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DETRENDED FLUCTUATION ANALYSIS OF BULGARIAN SURFACE TEMPERATURE RECORDS: COMPARISION OF COASTAL AND INLAND STATIOINS

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Милен Цеков, Елисавета Пенева. ФЛУКТУАЦИОНЕН АНАЛИЗ С ПРЕМАХВАНЕ НА ТРЕНДОВЕТЕ НА ТЕМПЕРАТУРНИ РЕДИЦИ ОТ БЪЛГАРСКИ МЕТЕОРОЛОГИЧНИ СТАНЦИИ: СРАВНЕНИЕ НА РЕЗУЛТАТИТЕ ЗА КРАЙБРЕЖНИ И ВЪТРЕШНОКОНТИНЕНТАЛНИ СТАНЦИИ

В настоящата статия ние изучаваме далечните корелации в 22 температурни редици от български крайбрежни и вътрешноконтинентални метеорологични станции. Установяваме, че далечните корелации са по-силни в крайбрежните райони, отколкото във вътрешността на страната, като наблюдаваните стойности на скейлинговия показател са характерни за корелационните свойства на повърхностната температура на морската вода. Ние установяваме също, че за станциите във вътрешността на страната се наблюдава по-силна статистическа памет в температурните редици от Северна България, отколкото в тези от Южна България.

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Milen Tsekov, Elisaveta Peneva. DETRENDED FLUCTUATION ANALYSIS OF BULGARIAN SURFACE TEMPERATURE RECORDS: COMPARISION OF *COASTAL AND INLAND STATIOINS*

We study long-term correlations in 22 temperature records from coastal and inland regions in Bulgaria. We find that temperature records from coastal regions exhibit higher long-term correlations than temperature records from inland regions. For coastal stations persistence is characterized by scaling exponents which are typical of sea surface temperature persistence. We also find that inland temperature records from North Bulgaria exhibit stronger persistence than inland temperature records from South Bulgaria.

Keywords: detrended fluctuation analysis (DFA), temperature records
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1. INTRODUCTION

Characterizing long-term correlations in climate records is of prime importance for understanding natural variability of the climate system. In the recent years several research groups studied scaling and correlation properties in great number of climate records and their geographical distribution [1–8]. Koscielny-Bunde et al. analyzed 14 daily temperature records from Europe, North America and Australia, and found that all these records exhibit long-term power-law correlations with scaling exponent indicating persistence [1]. Scientists from the same research group later found stronger persistence over the oceans and for small islands than for inland stations [2–3]. Talkner and Weber found that the strength of the long-term correlations depends on the altitude [4–5]. They also analyzed long-term correlations in climate variables other than the temperature. Fraedrich and Blender analyzed temperature records over a grid set covering the globe and found strong persistence over the oceans, lack of persistence over the inner continents and transient behavior in the coastal regions [6]. Kiraly and Janosi reported latitude dependence of the value of the scaling exponent characterizing persistence in temperature records from Australian weather stations [8].

Due to the lack of enough detailed studies one of the open questions is whether temperature records from locations in proximity to sea coasts exhibit strong long-term correlations with scaling exponent $\alpha \approx 0.65$ which is typical for the persistence of sea surface temperature or weaker long-term correlations typical for atmospheric persistence. In this study we consider long-term correlations in 22 monthly temperature records from Bulgarian weather stations. We compare results for 11 coastal weather stations situated within distance of ten kilometers from the Black Sea coast with those for 11 temperature records from Central and West Bulgaria. We find that temperature records from coastal regions exhibit higher long-term persistence than temperature records from inland regions. Moreover, for the coastal temperature records we obtain estimates of the scaling exponent characterizing long-term correlations which are typical for the strong persistence of the sea surface temperature and are higher than reported values of the scaling exponent for temperature records from other coastal regions. We also analyze latitude dependence of the values of the scaling exponent and we find that inland temperature records from North Bulgaria exhibit stronger persistence than inland temperature records from South Bulgaria.

The outline of the paper is as follows. In Section 2 we describe the data and we review the method of analysis. In Section 3 we present and discuss the results. Finally, in Section 4 we summarize our findings.

