Atmos. Chem. Phys. Discuss., 6, 11957–11970, 2006
www.atmos-chem-phys-discuss.net/6/11957/2006/

Atmospheric Chemistry and Physics Discussions

Technical Note: Long-term memory effect in the atmospheric CO_2 concentration at Mauna Loa

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Received: 23 October 2006 – Accepted: 17 November 2006 – Published: 24 November 2006

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Abstract

The monthly mean values of the atmospheric carbon dioxide concentration derived from in-situ air samples collected at Mauna Loa Observatory, Hawaii, during 1958–2004 (the longest continuous record available in the world) are analyzed by employing the detrended fluctuation analysis to detect scaling behavior in this time series. The main result is that the fluctuations of carbon dioxide concentrations exhibit long-range power-law correlations (long memory) with lag times ranging from four months to eleven years, which correspond to 1/f noise. This result indicates that random perturbations in the carbon dioxide concentrations give rise to noise, characterized by a frequency spectrum following a power-law with exponent that approaches to one; the latter shows that the correlation times grow strongly. This feature is pointing out that a correctly rescaled subset of the original time series of the carbon dioxide concentrations resembles the original time series. Finally, the power-law relationship derived from the real measurements of the carbon dioxide concentrations could also serve as a tool to improve the confidence of the atmospheric chemistry-transport and global climate models.

1 Introduction

A very important aspect of the climate problem consists in recognition of anthropogenically induced changes caused by increased CO_2 emissions to the atmosphere, taking, however, into account the complexity of all interactive processes including chemistry and dynamics of the atmosphere and hydrosphere (Jacovides et al., 1994; Crutzen et al., 1999; Kondratyev and Varotsos, 2001a, b, 2002a; Varotsos et al., 2001; Schulz et al., 2001; Asher et al., 2004; Aziz et al., 2005; Dameris et al., 2005). In this respect, highly uncertain quantitative estimates of anthropogenic impacts on global climate deserve special attention (Berger and Dameris, 1993; Hein et al., 2001; Dameris et al., 2005; Eyring et al., 2005).

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Recent years have been marked by an undoubtedly growing interest in the problem of complex studies of atmospheric CO_2 in connection with the necessity to obtain reliable estimates of the CO_2 (both natural and anthropogenic) impact on global climate. The global climate numerical simulation performed recently with consideration of not only anthropogenically induced growth of greenhouse gases concentrations, but also increasing content in the atmosphere of anthropogenic sulphate aerosol revealed a much more complicated pattern of climate formation than it was supposed before: the aerosol-induced climate cooling is mostly compensated from the greenhouse warming (Kondratyev and Varotsos, 1995; Varotsos, 2002; Cartalis and Varotsos, 1994).

One of the main uncertainties and difficulties in assessment of the role of atmospheric CO_2 in climate changes is connected with the absence of adequate information about its temporal variability values, and, in particular, whether CO_2 observations remain residually correlated with one another even after many years (long-range dependence).

In an attempt to resolve the aforesaid problems, a modern method of statistical physics is herewith applied to the CO_2 observations that are collected at Mauna Loa, Hawaii. The necessity to employ a modern method of CO_2 data analysis stems from the fact that most of the atmospheric quantities obey non-linear laws, which usually generate non-stationarities. These non-stationarities often conceal the existing correlations into the examined time series and therefore, instead of the application of the conventional Fourier spectral analysis on the atmospheric time series, new analytical techniques capable to eliminate the non-stationarities in the data should be utilized (Lovejoy, 1982; Schertzer and Lovejoy 1985; Tuck and Hovde, 1999; Hu et al., 2001; Chen et al., 2002; Tuck et al., 2003; Grytsai et al., 2005).

Nowadays, the wavelet technique (e.g., Koscielny-Bunde et al., 1998) and the detrended fluctuation analysis (DFA) (Peng et al., 1994) are among the most often used tools along these lines. Experience gained from recent studies testifies to the fact that DFA has already proved its usefulness in several complex systems (e.g., Stanley et al., 1999; Talkner and Weber, 2000; Zhu and Liu, 2003; Syroka and Toumi, 2001; Varotsos

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et al., 2002, 2003a, b, 2005; Chen et al., 2005). Very recently, the DFA method has been applied to the time series of the surface air-pollutants (Varotsos et al., 2005), the aerosol index (Varotsos et al., 2006), the total ozone content (Varotsos, 2005a, b) and the tropospheric temperature (Varotsos and Kirk-Davidoff, 2006). More information about the DFA method is given below (Sect. 2).

