Analysis of Antarctic Ice Core Data (EPICA Dome C) with Flicker-Noise Spectroscopy

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Introduction to Flicker-Noise Spectroscopy (FNS)

Flicker-Noise Spectroscopy (FNS) is a signal analysis toolset for information extraction from stochastic time or space series, which include both regular and chaotic components, based on the analysis of the correlation links for signal irregularities and regular components. The basic FNS tools to extract and analyze the information are power spectra and difference moments (structural functions) of various orders [1].

FNS can be applied to three types of problems:

1. Determination of parameters that characterize the dynamics or structural features of complex systems (parameterization);
2. Finding precursors of abrupt changes in the state of various complex systems based on a priori information about the dynamics of the systems (nonstationarity factors);
3. Determination of flow dynamics in distributed systems based on the analysis of dynamic correlations between stochastic signals that are simultaneously measured at different points in space (cross-correlations).

FNS has been successfully applied to the analysis of the structure and dynamics for various physicochemical, electrochemical, biological, geophysical, and astrophysical processes [1-3].

FNS Nonstationarity Factor

Consider the time series of a dynamic variable *V* with values recorded at equally spaced time intervals. A difference moment (transient structural function) of the second order $\Phi^{(2)}$ is defined as [1]

$$\Phi^{(2)}(n) = \frac{1}{N-n}\sum_{k=1}^{N-n}\left[V(k)-V(k+n)\right]^2 ,$$

where *n* is the time lag parameter, *k* is the index, and *N* is the number of points within the averaging time interval *T*. The difference moment is an aggregate estimate of differences within the averaging interval *T* between the values that are *n* points apart from each other.

An FNS nonstationarity factor for the difference moment of second order is defined as [1]

$$C_J(t_{k+1}+T) = \frac{Q_{k+1}^J - Q_k^J}{\Delta T} \times \frac{2T}{Q_{k+1}^J + Q_k^J} ,$$

where

$$Q_k^J = \frac{1}{N_1}\sum_{n_\tau=1}^{N_1}\left[\Phi_J^{(2)}(n)\right]_k ;$$

$J = R$ (low-frequency part), *F* (high-frequency part), or *G* (original signal); *t* is the time; $t_k = k\Delta T$; ΔT is the increment by which the averaging "window" is shifted; *k* is the index of the current averaging "window"; N_1 is the fraction of all points *N* in the averaging interval *T* for which reliable estimates of the difference moments can be calculated. The nonstationarity factor virtually represents a discrete derivative of the total sum of difference moments within the current "window" at all time lag values, with respect to the increment by which the analysis "window" is shifted. In other words, it gives an aggregate estimate of the rate of changes taking place at "all" time scales from one averaging "window" to another.

The FNS nonstationarity factor was successfully used for finding precursors of earthquakes [1, 4-5] and electric breakdowns in semiconductor systems [6].

EPICA Dome C Ice Core Data

The FNS nonstationarity factor is applied to the analysis of the EPICA Dome C ice core data for deuterium composition and dust concentration flux recorded for the past 800,000 years, which includes eight climate cycles [7]. The main purpose of the study is to locate and analyze the glacial terminations and frequencies that determine the climate transitions. The ice core data were converted into time series with a sampling interval of 500 years. The time series were then sorted chronologically so that precursors could be searched for.

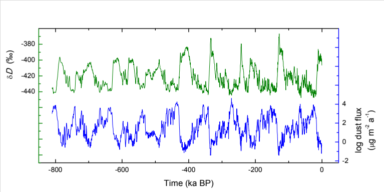

Figure 1. EPICA Dome C ice core data for deuterium (temperature proxy) and dust flux.

FNS Nonstationarity Factors for Deuterium and Dust Flux

We used *T* = 40 ka as the main averaging interval for the nonstationarity factor because obliquity (approximate period of 41 ka) and precession (approximate period of 21 ka) are considered to be the dominant factors in climate transitions [8]. The selected value of the averaging interval allows one to include the effects of both orbital frequencies. To check the validity of our results concerning the locations of glacial terminations, we compared them with the estimates obtained using RAMPFIT, a regression algorithm that locates ramps with high rates of change accompanying glacial terminations [9]. The FNS nonstationarity factor was used only for the analysis of the last seven glacial terminations because the first two glacial terminations occurred outside the time range for which reliable estimates of the nonstaturity factor can be obtained for the given data. The nonstationarity factors were built for three different averaging intervals to confirm the reliability of the results.