2. DATA AND METHOD

The data set we use in this study consists of 11 mean monthly temperature records from coastal regions and 11 inland mean monthly temperature records. For eight of the coastal stations we have monthly data over the time period 1961–1990 and the corresponding temperature records consist of 360 data points. Three of the coastal temperature records are shorter. For weather station Emine data are available for the period from January 1966 to December 1990 while for weather station Ahtopol we have data for the period from January 1971 to December 1990. Even shorter record is available for Burgas – from January 1973 to December 1990. All coastal stations (Ahtopol, Carevo, Burgas, Pomorie, Nesebar, Emine, Obzor, Staro Oriahovo, Varna, Kaliakra, and Shabla) are situated within distance of 10 kilometers from the Black Sea. To compare correlation properties of temperature records from coastal and inland regions we select 11 inland temperature records from weather stations in Central and West Bulgaria located at least 150 kilometers away from the Black Sea – Petrich, Sandanski, Krumovgrad, Haskovo, Chirpan, Sevlievo, Vratza, Kneja, Pleven, Lom, and Vidin. Thus we minimize maritime influence on inland temperature records. To avoid also possible altitude dependence we exclude high elevation stations. Highest station we use is Vratza with elevation of 309 meters. All temperature records in the used data set have a pronounced annual cycle which may shadow possible long-term correlations in the data. To remove the annual cycle we calculate the average over all years for each calendar month and then subtract the resulting mean annual cycles from the original records. Resulting temperature anomaly records are shown in Figs. 1 and 2.

To quantify long-term correlations in the studied time series we apply the DFA method [9] which consists of the following steps: (i) we first integrate the temperature anomaly records S_i to construct the profile $Y(k) = \sum_{i=1}^{k} (S_i - \langle S \rangle)$, where $\langle S \rangle$ is the mean value of the corresponding series over the period we consider; (ii) we partition the profile $Y(k)$ into consecutive segments of length s and fit the local trend in each segment with a least-squares polynomial fit; (iii) we then detrend the profile $Y(k)$ by subtracting the local polynomial trend in each segment of length s, and we calculate the root mean square fluctuation $F(s)$ for the detrended profile. For order-p DFA (DFA-1 if p = 1, DFA-2 if p = 2, etc.) a polynomial function of order p is applied for the fitting of the local trend in each segment of the profile $Y(k)$; (iv) this procedure is repeated for different time scales s.