The present paper examines the time scaling of the fluctuations of the atmospheric CO_2 concentrations by using the longest record of observations in the world (1958–2004). The results obtained, would help to the enhancement of the fidelity of the available climate models.

2 Methodology and data analysis

As has been mentioned above, the data employed in the present study, have been continuously collected at Mauna Loa Observatory, Hawaii (19°32′ N, 155°35′ W), since 1958. Four air samples are collected each hour and are analyzed by infrared spectroscopy for CO_2 concentrations. It has to be pointed out that Mauna Loa site is considered one of the most favorable locations for measuring undisturbed air because possible local influences of vegetation or human activities on atmospheric CO_2 concentrations are minimal and any influences from volcanic vents may be excluded from the records. In addition, the methods and equipment used to obtain these measurements have remained essentially unchanged during the 47-year monitoring program (Keeling and Whorf, 2005). The averaged mean monthly values of the CO_2 concentrations are herewith analyzed by employing the DFA method (detailed information is given in Varotsos and Kirk-Davidoff, 2006, and in references therein), which is briefly described below.

In DFA the nonstationary time series $y(t)$ is first integrated and then it is divided into segments of equal length, Δt. In each segment, a least squares line (or polynomial curve of order /, DFA-/) is then fitted, in order to detrend the integrated time series by subtracting the locally fitted trend in each segment. The root-mean-square fluctuations

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$F_d(\Delta t)$ of this integrated and detrended time series is calculated over all time scales (segment sizes).

More specifically, the detrended fluctuation function $F(\tau)$ is calculated as follows:

$$F^2(\tau) = \frac{1}{\tau} \sum_{t=k\tau+1}^{(k+1)\tau} [y(t) - z(t)]^2, \quad k = 0, 1, 2, \ldots, \left(\frac{N}{\tau} - 1\right) \tag{1}$$

where $z(t)=at+b$ is the linear least-square fit to the τ data points contained into a segment.

Without dwelling upon details, for scaling dynamics, the averaged $F^2(\tau)$ over the N/τ intervals with length τ is expected to obey a power-law, notably:

$$\left\langle F^2(\tau) \right\rangle \sim \tau^{2\alpha} \tag{2}$$

and the power spectrum function scales with $1/f^{\beta}$, with $\beta=2\alpha-1$ (Kantelhardt et al., 2002).

We briefly mention that the slope α of the line on a log-log plot relating the average fluctuation and the box size indicates the plausible presence of power law scaling. A slope $\alpha \neq 1/2$ implies the existence of long-range correlations, while $\alpha=1/2$ corresponds to the classical random (white) noise. If $0<\alpha<0.5$, power-law anticorrelations are present (antipersistence). If $0.5<\alpha\leq 1.0$, long-range power-law correlations prevail; the case $\alpha=1$ corresponds to the so-called $1/f$ noise. In addition, when $1<\alpha<1.5$, then long-range correlations are again present (but are stronger than in the previous case) (e.g., Talkner and Weber, 2000; Talkner and Weber, 2000).

It is worth to recall that a time-series is said to display long-range correlations when some properties of the time-series at different times are correlated and its correlation function decays much slower than exponential decay (e.g. power-law decay). It would be of interest to mention that wavelet-based estimators of self-similarity or long-range dependence scaling exponent lead to larger (smaller) mean squared errors for short (long) time-series comparing with DFA that is not wavelet-based (Chen et al., 2005).

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3 Application of DFA to the CO_2 time-series

In order to analyze the time series (shown in Fig. 1) it is important to investigate whether the CO_2 concentration at different times is actually correlated. The motivation for this investigation stems from the observation that many environmental quantities have values which remain residually correlated with one another even after many years (long-range dependence).

It is a truism that the standard tool to address this question is to derive the correlation function and the corresponding power spectrum (or frequency spectrum – spectral density) of the time series, which is simply the Fourier transform of the autocorrelation function. Usually, the short-range correlations are described by the autocorrelation function, which declines exponentially with a certain decay time. In opposite, the long-range correlations (long-range dependence) imply that the autocorrelation function declines as a power-law in time rather than exponentially. This implies that: a correctly rescaled subset of the original time series resembles the original time series. However, the direct calculation of the autocorrelation function is usually not appropriate due to noise superimposed on the collected data and due to underlying trends of unknown origin. Furthermore, in practice, we do not know the appropriate scaling transformation factors, in advance, or if one does exist.

