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Nonlinear Analysis of Climatic Time Series with Cross Recurrence Plots

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Abstract

A novel method to study nonlinear interrelations between time series introduced by Marwan and Kurths (2002) has been applied to climatic data. By using this tool we have analyzed long-term instrumental records of air surface temperature in Central England, Stockholm and St.Petersburg to find their complex relationships. We have also considered north and south average temperature data to study synchronization and difference between climatic changes in Northern and Southern Hemispheres. It is shown that temperature series exhibit near simultaneous phase transitions revealing their global origin. Interesting is that recurrent plots of sunspot numbers display transitions at the same time indirectly indicating evidence of solar activity impact on climate.

1 Introduction

Recurrence plot (RP) analysis is a graphical, statistical and analytical tool to study nonlinear dynamical systems. It was first introduced by Eckmann et al. (1987) as a technique for representation of multidimensional systems in two-dimensional plots [1]. Based on fundamental property of dissipative dynamical systems — *recurrence*, RP analysis can be applied to natural processes characterized often by short and nonstationary data.
In order to visualize time dependent behaviour of orbits x_i in phase space, it is necessary to calculate the $N \times N$ — matrix filled with 'one' and 'zero' values. These values can be marked by black and white dots, where black dots denote a recurrence, and white dots its absence:

$$\mathbf{R}_{i,j} = \Theta(\varepsilon - \|\overrightarrow{x_i} - \overrightarrow{x_j}\|), \qquad i,j = 1,\ldots,N, \tag{1}$$

where ε is a predefined cutoff distance, $\|\cdot\|$ is norm (e.g. the Euclidian norm) and $\Theta(x)$ is the Heaviside function. Depending on requirement, ε can be a fixed value or it can be changed for each i.
The structure of RP is characterized by *topology* and *texture*. The *topology* determines global characteristics of the patterns. The *texture* displays small scale features of the dots distributions. Single isolated points correspond to infrequent states or if they fluctuate; diagonal lines occur when evolution of states is similar at different times; vertical and horizontal lines marks the time length when state does not change or change very slowly (laminar states).

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Extension of RP to visualize coupling between two dynamical systems is called *cross recurrence plot* [2, 3]. CRP simultaneously display two time series at the same phase space. Thus we have two trajectories x_i $(i = 1,\ldots,N)$ and y_i $(j = 1,\ldots,M)$, and a $N \times M$ array in a result:

$$\mathbf{CR}_{i,j} = \Theta(\varepsilon - \|\overrightarrow{x_i} - \overrightarrow{y_j}\|). \tag{2}$$