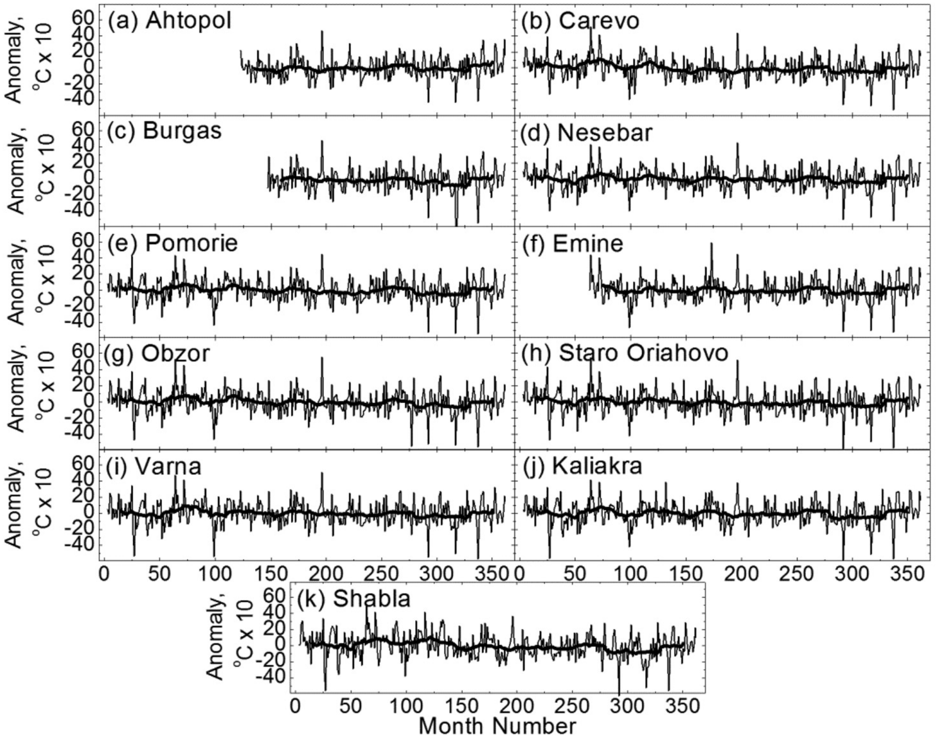

Fig. 1. Monthly temperature anomaly records obtained by removing annual cycle from the original temperature data measured at the coastal weather stations Ahtopol, Carevo, Burgas, Pomorie, Nesebar, Emine, Obzor, Staro Oriahovo, Varna, Kaliakra, and Shabla. For eight stations (Carevo, Pomorie, Nesebar, Obzor, Staro Oriahovo, Varna, Kaliakra, and Shabla) the data are for the period from January 1961 to December 1990 and consist of 360 monthly temperature anomaly values. For station Burgas the data are for the period from January 1973 to December 1990 and consist of 216 monthly temperature anomaly values. For station Ahtopol the data are for the period from January 1971 to December 1990 and consist of 240 monthly temperature anomaly values. For station Emine the data are for the period from January 1960 to December 1990 and consist of 300 monthly temperature anomaly values. Solid lines represent low frequency fluctuations obtained by "moving average" filter with window size of 25 months

A power-law relation $F(s) \propto s^{\alpha}$ indicates presence of scaling in theinvestigated series. Thus the fluctuations in S_i can be characterized by the scaling exponent α, a self-similarity parameter that quantifies the power-law correlation properties of the signal. To ensure sufficient statistics when calculating $F(s)$ for large box sizes s, and thus a more accurate estimate of the scaling exponent α at large time scales, we choose the maximum box size to be$s = N/4$, where N is the length of the temperature records. To increase additionally the statistics at large time scales we apply „sliding window" version of DFA removing the polynomial trend in each overlapping window.

The scaling exponent α is related to the autocorrelation function exponent γ ($C(s) \propto s^{-\gamma}$ when $0 < \gamma < 1$) and to the power spectrum exponent β ($S(f) \propto 1/f^{\beta}$) by $\alpha = 1 - \gamma/2 = (\beta + 1)/2$. A value of $\alpha = 0.5$ indicates that there are no correlations and the signal is uncorrelated (white noise). If $\alpha < 0.5$ the signal is said to be anti-correlated, meaning that large values are more likely to be followed by small values. If $\alpha > 0.5$ the signal is correlated and exhibits persistent behavior, meaning that large values are more likely to be followed by large values and small values by small values. The higher the value of α, the stronger the correlations in the signal. The DFA method is widely used in studies of long-term correlations in time series because of its ability to quantify persistence to much larger time scales than the autocorrelation function or the spectral density even in presence of trends in the data.

