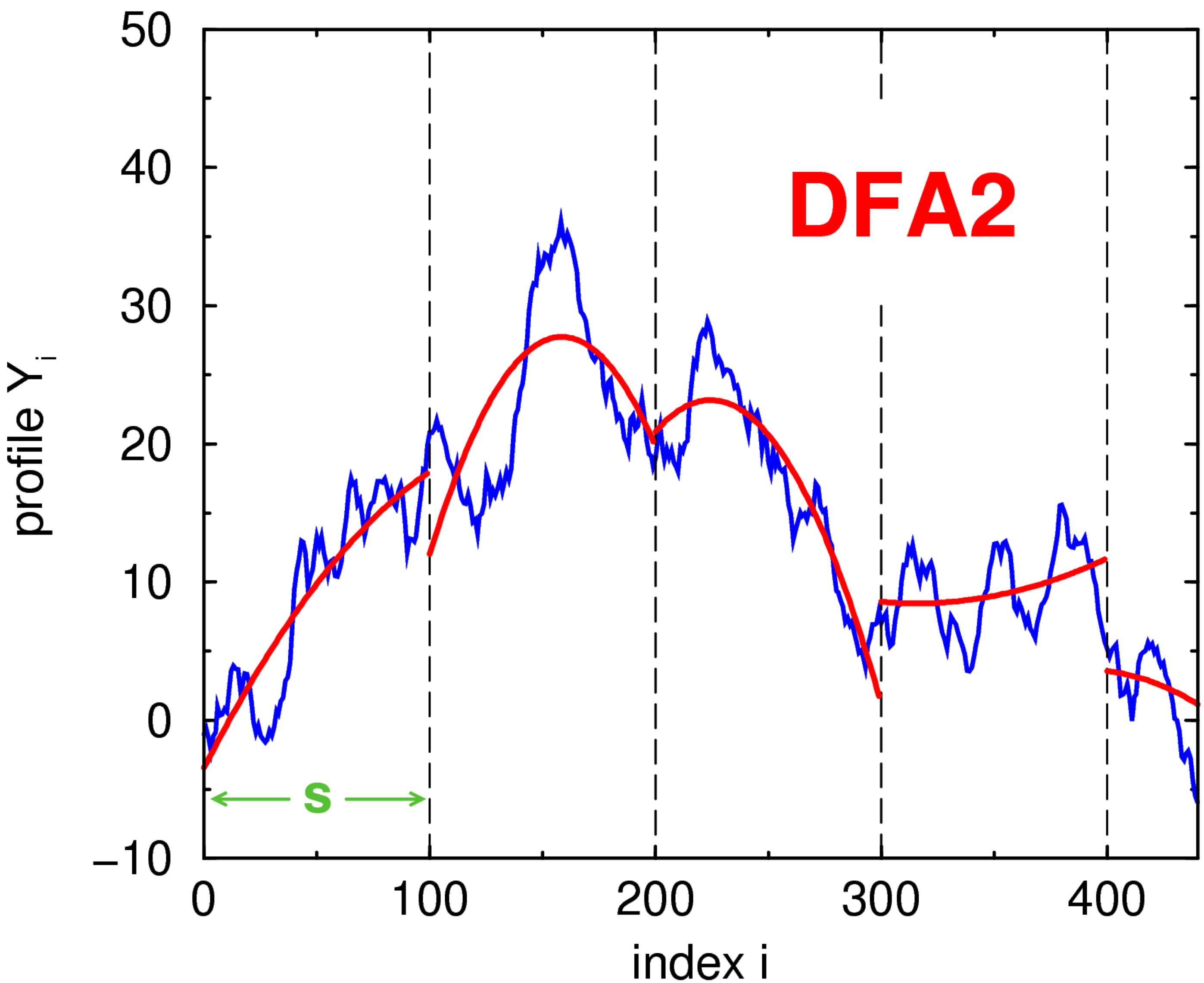
2. separate into windows

3. determine best polynomial fit in each

Detrended Fluctuation Analysis



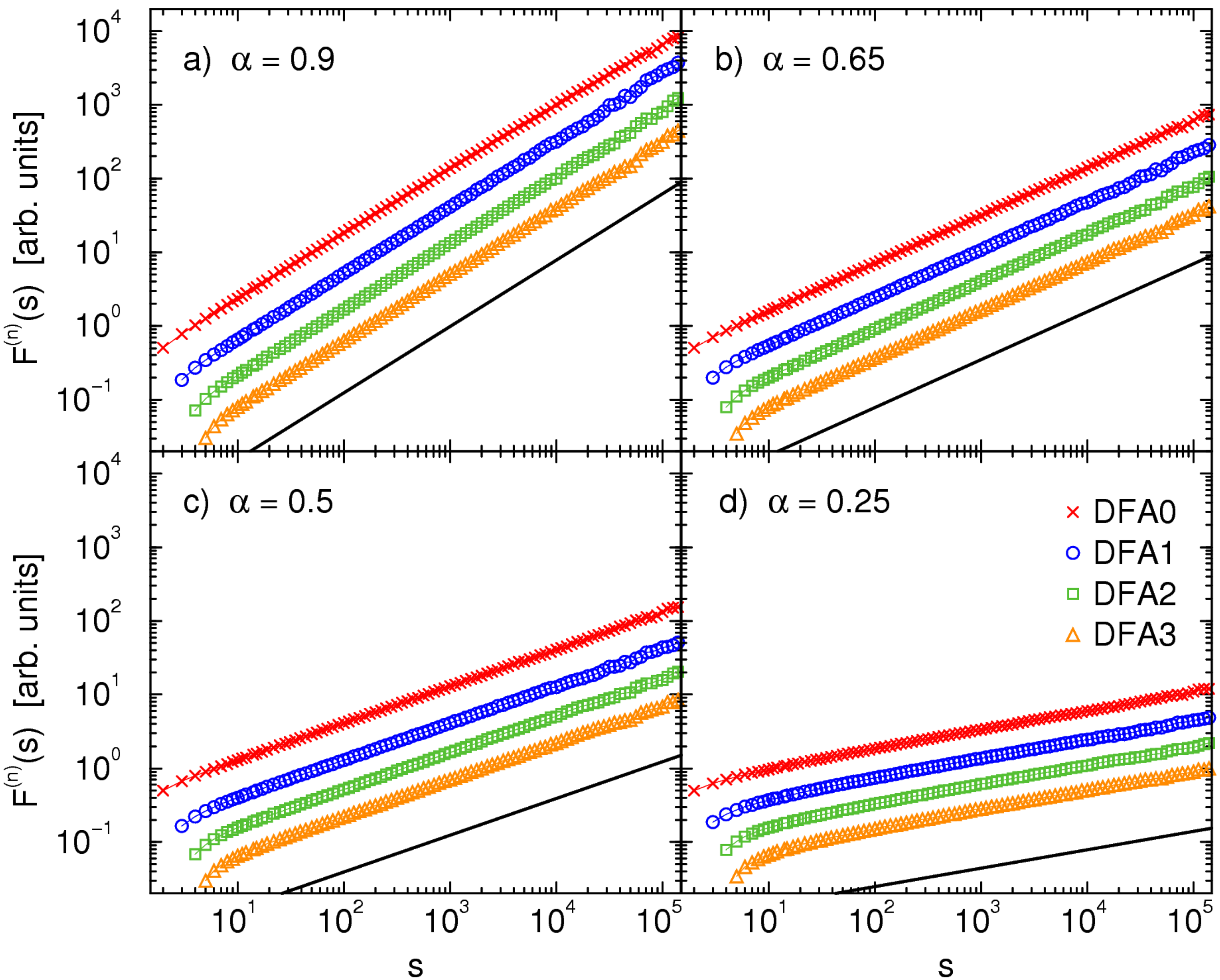
Detrended Fluctuation Analysis



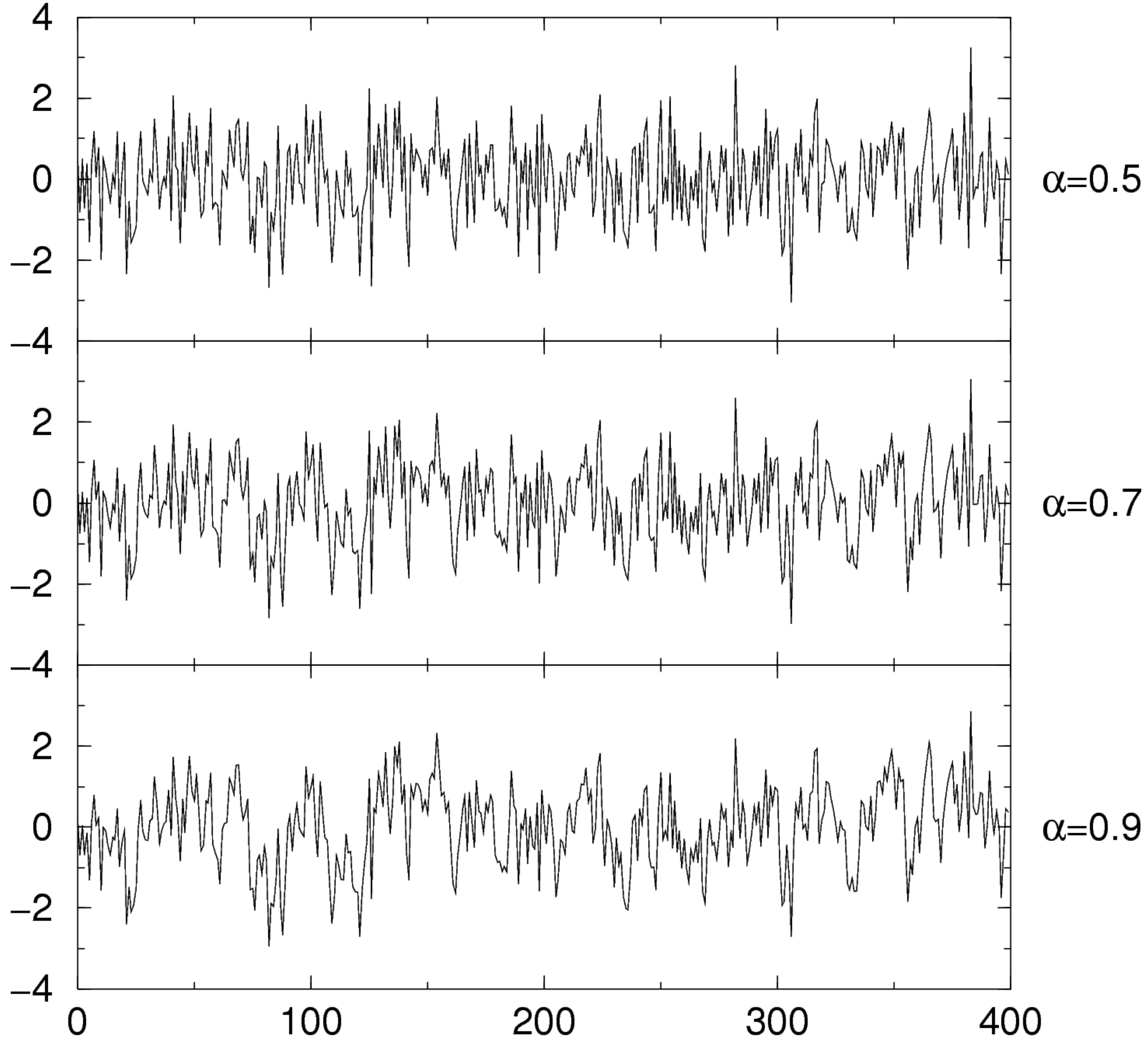
Detrended Fluctuation Analysis

1. cumulative sum $$Y_n = \sum_{i=1}^{n} \tau_i$$
2. separate into windows
3. determine best polynomial fit in each
4. residuals $$Y_i(S) = Y_i - p_\nu(i)$$
5. fluctuations in each window $$F_\nu^2(S) = \langle Y_i^2(S) \rangle = \frac{1}{S} \sum_{i=1}^{S} [Y_{(\nu-1)\cdot S+i}(S)]^2$$
6. average over all segments (fluctuation function) $$F(S) = \sqrt{\frac{1}{K_S} \sum_{\nu=1}^{K_S} F_\nu^2(S)}$$