To quantify the fluctuations of the measured CO_2 concentrations we analyze the data following the steps of DFA (described in Sect. 2). The application of DFA-1 to the deseasonalized and detrended CO_2 concentration time-series reveals α=1.05±0.04 (Fig. 2) for time scales between 4 months to 11 years. We found the same results by using a polynomial fit of order / (DFA-/) to the same time series of the CO_2 concentrations. More specifically, going from DFA-1 to DFA-5, the α-value was found to range from 0.98 to 1.08. Therefore, the fluctuations of the CO_2 concentrations exhibit 1/f – type long-range persistence. The strong persistence found signifies that the fluctuations in CO_2 concentration, from small time intervals to larger ones (up to 11 years) are positively correlated in a power-law fashion. In other words, persistence refers to the

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"memory" or internal correlation within the CO_2 concentration time-series. For example, there is a tendency an increase in the CO_2 concentration to be followed by another increase in the CO_2 concentration at a different time in a power-law fashion. The latter conclusion illustrates that the correlations between the fluctuations in CO_2 concentration do not obey the classical Markov-type stochastic behavior (exponential decrease with time), but display more slowly decaying correlations.

One fact that attracts attention is that the persistence found above provides, in principle, a forecast for the CO_2 concentration, which assumes that the value of the CO_2 concentration the "following time interval" (up to 11 years) will be the same as in the corresponding "current time interval". In reality, it apparently has a different meaning from the conventional forecast in climatology, which assumes that the value of CO_2 concentration in the "following" e.g. 11 years will be the same as the "overall climatological" CO_2 concentration mean.

Finally, it was investigated whether the persistence found in CO_2 concentration time series stems from the values of CO_2 concentrations by themselves and not from their time evolution. With this aim in view, the deseasonalized and detrended CO_2 concentrations were randomly shuffled. If the shuffled CO_2 values follow the random (white) noise, then the persistence found above does not come from the data, but from their time evolution (e.g., Varotsos et al., 2006). Indeed the application of the DFA-1 to the shuffled CO_2 data gives α=0.49±0.02, which reveals that the shuffled deseasonalized and detrended CO_2 data are practically uncorrelated. Therefore the power-law relationship derived from the real measurements of the carbon dioxide concentrations eventually stems from their time evolution. The latter could also be used to test the scaling performance of the climate prediction models under different scenarios of carbon dioxide levels (Ebel, 2001; Govindan et al., 2002).

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4 Conclusions

Long-range correlations of the fluctuations of CO_2 concentrations measured at Mauna Loa, Hawaii during 1958–2004 were investigated by applying the DFA method. The main finding is that the fluctuations of the CO_2 concentrations exhibit 1/f – type long-range persistence, which signifies that the fluctuations in CO_2 concentrations, from small time intervals to larger ones (up to 11 years) are positively correlated in a power-law fashion. This scaling comes from the time evolution and not from the values of the carbon dioxide data. The scaling property detected in the real observations of CO_2 concentrations could be used to test the scaling performance of the leading global climate models under different scenarios of CO_2 levels and to improve the performance of the atmospheric chemistry-transport models.

References

Asher, W. E., Jessup, A. T., and Atmane, M. A.: Oceanic application of the active controlled flux technique for measuring air-sea transfer velocities of heat and gases, J. Geophys. Res.-Oceans, 109(c8), C08S12, doi:10.1029/2003JC001862, 2004.

Aziz, M. A., Reising, S. C., Asher, W. E., Rose, L. A., Gaiser, P. W., and Horgan, K. A.: Effects of air-sea interaction parameters on ocean surface microwave emission at 10 and 37 GHz, IEEE Trans. Geosci. Rem. Sens., 43(8), 1763–1774, 2005.

Berger, U. and Dameris, M.: Cooling of the upper-atmosphere due to CO_2 increases – a model study, Ann. Geophys, 11(9), 809–819, 1993.

Cartalis, C. and Varotsos, C.: Surface ozone in Athens, Greece, at the beginning and at the end of the 20th-century, Atmos. Environ., 28(1), 3–8, 1994.

Chen, Z., Hu, K., Carpena, P., Bernaola-Galvan, P., Stanley, H. E., and Ivanov, P.: Effect of nonlinearities on detrended fluctuation analysis, Phys. Rev. E 71, 011104, doi:10.1103/PhysRevE.71.011104, 2005.