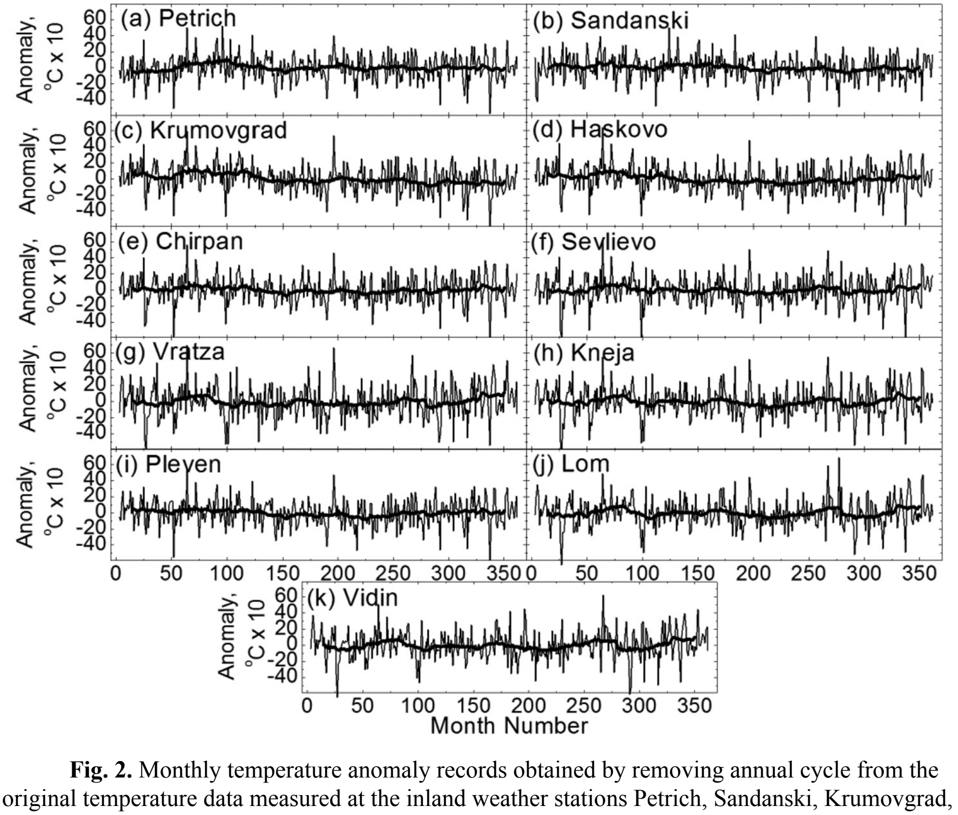

Fig. 2. Monthly temperature anomaly records obtained by removing annual cycle from the original temperature data measured at the inland weather stations Petrich, Sandanski, Krumovgrad, Haskovo, Chirpan, Sevlievo, Vratza, Kneja, Pleven, Lom, and Vidin. All individual records consist of 360 monthly temperature anomaly values for the period from January 1961 to December 1990. Solid lines represent low frequency fluctuations obtained by "moving average" filter with window size of 25 months.

3. RESULTS AND DISCUSSION

In Figs. 3 and 4 we show the results of our analysis for the coastal records (Fig. 3) and for the inland records (Fig. 4) obtained using the DFA-1, DFA-2 and DFA-3 methods. On double logarithmic plot we present the dependence of the fluctuation function $F(s)$ on the time scale s. In the presence of power-law correlations in the studied records $\log F(s)$ will increase linearly with $\log(s)$, where the slope is the scaling exponent α. DFA-1, DFA-2, and DFA-3 estimate the correlations in the fluctuations of the time series by removing constant, linear and quadratic trends respectively.

