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TIME SERIES ANALYSIS OF THE GLOBAL WARMING DYNAMICS

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Abstract. *Global warming is the observed increase in the average temperature of the Earths' atmosphere and oceans. The primary cause of this phenomenon is the greenhouse gases released by burning of fossil fuels, land cleaning, agriculture, among others, leading to the increase of the so-called greenhouse effect. An approach to deal with this important problem is the time series analysis. Different techniques can be applied in order to evaluate the global warming dynamics that could allows one to make better predictions increasing our comprehension of the phenomenon. Nonlinear tools are employed with this aim establishing state space reconstruction and time series prediction. Specifically, this article presents a time series analysis of temperature measurements using the simple nonlinear prediction in order to estimate future values. Results show the possibilty to apply these techniques in order to estimate the temperature evolution.*

Keywords*: Ecology, global warming, nonlinear dynamics, chaos, time series, state space reconstruction.*

1. INTRODUCTION

Global warming is a specific case of the more general term climate change that is induced either by natural processes or by human activities. Nowadays, this term is being used associated with the human induced changes. In brief, global warming is the observed increase in the average temperature of the Earths' atmosphere and oceans. The primary cause of this phenomenon is the greenhouse gases released by burning of fossil fuels and large-scale deforestation, leading to the increase of the so-called greenhouse effect that arises as a consequence of the presence of greenhouse gases in the atmosphere. Among others, the greenhouse gases are the carbon dioxide, the methane and the nitrous oxide.

From industrial revolution on, the amount of greenhouse gases in the atmosphere has significantly increased. Based on Intergovernmental Panel on Climate Change (IPCC, 2007) data, the carbon dioxide has increased by more than 30% and is still increasing at a rate of 0.4% per year mainly due to the burning of fossil fuels and deforestation. Others greenhouse gases are also increasing and there are evidences pointing to the anthropogenic cause of this phenomenon.

During the 20th century, the Earth's surface mean temperature has increased approximately 0.4 to 0.8°C. Most of this increase has occurred in two periods: from 1910 to 1945 (0.14°C/decade) and since 1976 (0.17°C/decade). The consequences of global warming is unpredictable, however, one could mention climate sensitivity and other changes related to the frequency and intensity of extreme weather events.

This contribution deals with the time series analysis related to the global warming dynamics. Temperature time series analysis is used as a representative variable of the system dynamics. The method of delay coordinates is employed for the state space reconstruction and the delay parameters are evaluated using the method of average mutual information and the method of false nearest neighbors. The simple nonlinear prediction is employed to model the time series evaluating the prediction of future values. This approach is verified considering known parts of the time series and afterwards, results are extrapolated for future values. Nonlinear time series analysis employs the TISEAN package (Hegger *et al.*, 1999).

2. GLOBAL WARMING PHENOMENON

Climate system has an inherent complexity due to different kinds of phenomena involved. The equilibrium of this system is a consequence of different aspects related to atmosphere, oceans, biosphere and many others, and the sun activity provides the driving force of this system. Figure 1 presents a schematic picture of the Earth climate system, showing some interactions of different aspects (IPCC, 1997).

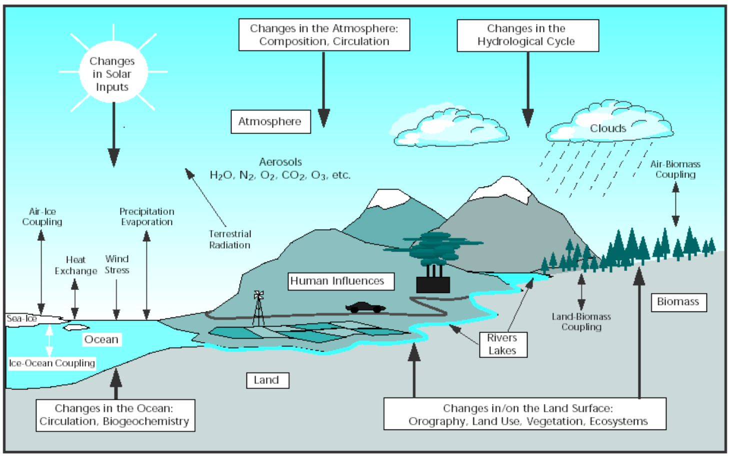

Figure 1. Schematic picture of climate system (IPCC, 1997).