Chen, Z., Ivanov, P. C., Hu, K., and Stanley, H. E.: Effect of nonstationarities on detrended fluctuation analysis, Phys. Rev. E, 65(4), 041107, doi:10.1103/PhysRevE.65.041107, 2002.

Crutzen, P. J., Lawrence, M. G., and Pöschl, U.: On the background photochemistry of tropospheric ozone, Tellus A, 51(1), 123–146, 1999.
Dameris, M., Grewe, V., Ponater, M., Deckert, R., Eyring, V., Mager, F., Matthes, S., Schnadt, C., Stenke, A., Steil, B., Bruhl, C., and Giorgetta, M. A.: Long-term changes and variability in a transient simulation with a chemistry-climate model employing realistic forcing, Atmos. Chem. Phys., 5, 2121–2145, 2005.
Ebel, A.: Evaluation and reliability of meso-scale air pollution simulations, Lect. Notes Comput. Sci., 2179, 255–263, 2001.
Eyring, V., Harris, N. R. P., Rex, M., Shepherd, T. G., Fahey, D. W., Amanatidis, G. T., Austin, J., Chipperfield, M. P., Dameris, M., Forster, P. M. F., Gettelman, A., Graf, H. F., Nagashima, T., Newman, P. A., Pawson, S., Prather, M. J., Pyle, J. A., Salawitch, R. J., Santer, B. D., and Waugh D. W.: A strategy for process-oriented validation of coupled chemistry-climate models, Bull. Am. Meteorol. Soc., 86(8), 1117, 2005.
Govindan, R. B., Vyushin, D., Bunde, A., Brenner, S., Havlin, S., and Schellnhuber, H. J.: Global climate models violate scaling of the observed atmospheric variability, Phys. Rev. Lett., 89(2), 028501, doi:10.1103/PhysRev.Lett.89.028501, 2002.
Grytsai, A., Grytsai, Z., Evtushevsky, A., and Milinevsky, G.: Interannual variability of planetary waves in the ozone layer at 65 degrees S, Int. J. Remote Sens., 26(16), 3377–3387, 2005.
Hu, K., Ivanov, P. C., Chen, Z., Carpena, P., and Stanley, H. E.: Effect of trends on detrended fluctuation analysis, Physi. Rev. E, 64(1), 011114, doi:10.1103/PhysRevE.64.011114, 2001.
Jacovides, C. P., Varotsos, C., Kaltsounides, N. A., Petrakis, M., and Lalas, D. P.: Atmospheric turbidity parameters in the highly polluted site of Athens basin, Renewable Energy, 4(5), 465–470, 1994.
Kantelhardt, J. W., Zschiegner, S. A., Koscielny-Bunde, E., Havlin, S., Bunde, A., and Stanley, H. E.: Multifractal detrended .uctuation analysis of nonstationary time series, Physica A, 316(1–4), 87–114, 2002.
Keeling, C. D. and Whorf, T. P.: Atmospheric CO_2 records from sites in the SIO air sampling network. In Trends: A Compendium of Data on Global Change. Carbon Dioxide Information Analysis Center, Oak Ridge National Laboratory, U.S. Department of Energy, Oak Ridge, Tenn., USA, (http://cdiac.esd.ornl.gov/trends/co2/sio-mlo.htm), 2005.
Kondratyev, K. Ya. and Varotsos, C.: Atmospheric greenhouse effect in the context of global climate change, NUOVO CIMENTO C 18(2), 123–151, 1995.
Kondratyev, K. Y. and Varotsos, C.: Global tropospheric ozone dynamics –Part I: Tropospheric