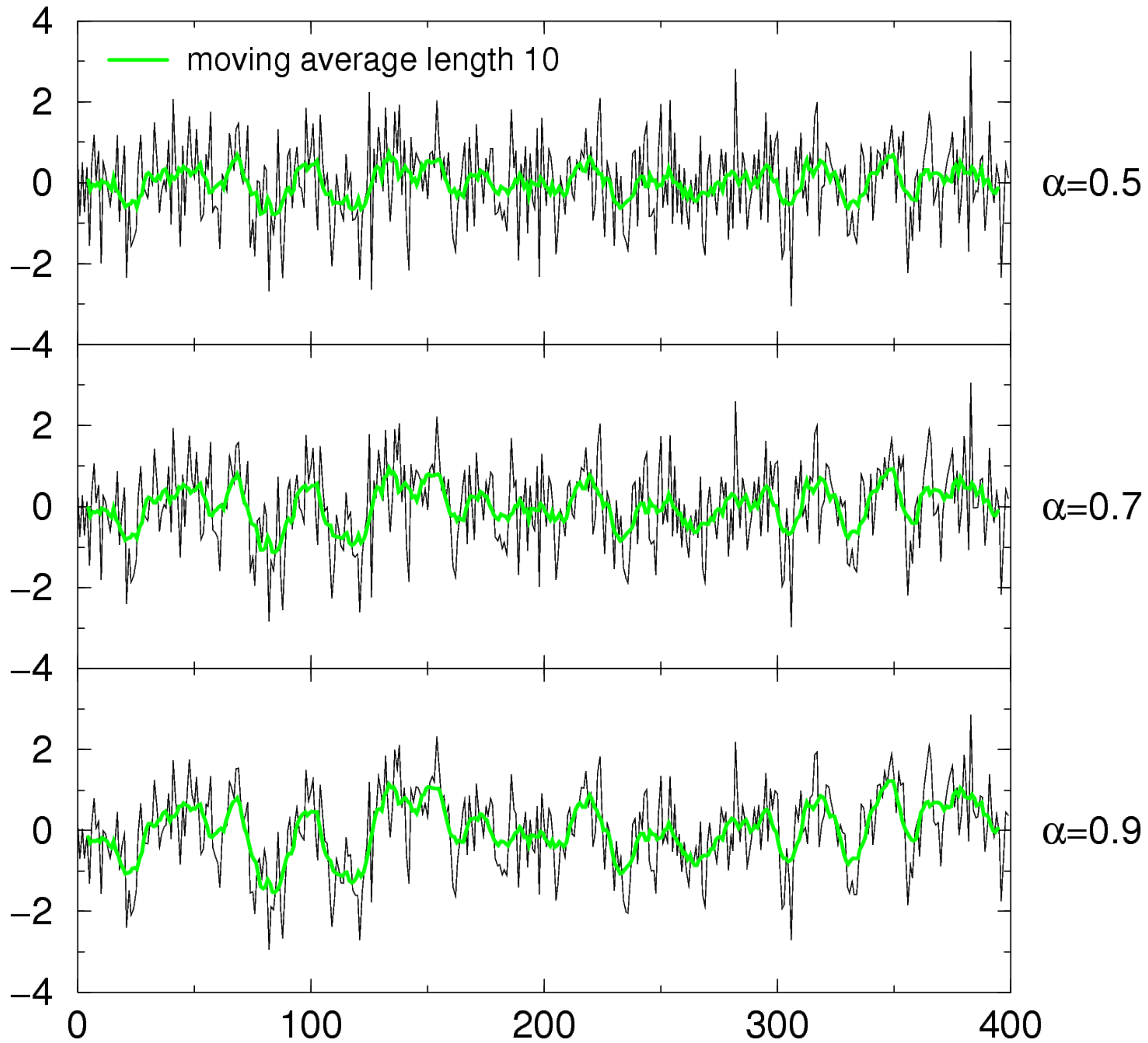
Detrended Fluctuation Analysis



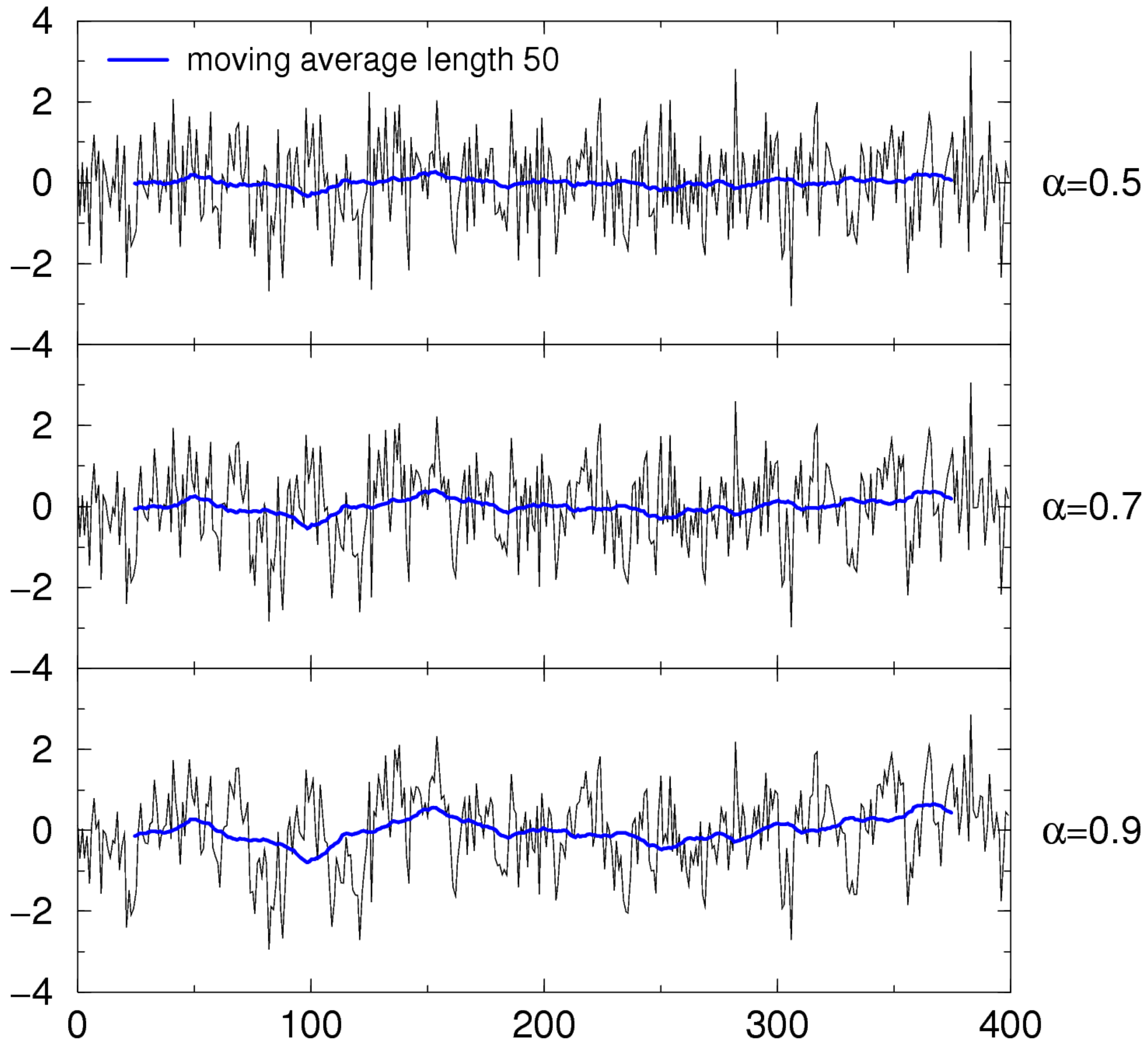
Effects of long-term correlations



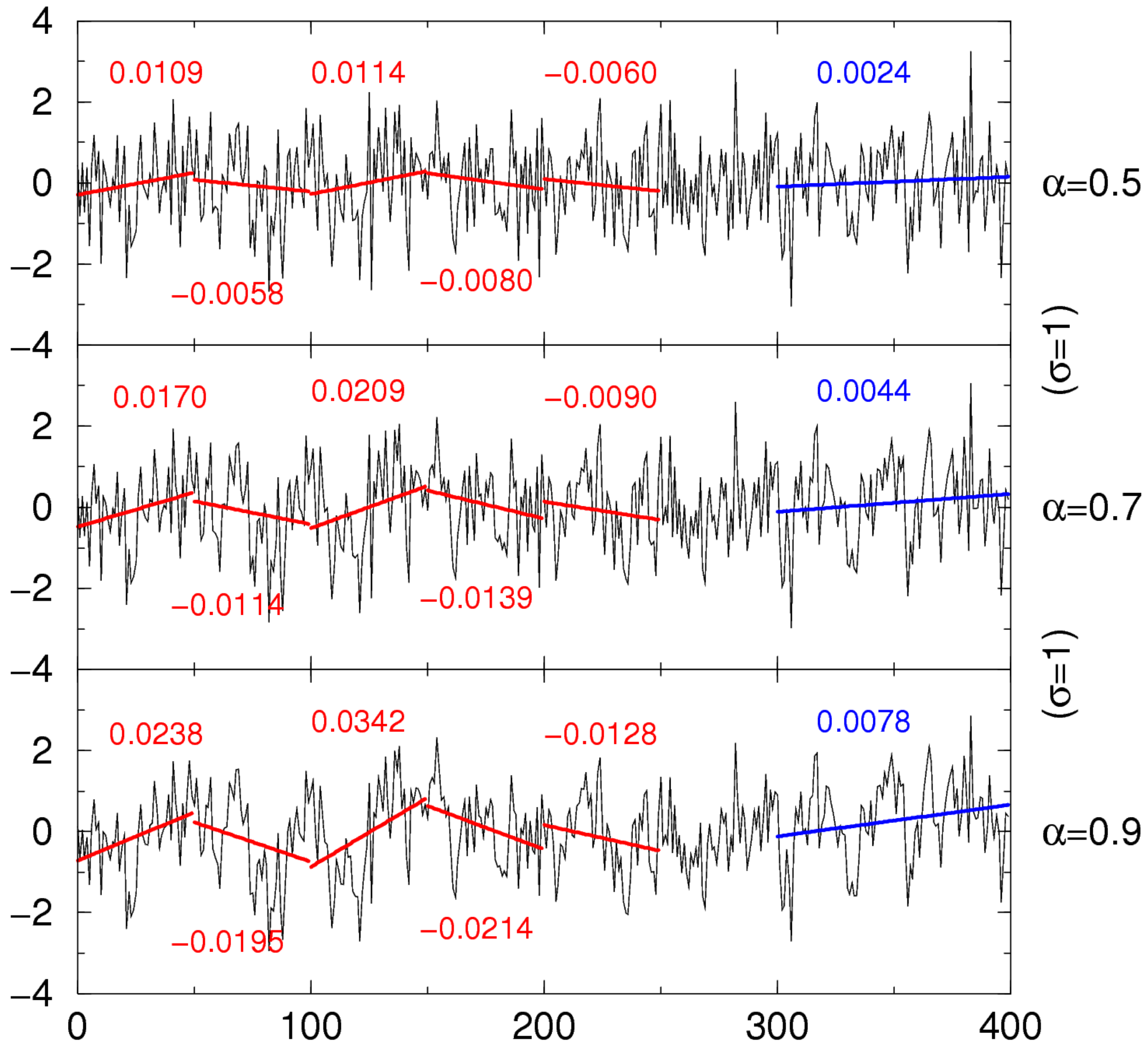
Moving average



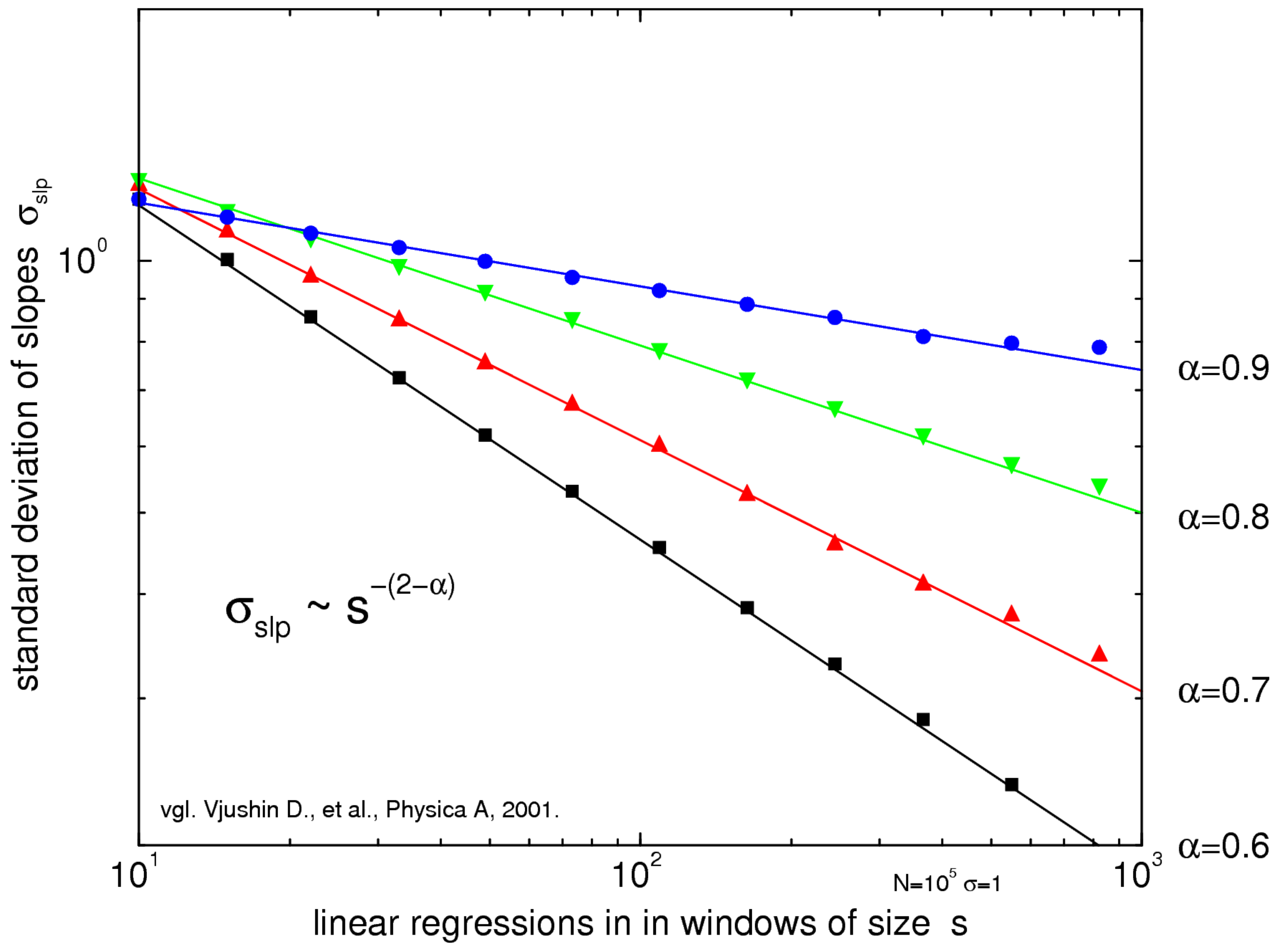
Moving average



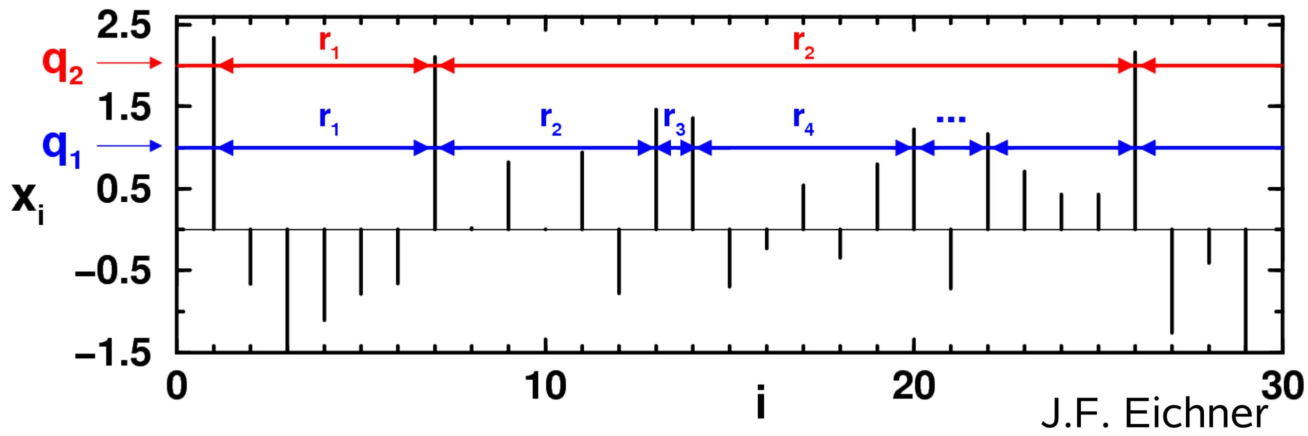
Occurring slopes

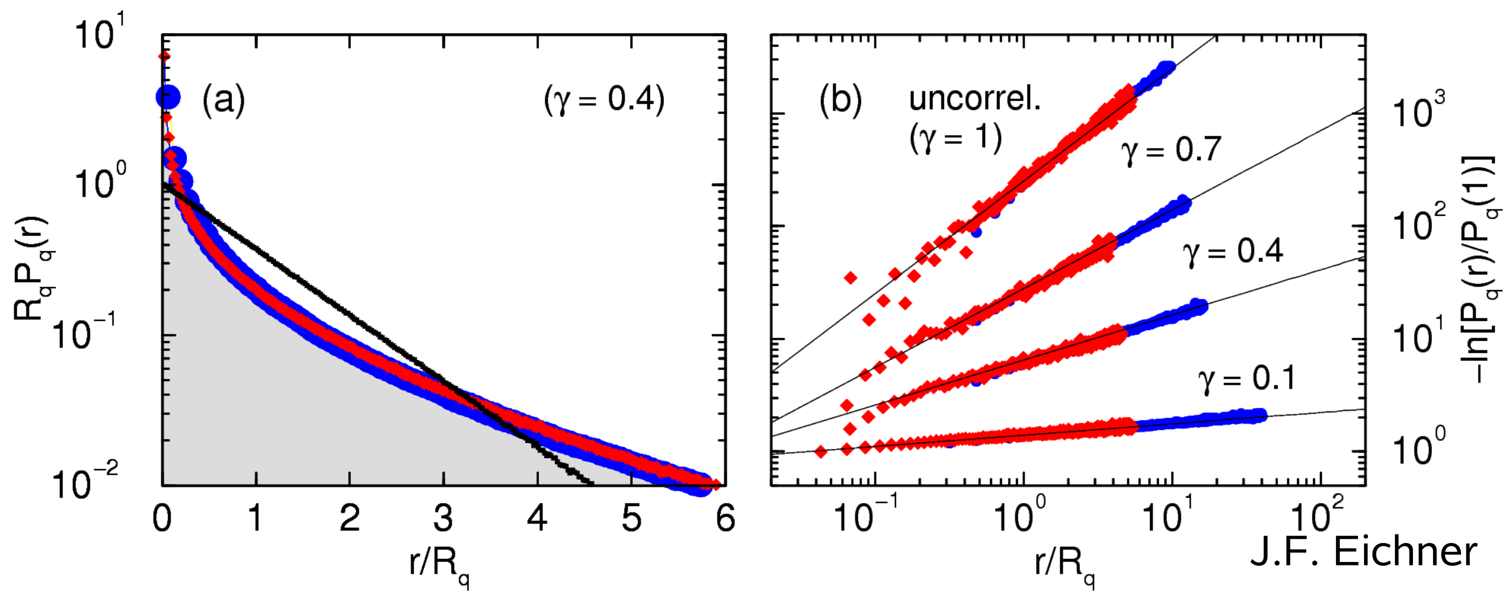


Occurring slopes



Clustering of extreme events

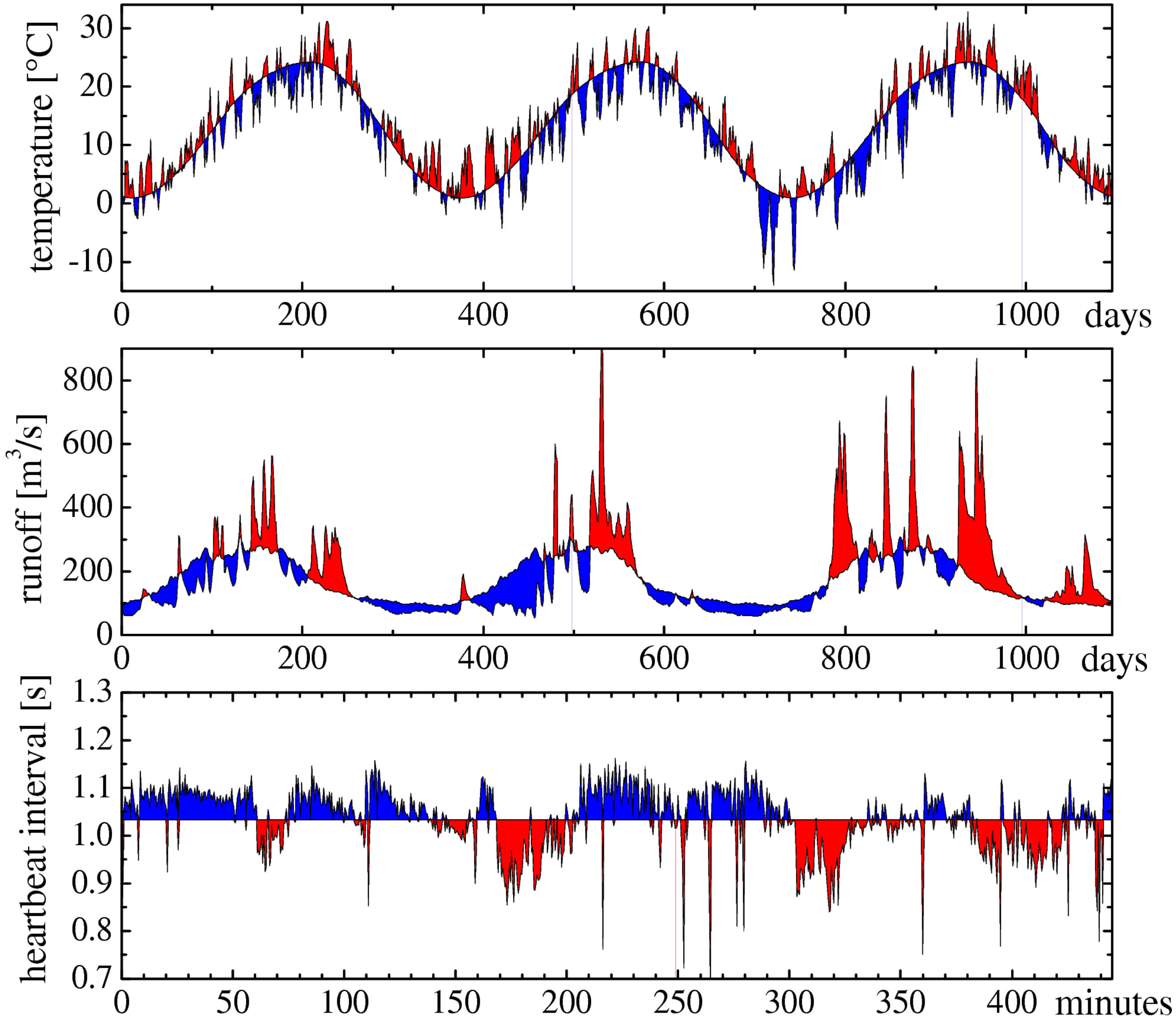




$$P_q(r) = \frac{a_\gamma}{R_q} \exp[-b_\gamma (r/R_q)^\gamma]$$

Bunde, A., Eichner, J.F., et al. PRL 2005

Examples of time series