The Earth's heating mechanism may be understood as the balance of the energy radiation from the sun and the thermal radiation from the Earth and the atmosphere that is radiated out to space. The presence of greenhouse gases tends to break this balance since they are transparent to the sun short wave radiation, however, they absorb some of the longer infrared radiation emitted from the Earth. Therefore, the increase amounts of these gases makes the Earth cool more difficult increasing the Earth's surface temperature.

In general, it is possible to say that the global warming is a spatiotemporal phenomenon, however, the analysis of temporal aspects of this system can provide important information for the comprehension of this complex phenomenon. In this regard, time series analysis is of special interest. All over the world, there are numerous measurements concerning temperature time series. The National Oceanic and Atmospheric Administration (NOAA, 2006) has 9,000 weather stations with measurements from 1929. Actually, data from 1973 are more complete and include a great number of stations.

In order to give an idea concerning this kind of phenomenon, four different time series are presented: Cold Lake (Canada), from 1976 to 2008; Beijing (China), from 1973 to 2008; Los Angeles (USA), from 1976 to 2008; and Rio de Janeiro (Brazil), from 1976 to 2007. Figure 2 presents the localization of the weather stations while Figure 3 shows the time series.

Figure 2. Weather stations.

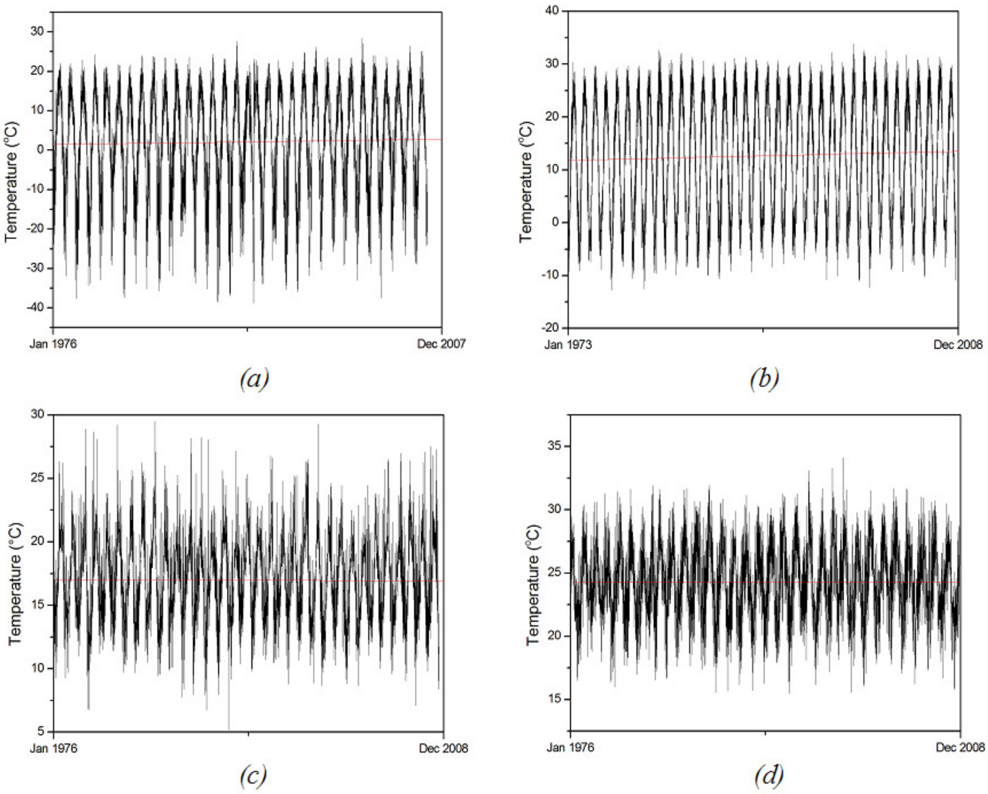

Figure 3. Temperature time series.
(a) Cold Lake (Canada); (b) Beijing (China); (c) Los Angeles (USA); (d) Rio de Janeiro (Brazil).