ozone precursors – Part II: Numerical modelling of tropospheric ozone variability, Environ. Sci. Pollut. Res., 8(1), 57–62, 2001a.
Kondratyev, K. Y. and Varotsos, C.: Global tropospheric ozone dynamics – Part II: Numerical modelling of tropospheric ozone variability – Part I: Tropospheric ozone precursors [ESPR 8(1) 57–62 (2001)], Environ. Sci. Pollut. Res., 8(2), 113–119, 2001b.
Koscielny-Bunde, E., Bunde, A., Havlin, S., Roman, H. E., and Goldreich, Y., Schellnhuber, H. J.: Indication of a universal persistence law governing atmospheric variability, Phys. Rev. Lett., 81(3), 729–732, 1998.
Lovejoy, S.: Area-perimeter relation for rain and cloud areas, Science, 216(4542), 185–187, 1982.
Peng, C. K., Buldyrev, S. V., Havlin, S., Simons, M., Stanley, H. E., and Goldberger, A. L.: Mosaic organization of DNA nucleotides, Phys. Rev. E, 49(2), 1685–1689, 1994.
Stanley, E.: Scaling, universality, and renormalization: three pillars of modern critical phenomena, Reviews of Modern Physics, 71(2), S358–S366, 1999.
Schertzer, D. and Lovejoy, S.: The dimension and intermittency of atmospheric dynamics, in Turbulent Shear Flows, 4, Springer, New York, 7–33, 1985.
Schulz, A., Rex, M., Harris, N. R. P., et al.: Arctic ozone loss in threshold conditions: Match observations in 1997/1998 and 1998/1999, J. Geophys. Res.-Atmos., 106(D7), 7495–7503, 2001.
Syroka, J. and Toumi, R.: Scaling and persistence in observed and modelled surface temperature, Geophys. Res. Lett., 28(17), 3255–3258, 2001.
Talkner, P. and Weber, R. O.: Power spectrum and detrended fluctuation analysis: application to daily temperatures, Phys. Rev. E, 62(1), 150–160 Part A, 2000.
Tuck, A. F. and Hovde, S. J.: Fractal behavior of ozone, wind and temperature in the lower stratosphere, Geophys. Res. Lett., 26, 1271–1274, 1999.
Tuck, A. F., Hovde, S. J., Gao, R. S., and Richard, E. C.: Law of mass action in the Arctic lower stratospheric polar vortex January–March 2000: ClO scaling and the calculation of ozone loss rates in a turbulent fractal medium, J. Geophys. Res.-Atmos., 108(D15), 4451, doi:10.1029/2002JD002832, 2003.
Varotsos, C., Kondratyev, K. Y., and Efstathiou, M.: On the seasonal variation of the surface ozone in Athens, Greece, Atmos. Environ., 35(2), 315–320, 2001.
Varotsos, P. A., Sarlis, N. V., and Skordas, E. S.: Long-range correlations in the electric signals that precede rupture, Phys. Rev. E, 66, 011902, doi:10.1103/PhysRevE.66.011902, 2002.

Varotsos, C.: The southern hemisphere ozone hole split in 2002 Environ, Sci. Pollut. R, 9(6), 375–376, 2002a.
Varotsos, C.:Climate Change problems and carbon Dioxide Emissions: Expecting “Rio+10”, Environ. Sci Pollut Res., 9(2), 97–98, 2002b.
Varotsos, P. A., Sarlis, N. V., and Skordas, E. S.: Long-range correlations in the electric signals that precede rupture: further investigations, Phys. Rev. E, 67, 21 109–21 121, 2003a.
Varotsos, P. A., Sarlis, N. V., and Skordas, E. S.: Attempt to distinguish electric signals of a dichotomous nature, Phys. Rev. E, 68(3), 031106, doi:10.1103/PhysRevE.68.031106, 2003b.
Varotsos C., Ondov, J., and Efstathiou M.: Scaling properties of air pollution in Athens, Greece and Baltimore, Maryland, Atmos. Environ., 39(22), 4041–4047, 2005.
Varotsos, C.: Power-law correlations in column ozone over Antarctica, Int. J. Remote Sens., 26(16), 3333–3342, 2005a.
Varotsos, C.: Modern computational techniques for environmental data; Application to the global ozone l ayer, (Proceedings of the ICCS 2005) Lect. Notes Comput. Sci., 3516, 504–510, 2005b.
Varotsos, C. and Kirk-Davidoff, D.: Long-memory processes in ozone and temperature variations at the region 60 degrees S-60 degrees N, Atmos. Chem. Phys., 6, 4093–4100, 2006.
Varotsos, P. A., Sarlis, N. V., Skordas, E. S., Tanaka, H. K., and Lazaridou, M. S.: Attempt to distinguish long-range temporal correlations from the statistics of the increments by natural time analysis, Phys. Rev. E, 74, 021123, doi:10.1103/PhysRevE.74.021123, 2006.
Zhu, J. and Liu, Z.: Long-range persistence of acid deposition, Atmos. Environ., 37, 2605–2613, 2003.