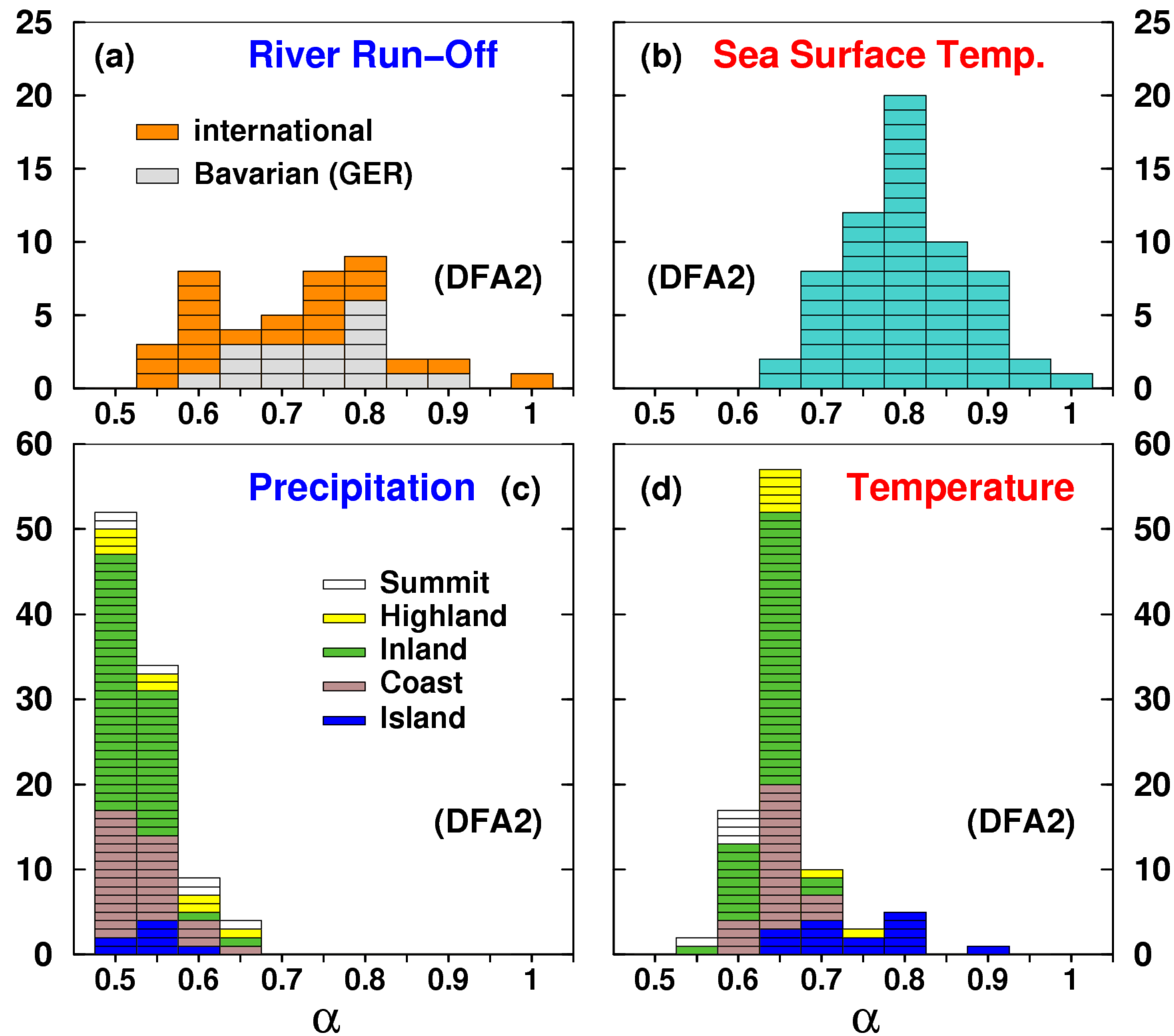
J.W. Kantelhardt

Occurrence of long-term correlations

- Hydrology (Hurst, H.E. 1951, ...)
- DNA sequences (Peng et al. 1994, ...)
- temperature records (Koscielny-Bunde et al. 1996, ...)
- heart rate (Bunde et al. 2000, ...)
- ...

Part 2 – Long-term correlations in climate

Overview



(a) Koscielny-Bunde, E., et al., 2006

(b) Monetti, R.A., et al., 2003

(c) Kantelhardt, J.W., et al., 2006

(d) Eichner, J.F., et al., 2003

Long-term correlations in temperature records

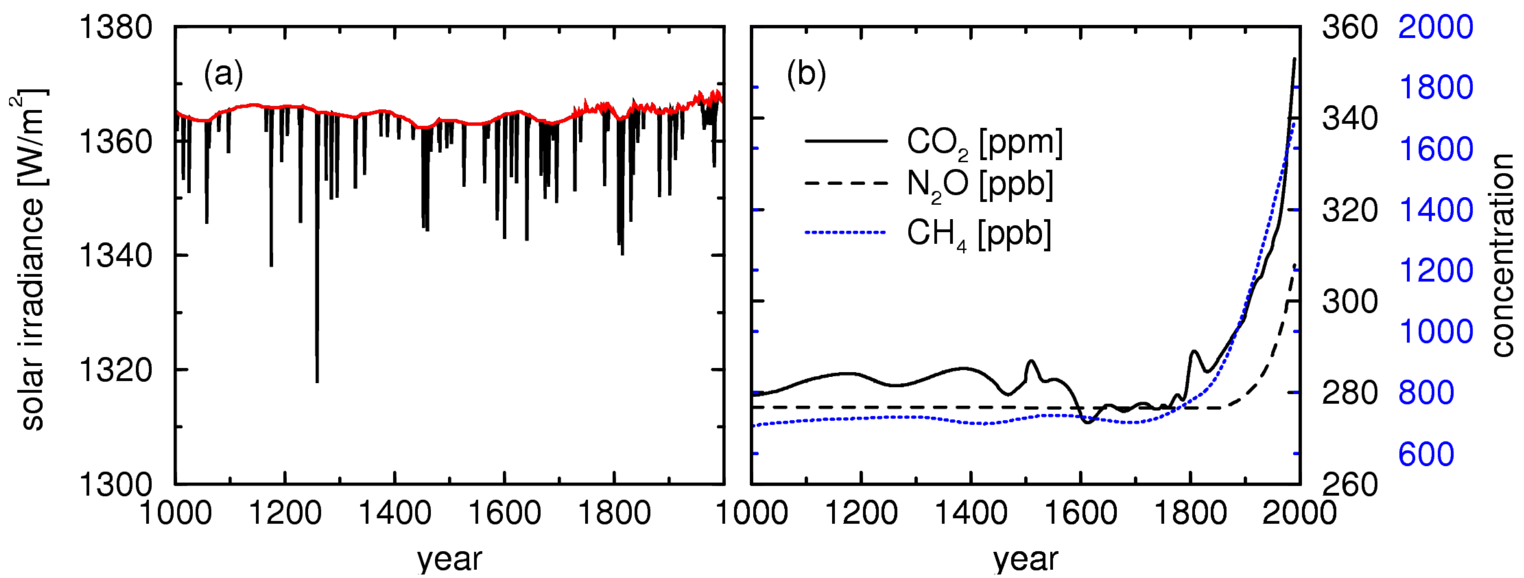
- **Eichner et al., PRE, 2003:**
  fluctuation exponents close to **0.65** for continental sites,
  larger values for island sites (broad range)
- **Monetti et al., Physica A, 2003:**
  values around **0.8** (broad range) for sea surface temperatures (SST)
  (temperature reconstructions)
- **Fraedrich et al., PRL, 2003:**
  vanishing correlations for inner continental sites,
  1/f-noise for SST (real and model records)
- **Kiraly et al., Tellus A, 2006:**
  complex spatial patterns (around 0.67 - continental)
- **Huybers et al., Nature, 2006:**
  latitude dependence, large at the Equator (climate model)