The analysis of these series shows different patterns. By establishing a linear match, it is possible to observe an increase in temperature in Cold Lake (+1.64°C), Beijing (+1.93°C) and Rio de Janeiro (+0.08°C), however, there is a decrease of temperature in Los Angeles (−0.15°C). This work develops a time series analysis of the Beijing (China) temperature that has 13,123 data points corresponding to 36 years. The idea is that this analysis is representative from the global dynamical behavior.

3. TIME SERIES ANALYSIS

The basic idea of the state space reconstruction is that a signal contains information about unobserved state variables that can be used to predict the present state (Savi, 2006). Therefore, a scalar time series, S_n, may be used to construct a vector time series that is equivalent to the original dynamics from a topological point of view. The state space reconstruction needs to form a coordinate system to capture the structure of orbits in state space, which could be done using lagged variables, $S_{n+\tau}$, where τ is the time delay. Then, it is possible to use a collection of time delays to create a vector in a D_e-dimensional space,

$$U(t) = \{S_n, S_{n+\tau}, ..., S_{n+(D_e-1)\tau}\}^T \tag{1}$$

The mutual information method (Fraser & Swinney, 1986) is a good alternative to evaluate the time delay, τ. The determination of embedding dimension, D_e, on the other hand, may be evaluated from the method of the false nearest neighbors (Kennel *et al.*, 1992). This reconstructed space can be used for the forecast and the simple nonlinear prediction is a good alternative for this aim. Figure 4 presents the sequence of the time series analysis developed in this work. The forthcoming sections present a brief discussion of each of the employed methods.

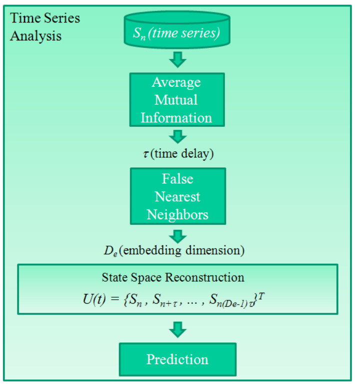

Figure 4. Schematic of time series analysis.

3.1 - Method of Average Mutual Information

Fraser & Swinney (1986) establishes that the time delay τ corresponds to the first local minimum of the average mutual information function $I(\tau)$, which is defined as follows,

$$I(\tau) = \sum_{n=1}^{N-\tau} \Gamma(S_n, S_{n+\tau}) \log_2 \left[\frac{\Gamma(S_n, S_{n+\tau})}{\Gamma(S_n)\, \Gamma(S_{n+\tau})} \right] \tag{2}$$

where $\Gamma(S_n)$ is the probability of the measure S_n, $\Gamma(S_{n+\tau})$ is the probability of the measure $S_{n+\tau}$, and $\Gamma(S_n, S_{n+\tau})$ is the joint probability of the measure of S_n and $S_{n+\tau}$. When the measures S_n and $S_{n+\tau}$ are completely independent, $I(\tau) = 0$. On the other hand, when S_n and $S_{n+\tau}$ are equal, $I(\tau)$ is maximum. Therefore, the analysis of the $I(\tau)$ curve allows one to determine the best time delay to be used in the state space reconstruction.

3.2 - Method of the False Nearest Neighbors

The method of the false nearest neighbors was originally developed for determining the number of time delay coordinates needed to recreate autonomous dynamics, but it is extended to examine the problem of determining the proper embedding dimension. In an embedding dimension that is too small to unfold the attractor, not all points that lie close to one another will be neighbors because of the dynamics. Some will actually be far from each other and simply appear as neighbors because the geometric structure of the attractor has been projected down onto a smaller space (Kennel *et al.*, 1992).