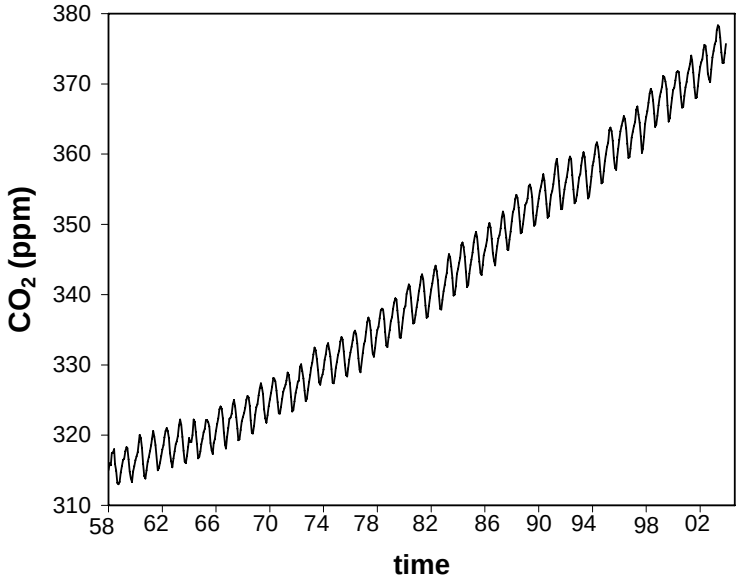

Fig. 1. Time series of CO_2 concentration observed at Mauna Loa Observatory, during 1958–2004.

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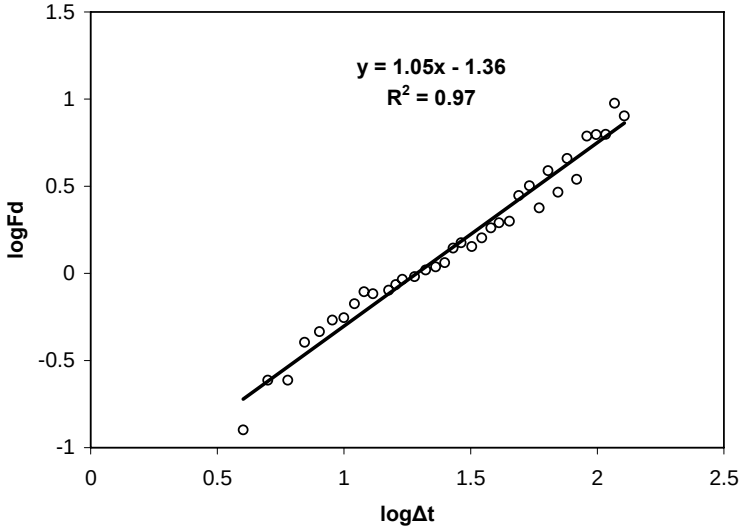

Fig. 2. Log-log plot of the DFA-function versus temporal interval Δt (in months) for detrended and deseasonalized CO_2 concentrations, during 1958–2004.

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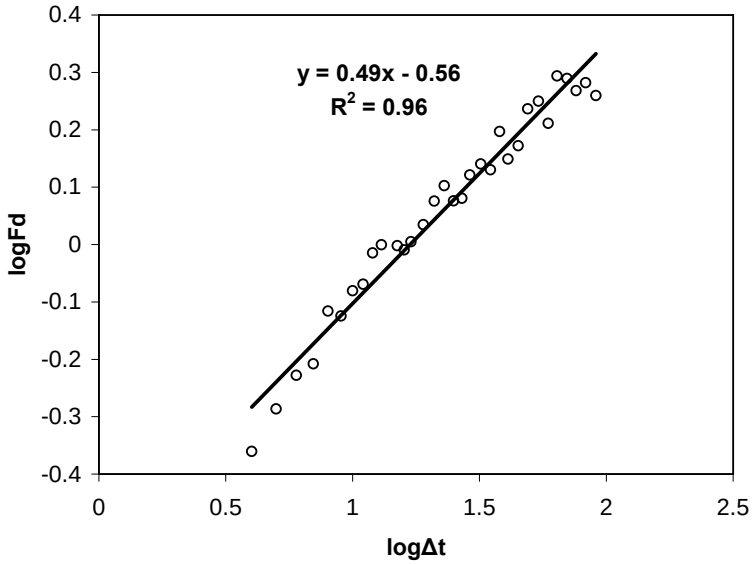

Fig. 3. Log-log plot of the DFA-function versus temporal interval Δt (in months) for the shuffled detrended and deseasonalized CO_2 concentrations, during 1958–2004.

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