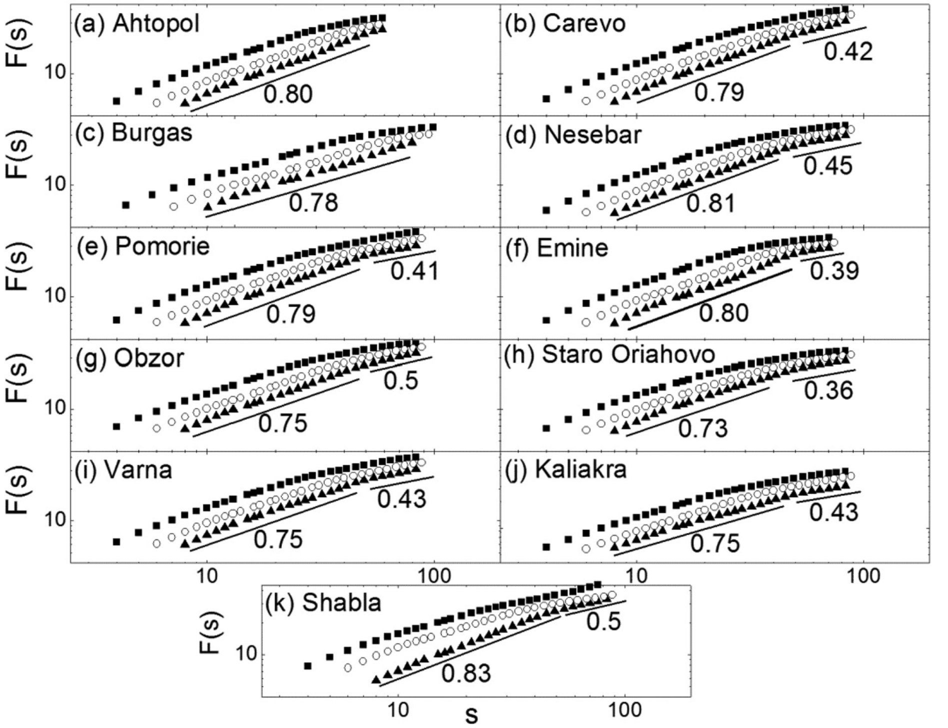

Fig. 3. Root mean square fluctuation, $F(s)$, obtained using DFA-1, DFA-2 and DFA-3 for monthly records of temperature anomalies from 11 coastal weather stations over the periods summarized in Section 2. Stations are indicated in the corresponding panels. Filled squares: DFA-1, empty circles: DFA-2, and filled triangles: DFA-3. On time scales up to about 30 months all temperature records exhibit positive power-law correlations. The value of the scaling exponents characterizing this persistent behavior is indicated in every panel. On large time scales the scaling curves for all records exhibit lower slopes. For more discussion see the text

Our results show that all temperature records exhibit positive long-term correlations on time scales up to about 30 months. At larger time scales we observe change in the scaling behavior for all records. The DFA-1 scaling curves for all temperature records exhibit a crossover at time scales about 30 months from a region with positive correlations ($\alpha > 0.5$) to a region with negative slope ($\alpha < 0.5$). Higher orders of the DFA method shift the position of the observed crossovers to larger time scales for all temperature records in accordance with the findings of Hu et al. [10]. The values of the scaling exponent $\alpha < 0.5$ we observe suggest antipersistent behavior at large time scales, however we do not interpret this result as an indication of intrinsic atmospheric antipersistence. Correlation studies of longer temperature records indicate that power-law scaling persists up to years and even decades [1–8]. We suggest that the apparent antipersistent behavior at time scales longer than 30 months results from usage of very short temperature records and it is manifestation of statistical fluctuation due to low number of windows of large width over which we estimate fluctuations.