In order to use the method of the false nearest neighbors, a D-dimensional space is considered where the point U_n has r-th nearest neighbors, U_n^r. The square of the Euclidean distance between these points is,

$$r_D^2(n,r) = \sum_{k=0}^{D-1} \left[S_{n+k\tau} - S_{n+k\tau}^r \right]^2 \tag{3}$$

Now, going from dimension D to D+1 by time delay, there is a new coordinate system and, as a consequence, a new distance between U_n and U_n^r. When these distances change from one dimension to another, these are false neighbors. A proper space dimension may be obtained when there are no false neighbors after a dimension increase.

3.3 – Prediction

Prediction is a particular application related to system modeling that has the objective of estimate future values from a known time series, called past, $S_n, n = 1,..., N$. Therefore, it is necessary to estimate future time series, employing some prediction technique that results in an estimated series: $P_{N+1}, P_{N+2}, \ldots, P_{N+p}$. Figure 5 shows a schematic plot related to the prediction problem. From a known time series, called past, some predictor model the system dynamics, estimating future values of time series, prediction. These estimated values can be compared with future values associated with the original series in order to establish prediction accuracy (Pinto & Savi, 2003; Savi, 2006).

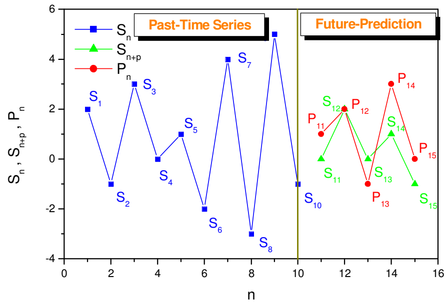

Figure 5. Time series prediction.

In general, techniques for time series prediction may be classified in linear and nonlinear methods. Other classification reported in literature considers local and global methods. An overview of the main aspects related to nonlinear time series analysis and prediction is provided in the following references: Kantz & Schreiber (1997); Abarbanel (1995); Casdagli (1989); Schreiber (1999); Weigend & Gershenfeld (1994); Pinto & Savi (2003).

Simple nonlinear prediction is based on the state space reconstruction. After the reconstruction, in order to predict a time instant Δn (Δn = 1, ..., p) ahead N, it is necessary to define a parameter ε that is related to the size of the neighborhood $V_\varepsilon(U_N)$ around point U_N. Therefore, for all points U_n closer than ε to U_N $(U_n \in V_\varepsilon(U_N))$ look up the individual prediction $S_{n+\Delta n}$. The prediction $P_{N+\Delta n}$ is then calculated from the average of the individual predictions $S_{n+\Delta n}$.

$$P_{N+\Delta n} = \frac{1}{|V_\varepsilon(U_N)|} \sum_{\mathbf{U}_n \in V_\varepsilon(U_N)} S_{n+\Delta n} \tag{4}$$

where $|V_\varepsilon(U_N)|$ denotes the number of elements of the neighborhood $V_\varepsilon(U_N)$. Figure 6 presents a schematic representation of the simple nonlinear prediction applied to a time series with 10 elements and D_e = 2. For a parameter ε, points U_2, U_4, U_5, U_7 and U_8 are inside the neighborhood and hence, the first prediction, P_{11}, is evaluated from the average of these values.

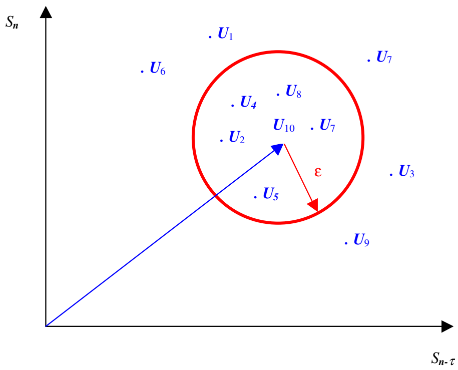

Figure 6. Simple nonlinear prediction.