Global coupled general circulation model ECHO-G

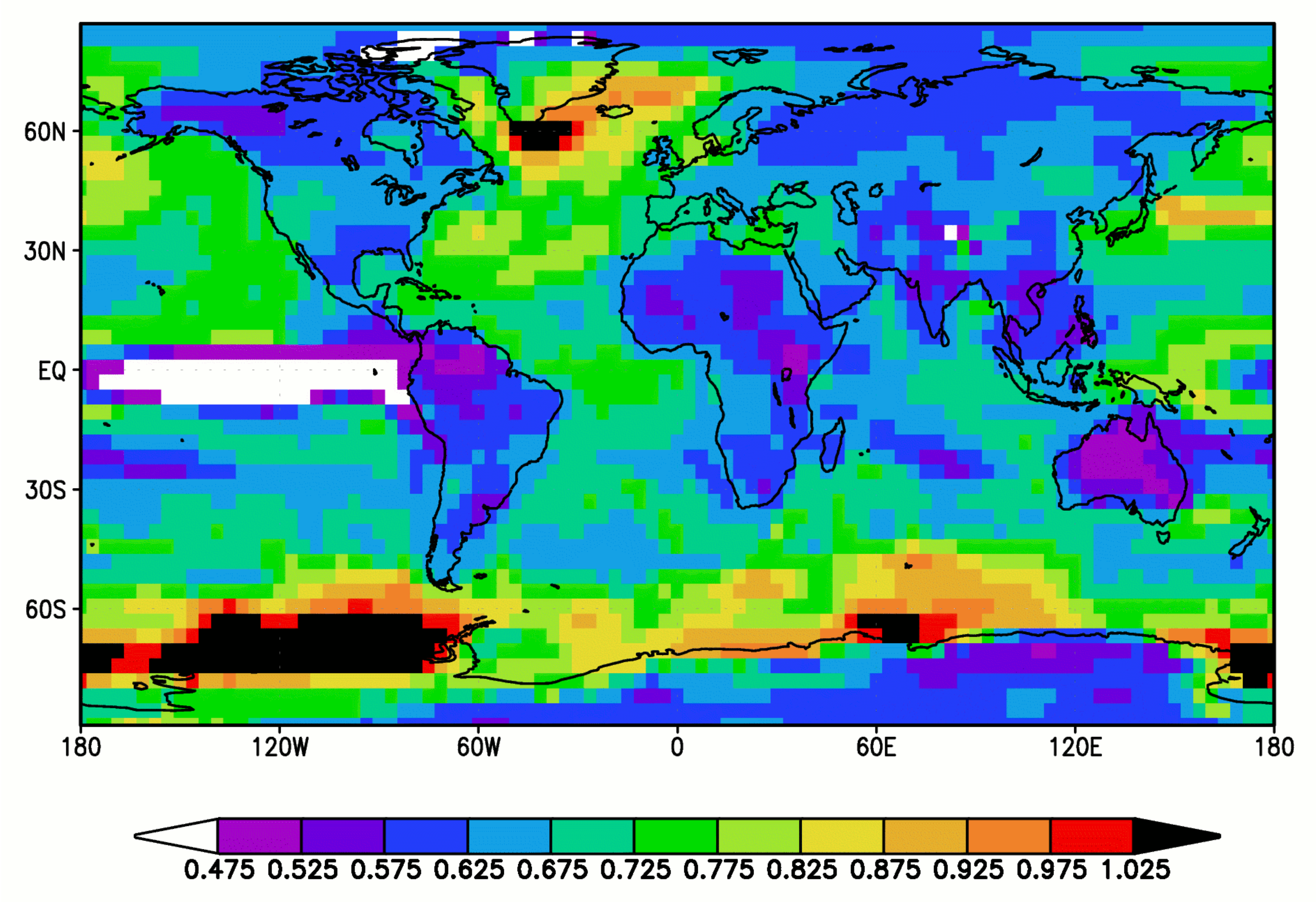
Model with 96 x 48 = 4608 grid-points,

two runs:

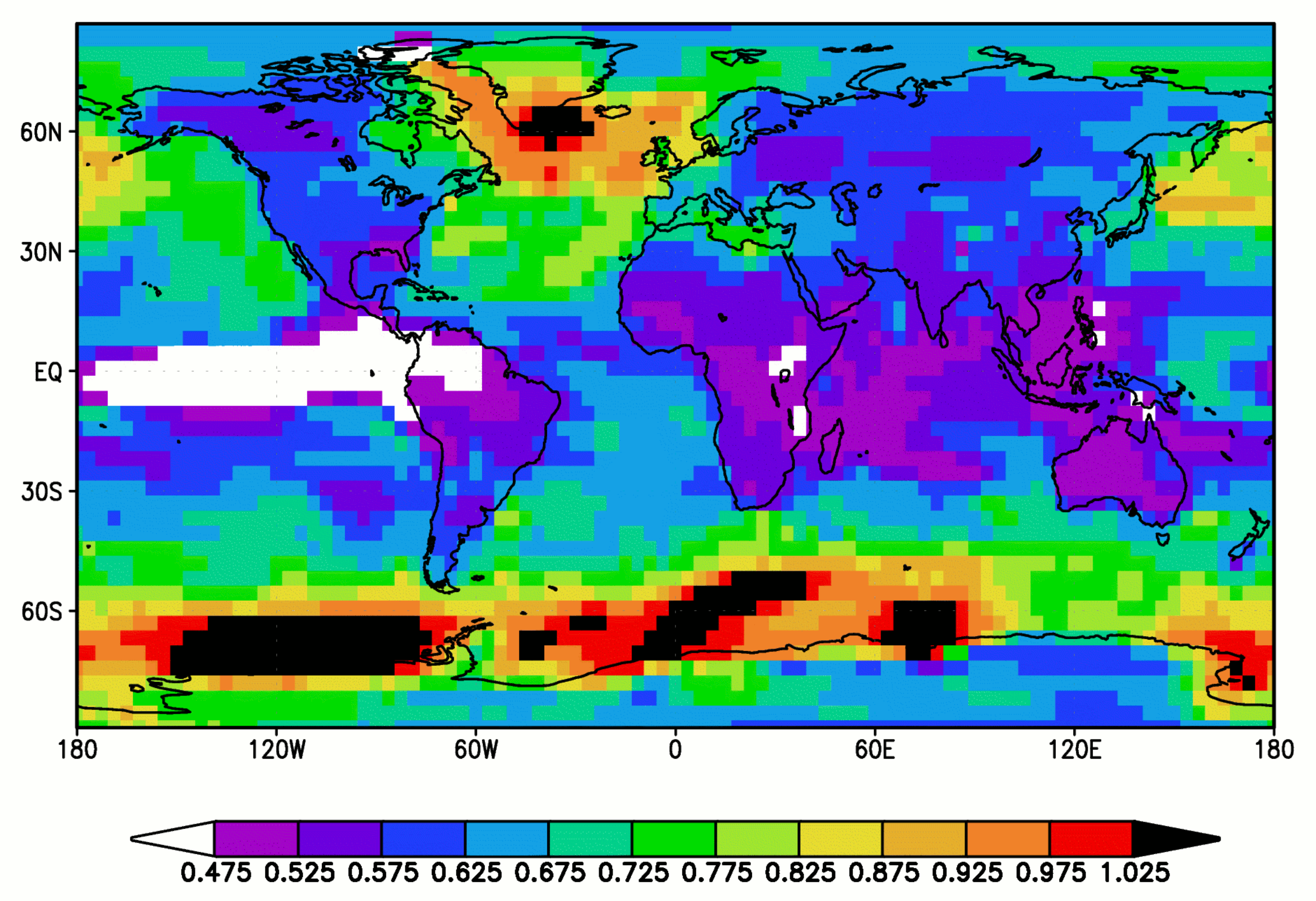
- historical simulation (1000-1990, 991 years)
- control run (1000 years)



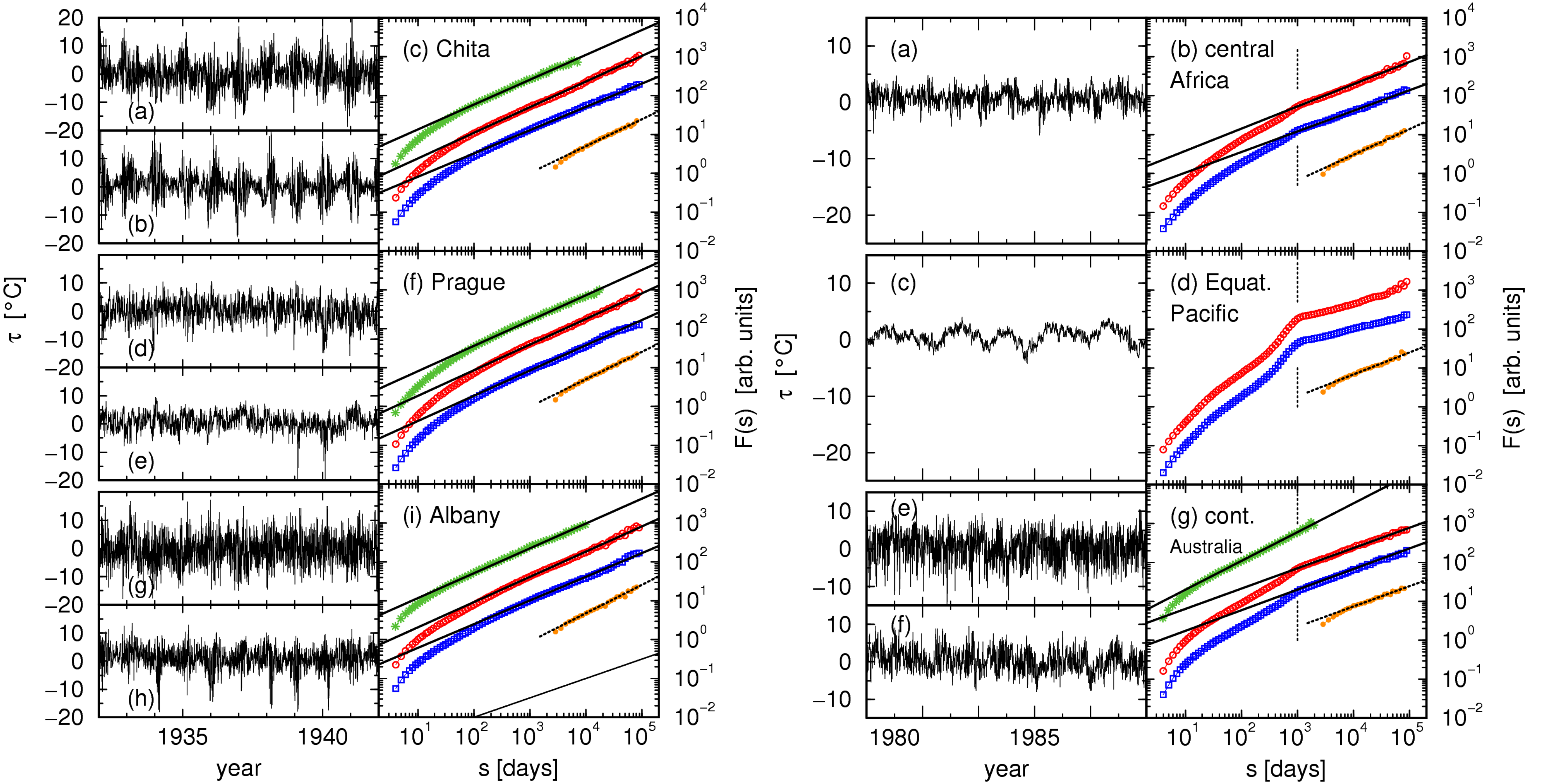
ECHO-G: DFA of 2m-temperatures historical simulation