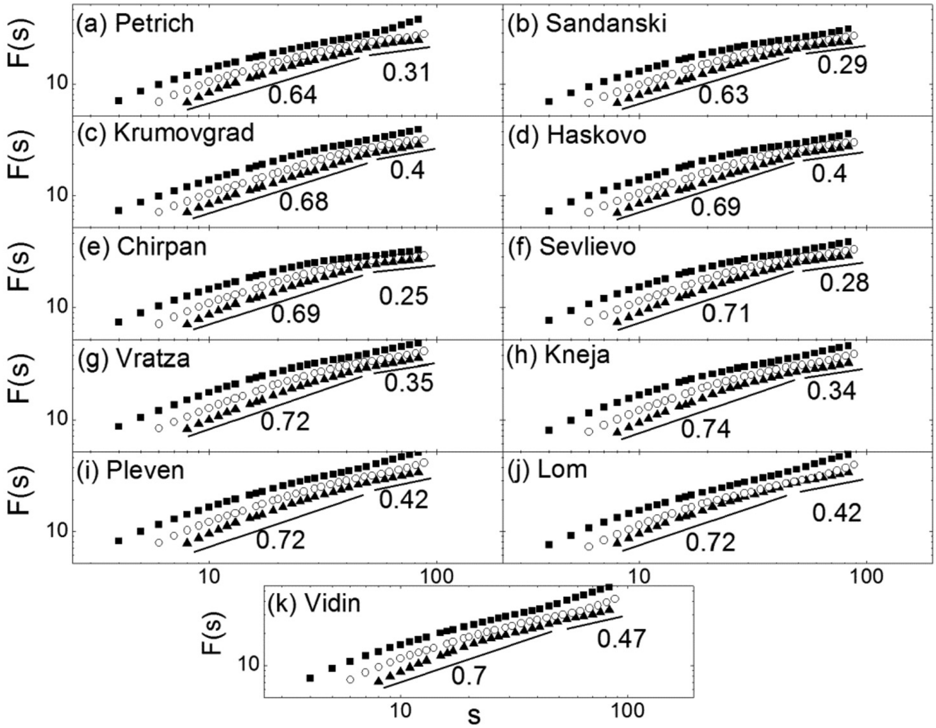

Fig. 4. Root mean square fluctuation, F(s), obtained using DFA-1, DFA-2 and DFA-3 for monthly records of temperature anomalies from 11 inland weather stations over the period 1961–1990. Filled squares: DFA-1, empty circles: DFA-2, and filled triangles: DFA-3. Stations are indicated in the corresponding panels. On time scales up to about 30 months all temperature records exhibit positive power-law correlations. The values of the scaling exponent characterizing this persistent behavior are indicated in every panel. On large time scale the scaling curves for all records exhibit lower slopes. For more discussion see the text

To confirm this suggestion we study the scaling properties of synthetic correlated signals of length 360 data points equal to the length of the investigated temperature records. Using the algorithm of Makse et al. [11] we generate a correlated noise signal with scaling exponent $\alpha = 0.7$ and length 3600 data points. We apply DFA-2 to quantify scaling properties of the signal and we observe a linear increase of the scaling curve indicating power-law scaling up to time scale of about 350 data points (Fig. 5). Next we split the correlated signal into 10 segments of length 360 data points and we estimate the correlations in each segment (Fig. 6). Four of the segments exhibit power-law scaling over the entire range of scales (panels (b), (d), (e), (h) in Fig. 6). For the other six segments we observe crossovers in the scaling curves from regions with power-law scaling characterized by $\alpha \approx 0.7$ at small time scales to regions with higher or lower slopes of the scaling curves at large time scales. Positions of the observed crossover differ for the different segments and range between 25 and 50. For the segments exhibiting crossovers the DFA-2 method can estimate properly the scaling exponents of the correlated noise signals only on time scales lower than the positions of the crossovers. At large time scales for some of the segments we observe higher fluctuations than is expected for correlated signals with scaling exponent $\alpha = 0.7$ while for other segments we observe lower than expected fluctuations. This results from statistical fluctuation due to the low number of boxes with large box sizes over which we estimate fluctuations at large time scales. In a long term segments of the signal with low and high fluctuations at large time scales balance each other and the power-law scaling extends to larger time scales (Fig. 5). However, for short signal segments we observe crossovers from regions in the scaling curves with a slope reflecting true correlations to regions with higher or lower but false persistence. Moreover, we find that correlated noise signals of length equal to the length of the studied temperature records may exhibit crossovers at the same time scales where we observe crossovers in the temperature records. In conclusion, our experiments with synthetic correlated signals and the observation of power-law scaling behavior up to many years and even decades when large enough temperature records are available [1–8] indicate that our finding of crossovers to apparent antipersistent behavior for temperature records at time scales above 30 months most probably does not reflect intrinsic atmosphere dynamics but results from the fact that the temperature records we study are very short.

Thus, we conclude that the analyzed temperature records may exhibit positive power-law correlations to even larger time scales than 30 months, however the insufficient length of the records precludes observation of correct power-law scaling behavior at large time scales. We quantify the strength of the long-term correlations by estimating the slope of the segments of the DFA scaling curves exhibiting positive power-law scaling behavior. To facilitate comparison between different stations we estimate the scaling exponent for all temperature records by the DFA-3 scaling curve in one and the same range of scales – from 8 to 45 months. This is the largest range of scales for which we observe positive power-law correlations in the DFA-3 scaling curves for all temperature records.