4. PREDICTION ANALYSIS

Temperature time series measured in Beijing (China) is used for the analysis developed in this work. This series has 13,123 data points corresponding to 36 years. Initially, a verification procedure is carried out considering three different situations defined by distinct parts of the series: 1973 to 1999 (27 years) performing the prediction from 2000 to 2008 (9 years); 1989 to 1998 (10 years) performing the prediction from 1999 to 2008 (10 years); 1989 to 1993 (5 years) performing the prediction from 1994 to 2008 (15 years). These choices are made considering the number of data points and the possibility to consider data without missing points. After this verification, a different analysis is performed by considering a series from 1989 to 2008 in order to predict future values from 2009 to 2028 (20 years). Figure 7 presents an overview of the treated cases.

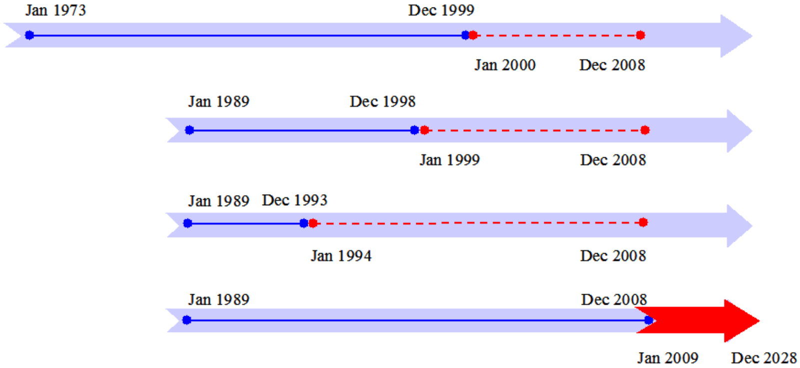

Figure 7. Analyzed time series (blue solid line) and their prediction periods (red dashed line).

Initially, a time series corresponding to 27 years corresponding to 9,836 data points (from 1973 to 1999) is of concern. The analysis starts by evaluating delay parameters. Figure 8 presents average mutual information and false nearest neighbors analyses. From these, it is possible to conclude that time delay is τ = 103 and embedding dimension is D_e = 45. It should be highlighted that this series has missing data that were not treated. Afterwards, simple nonlinear prediction is employed to model the series, predicting future values from 2000 to 2008 (9 years), as shown in Figure 9. Results show a good agreement between the original and the predicted series and it is important to notice that both series has average values that are very close (respectively, 12.99°C and 13.04°C representing a difference of 0.4%).

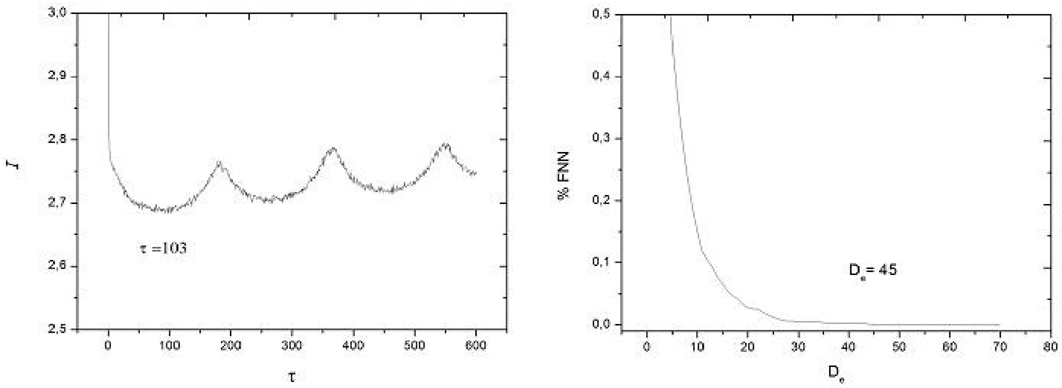

Figure 8. Delay parameters for a 27 year time series (1973 to 1999).