The table listed below shows that the peaks in the deuterium nonstationarity factors calculated for the averaging intervals of 40, 50, and 60 ka (Fig. 2) were able to accurately estimate the time when the interglacial periods were reached for all glacial terminations except for VI. The coordinates of the peaks above a threshold of 10 (T = 40ka) in the deuterium nonstationarity factor provide a simple way of estimating the location of each glacial termination. No precursors in the data for both deuterium (Fig. 2) and dust flux (Fig. 3) were observed as the transitions occurred very quickly. Fig. 3 shows that the dust flux nonstationarity factor did not capture the glacial termination III.

Termination	Begin [9]	End [9]	FNS (T=40ka)	FNS (T=50ka)	FNS (T=60ka)
I	-11686	-17630	-11000	-11000	-11000
II	-129459	-135402	-130500	-130500	-129500
III	-242867	-251915	-243000	-243000	-243000
IV	-334103	-341121	-334500	-334500	-334000
V	-425813	-430693	-424500	-424500	-424500
VI	-529157	-531284	-	-	-
VII	-626073	-629486	-626000	-625500	-625500

FNS Nonstationarity Factors for Deuterium and Dust Flux (Continued)

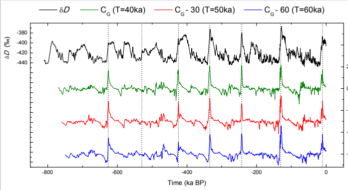

Figure 2. Deuterium composition change and its FNS nonstationarity factors at three different averaging intervals.

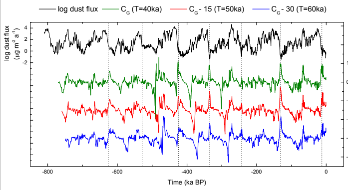

Figure 3. Dust flux and its FNS nonstationarity factors at three different averaging intervals.

Power Spectrum Estimates for FNS Nonstationarity Factors

Fig. 4 and Fig. 5 show FFT-based power spectrum estimates for the source signals (Fig. 1) and their nonstationarity factors (*T*=40ka), marked as S_V and S_G respectively. It is seen the power spectrum estimates for the nonstationarity factors show more pronounced resonances for several frequencies. This implies that those frequencies may play a more significant role in the climate transitions as compared to what the analysis of the power spectra for the source signals indicates.

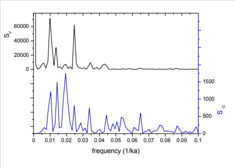

Figure 4. Power spectra for deuterium composition and its nonstationarity factor.

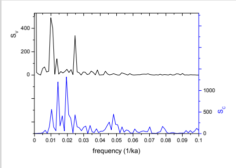

Figure 5. Power spectra for dust flux and its nonstationarity factor.

Conclusions

- Peaks in the FNS nonstationarity factor for deuterium composition built at *T* = 40ka provide a simple and accurate way of identifying all the glacial terminations except for VI, which implies that the transitions are accompanied by major system changes the precursors of which may be located from the analysis of other climate data series.
- The absence of any peaks for glacial termination VI indicates that there are no major changes for that transition, which may be associated with some geophysical processes specific to that glacial termination.
- There is no peak in the dust flux nonstationarity factor for glacial termination III.
- There are no precursors in the nonstationarity factors for both dust composition and dust flux. At the same time, the peaks imply that there should be some preliminary buildup in other dynamic variables, as is the case with earthquakes.
- Power spectrum estimates for nonstationarity factors show that there are other important frequencies in addition to the traditional ones associated with orbital parameters, which play a significant role in climate transitions.
- The results of this study demonstrate the potential of FNS in the analysis of climate data series and may be used in refining climate transition models.

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Acknowledgements

This study was supported by the Russian Foundation for Basic Research, project no. 08-02-00230*a*.