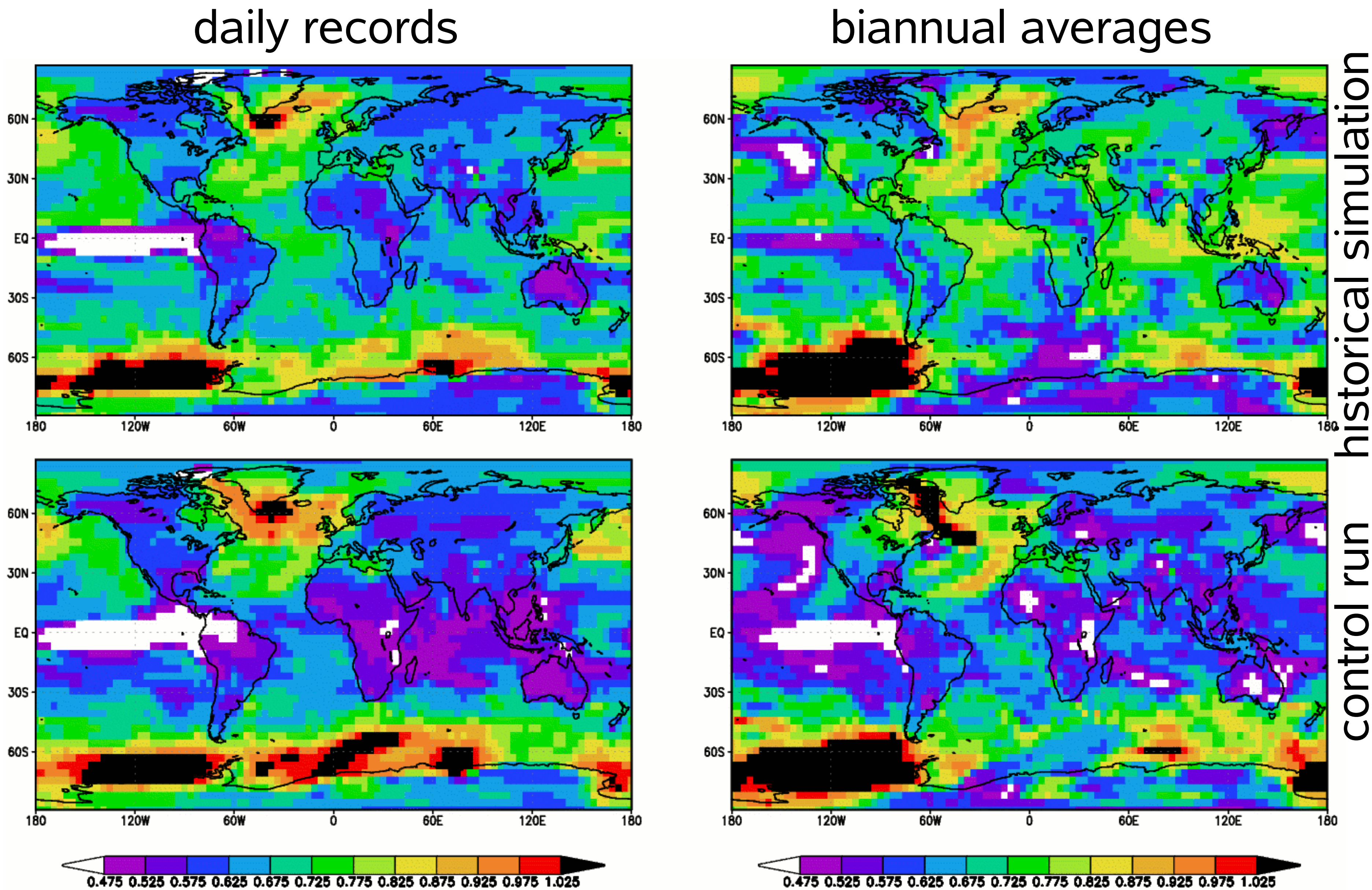
ECHO-G: DFA of 2m-temperatures control run



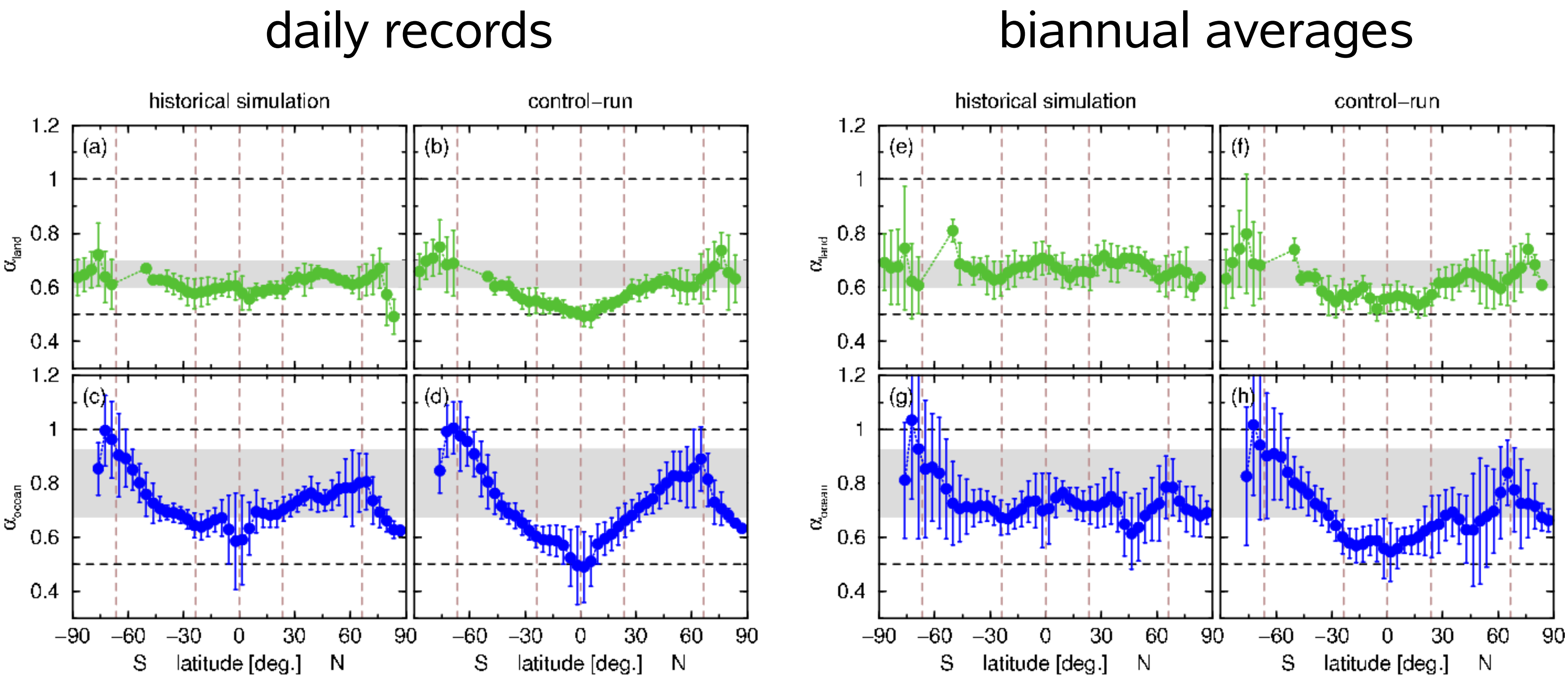
Examples of fluctuation functions



ECHO-G: DFA of 2m-temperatures



ECHO-G: DFA of 2m-temperatures



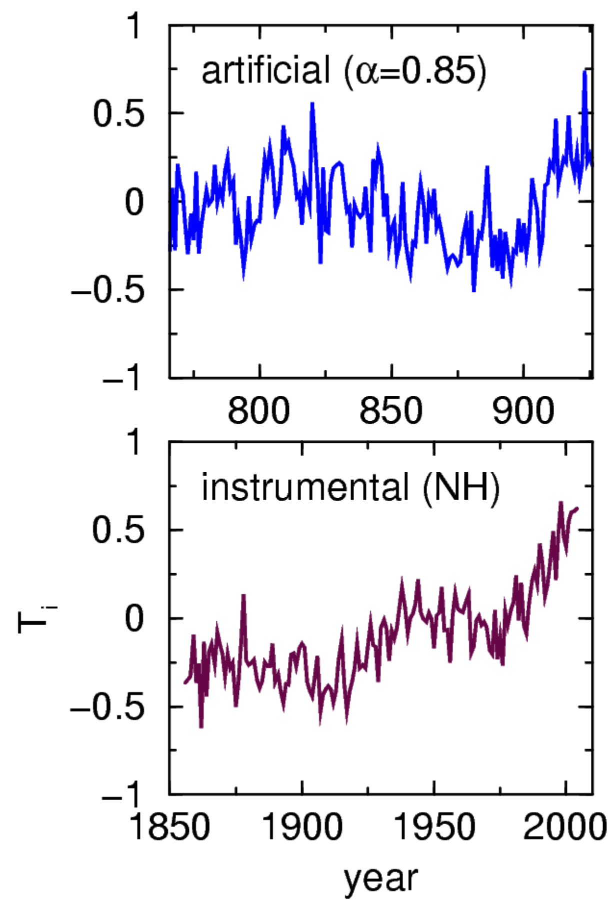
ECHO-G: summary

We find:

- long-term persistence on scales up to 200 years
- continental sites have fluctuation exponents between **0.6** and **0.7** (historical simulation)
- near the Equator the exponents are smaller (ENSO)
- for ocean sites the exponents depend on the latitude, small values at the Equator (opposite of Huybers2006)
- in the control run the long-term correlations are weaker, the latitude dependence is more pronounced (forcings are important, see Vyushin et al., GRL, 2004)
- biannual averages: stronger long-term correlations, less pronounced latitude dependence

We know:

- Long-term correlations exist in temperature records and lead to
  - a large variability and
  - a pronounced mountain-valley structure that resembles trend-like behavior



Question:

- Can the recent increase in the temperature of the Northern Hemisphere (NH) be attributed to these long-term correlations?

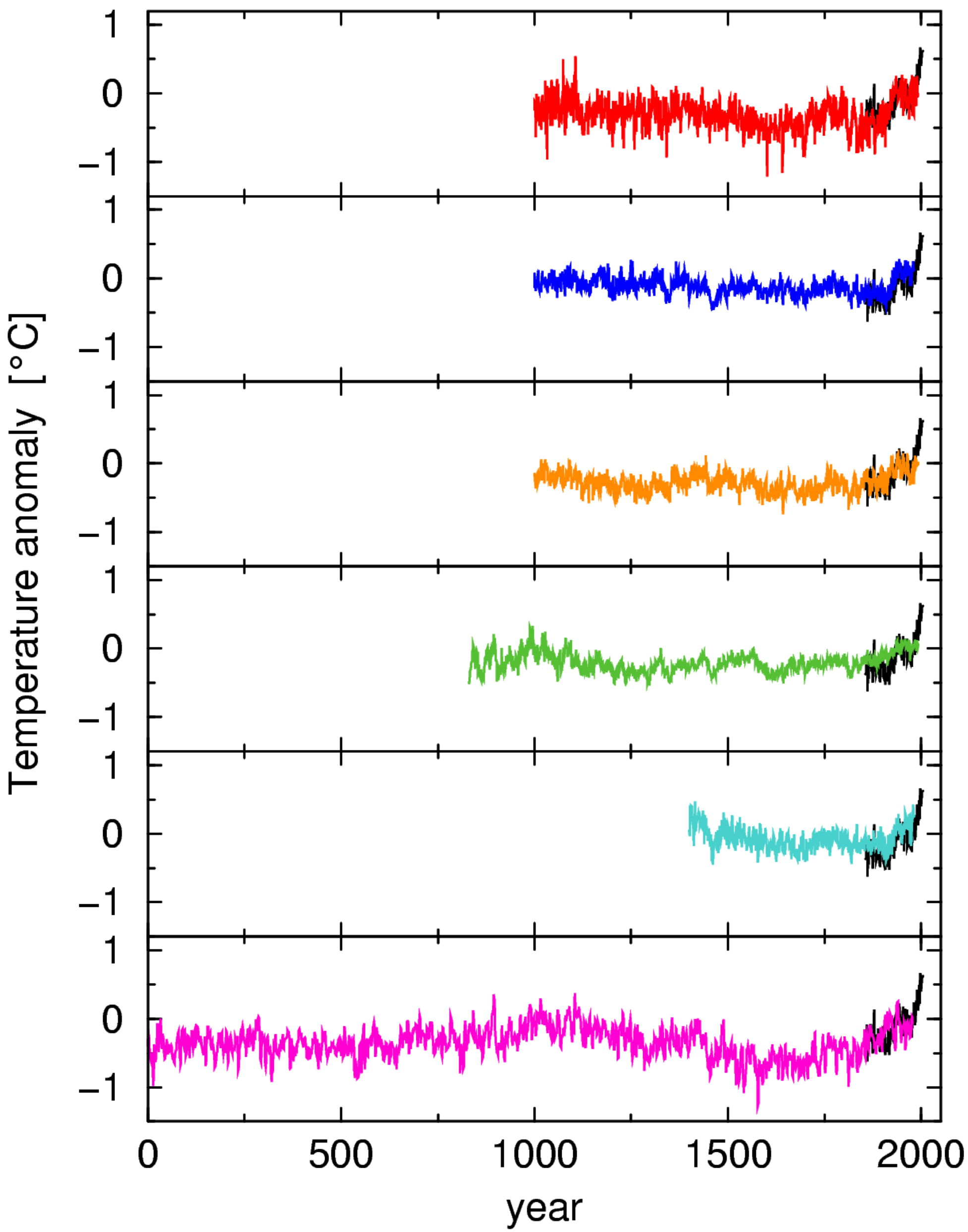
Our approach:

a) We analyze several centennial NH temperature reconstructions applying *Detrended Fluctuation Analysis* (DFA) and find that their variability can be attributed to long-term correlations.

b) We compare the variations of the reconstructions with the most recent temperature changes in the instrumental record.

c) We obtain an indication whether the recent warming can be related to natural factors or not.