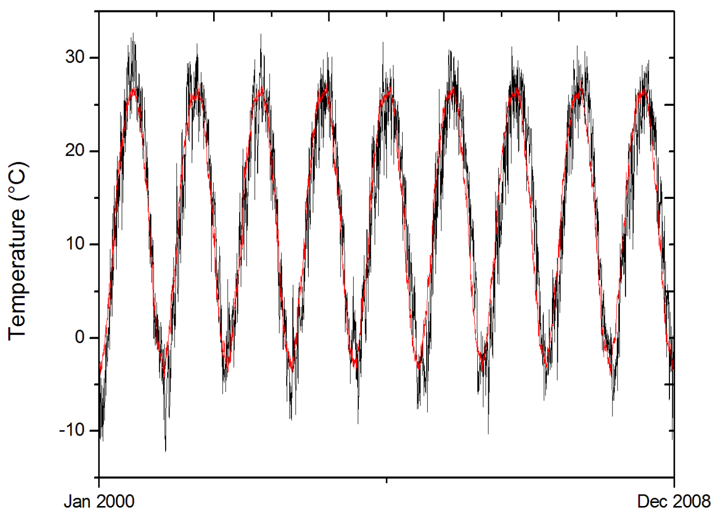

Figure 9. Comparison between time series (black line) and prediction (red line), from 2000 to 2008.

Time series is now representing 10 years being associated with the period from 1989 to 1998, representing 3,652 data points. Delay parameters are analyzed in Figure 10 indicating a time delay $\tau = 71$ and an embedding dimension $D_e = 14$. These results are used in order to perform predictions from 1999 to 2008, representing 10 years. Figure 11 presents the original time series together with the prediction made by the simple nonlinear prediction. Once again, the forecast capture the general behavior of the time series, presenting average values of 13.00°C for the time series and 13.09°C for the prediction, which means a difference of 0.7%.

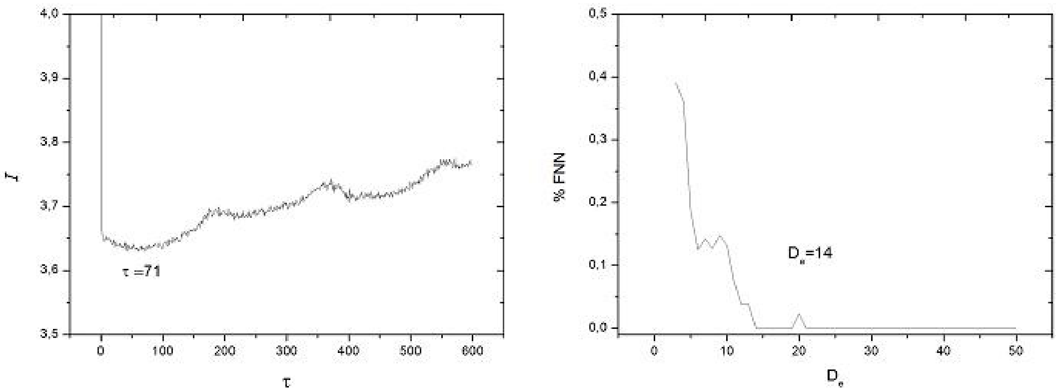

Figure 10. Delay parameters for a 10 year time series (1989 to 1998).

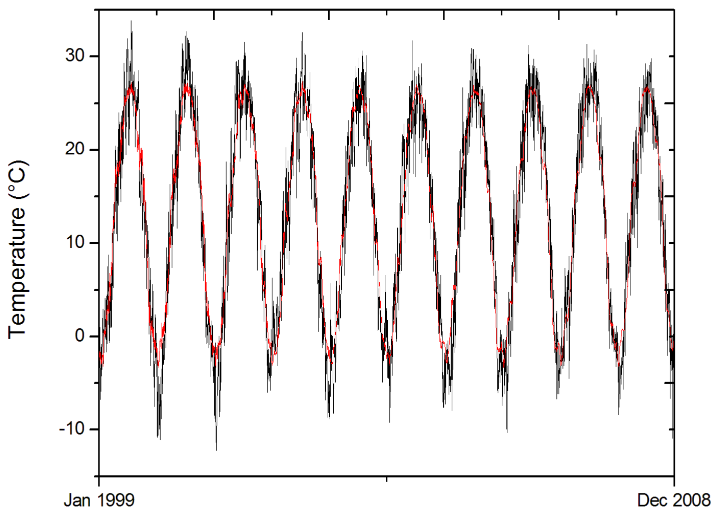

Figure 11. Comparison between time series (black line) and prediction (red line), from 1999 to 2008.