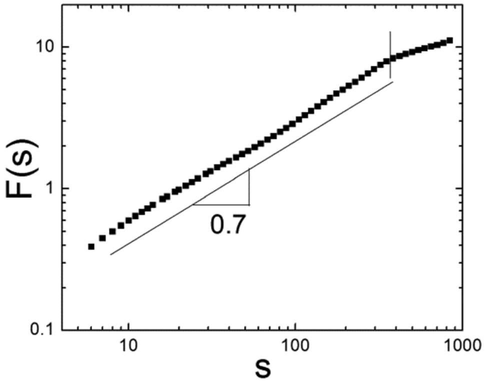

Fig. 5. Root mean square fluctuation, F(s), obtained using DFA-2 for a correlated noise signal with scaling exponent $\alpha = 0.7$ and size 3600 data points. The scaling curve exhibit linear increase indicating power-law correlations up to time scale of about 350 data points. A line with slope $\alpha = 0.7$ is drawn to guide the eye

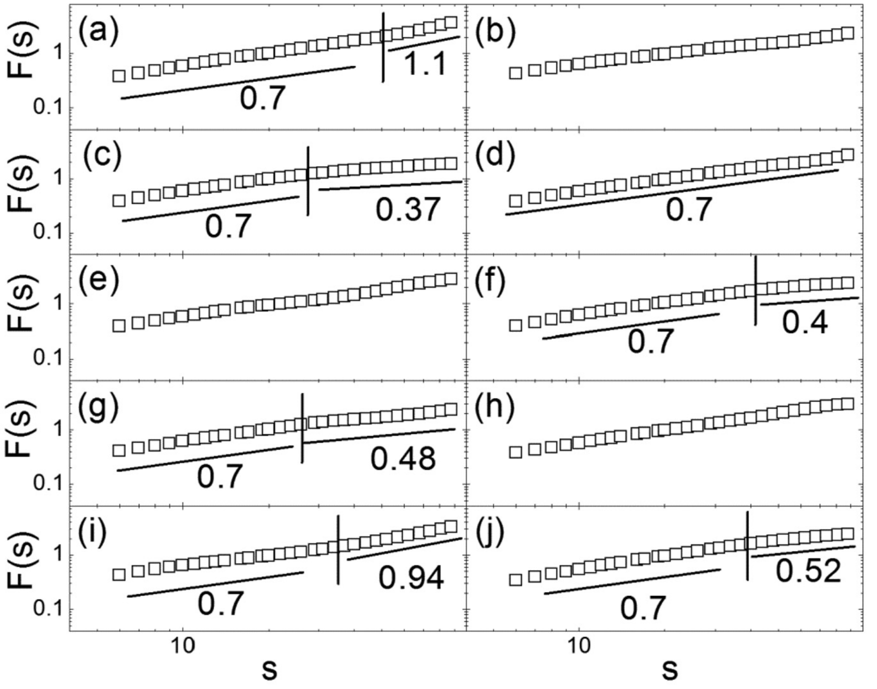

Fig. 6. Root mean square fluctuation, F(s), obtained using DFA-2 for segments of correlated noise signal with scaling exponent $\alpha = 0.7$. Each segment consists of 360 data points. Four of the records exhibit power-law correlations over the entire range of scales. Scaling curves for the other segments exhibit crossovers from regions with slope $\alpha \approx 0.7$ to regions with different slope. Slopes of the DFA-2 scaling curves above the crossover time scales are calculated and indicated in the figure

Obtained values of the scaling exponents are indicated in the individual panels in Figs. 3 and 4 and are summarized in Fig. 7. We observe stronger persistence for coastal stations than for inland stations. The mean value of the scaling exponent for coastal temperature records is 0.78 while for inland temperature records it is 0.7. The values of the scaling exponent we observe for coastal stations are high and are typical for the sea surface temperature persistence and atmospheric temperature persistence on small islands [2, 3]. We note that in previous studies temperature records from coastal regions have been observed to exhibit persistence characterized by scaling exponent $\alpha \approx 0.65$ which is weaker than the persistence of the sea surface temperature characterized by scaling exponent $\alpha \approx 0.8$ [3, 6]. Thus, our finding that the scaling behavior of coastal temperature records is analogous to the scaling behavior of sea surface temperature is not trivial and not even typical. For the inland stations we observe stronger long-term correlations for North Bulgaria than for South Bulgaria. Previously latitude dependence of the scaling exponent has been reported for Australia [8]. As a consequence the contrast in the correlation properties between coastal and inland regions is greater in South Bulgaria than in North Bulgaria (Fig. 7). We hypothesize that this difference may be related to the different topography of North Bulgaria and South Bulgaria. The flatter topography of North Bulgaria favors stronger maritime influence on the temperature fluctuations which, in turn, mitigate the difference in strength of long-term correlations between coastal and inland regions.