Considered temperature reconstructions (NH)



Jones, P.D., et al.,
Holocene 8(4), **1998**

Mann, M.E., et al.,
Geophys. Res. Lett. 26(6), **1999**

Briffa, K.R.,
Quat. Sci. Rev. 19(1-5), **2000**

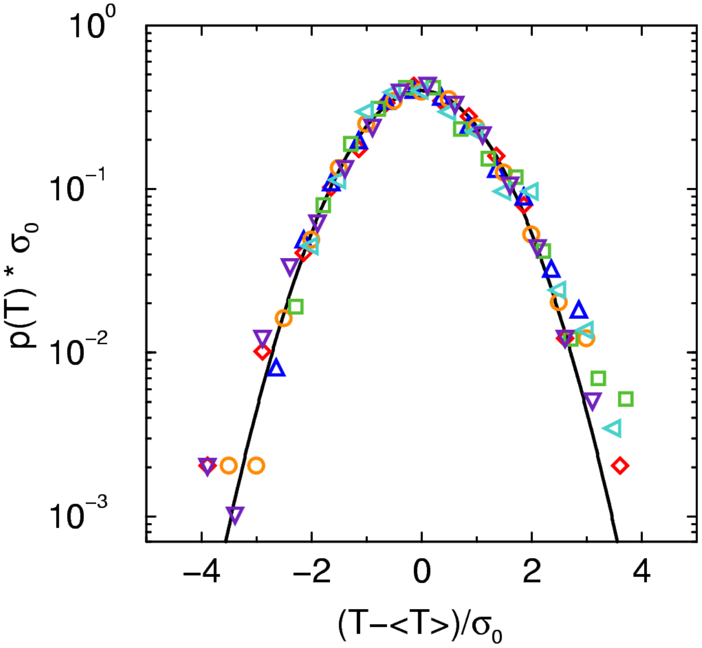
Esper, J., et al.,
Science 295(5563), **2002**

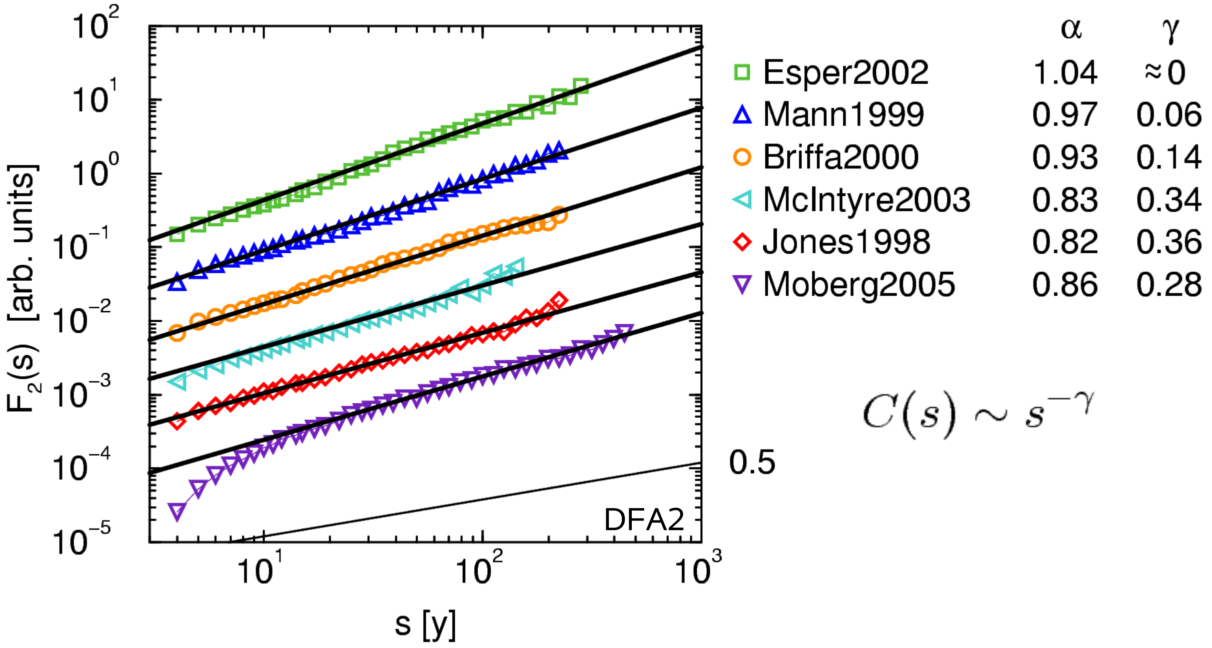
McIntyre, S. and McKitrick, R.,
Energy Environ. 14(6), **2003**

Moberg, A., et al.,
Nature 433(7026), **2005**

http://www.ncdc.noaa.gov/paleo/recons.html

Distribution and correlation



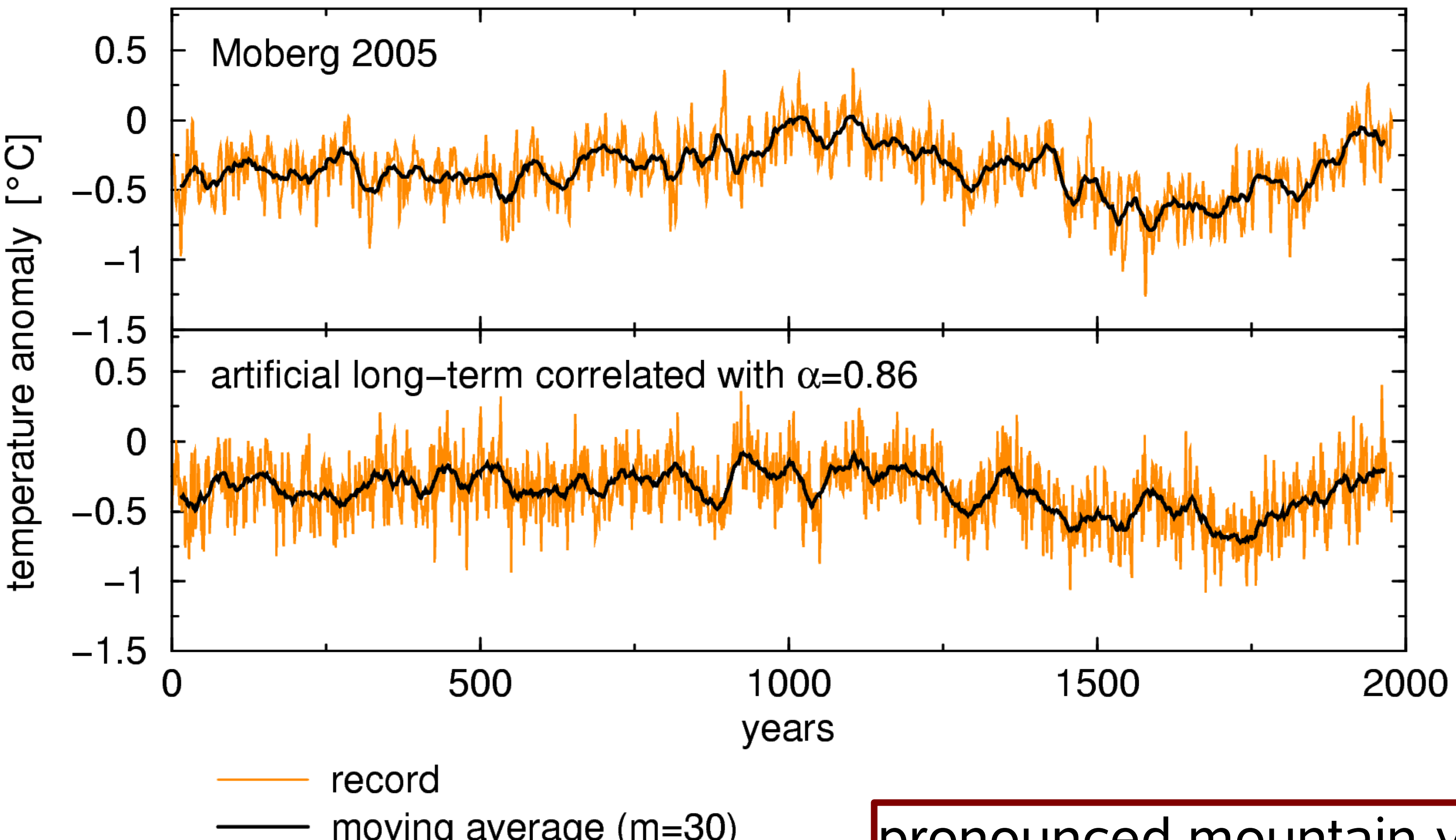


$$C(s) \sim s^{-\gamma}$$

approximately Gaussian

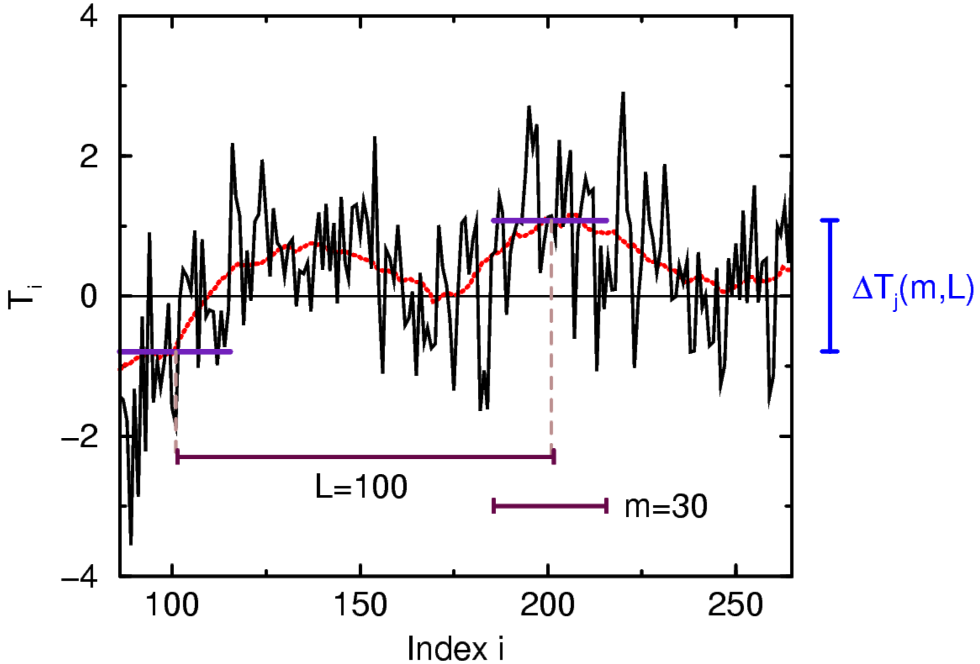
long-term correlations on scales up to centuries