At this point, our analysis is focused on a short time series with 1,826 data points from 1989 to 1993 (5 years). The idea is to perform the prediction from 1994 to 2008 (15 years). Once again, the delay parameters are evaluated from the average mutual information and false nearest neighbors, as presented in Figure 12, indicating that time delay is $\tau = 44$ and embedding dimension is $D_e = 14$. It should be observed that these values are not easily obtained, certainly due to the number of data points. These results are used for state space reconstruction that is employed for nonlinear prediction. Figure 13 presents the time series and the prediction from 1994 to 2008 (15 years). Although a short time series is used to establish the prediction, the general behavior is still captured. As observed in the previous cases, average values are still very close, being 13.03°C for the time series and 13.09°C for the forecast, which represents a difference of 0.5%.

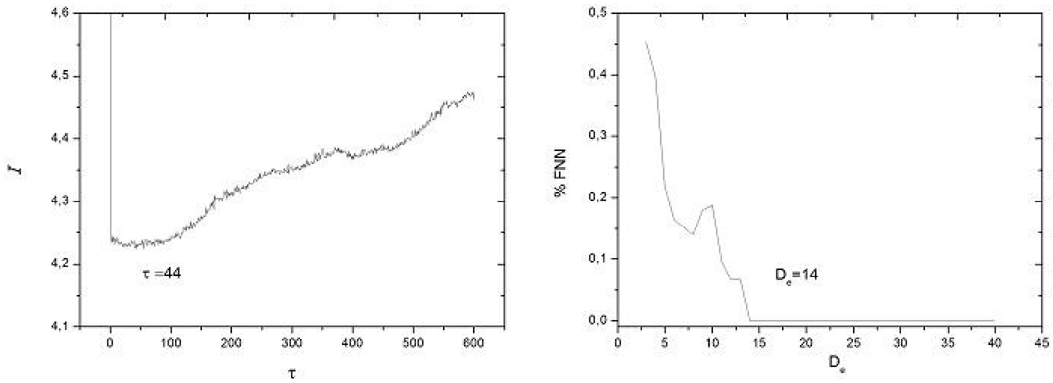

Figure 12. Delay parameters for a 5 year time series (1989 to 1993).

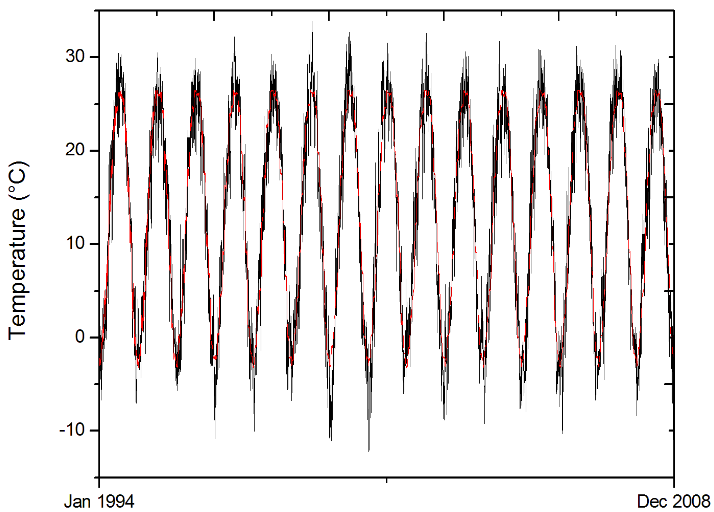

Figure 13. Comparison between time series (black line) and prediction (red line), from 1994 to 2008.