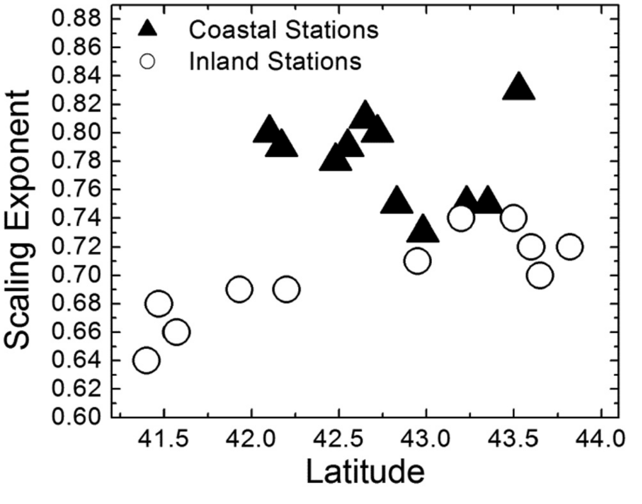

Fig. 7. Obtained values of the scaling exponent characterizing long-term correlations as a function of the station latitude. Filled triangles: coastal stations. Empty circles: inland stations

4. SUMMARY

The main findings of our study may be summarized as follows. Temperature records from coastal regions in Bulgaria exhibit stronger long-term correlations than temperature records from inland stations. The values of the scaling exponent characterizing persistence in coastal temperature records are typical for the observed persistence of sea surface temperature. Scaling properties of inland temperature records exhibit latitude dependence with stronger persistence observed for North Bulgaria than for South Bulgaria. Contrast in scaling properties of temperature records between coastal and inland regions is higher in South Bulgaria than in North Bulgaria.

REFERENCES

[1] Koscielny-Bunde, E., A. Bunde, S. Havlin, H. E. Roman, Y. Goldreich, H. J. Schellnhuber, *Phys. Rev. Lett.*, 1998, **81**, 729.

[2] Monetti, R. A., S. Havlin, A. Bunde. *Physica A*, 2003, **320**, 581.

[3] Eichner, J.F., E. Koscielny-Bunde, A. Bunde, S. Havlin, H.J. Schellnhuber. *Phys. Rev. E*, 2003, **68**, 046133.

[4] Talkner, P., R.O. Weber. *Phys. Rev. E*, 2000, **62**, 50.

[5] Weber, R.O., P. Talkner. *J. Geophys. Res.,* 2001*,* **106**, 20131.

[6] Fraedrich, K., R. Blender. *Phys. Rev. Lett*., 2003, **90**, 108501.

[7] Blender, R., K. Fraedrich. *Geophys. Res. Lett*., 2003, **30**, 14, 1769.

[8] Kiraly, A., I. M. Janosi. *Meteorol. Atmos. Phys*., 2005, **88**, 119.

[9] Peng, Ch.-K., S.V. Buldyrev, S. Havlin, M. Simons, H.E. Stanley, A.L. Goldberger. *Phys. Rev. E*, 1994, **49**, 1685.

[10] Hu, K., P. Ch. Ivanov, Zh. Chen, P. Carpena, H. E. Stanley. *Phys. Rev. E*, 2001, **64**, 011114.

[11] Makse, H. A., S. Havlin, M. Schwartz, H. E. Stanley. *Phys. Rev. E*, 1996, **53**, 5445.