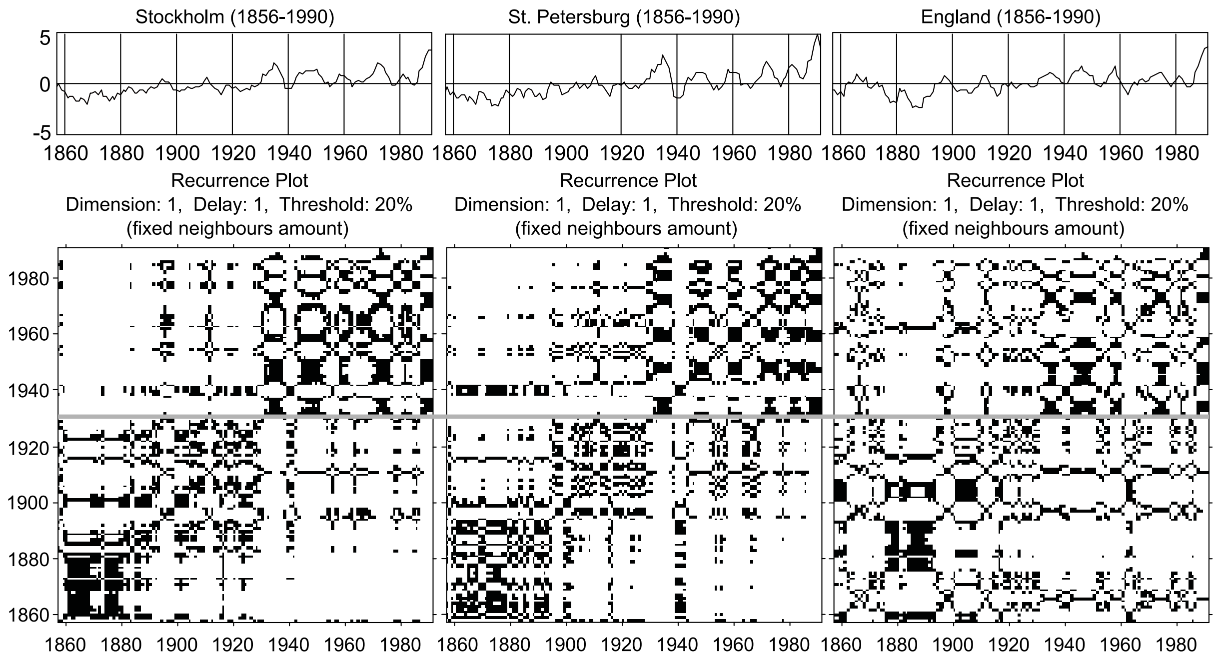

Figure 1: RP of average annual data for Central England, Stockholm and St.Petersburg. Dimension: 1, delay: 1, threshold: 20 percent, fixed amount of nearest neighbors. Time when patterns were changed is marked by horizontal line.

Visualization of CRP help to reveal hidden non-linear interrelations between time-series. Deviations of the line from the *main diagonal* in the plot are of special interest. The RP *main diagonal* denotes the line when $\mathbf{R}_{i,i} = 1$ $(i = 1,\ldots,N)$ and thus is called *line of identity.* While analyzing two different time series the *line of identity* is replaced by *line of synchronization* (if exists). Coupling between two systems often means some changing delay between time series and results in wandering of *line of synchronization*.

2 Analysis of experimental data and discussion

In this paper we have analyzed synchronization and difference of regional and global climate changes described by air surface temperature data. For this purpose we used CRP toolbox available through http://www.agnld.uni-potsdam.de/~marwan/toolbox/.
For our analysis the long-term instrumental records of air surface temperature recorded in Central England, Stockholm and St.Petersburg from 1805 to 1990 were taken into account. Linear correlations between time series correspond to: 0.83 (Stockholm–St.Petersburg), 0.64 (Central England–Stockholm), 0.47 (Central England–St.Petersburg).

Temperature series reveal weak linear correlations between them. However, when analyzing RP plots (Figure 1) one can observe similar topological patterns and near simultaneous changes of the texture. Similar changes are presented in the global temperature data (Figure 2). These transitions indicate different behavior of the global climate before and after 1940's.