Since the proposed procedures have captured the general behavior of the temperature evolution, we are encouraged to use this approach in order to make predictions for the future. Therefore, we use a 20 year time series, from 1989 to 2008, with 7,303 data points, establishing a prediction of 20 years (from 2009 to 2028). Initially, delay parameters are evaluated as presented in Figure 14, pointing to a time delay $\tau = 92$ and an embedding dimension $D_e = 61$. Afterwards, simple nonlinear prediction is employed and the forecast is shown in Figure 15. By establishing a linear match, it is possible to observe an increase of 0.37°C over these 20 years.

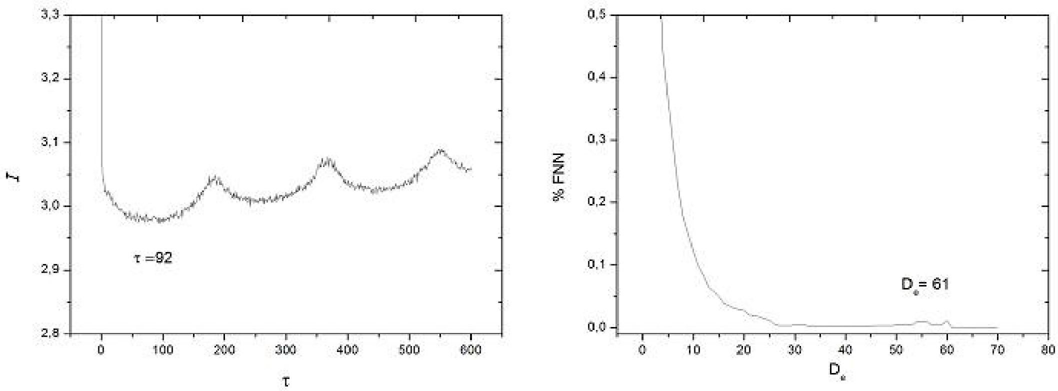

Figure 14. Delay parameters for a 20 year time series (1989 to 2008).

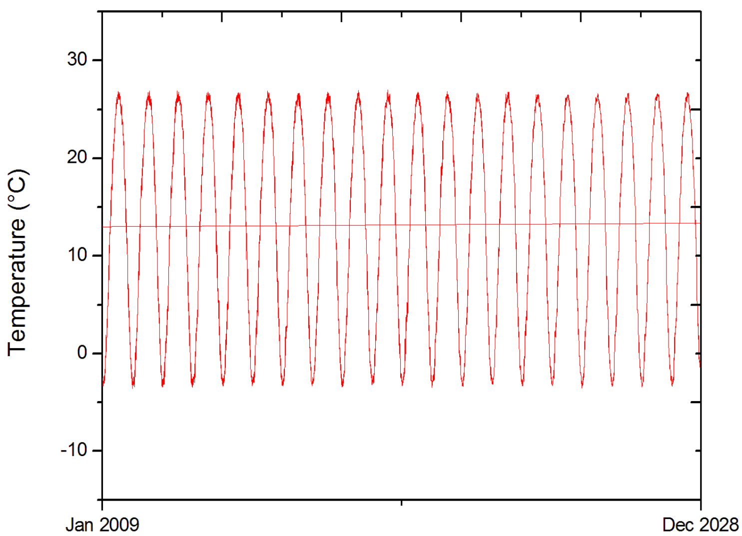

Figure 15. Prediction from 2009 to 2028.

5. CONCLUSIONS

This paper deals with the nonlinear time series analysis related to global warming dynamics. Temperature time series from Beijing (China) is employed in order establish a model for prediction. State space reconstruction is done using the method of delay coordinates and delay parameters, time delay and embedding dimension, are respectively calculated by the method of average mutual information and the method of false nearest neighbors. Prediction is performed using the simple nonlinear prediction technique. Different number of data points is employed for model verification. Results show that the method captures the general behavior of the time series. Average value of the forecast is close to the real time series with differences that are less than 0.7%. After this verification, the procedure is employed to establish prediction of future values. In this regard, 20 years forecast is performed evaluating the temperature until 2028. These results present an increase of 0.37°C. The authors agree that the nonlinear tools employed in this work can be useful for the analysis of global warming.

6. ACKNOWLEDGEMENTS

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