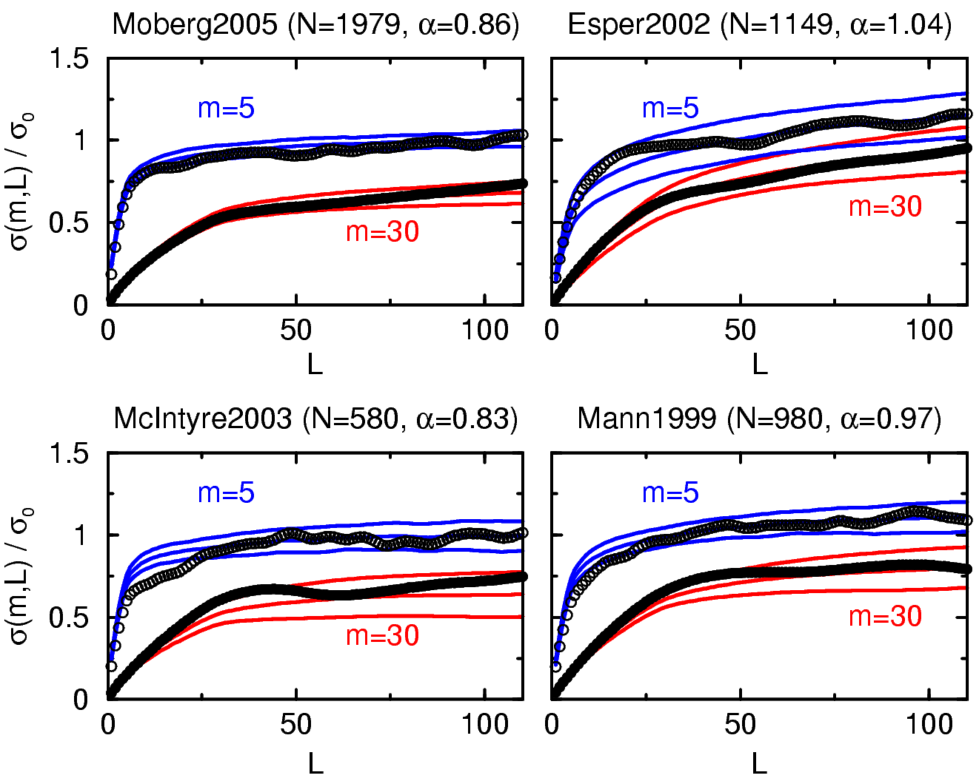
Enhanced variability



pronounced mountain-valley structure by long-term correl.

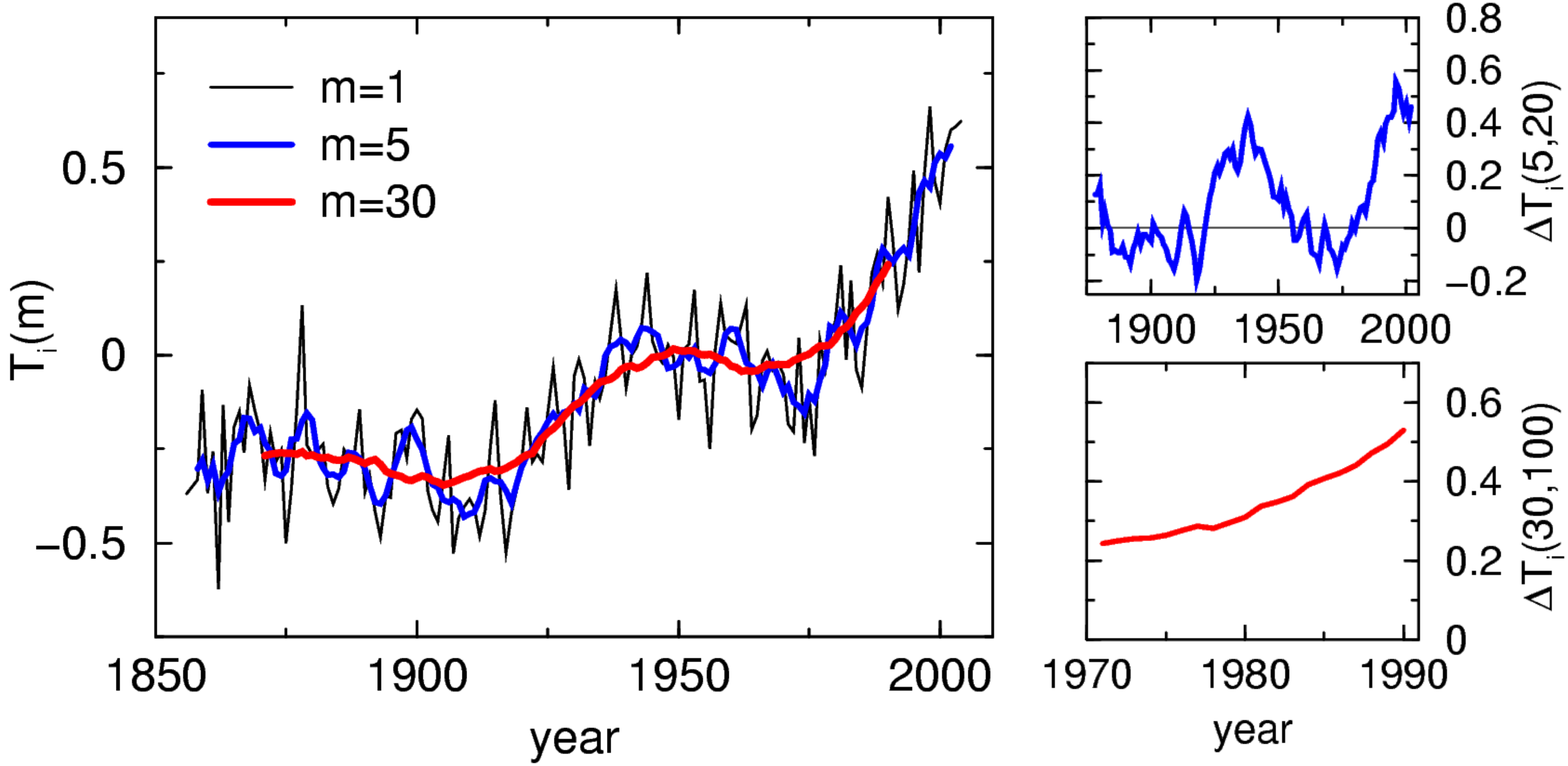
Moving average differences $\Delta T_j(m, L)$ and standard deviation $\sigma(m, L)$



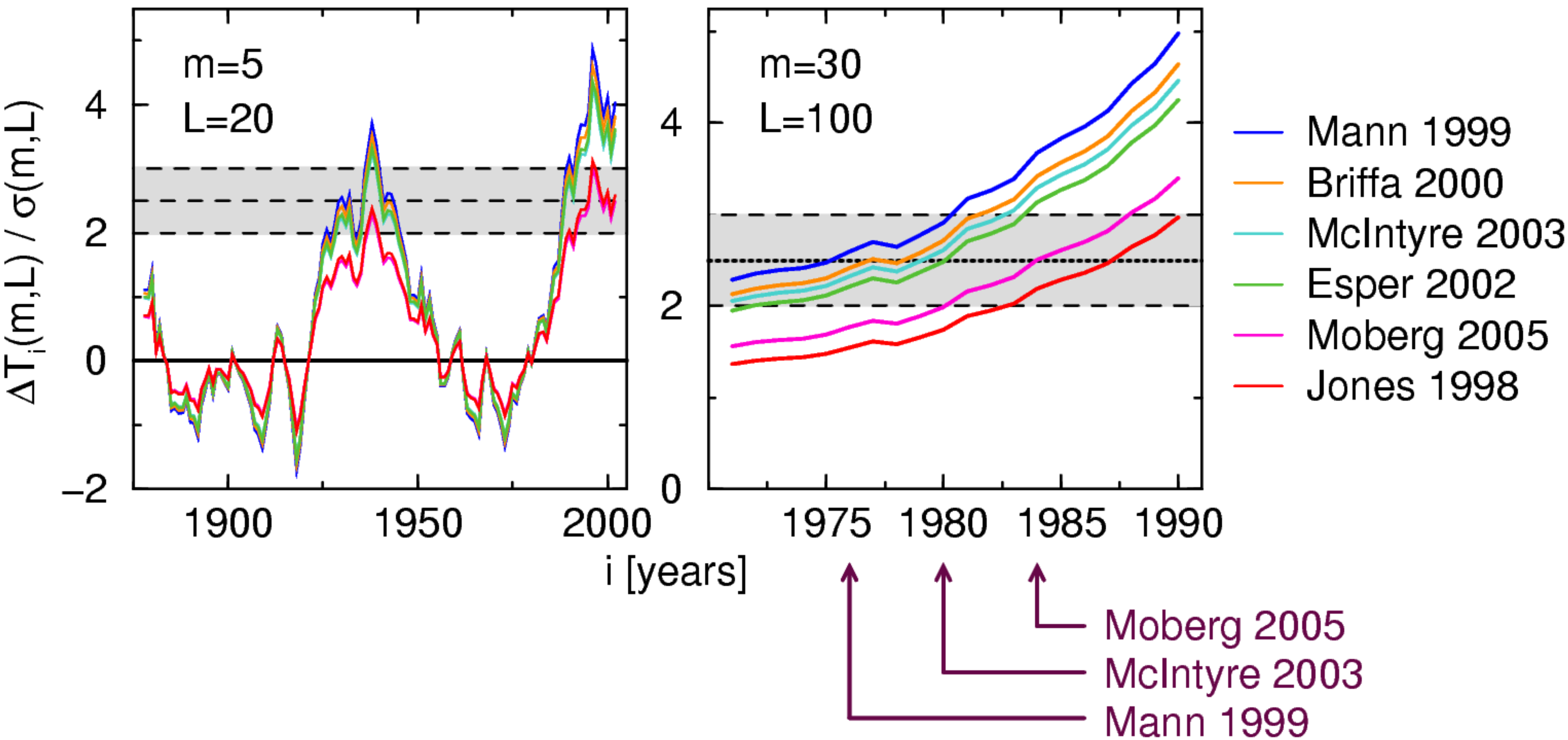


Since the T_j are Gaussian-distributed, the $\Delta T_j(m,L)$ also Gaussian distributed, characterized by standard dev. $\sigma(m,L)$

Instrumental temperature record (NH)



Probability analysis



Details:
D. Rybski, A. Bunde, S. Havlin, H. v. Storch,
GRL 33, L06718, 2006.

Summary

- Reconstructed Northern Hemisphere temperature records show pronounced long-term correlations

- Our analysis does not support the claim, that the most recent warming, observed by quality controlled instrumental data, is consistent with the hypothesis of purely natural dynamics.

Thank you for your attention