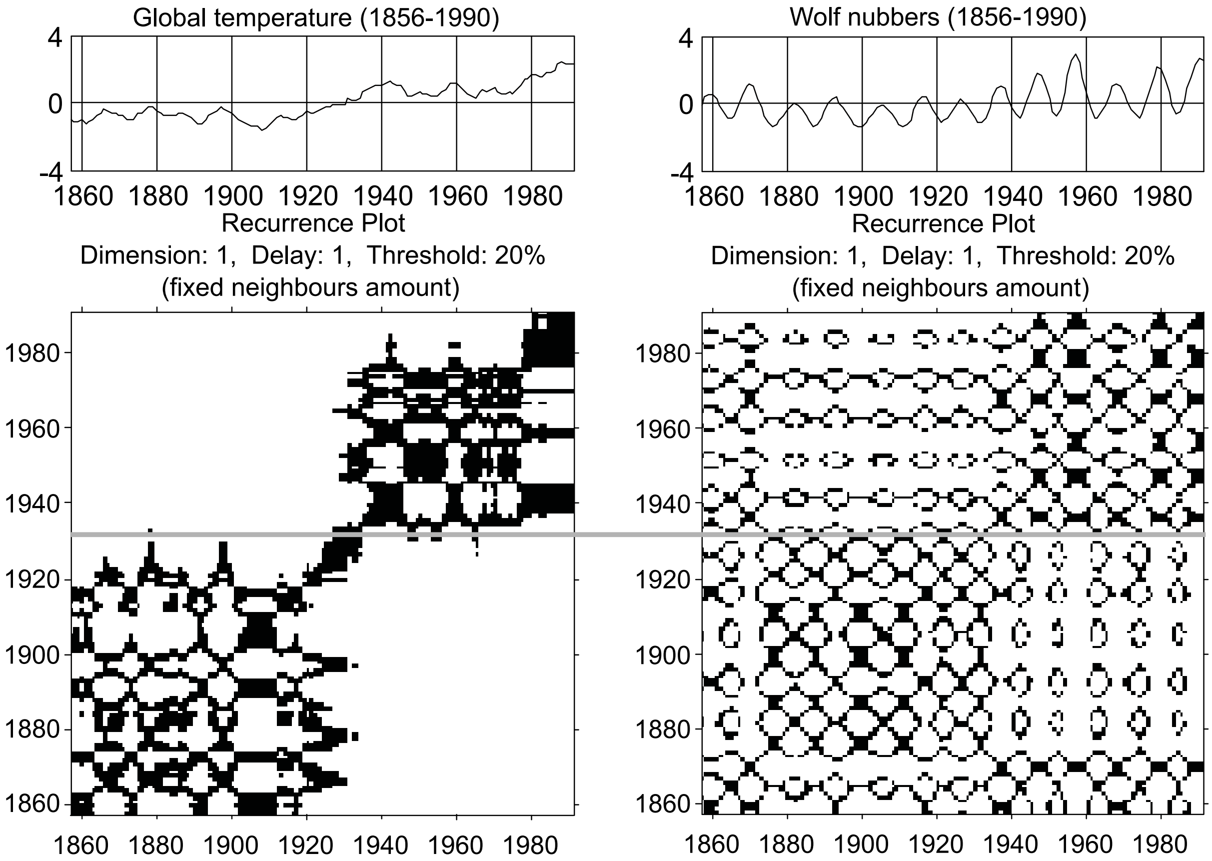

Figure 2: RP plots of the global temperature and sunspots (Wolf numbers). Dimension: 1, delay: 1, threshold: 20 percent, fixed amount of nearest neighbors. Time when patterns were changed is marked by horizontal line.

Interesting is that recurrent plots of sunspot numbers display transitions at the same time (Figure 2). Recent reconstruction of solar activity from Be^{10} concentration in polar ice shows that solar activity was unprecedented high during the last 60 years compared with the past 1000 years [4]. The last 60 years show also unprecedented warming at global scales [5]. This synchronization may indirectly indicate evidence of solar activity impact on climate.

Climatic systems of the Northern and Southern Hemispheres are highly interconnected and can be synchronized by the solar signal that is evident from inspection of CRP plots (Figure 3). The Sun plays a role of external signal coupling hemispheric climates on centennial scale.

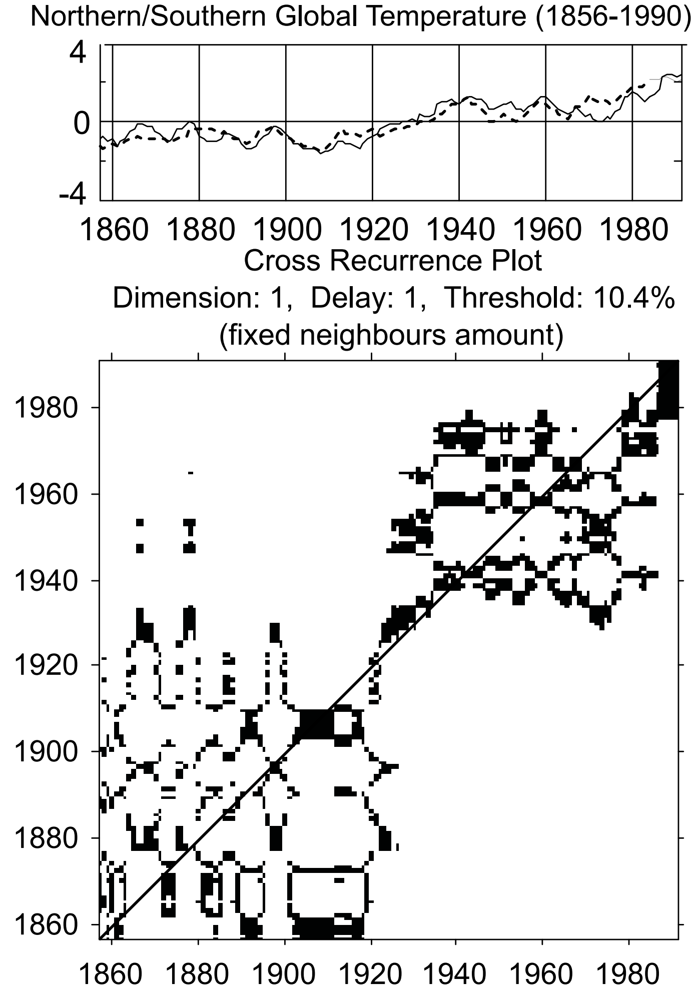

Figure 3: CRP plots of temperature data of the Northern and Southern Hemispheres. Dimension: 1, delay: 1, threshold: 20 percent, fixed amount of nearest neighbors. Dashed line corresponds to the Southern Hemisphere.

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